A FRAMEWORK FOR THE DESIGN OF SYSTEMS WITH INTELLIGENT AND INTERACTIVE INFORMATION FLOW

A Thesis
Presented to
The Academic Faculty

by

Mukul Singhee

In Partial Fulfillment
of the Requirements for the Degree of
Master of Science in the
School of Mechanical Engineering

Georgia Institute of Technology
August 2010

A FRAMEWORK FOR THE DESIGN OF SYSTEMS WITH INTELLIGENT AND INTERACTIVE INFORMATION FLOW

Approved by:

Dr. Janet K. Allen, Advisor
The School of Industrial Engineering
The University of Oklahoma,
Norman, Oklahoma, USA

Dr. Farrokh Mistree,
The School of Aerospace and
Mechanical Engineering
The University of Oklahoma,
Norman, Oklahoma, USA

Dr. Magnus Egerstedt,
School of Electrical and Computer
Engineering,
Georgia Institute of Technology

Date Approved: May 17, 2010

ACKNOWLEDGEMENTS

Firstly, I would like to thank my parents, my brother and sister, for continued support, affection and in a few cases even ideas on my research. When things got tough and unmanageable, help and motivation was but a phone call away for me due to my family.

I would like to thank my advisor Dr. Janet K. Allen who has not only provided support for my stay and studies, but has been the driving force behind the vision and problem formulation for this work. She has provided me invaluable counsel both professionally and on a personal level and has maintained confidence in me at times even when I had little.

I would like to thank Jonathan F. Holmes, who played a key role in the definition of my example problem, and has worked with me evenings as well as weekends to make our system a possibility. Every meeting we have had has been a huge learning experience for me.

I would like to thank Dr. Farrokh Mistree and Dr. Dirk Schaefer for providing the foundation for the tasks carried out in this thesis, through ME6101, as well as through innumerable suggestions and advice, both professional and personal.

I would like to thank the professors of Systems Realization Laboratory, for a number of evaluations of my work, ideas, and in many cases for condoning my inane laboratory habits.

I would like to acknowledge the Georgia Tech Research Institute for providing the facility, equipment and technical help to both Jonathan and I for implementing our system.

I would like to thank my lab mates Patrick Chang, Aditya Shah, Jiten Patel, Ayan Sinha and all the others. Some of them were partners for my course projects and have taught me volumes in terms of work ethic, engineering skills and maintaining my focus and sanity during interminable periods (sometimes stretching into days) in the lab.

On a special note, I would like to acknowledge the GT-IITKgp alliance, without which I may not have received the opportunity to study at Georgia Tech. To all members including Dr. Madhusudan Chakraborty, Dr. Farrokh Mistree, Dr. David McDowell, Dr. Janet K. Allen, Dr. Sudipto Ghosh, Dr. C.S. Kumar, and all the other students who came along with me in the internship program, I am indebted for helping me take a big step in my career and future.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Frame of Reference

1.1 Desired framework

1.1.1 Vision

Potentially transformational ideas in several applications of human and computer interaction form the motivation for this work. It is targeted towards a systematic approach to the design of systems with complex, intelligent and interactive exchange of information between a system and the environment it is meant to monitor, and gather knowledge about. Imagine a world for instance, where a robot trains you to exercise, or a kitchen keeps itself restocked, prepares meals and cleans up by itself. Once the realm of science fiction, systems like these are becoming increasingly possible. In this work, the challenge of designing such complex, interactive systems is seen as an opportunity to implement systematic design procedures towards bridging the gap between resources amassed through multi-disciplinary technologies, and intelligent applications in sensing [1].

The range of applications of sensor networks in such intelligent systems is limitless. They offer a way of automating the process of converting the information available in its environment into knowledge which can help humans make decisions in all kinds of disciplines.

A literature survey of pertinent applications yields some of the challenges and gaps towards systematic design and implementation of such systems. For example, Kullgren and Krafft [2] have combined objective measurement of impact severity through crash recorder data and a statistical paired comparison technique to derive injury risk functions in a crash test scenario for better design for safety of automobiles [2]. The work holds merit in terms of modeling of injury risk scenarios with empirical injury risk functions. However, it warrants the design of a system which allows us to measure crash related data objectively and develops individualized injury risk functions to create knowledge about crash scenarios to aid in custom design for safety. Davidsson et. al. explore the use of sophisticated crash test dummies for simulating effects of the rear impact on the spine and neck in [3]. Subsequent research in a number of papers have even yielded a comprehensive evaluation and validation of the BioRID dummy for neck injuries in [4]. However, developing crash test dummies is a long drawn and expensive process requiring the use of cadavers and sometime live human volunteers. Given that we have the pool of data from prior crash tests, imagine a scenario where the use of dummies can now be precluded and objective measurement of minor crash tests on live volunteers can be extended to drastic crash scenarios. The design of such systems requires a better understanding of what information we need to gather in such tests, and exactly how to derive the required extrapolated knowledge from these test scenarios.

Another application which has excited a lot of interest is Ambient Intelligence (AmI) [5-7]. Particularly in the case of healthcare, AmI systems provide the potential for comprehensive monitoring of patients and health-risk prone individuals and automated alerting in the case of any health emergencies. Due to the rising age of the average

American citizen, there are increasingly more and more strains on the health care system [5]. Consequently, health care costs are rising and hospitals are becoming more crowded. Nursing homes and elderly care centers are also becoming crowded and expensive. In many ways, nursing homes are becoming a luxury that most people cannot afford. As a result, more elderly people are staying home and only going to hospitals to seek care under the most critical conditions. The primary concern now is to deal with situations when they have a heart-attack, stroke, seizure, etc. without any supervision around them. According to the "National Awareness Program Urges Americans to 'Act in Time to Heart Attack Signs'" (2006), only "two in five U.S. adults would seek medical attention if they experience common heart attack symptoms." Thus, chances of a seemingly harmless situation turning into a fatal one are high. Alternatively, there are many times where serious health conditions leave the victim in a state in which they cannot call for help themselves, and if alone in the homes, could not get the medical help they need. There is clearly a demand for an individualized and effective product in the home that can monitor for these situation and alert emergency services if a problem arises.

Clearly, attempts are being made to design systems with human interactions with different kinds of environments. The demand for increasingly complex sensing systems is felt in ergonomic motion capture [8-11], crash effects in transport systems [2], intelligent homes [5-7] and a number of other applications. A report submitted in May 2009 by a consortium of universities across the United States labeled "A Roadmap for US Robotics" identifies opportunity for research, development and creation of value for the common man through advanced technology, products and new jobs in the domain of manufacturing, logistics, medical care, healthcare, services and several other aspects [1].

The design of complex systems with multiple sensing capabilities, custom functionality and individualized monitoring is identified as a high priority requirement.

At this the meaning of information is provided for the purpose of this thesis. As per Wikipedia, in its most restricted technical meaning, information is an ordered sequence of symbols[1]. In the dictionary[2], it is defined as knowledge communicated or received concerning a particular fact or circumstance or knowledge gained through study, communication, research, instruction, etc. or factual data. In this thesis, information will be referred to as a more specific concept or a subset of these definitions, with some inherent assumptions about its nature and origin.

Information in this thesis is any data, factual or implicit, that is gathered from the environment, and can be communicated and integrated within a system to be converted to knowledge about the environment.

To support this definition a contextual definition of "environment" and a "system" must be provided. Wikipedia[3] defines "environment" as the surrounding of a physical system that may interact with the system by exchanging mass, energy or other properties. In the context of the domain of human – computer interaction applications that we are considering in this work, this definition can be extended and adapted to the following:

---

[1] http://en.wikipedia.org/wiki/Information
[2] www.dictionary.com
[3] http://en.wikipedia.org/wiki/Environment_(systems)

An environment is all that is of interest to the designer including the surroundings of a physical system that interacts with the system by exchanging information and other entities like mass and energy.

A system[4] derived from Greek, *is defined as a set of interacting or interdependent entities forming an integrated whole*. This definition in fact applies very well to this thesis, as it does not assume that the entities must be tangible or have shape and geometry, unlike a physical system.

A boundary[5] is defined in thermodynamics as the edge of a thermodynamic system across which heat, mass, or work can flow. To maintain the context of information flow, a boundary can be defined as:

A boundary is the edge of the system across which information flows from the environment to the system. This may coincide with a physical boundary between entities or not.

The design of such systems with intelligent and interactive information flow and exchange with the environment offer a unique challenge since prior work on the design

[4] http://en.wikipedia.org/wiki/System
[5] http://en.wikipedia.org/wiki/Boundary

methodology for such systems, though extremely valuable and pertinent to their application in specific domains, do not propose abstractions of their methods and solutions which may be used in other applications or shed some light on the design approach to their problem. In the context of information flow and its subsequent integration and conversion to knowledge about the environment, design approaches need to make use of tools, representation schemes and ontological concepts that can ensure the fulfillment of requirements of intelligent and interactive systems. Existing research in the domain of applications that are being considering, do not explicitly define or use such ontologies or tools, which often lead to certain requirements remaining unfulfilled.

An example of such a domain of application is in the design of systems for ergonomic monitoring using complex motion capture and analysis systems. In [12], Keir and co-authors provide a culmination of several of their publications in proposing aids to designers in designing ergonomically suitable tools and practices for hand intensive activities. They use statistical tools such as curve fitting, and confidence intervals to post-process the information collected from their experiments on carpal tunnel pressure and wrist angles and convert it into knowledge on wrist angle ranges that are preferable for the population in general to reduce the risk of carpal tunnel syndrome. However, there is a noted lack in their discussions in terms of their methods of arriving at this knowledge. Through their work from 2003 – 2007 [8, 12-13], they have focused on different aspects of ergonomic safety for the human arm in particular but the methods of integrating the information collected are invariably through statistical curve fitting techniques. Certain system level requirements associated with a more intelligent and individualized product or system are compromised in the process. For instance, their work makes use of post processing of collected information to create knowledge. Ideally, we would like this to happen in real time with the data collection process. The assumptions that they make during post processing and in their integration methods are applied to a population as a whole, and in some cases also relies on experiments carried out on animals [12]. In order to implement their suggestions in practice, we have no choice but to accept these assumptions which do not cater to individualized information collection and integration. At this juncture, it can be said that the design of such complex systems with requirements pertaining to intelligence in the information flow and integration require the "programming" of the knowledge that the designer possess about the overall system and its requirements into the system itself. This programming would involve the integration of ontologies into the design approach that the designer adopts. The design method must draw varying levels of genericity and abstractness from ontologies, and facilitate its objects, tools and methods into the system's function.

Several researchers in the field of computer science and human-computer interaction have established the role and usage of ontologies in complex industrial applications. Borst and Akermans demonstrate the practical use of ontologies in large-scale applications for the domain of engineering systems modeling, simulation and design [14]. Within the context of intelligent information systems, they propose and support the use of ontologies to provide support by shifting the burden of generating adequate interpretations of information from the end users to the system. In developing the proposed PhysSys ontology in their work, the authors classify different types of ontologies, their role in formalizing generic concepts fundamental to physical systems and describe the ontology projections which relate these ontologies to each other. The concepts developed in their paper are a rich source for adapting to the specific context of designing systems with the information flow as the focus.

A number of constructs can be used as ontological concepts for the design of these systems. The Pahl and Beitz design method (P&B) uses the function structure in its conceptual design phase to represent the overall function of a product or system [15]. It contains several sub-functions connected with the flow of signals, matter and energy. The Pahl and Beitz design method attributes the function of any system with the conversion of these three entities as they flow through the system. Fundamental to systems which interact with the environment continuously is the flow of information, since it is often signals that travel from the environment into the system for making decisions and initiating action.

The use of OWL Web Ontology Language is designed for use by applications that need to process the content of internet based information instead of just presenting it to humans [16]. Though this ontology is meant for enhancing the function and interoperability of web based content, and is meant for a domain of application unrelated to this work, the language has been extended for use, especially in semantics in various application domains. Patil and co authors have developed a Product Semantic Representation Language based on OWL constructs in [17]. Of particular importance to this thesis are the requirements for representation of product semantics identified by them. These include application independence, expressiveness and unambiguity; all of which can be projected into corresponding requirements for the design method I wish to develop.

Living Systems Theory (LST) is another source of ontological objects for functional and flow modeling of information in systems that is explored in this work. LST provides taxonomy for generic sub-systems and the flow of information, matter and energy through them to “present a unified theory that deals with the hierarchical structure of life at many levels” [18]. LST, “a conceptual framework developed to integrate the findings of system theorists and scientists in biology, physiology, neurology, the social science, economics and management offers a useful paradigm for designing concrete, nonliving systems, i.e. engineering (or physical) systems”. In particular, Miller’s critical subsystems [19] have been used to represent generic subsystems for use by engineers in partitioning and planning [18]. One of the major categories of subsystems is subsystems which process information. In this work, these subsystems will be crucial to the development of design methodology and representation of systems with interactive and intelligent information flow, to ensure smooth information flow with minimal loss.

Based on the above discussions a need has been identified for systematic approaches to the design and representation of systems which are complex, involve several interacting entities consisting of humans, sensors, computers and communication networks. The vision can thus be defined as facilitating a framework for designers within which they can design fully individualized, intelligent systems with interactive information flow and integration of information into knowledge for custom applications. The overall motivating gap is thus defined by the lack of an abstraction of the functional requirements of systems with intelligent and interactive information flow specific to the information flow in such systems, and a systematic approach towards converting these requirements into a design relying on multi-disciplinary and innovative solutions to harbor better collaboration, lower costs and better business and engineering practice.

As shown in Figure 1 there is a gap between a large resource of multidisciplinary technologies and the applications we wish to design with the need for a systematic design method, which allows us to design products as systems which must satisfy certain requirements. Specifically, in the case of products which are intelligent systems with the prime function of monitoring and collecting information from the environment to integrate it into knowledge, the systematic design approach needs to focus on the information flow.

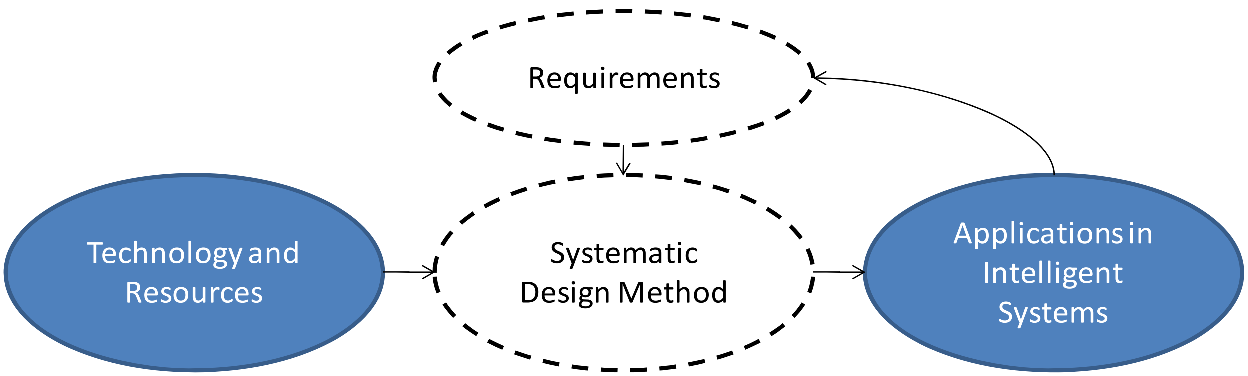


Figure 1: Gap analysis for this work

These requirements need to be defined based on the need and wishes of the end user of the application we want to design. Since the focus is on systems with intelligent and interactive information flow, the first step is to be able to represent such systems in the early stages of design. Systems such as these are unique because they are highly complex, and must respond to multiple input and the actions required of the system based on this input may be equally complex and there is no clear-cut division between the system and its environment. As such representation of these systems, and subsequent representation of the environment and boundary is a challenge that needs to be dealt with. The three specific requirements that such representations need to fulfill are:

- Boundaries need to be represented for scenarios where they cannot be defined in the physical domain
- Extract embodiment determining requirements from the information flow representation
- Base design activities and actions on the representations which are based on the design of information flow

It is expected that existing ontological tools and objects such as the taxonomy of generic sub-systems proposed by Living Systems Theory (LST) [19] can be used to adapt constructs of the Pahl and Beitz design method to fulfill these requirements.

Also, the focus on collecting information from the environment entails consideration of the customizability of the system's function and design to support performance in varying environments. This requirement entails the development of a customizable framework, with approaches which can be adopted by subsequent designers and engineers in order to adapt the design method better to the environments they would be dealing with. Validation will be carried not just for the proposed design method, but the approach taken towards building the framework around the method as well. Thereby, a construct is required which evaluates not just the design method but the logic behind the modifications and adaptations suggested for the method. The Validation Square will be used for this purpose in this thesis.

1.1.2 Mission of thesis

My goal in this thesis is to propose a framework for designing systems with intelligent and interactive information flow and validate aspects of the framework, including an approach to adapting an existing design method as well as the use of ontological and modeling tools for representation and design of systems with intelligent and interactive information flow. This framework should be characterized with requirements which the design method must follow, and a library of design solutions and categories that can be used as tools and representation schemes. Subsequently, the requirements must be used to modify an existing design method, to propose a systematic design method for designing systems with intelligent and interactive information flow. The purpose of abstracting requirements that the design method must satisfy is to adapt existing design methods in the context of designing individualized systems with intelligent information flow and integration. The library of design tools should include semantics, objects and tools drawn from information ontologies which can be used to represent and describe systems with intelligent and interactive information flow and their function in that context. It will include additional design tools that can be used for certain design activities, as well as in some cases, as working principles to satisfy sub-functions in the system. The two deliverables of this goal are not mutually exclusive, and it is expected that certain requirements for the design method may directly refer to a particular design tool that is useful. Drawing from existing ontologies will also aid us in coming up with requirements for the design method. For instance, Patil and co authors identify requirements in their work on ontology formalization of product semantics that the developed ontology must satisfy to properly represent product semantics in product lifecycle management [17]. With the context of aiding designers using ontological frameworks and objects, these requirements for the ontologies translate directly to requirements for a design method.

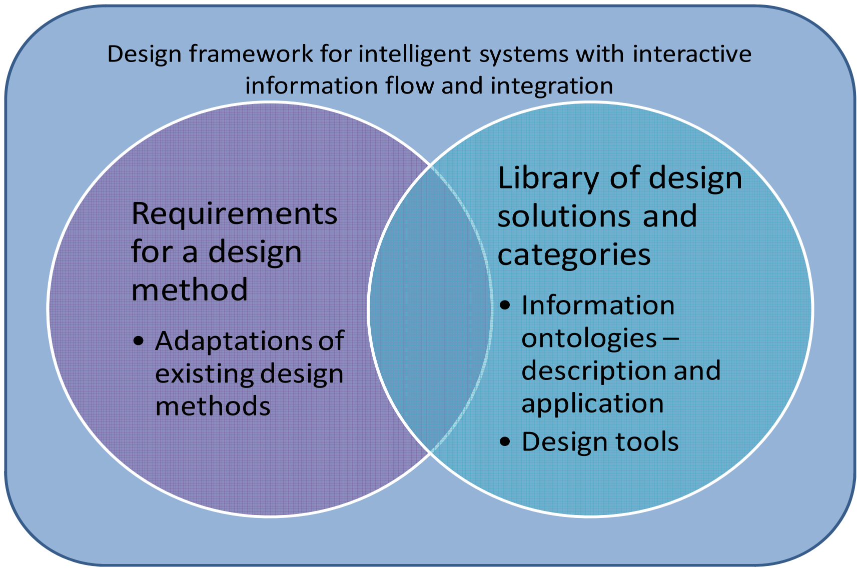


Figure 2: Mission for the thesis

In Figure 2, this framework is shown. As expected, the requirements and the library of design tools are shown to intersect. An important aspect of this framework is its customizability. Different designers with a background consisting of a different class of examples from those considered in this work can work with this approach and modify the method with their own steps As we progress through the thesis, this framework will be augmented with further detail and it will lend to a structurally consistent development of the design method to be proposed and validated. In terms of validating the proposed framework, all the examined tools, semantics and potentially applicable concepts suggested will not be used in the example problem, or in the proposed design method. The aim is to propose concepts and their applicability based on an abstraction of requirements of the domain of applications in consideration, and design requirements, and subsequently to validate some of the suggestions made by adapting a design method for our purpose and using some specific tools and representation schemes for various design activities.

1.2 Research Focus

1.2.1 The Research Questions

Our ambition for intellectual scholarship in this thesis is defined by the following two research questions. Note that the hypotheses for these research questions are provided in the next sub-section.

RQ1: Is it possible to describe/represent systems with interactive and intelligent information flow at different levels of abstraction to suit design purposes?

The very first step to designing any system is to have a representation scheme. For instance, for the design of mechanical systems the Pahl and Beitz design method uses the function structure to represent systems. The representation includes the flow of information, energy and material. However, the function structure does not include formalized ways of representing interactive and intelligent systems, wherein the physical boundaries may not be easily defined, or when the flow of information needs to be augmented with a description how it changes form and when it needs to be released or transmitted. For these reasons hierarchies or classes of semantics or objects which are specific elements of an ontology are very useful [15]. Additionally, implicit to the problem of representing the system, is the problem of identifying the boundary of the system. During the earlier phases of design, representations will thus need to incorporate semantics, objects, and functionalities at a considerable level of generality in the interest of repeatability as well as maintaining design freedom[6] of the method. In systems which are seamlessly integrated with the environment, a physical boundary may not be a possible representation under the final design. Thus, it is important to consider time and event based descriptions as well. Optimal control algorithms of systems on an event basis have been explored in the control systems literature [20-22]. An event based representation could perhaps be merged with these algorithms to provide a complete description of the system's functioning.

RQ2: Can a system with interactive information flow gathered from its environment be designed systematically?

This research question suggests that we are adopting a viewpoint which has been missing before. Prior research in the design of complex sensing systems is based primarily on the specific application in question [2-4, 8, 12-13]. A certain fixation on the relevant application specific research hinders designers from exploring and applying multi-disciplinary working principles and concepts to output designs which are lower in cost, efficient, with better customizability and are user-friendly. The design steps involved for designing these systems need to be abstracted to the level wherein we are designing from the point of view of the flow of information, which is the prime functionality of these systems.

Sensor technology has advanced significantly and there is very little information that sensors cannot gather in terms of the environment. Having drawn from existing

[6] Design freedom is defined as a qualitative measure of the working options that are left open for a designer to explore, which satisfy the requirements in consideration. With every decision made by a designer, some design freedom is removed.

biological sensors, that are the specialized cells in living organisms, we are at a point where we can design specialized sensors which are sensitive to light, motion, temperature, magnetic fields, gravity, humidity, vibration, pressure, electric fields and sound.[23] A designer's challenge is to make the best possible use of these sensors in satisfying the purpose for which sensor networks and systems are built. Choices need to be made on issues such as which sensors to use, how many sensors to use, where to place these sensors, and how to design for low energy consumption and meaningful assimilation of the information that is gathered.

When a systematic design for a sensor network is carried out, there are certain key questions that must be dealt with repeatedly. As humans, when we read information from the environment around us, these questions are answered implicitly. In order to provide a system (with interactive information flow) the intelligence to answer these questions in real time operation, we have to consider how the added requirements would have an effect on the design methodology before we even go about designing the system.

For instance, let us take an AmI system. One of the key applications which was explored conceptually in AmI systems is that of health and safety monitoring. The product proposal is a sensor network which will work as an Ambient Intelligence system. It will monitor the customer/subject and identify the situations when the customer/subject requires help and will actuate the necessary procedure.

Implicitly, while designing, there are certain fundamental questions with respect to the information flow which we answered. These questions are:

- What information can a system get in its current state?

- How is it getting this information?
- How is it using that information?

These are directly concerned with the function of the design. However, in context of the research question I am trying to answer, they pertain specifically to the information flow rather than matter and energy flow, amongst the three basic entities which flow through any system.

1.2.2 Proposed hypothesis

Following are the hypotheses put forth to answer the research questions

RQ1: Is it possible to describe/represent systems with interactive and intelligent information flow at different levels of abstraction for design purposes?

Hypothesis

Yes, objects, semantics and representative schemes and diagrams from existing ontologies can be leveraged upon to describe systems for design purposes at varying levels of abstraction. Specifically, Living Systems Theory (LST) and the proposed generic sub-systems within the theory accompanied with symbolic representations of these sub-systems can be incorporated into the Pahl and Beitz conceptual design phase to represent a working structure in terms of high level information flow diagram for systems with interactive and intelligent information flow. The function structure employed by the Pahl and Beitz design method can be used as an object to describe the overall function of the system including the matter and energy flows in addition to the information flow. The description of event and time based boundaries is also made possible with the ontological objects provided by the taxonomy of LST. In the embodiment and detail design phases, SysML can be used for adequate representation and evaluation of the systems level as well as component level layout, with adequate traceability of design requirements.

RQ 2: How can a system with interactive information flow gathered from its environment be designed systematically?

Hypothesis

The Pahl and Beitz systematic design method can be adapted for the design of such systems. The requirements that the design method must fulfill can be abstracted through a gap analysis of a system which is able to perform the functions that we require it to, and the requirements that the existing design method is able to build into the system. These requirements must be then translated into the steps of a generic and systematic design method. Much of the proposed design method's structure and the constructs it uses will be the same as the Pahl and Beitz method. However, the conceptual representation of the system, i.e. the function structure is augmented with the use of objects from Living Systems Theory, and embodiment and detail design phases can be augmented with the use of SysML and graph theory to better represent and design different aspects of these systems. The modified design method and the integration of proposed tools, representation schemes, and ontological objects can be validated in the context of the validation square with the use of a Wii™ based motion capture system.

Thus, augmenting our design framework figure with the understanding of the research questions, the logical connections of the research questions with their hypotheses to the elements of the framework are shown in the Figure 3. Note that :

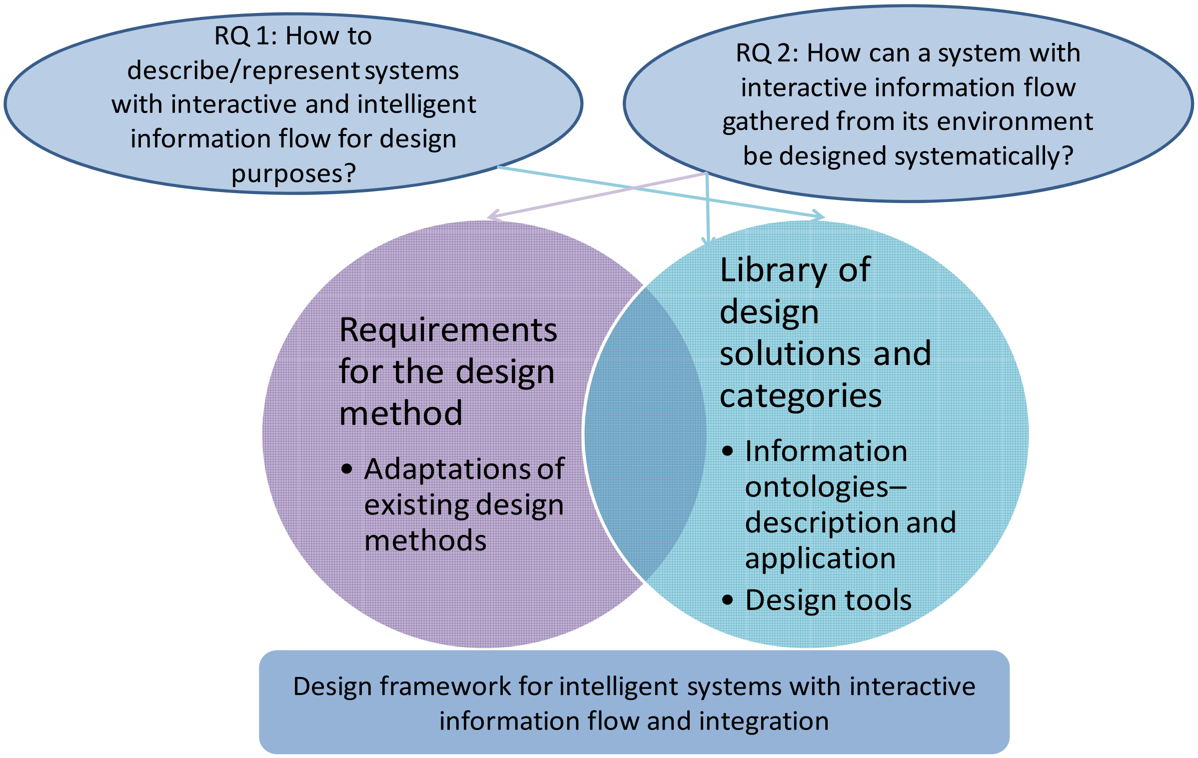


Figure 3: The vision as an answer to the research questions

1.2.3 A brief description of the example problem and how it will be used to validate the proposed work

In order to validate the design method proposed in this work, an example problem is selected, which satisfies the key characteristics of the domain of application established in the vision. The validation of the overall framework which constitutes the approach taken towards designing the design method is performed in context of the validation square, which is described later in this chapter and is established throughout this thesis. The example problem forms one part of this validation strategy, contributing to the empirical performance validity of the method. This example problem is the design of a motion capture system based on the Nintendo Wii Remote™. The current devices employed for the purpose of objective capture of ergonomic motion data have drawbacks in the form of a need for a controlled environment and a high cost of implementation. A systematic consideration of the requirements for the intended application and ongoing efforts in the Georgia Tech Research Institute led to the consideration of the platform of the Nintendo Wii™ remote. This example system is based on the custom requirements for a manufacturing environment where workers are at a high risk for repetitive stress injuries. The performance of the example system and an evaluation of the decisions made in the design process for the motion capture system are verified by the generation of a prototype which is then tested on human beings. In the context of the second quadrant of the validation square (i.e. empirical structural validity), this example problem can be shown to be an appropriate choice. The requirements of the design are considerably complex in terms of the information that needs to be collected, and the requisite knowledge about the environment. The system consists of more than a single sensor, and as such has issues of synchronization, and relative placement. Conflicting performance requirements need to be modeled using tools of modeling and optimization. There are varying levels of abstract design requirements which have to be considered. In Section 4.1, a more objective approach towards establishing the problem's appropriateness will be shown.

1.2.4 Research Contributions

In this thesis, the research contributions are made by justifying the research questions and by validating the hypotheses.

The first contribution is the demonstration of the need for a systematic approach to complex and intelligent systems in the context of the interactive information flow within the system and from the environment. In literature, such an explicit approach in the context of the information flow has not been adopted. Although, there are representations of the information flow through complex sensing systems, these have not been integrated into a systematic design method. Systematic approaches in design methods provide a number of advantages such as a structured approach towards searching for solutions, maintenance of design history, customization in product and process, traceability of requirements and maximizing the incorporation of user needs and wishes.

The second contribution is the adoption of existing ontological objects, semantics and representation schemes for the representation of systems with intelligent and interactive information flow in different stages of design. Specifically, the generic sub-systems identified by Miller [19], augmented with the symbolic representation by Shupe [24] in Living Systems Theory have been shown to adequately represent the information flow in these systems at the conceptual design phase. SysML's nine diagrams have also been shown to satisfy embodiment and detail design requirements that the design method must fulfill with respect to representation of the system and its function at various levels of abstraction. Graph Theory has been identified as a construct to satisfy the representation and design requirements with respect to the combinatorial aspects of systems with multiple agents for information collection.

The third contribution is the overall framework developed for designing systems with intelligent and interactive information flow. The design methodology proposed, incorporates some of the suggested ontological objects, semantics and representation schemes, and is shown to satisfy the requirements proposed for the design method. The requirements for the modified design method are valuable for further research into the design methodology for such systems. The context of the validation square has kept in place the consistency of every step taken towards building the framework thereby building confidence in its applicability both to the examples that were explored in this work, as well as other designs which possess similar characteristics as the ones specified in this work.

1.3 Systematic Design - The Pahl and Beitz Systematic Design Method

1.3.1 A systematic approach to design

The Pahl and Beitz systematic design method is based on a sound understanding and appreciation for the history, requirements, needs and current applications of systematic approaches to design [15]. "In view of the central responsibility of designers for the technical and economic properties of a product, and the commercial importance of timely and efficient product development, it is important to have a defined design procedure that finds good solutions. This procedure must be flexible and at the same time be capable of being planned, optimized and verified." [15] A large amount of literature precedes and supports the conclusions made by Pahl and Beitz in their treatise on engineering design. Hansen and other members of the *Ilmenau School* (Bischoff, Bock) first put forward their systematic design proposals in the early 1950s [25-26]. Hansen presented a more comprehensive design system in the second edition of his standard work published in 1965 [27]. Hansen's approach is defined in a so-called *basic system*. The four working steps in this approach are applied in the same way in conceptual, embodiment and detail design as is adopted in the Pahl and Beitz design method. Hansen begins with the analysis, critique, and specification of the task, which leads to the *basic principle* of the development (the crux of the task). The second working step is a systematic search for solution elements and their combination into *working means* and *working principles*. Hansen attaches great importance to the third step, in which any shortcomings of the developed working means are analyzed with respect to their properties and quality characteristics, and then, if necessary, improved. In the fourth and last step, these improved working means are evaluated to determine the optimum working means for the task. After Hansen, it is Rodenacker [28] who became preeminent by developing an original design method. His approach is characterized by developing the required overall *working interrelationship* by defining in sequence the *logical*, *physical* and *embodiment* relationships.

With this history and a large number of other references, Pahl and Beitz describe the requirements a design methodology must satisfy as [15],

“A design methodology must,

- allow a problem-directed approach; i.e. it must be applicable to every type of design activity, no matter which specialist field it involves
- foster inventiveness and understanding; i.e. facilitate the search for optimum solutions
- be compatible with the concepts, methods and findings of other disciplines
- not rely on finding solutions by chance
- facilitate the application of known solutions to related tasks
- be compatible with electronic data processing
- be easily taught and learned
- reflect the findings of cognitive psychology and modern management science; i.e. reduce workload, save time, prevent human error, and help to maintain active interest

- ease the planning and management of teamwork in an integrated and interdisciplinary product development process
- provide guidance for leaders of product development teams."

In addition to these requirements already incorporated by Pahl and Beitz in their method, customizability is a crucial characteristic that needs to be satisfied by a design method for the purpose of this work. The Pahl and Beitz method is an excellent choice for this purpose as well. The step wise nature of the method and the generality of the steps in each of the method's phases make it customizable to the domain of applications in consideration and the specific competencies of the designer using the method. In the case of the applications of interest for this work i.e., systems with intelligent and interactive information flow, the most important changes that are required have to do with the representation constructs at different levels of abstraction that are provided in the Pahl and Beitz design method. These representation schemes are inadequate to design for information flow, as is already described when elaborating upon research question 1 (Section 1.2.1)

With this context of systematic design, we will now delve into the Pahl and Beitz design method, in order to both internalize the method, as well as adapt it for the design of systems with intelligent and interactive information flow.

1.3.2 The Pahl and Beitz Design Method

The Pahl and Beitz design method is comprised of several systematic steps which are classified into 4 phases of execution. A brief summary of the 4 phases follows:

a. Task Clarification – The purpose of this phase is to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance. This involves an analysis of the needs in the market, the competencies of the designer/company and the specification of information in the form of a requirements list.

b. Conceptual Design – In this phase, the designer determines the principle solution. This is achieved by abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure. Conceptual design results in the specification of a principle solution or a concept

c. Embodiment Design – During this phase, designers, starting from a concept (working structure, principle solution), determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. The activities in this phase result in the specification of a layout.

d. Detail Design – This is the phase of the design process in which the arrangement, forms, dimensions and surface properties of all the individual parts are finally laid down, the materials specified, production possibilities assessed, costs estimated and all the drawings and other production documents produced. The detail design phase results in the specification of information in the form of product documentation.

There are several steps in each of these phases which the designer must go through to ensure a systematic flow of design activities from the abstract to the specific, to prevent design fixation, and to ensure that the most satisfactory working principles are selected. This flow of information through the design phases is marked by milestones which are considered to be core transformations in the design process. A pictorial representation of the complete design process is shown in Figure 4.

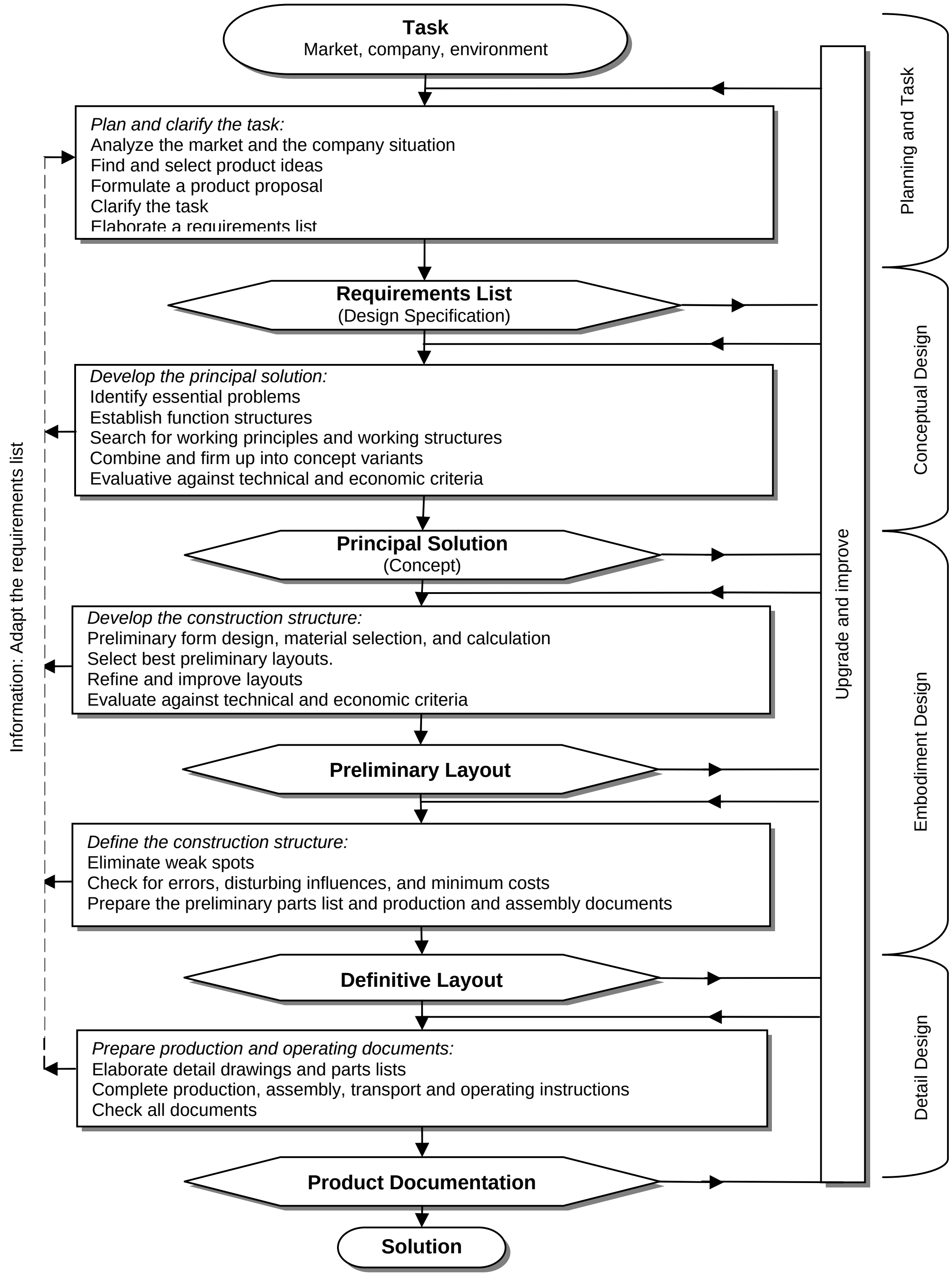


Figure 4: Overview of the Pahl and Beitz design method [15]

1.3.3 Information flow in Pahl and Beitz design method

Pahl and Beitz identify matter, energy and information as basic concepts as far as we are concerned with events in reference to time. However, they specify information as signals, the physical form in which information flows. What makes their treatment of these concepts valid to the cause of this work, is that they accept that in a technical process, the flow of one of the concepts may be more significant than the others. Thus, this freedom is maintained throughout their design phases, and several examples are provided with conversions of any one or two of the three missing in the function structure. Thus, we can comfortably adopt their constructs for systematic design with the focus on the information flow, conversion and integration in our systems.

A modification or augmentation of the information flow representation is required, as is addressed in research question 1. This is because some of the key requirements of systems with intelligent and interactive information flow at an abstract level require the designer to ask some questions and consider a representation in terms of the answers to these questions. These are:

- What information does the system need to get from the environment?
- What information can a system get in its current state?
- How is it getting this information?
- How is it using that information?

These are found to be important concerns when designing from the point of view of the information flow. The answers to these questions simplify the complexity of designing systems with a large number of diverse interacting agents like in an ambient intelligent system. The definition of the system and the environment and thus the boundary between the two also becomes clearer. These need to be incorporated into a high level representation scheme. The function structure, as the only representation scheme in the Pahl and Beitz design method does not perform this function adequately.

1.4 Closure

As closure to this chapter, the context for the validation of this work is provided. Within this context, the organization of the content in this document is outlined. Continuous reference to this section will be provided in the thesis, to ensure the context is clear, and the focus is on the approach adopted towards the design of systems with intelligent and interactive information flow, and not the specific implementation of the design method in this work alone.

1.4.1 The validation square

The thesis is organized in the context of the Validation Square. The Validation Square is a rigorous framework that can be used for validating engineering design methods [29-30]. This framework builds on research in system dynamics as well as a tradition of using posits in engineering design. In [29], the validation square presented extends these efforts by offering a prescriptive approach that is comprehensive and systematic. The validation square consists of four quadrants as shown in Figure 5.

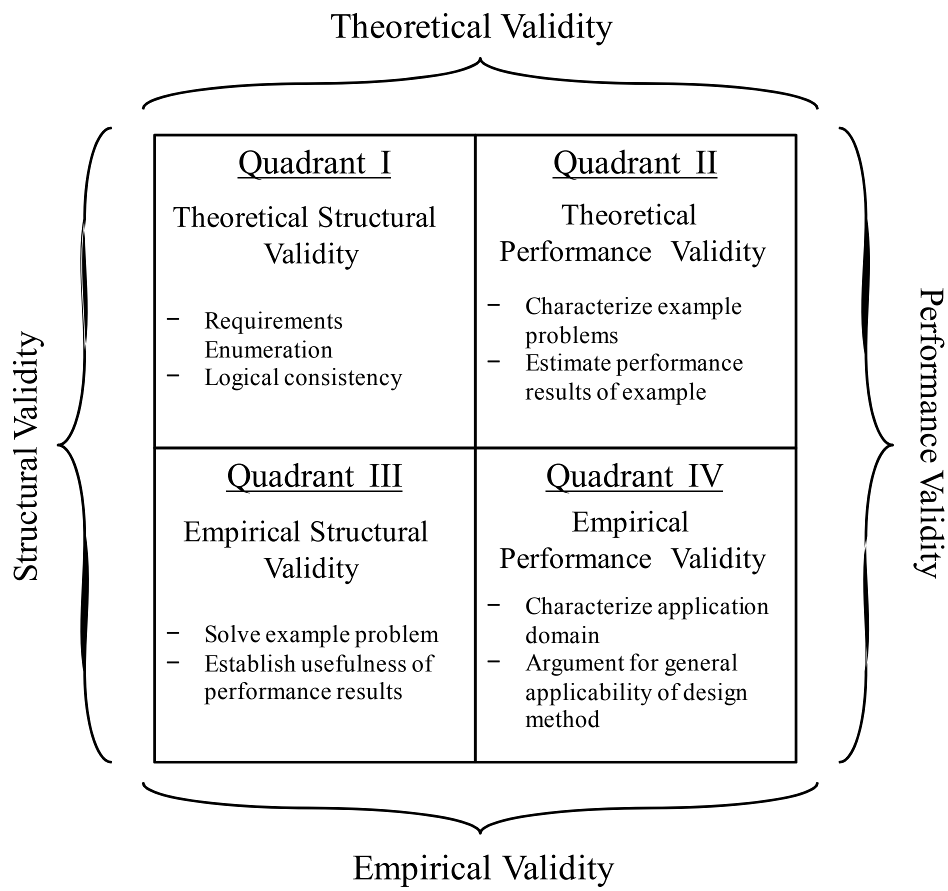


Figure 5: The Validation Square

The first quadrant is theoretical structural validity. The primary consideration in the first quadrant is the logical consistency of the proposed design method. The first step is to determine the requirements for the outcomes of the method and for the process by which the method generates these outcomes. These requirements provide the foundation for metrics that are used to evaluate the usefulness of the method throughout the validation process. The next step is to search the technical literature related to each parent construct being used in the proposed design method and critically evaluate its established advantages, limitations and accepted domains of application. With respect to this thesis, the first quadrant consists of the requirements that the design method must fulfill to design systems with intelligent and interactive information flow. In addition, the logical formulation of ontological constructs and theories such as Miller's generic sub-systems abstracted from Living Systems Theory, Algebraic Graph Theory and the Pahl and Beitz design method will be critically evaluated. Moreover, the functionalities that these tools offer will be mapped against the requirements for the modified design method in order to build confidence in their selection and utility for the designer.

Thereafter, the internal consistency of the proposed design method must be evaluated in its entirety. In this work, we stick largely to the structure of the original Pahl and Beitz design method in our proposed design method. Thus a logical flow, showing adequate inputs and outputs from the design steps, with documented milestones in the form of core transformations such as the product requirements list, or the design layout can represent the validation of the internal consistency of the proposed method. The logic and consistency of the approach used to modifying the original method, is validated by the framework which is developed systematically throughout the thesis.

In the second quadrant, the first step is to document appropriate example problems for illustrating and verifying the performance of the design method. These are problems which are similar to the problems for which the design method and its constituent constructs are generally accepted or intended. In this work, we shall borrow from the vision section, wherein we have established the broad domain of applications that our design method is intended to support. Appropriate problems include motion capture systems, ambient intelligent systems and a broad class of problems which can be characterized by the nature of the equipment, i.e. sensors. The next step is to evaluate whether data that can be collected in the example problems could support conclusions with respect to the performance of the design method. The simplifying assumptions that are made in these problems need to be identified explicitly, in order to verify that these problems are actual and representative of real world problems. In the thesis, this will be carried out with a literature survey and the corresponding match with design parameters in consideration.

In the third quadrant, a representative problem is used to evaluate the results of applying the proposed design method in terms of the outcome and process related design method requirements documented in the first quadrant. In this thesis, the example problem chosen is the design of a Wii-based motion capture system, which satisfies for instance, the outcome related requirement of generating a customizable system with interactive information flow between system and environment. The implementation of its design using the proposed design method includes usage of the ontological objects that are integrated into the design method. Performance measures related to accuracy and precision are also evaluated with simulated and experiment results, thereby providing confidence in the process effectiveness of the design method.

In the fourth quadrant, the characteristics of the intended application domain for the proposed design method are revisited, and an intuitive argument needs to be made for the applicability of the design method to a generic class of problems with these characteristics. In this work, these characteristics have primarily to do with the flow of information from the environment into the system, and its subsequent integration to create knowledge about the environment. Aspects of intelligence in the system to affect this information flow smoothly are also important characteristics. Demonstrating the satisfaction of these characteristics by the example problem, and the fulfillment of the requirements posed for the design method will allow us to take a leap of faith to claim that the proposed design method is applicable to a generic class of problems.

1.4.2 Organization of thesis

In **Chapter 1,** the foundation of this thesis is laid with the presentation of the motivation and the frame of reference. The motivation is backed up by a literature survey which establishes the domain of applications that is considered in this thesis. The research questions and hypotheses are introduced and explained and the expected contribution is summarized. Based on the validation strategy, the outline is developed (Figure 6) and a brief overview for each chapter is given.

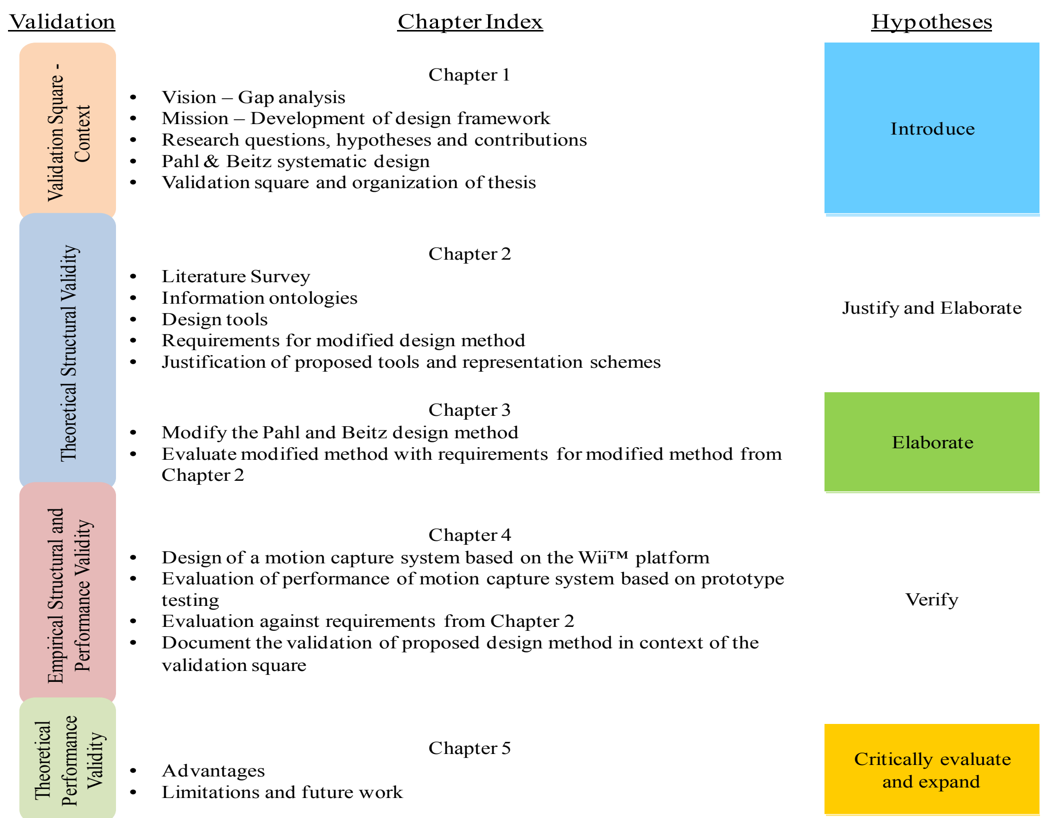


Figure 6: Outline for thesis

In **Chapter 2**, the theoretical foundation for the method developed in this thesis are explained and discussed. This foundation is primarily based on Living Systems Theory and other tools and constructs such as SysML and Graph Theory. Understanding the foundations and underlying theories is crucial to fully understand the research questions and hypotheses proposed in this thesis. In particular, this is where the first research question is answered. In order to support the theoretical structural validity of the introduced methods, relevant literature for the building blocks is referenced, analyzed and critically discussed in this chapter. By establishing the internal consistency of the components, the basis for the theoretical structural validity of the new method is laid down. The requirements that the modified design method must satisfy are proposed in this chapter. In order to maintain the internal consistency of this approach, each requirement is justified with references and critical thinking.

In **Chapter 3**, the modified Pahl and Beitz design method is proposed for the design of systems with intelligent and interactive information flow. This is where the answer to the second research question is tested. Again, to maintain the theoretical structural validity, every adaptation and modification to the original design method is justified with the help of context and references.

In **Chapter 4**, the example problem of the design of the Wii™ based motion capture system is carried out. The essential characteristics of this problem, identified through an analysis of existing products and competencies and the needs of motion capture systems for ergonomic data capture, are verified with the characteristics of the domain of applications that has been established in Chapter 1 under the vision. In this way empirical structural validity is assured. The system is then designed step-wise using the proposed design method in Chapter 3. Thereafter, performance evaluations are carried out. In addition, the design method's efficacy is validated by verifying the fulfillment of the requirements proposed in Chapter 2. In this way, the empirical performance validity is demonstrated. Application of the proposed representation for systems within the domain of consideration and the proposed design method for the same are used to verify the hypotheses which are elaborated in previous chapters.

In **Chapter 5**, the thesis is summarized, and the research questions are answered. The work is critically reviewed in terms of the contributions and the limitations. In this chapter, emphasis is placed on the assumptions and conditions under which the proposed method works. For the theoretical performance validation, it is argued that the method and representation presented in this thesis as well as the conclusions are relevant and valid beyond the example problem. Finally, potential future research topics are identified that could enhance the proposed methods and make them more efficient or applicable to a broader range of engineering design problems.

1.4.3 Synopsis

In the context of the first quadrant of the validation square, i.e. the theoretical structural validity, it is essential that an argument be put forth to establish the veracity and the logicality of all the constructs and methods that have been used, referred to, and synthesized to construct and propose a design method. A tangible way to do this is to build the structure of the framework which supports the proposed design method as the relevant constructs and arguments are put forth in the thesis chapters. For instance in Figure 2, the mission of the thesis is clarified, with the accompanying arguments in the context of my vision for this work, and the overall domain within which we are exploring design methodology. Thereafter the next logical step is made to clarify the motivation of my research using the research questions and tying them to the proposed framework. Correspondingly, this is shown in Figure 3. At a later stage, this picture is augmented with all the constructs, tools and tasks that are discussed and carried out in this thesis.

CHAPTER 2

Adapting the Pahl and Beitz Design Method for Systems with Intelligent and Interactive Information Flow

In the preceding chapter, a frame of reference was established in terms of the vision, mission and the key elements of this work. In particular, the research questions were highlighted, hypotheses stated, and the validation for my work was set up in the context of the validation square. In this chapter, the first hypotheses is tested, by integrating the proposed design tools, ontological objects and representation schemes into the Pahl and Beitz design method in order to better represent and describe systems with intelligent and interactive information flow. In the context of the first quadrant of the validation square, i.e. theoretical structural validity, a critical evaluation of the design tools, ontological objects and representation schemes is carried out with a literature survey on their prior use. The most important task carried out is the modification of the Pahl and Beitz design method for systems with intelligent and interactive information flow.

2.1 Ontological tools, objects and representations

In this section the usage of existing design tools, system representations and ontologies which can be used for the same in the design of systems with intelligent and interactive information flow is proposed and evaluated. Research has been carried out for building overall ontologies which inherit higher level and smaller ontologies, objects and tools [14, 31-32]. Though some research has been carried out in building web-based ontologies for the field of genetics [33-35], domain specific ontology research has been primarily carried out in the field of information[7] handling, knowledge sharing and web services [31, 36-39]. In his work on formal ontology in information systems, Guarino [31] argues that ontologies present their own methodological and architectural peculiarities. Of importance to this work is the stress put on the adoption of a highly interdisciplinary approach in the methodological side of ontologies. On the architectural side the aspect highlighted by Guarino is the centrality of the role ontologies play in an information system, leading to "a perspective of ontology-driven information systems" [31]. However, the information systems that he refers to are in applications of knowledge engineering, database design and integration and information retrieval and extraction. At the same time, this work is valuable in its treatment of the word "ontology". The author has deliberately assumed an interdisciplinary audience for his work and thus clarifies the meaning of ontology in its most prevalent use in the artificial intelligence (AI) community. "An ontology refers to an engineering artifact, constituted by a specific vocabulary used to describe a certain reality, plus a set of explicit assumptions regarding the intended meaning of vocabulary words". This definition suits the purpose of proposing ontological objects in this work as well.

Most of the research that has been carried out on ontologies for information systems and integration of information are in the domain of computer based information systems. An extension of these ontologies to the domain of human computer interactive systems with information generated on both sides of the intelligence barrier needs to be

[7] The context in which the term "information" is used in much of literature is different from this work, in that the sources of information collection are not necessarily sensors. Information in ontology literature refers in most cases to online data in electronic format.

carried out. Problems which will remain common to both kinds of information systems can be explored and literature exists on the solutions for such problems.

For instance, finding suitable information sources is a problem addressed in the areas of information retrieval and information filtering. Belkin and Croft [36] provide insight in this respect based on the fact that each of the information sources, once found, has to work with the system which queries the information. Though the models presented in their work are focused on computer based information systems, the comparison drawn by them between information retrieval and information filtering is interesting from the point of view of metrics such as the reason for query, adequacy of queries as representations of information needs, collection and organization of information, selection of information to create knowledge, timeliness of text, definition of user communities, and issues of the environment such as privacy [36].

Problems arising due to heterogeneity of data in interoperable systems over the internet are well known in the distributed database systems community [37-38]. Wache et. al. evaluate and compare the languages used to represent ontologies and the use of mappings between ontologies as well as to connect ontologies with information sources [39]. They perform a systematic analysis of issues such as interoperability between heterogeneous information sources, the role of ontologies in single multiple and hybrid ontology approaches, existing ontology representations, mappings between ontologies and ontological engineering. In a section on open questions the authors mention that “The comparison of different approaches, however, revealed that requirements concerning ontology language and structure depend on the kind of information to be integrated and the intended use of the ontology.” The literature survey carried out builds confidence that given the correct objects and semantics are utilized, problems to do with using them in an ontology can be dealt with. In addition, an understanding of the characteristics of ontologies in general, especially the definition provided by Guarino [31], as mentioned above, provides the basis for selection of existing representation schemes and tools which might not yet be characterized as ontologies, but nevertheless serve the purpose for this work.

The focus in this thesis though, is not to develop ontologies for representation of a generic system, but rather on proposing a framework within which designers can use the objects, tools and semantics offered by existing ontologies to satisfy requirements of intelligent and interactive systems in the established domain of applications. Thus, a formalization or methodological development of ontology for our domain of systems is avoided, although certain objects, semantics and representations are proposed for use as generic tools in the proposed design method. Based on the domain of applications and the focus on information flow in the context of collecting information about the environment and converting it into knowledge, some key tools, objects and representation schemes are highlighted in this section.

2.1.1 Taxonomy of Living Systems Theory

As mentioned in the mission of the thesis, my goal is to postulate a design framework within which we can design specifically for the information flow. As hypothesized in the first research question, the generic representation of information flow through systems can be characterized in terms of the Living Systems Theory (LST). LST is a conceptual framework that has been developed to integrate the findings of system theorists and scientists in biology, physiology, neurology, the social sciences, economics and management, for the purpose of developing a unified theory that deals with the hierarchical structure of life at many levels [18]. Miller's articles identify the hierarchy of living systems including the cell [40], the organ [41], the organism and the group [42] and the organization [43]. From the point of view of a general system theorist, Miller endorses the "daring and controversial position that though every living system and every level is obviously unique, there are important formal identities of large generality across levels". The use of living systems theory in engineering systems has been proposed and explored by Mistree, Smith, Bras and Allen [18]. By modeling design problems in engineering as a combination of decision support problems, they approach the decomposition of a design problem with partitioning of systems into generic sub-systems. These generic sub-systems are borrowed from Miller's critical sub-systems [19], serving as "a point of departure for engineers in developing a set of generic subsystems on which to base the design of classes of engineering artifacts".

Similar to sketching, using the living systems theory approach permits the user "to see the broad outlines of information, matter and energy flow without becoming enmeshed in the defining the detailed implementation explicitly" [18]. The theory proposes taxonomy for generic subsystems based on the manipulation and transfer of matter, energy and information. These generic subsystems can be used to represent the interactive flow of information in systems and environments. A symbolic representation scheme for these critical subsystems has been developed by Shupe [24]. Symbols associated with information flow are summarized in Table 1.

Table 1: Generic sub-systems pertaining to information flow and processing [19, 24]

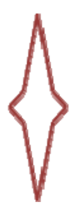
Representation	Name	Description
	Input Transducer	The *input transducer* is the sensory subsystem that transports markers bearing information into the system and, if necessary, transforms them into other matter-energy forms suitable for transmission within the system
	Internal Transducer	The *internal transducer* is the sensory subsystem that receives, from other subsystems or components in the system, markers bearing information that deal with significant alterations in those subsystems or components, transforming them to other matter-energy forms suitable for transmission within the system.
	Channel and net	The *channel and net* is the subsystem of direct channels or routes through physical space by means of which markers bearing information are moved to all parts of the system.
	Decoder	The *decoder* is the subsystem that alters the code of information input to it through the *input transducer* or *internal transducer* into a private code that can be used internally in the system.
	Associator	The *associator* is the subsystem that deals with learning in its first stages by forming enduring associations among the items of information in the system. A system forms a new association to an item of information when its response to subsequent transmissions of that item or one sufficiently similar, from the environment or from a source within the system, is altered; by the new association that triggered this altered response, the system can be said to have learned.
	Memory	The *memory* is the subsystem that conducts the second stage of learning, the storing of items of information for different periods of time, from the transient to the archival.
	Decider	The *decider* is the executive subsystem that receives information inputs from all other subsystems, processes what it receives, chooses a course of action and then transmits the decision to all parts of the system, thereby controlling the system's activities from the micro- to the macro-level.

Table 1 continued

Representation	Name	Description
	Encoder	The *encoder* is the subsystem that alters the code of the information-processing subsystems, from a private code used internally by the system to a public code that can be interpreted and used by other systems in its environment.
	Output Transducer	The *output transducer* is the subsystem that transforms information markers used within the system into other matter-energy forms that can be transmitted over channels in the system's environment.
	Timer	The *timer* is the subsystem that transmits to the *decider* information about time-related states of the environment or of components of the system.

With the help of these sub-systems, it becomes possible to represent systems in terms of a high level information flow diagram. None of the physical or structural aspects of the system are explicitly represented or modeled at the level of abstraction of these sub-systems. This is exactly what was proposed in the hypothesis to research question 1. To reiterate, research question 1 is,

Is it possible to represent systems with intelligent and interactive information flow at different levels of abstraction to suit design purposes?

The representation of such systems at a conceptual level can be achieved with the proposed generic sub-systems from the taxonomy for living systems theory. Thus, part of the hypothesis is elaborated in this section. In the context of the validations square, progress is achieved in theoretical structural validity with the literature survey that was performed in this section. A tie up of discussions carried out here with the requirements for the modified method will further setup the theoretical structural validity. The validation of empirical performance of this constructs is demonstrated in Section 4.1.2, wherein these sub-systems are used for representing a conceptual working structure of the example design.

2.1.2 Modeling and simulation tools

Apart from the focus on information flow, the modification of the Pahl and Beitz method must also incorporate a critical evaluation of the design tools that the method makes room for. These design tools are useful in reduction of development and testing cost, and production time, and are applicable to the design of any system regardless of the specific context.

Modeling and simulation tools are essential for effective and efficient testing and evaluation of design variants at the conceptual as well as embodiment design stages. A large amount of research has been done in the viability, application and utility of modeling and simulation tools and methods in the design of engineering and other systems. Modeling and simulation tools have been applied in virtually every field or discipline of study, including, mechanical engineering concepts such as machining [44], fluid mechanics [45], material design [46], tissue engineering [47], rapid tooling and prototyping [48]. Virtually every other practice in engineering makes use of these tools as well. They include computer-aided design tools (CAD) such as ProEngineer and SolidWorks, finite element analysis (FEA) tools such as ABAQUS and ANSYS, modeling language tools such as SysML and Modelica and a number of other tools.

Specific to complex systems with involved interaction between the environment which is often human and the system which often consists of a computer, modeling and simulation of real world scenarios and physical appearances are crucial. For instance, as pointed out in Chapter 1, crash tests are often conducted using dummies which require expensive implementation. In order to realize systems with the ability to perform motion and test data capture and then derive knowledge about real world crash scenarios, the availability, limitations and capability of existing modeling and simulation tools need to be taken into account while searching for solutions to designing such systems. This holds true for all complex systems within the domain of applications with intelligent and interactive information flow. The Pahl and Beitz design method does not specifically address the use of such tools and their impact on its design methodology needs to be explored. Sinha and co authors, for instance, present an overview of modeling and simulation and studies on simulation methods which provide support for the design process [49]. The focus in their work is on the use of language and graph based methods for simulation of real world systems. Bernard and co authors have published a book [50] on the theory of modeling and simulation which "concentrates on integrating the continuous and discrete paradigms for modeling and simulation". Key ideas in the book "underlie a sound methodology for construction of complex system models" based on a rigorous mathematical foundation.

In [51], Abelha and co authors research on objective measures of human behavior for the use of simulators to evaluate the skills and training of medical practitioners and teams. The ambient intelligent system proposed in their work is characterized by a logical theory of situation awareness within the context of an entirely simulated medical environment. Networks with larger number of agents are often simulated based on the modeling of herd behavior in real animal herds. Couzin and co authors develop their own model for simulating leadership and decision-making in animal groups on the move [52]. Their model shows how information can be transferred within groups without signaling and provides new insights into the mechanisms of effective leadership and decision-making in biological systems. The significance of modeling and simulation is evident in the entire domain of applications that is the context of this work, and is thus important to consider their role in the overall design process.

Key requirements which existing tools of modeling and simulation satisfy with respect to the design method include, repeatability of variants, lower costs of evaluation and testing, decentralized and distributed design of complex systems with a large number of assembly components, and evaluation and reverse engineering of existing product ideas. They also aid in the partitioning of the system requirements into specific functional representations of the system. In this work, modeling is demonstrated as an important tool to parameterize the flow of information with the use of existing computer-aided design software. The literature survey carried out in this section builds upon the theoretical structural validity. This section in particular provides an elaboration of the hypothesis to the first research question. At lower levels of abstraction these tools can be used to not just represent systems with intelligent and interactive information flow, but describe these systems with the help of analytical tools that come with these representation tools. In context of the third quadrant in Figure 5, the empirical performance validity is performed specifically for these tools through their explicit use in the later steps of conceptual design, and throughout embodiment design. For example, the models created in CAD software are used to determine layout parameters and constraints on the design space as a function of the individual's geometric parameters in Section

4.1.3 for the motion capture example which is described briefly in Section 1.2.3. The domain of modeling languages in the context of model based systems engineering is further explored in Section 2.1.4.

2.1.3 Graph Theory

It is evident that for applications involving sensors, wireless networks, Bluetooth™ communications, and interfacing of multiple information sources with a computer, the modeling and representation of purely combinatorial aspects becomes an integral part of the conceptual and layout design of the system. Control algorithms for a network of physical sensors need to incorporate spatial and communication interrelationships between the agents.

Particularly for sensor network systems, solutions to control problems have often been modeled using tools such as graph theory. "Graphs provide natural abstractions for how information is shared between agents in a network" [53]. The abstractions provided within graph theory serve to do away with all the complexity of multi-agent networks, preserving only the combinatorial properties of the networks. The algebraic theory of graphs provides matrix objects associated with graphs which make decentralized control of multi-agent networks possible in most cases. Graph theoretic methods have been employed for data clustering applications [54], cellular production [55], computational organization [56], sensor networks [57-60], ambient intelligence [61-62] and a number of other applications in robotics and sensing. Of particular interest is its applicability to designing the communication architecture in sensor networks and ad hoc networks, which encompass the domain of applications that is the context in this thesis.

In Section 1.2.1 some of the challenges faced by designers are elaborated upon to provide justification for the second research question, i.e.,

Can a system with interactive information flow gathered from its environment be designed systematically?

Given the extensive functionality provided by sensor technology, a designer's challenge is to make the best possible use of these sensors with choices arising on issues such as how many sensors to use, where to place these sensors and to design for minimum energy consumption and meaningful assimilation of knowledge about the environment. One of the fundamental issues is in designing sensor networks for complete and efficient coverage of the environment that the system is monitoring. Meguerdichian and co authors [57] deal with this problem using a graph theoretic construct, the Voronoi diagram which models the location of different sensors and the coverage areas allotted to each sensor in the network. The model can be configured for best case and worst case surveillance coverage of an agent passing through the field of sensors. An inverse principle with a similar model can be used to determine the best distribution of sensors to match a known path for maximum surveillance. The purely combinatorial nature of the graphs thus helps in partitioning of the design of networked systems and deals with issues such as ensuring coverage and designing the control algorithm by modeling the location of sensors, communication and linkages in the sensor network. For instance, Kuhn and co authors present approximation schemes for problems in wireless networks [60] modeled in the form of unit disk graphs or coverage area graphs. These problems deal with optimizing the location of sensors and wireless agents.

It is clear that graph theory offers a way of satisfying certain key requirements with the aid of its simplistic approach to representation of networks, and the linkages between the agents in these networks. It can thus act as a useful tool for evaluation of conceptual design variants in the context of coverage requirements and agent specific constraints, such as the field of view of a sensor. The nature of this research being exploratory, the scope in the example problem in the thesis is narrowed to little more than a couple of sensors. However, the evaluation and literature survey provided in this section applies well to the requirements of theoretical structural validity, thereby validating the consistency of the approach being taken in this work towards identifying constructs that can be used for the design of systems with intelligent and interactive information flow. At the same time, empirical performance validity of this construct in particular is not performed in this thesis due to constraints on the choice of an example which is complex enough in terms of the number of sensors and the scope of communication problems that can be dealt with which would require the use of graph theory. Thereby, the use of graph theory is precluded in the actual design method which is implemented in this thesis. However, the representation, theorems and algorithms of graph theory are conducive to the context of this thesis, which is to focus on the information flow and interaction between system and environment, as well as between the system's components. In the adaptation of the design method, its use and significance is identified as an augmentation to the conceptual and layout design of systems involving networks of multiple agents.

2.1.4 Model Based Systems Engineering – SysML

Systems engineering is a multidisciplinary approach to develop balanced system solutions in response to diverse stakeholder needs [63]. Model based systems engineering

(MBSE) applies systems modeling as part of the systems engineering process. The concept of MBSE largely arose out of the software engineering field. The importance of MBSE in this work with the context of exploring its advantages in representing and designing systems with intelligent and interactive information flow is made evident by analyzing the importance of software engineering in the systems within the domain of application being explored. Most of the applications that we are considering involve a human computer interface which cannot be easily defined with structural aspects alone. This integration of the physical and structural aspects of the system with the environment it is meant to collect information from, involves the use of sensor technology backed by control algorithms and a number of other software applications. Moreover, the integration of the information collected from disparate sources is most likely going to be done in a computer or a processor, with precoded applications. Thus, software design, and engineering is a big part of the applications we are considering, and is crucial to the essential function that we want our systems to carry out with respect to collecting information from disparate sources intelligently and then integrating it to create knowledge about the environment. MBSE is intended to facilitate systems engineering activities that have traditionally been performed using the document-based approach and result in enhanced communications, specification and design precision, system design integration, and reuse of system artifacts. The output of the systems engineering process in such an approach is “a coherent model of the system where the emphasis is placed on evolving and refining the model using model-based methods and tools”[63]. These tools enable the modeler to create, modify, and delete individual model elements and their relationships in a model repository. The modeler uses the symbols on the diagrams to enter the information into the model repository and to view model repository information. The specification, design, analysis and verification information previously captured in documents is now captured in the model repository. The model can be viewed in diagrams or tables or in reports generated by querying the model repository. The advantages of using a MBSE language such as SysML from the point of view of maintaining design decision history, recording requirements and their progression from a systems level to the component and detail level are widely accepted and have been the motivation for a wealth of research and application using SysML [64-66]. Specific to this research the functionality offered by SysML has been explored from the perspective of integrating its modeling capacity and to facilitate the execution of system functions based on a coherent model definition. To this effect, SysML includes nine diagrams which are shown in the diagram taxonomy shown below.

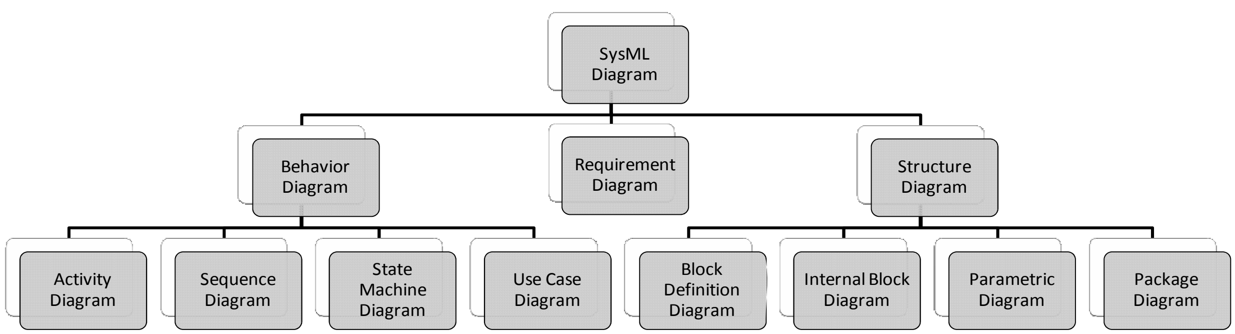


Figure 7: SysML Diagram Taxonomy [63]

In the context of adapting the Pahl and Beitz method to include the advantages of MBSE, and to satisfy the requirements posed in Section 2.2, some conceptual propositions are made on the integration and application of these diagrams for the design of systems with intelligent and interactive information flow.

Requirement Diagram – text based requirements and their relationship with other requirements, design elements and test cases to support requirements traceability.

This can be used to represent systems level requirements explicitly. These being complex systems, there are a number of interacting entities, amongst which many requirements will have to do with the structural aspects of the system specifically, whereas other requirements might involve a number of considerations and cannot be broken down as easily. Thus, a formalized manner of representing and defining relationships for such requirements will be a great boon to the adapted design method.

Activity Diagram – represents behavior in terms of the ordering of actions based on the availability of inputs, outputs, and control, and how the actions transform the inputs to outputs

This can be used in conjunction with an information flow schematic which is bound to be a feature in the proposed design method. Small activity diagrams can be used to represent subsets of an information flow diagram. The flow of events can be modeled based on the flow of information designed in the diagram, and the events can be integrated with system's structural components to formulate the activity diagram (which involves the context of structural components, as well as event based progress). SysML's model repository allows us to create elements which define relationships between different diagrams.

Sequence Diagram – represents behavior in terms of a sequence of messages exchanged between parts

The concept of messages is important. Messages represent a class of information which is used in wireless and Bluetooth communications, both essential solutions for systems with sensors. Thus a sequence diagram works well to represent that part of the information flow which has packets of information which are defined with clear semantics and can be represented as data packets or “messages”.

State machine diagrams – represents behavior of an entity in terms of its transitions between states triggered by events

These diagrams would work well in conceptualizing how changes in environment should affect the system and the boundary. A key aspect of the second research question is to design the function in the system with the ability to answer these questions

- What information can a system get in its current state?

State machines can be used to represent the behavior of systems and sub-systems within them. The behavior and activity related to each state can be used to represent what information the system is capable of gathering and subsequent state changes that need to be made in order to satisfy functional requirements. From the discussion on graph theory, it is clear that algebraic graph theory can be used to represent and evaluate certain performance characteristics of a network of agents or sensors. Thus, an underlying module inside the evaluation blocks in a state machine diagram can be comprised of a graph theoretic algorithm to evaluate performance measures related to the information the network can collect at a given point in time, such as the coverage of the network as a whole, and the communication capability in the network based on which sensors are within communication range of each other.

- How is it getting this information?

Block definition diagram and internal block diagram can be used to model components of the system. Each block can possess a state machine which can thus augment the structural component's ability to perform its function of collecting information and transmitting it to the correct place in the system.

- How is it using that information?

The state machine diagram compounded with the activity being carried out by each block will describe the mode in which information is currently, and the subsequent usage of the information.

Use case Diagram – represents functionality in terms of how a system or other entity is used by external entities (i.e. actors) to accomplish a set of goals

This is an important construct which can aid in converting requirements imposed at internal transducers or at any specific node at the beginning of a channel/net as described in the taxonomy of Living Systems Theory. This is because what flows from an entity or sub-system may need to be further transmitted or processed for use in another entity or sub-system part of the overall system

Block definition Diagram – represents structural elements called blocks and their composition and classification

The block diagram is similar to a function diagram in the Pahl and Beitz and is useful for designing a system with the overall tasks and system requirements fulfilled.

Internal block Diagram – represents interconnection and interfaces between the parts of a block

Another level of detail can be added at this stage to the function structure to specify the entry and ending points of transfer of information, energy and matter in it.

Parametric diagram – represents constraints on property values, such as F = m*a, used to support engineering analysis

During the embodiment and detail design of any system, several details need to be finalized in order to complete the design, and satisfy all the requirements of the system. At this stage, the level of abstraction is lower than the conceptual stage, and as such requirements are expressed quantitatively and often as mathematical or logical relationships. The parametric diagram can be used as an essential construct for this purpose. Additionally, for systems designed for the information flow, layout diagrams will include algorithms, and flowcharts, with platform and medium specific standards and requirements to be met. To incorporate such requirements along with structural and mechanical requirements, the parametric diagram offers a representation and a model based approach to implementation of all these multi-disciplinary concepts at the implementation level.

Package diagram – represents the organization of a model in terms of packages that contain model elements

Its utility for our cause needs to be explored further. At this point, this diagram doesn't seem to offer any particular use to the design of intelligent systems.

It is important to note that SysML provides a framework in itself which allows for creation of new ontologies and representative schemes with objects in the form of text, blocks, flows and relationships. Thus, it can be used to model the Living Systems Theory objects that are being used in this thesis. However, the amount of designer hours and computational expense that go into customizing SysML and the consequent interfacing of SysML with implementation platforms such as programming languages, optimization software and other modeling software is immense [63, 67] and SysML would be better used in a sparing format in the early stages of design rather than as the overall framework. SysML is identified as an important construct, and an abstraction of the functionality of its nine diagrams clearly link to some of the representation requirements that are mentioned in Section 1.2.1 in order to justify research question 1 and its relevance to this work. The arguments provided support the logical consistency of its choice as a design tool for systems with intelligent and interactive information flow, thereby building on the theoretical structural validity. At the same time, it is not used in the example system provided in the thesis owing to constraints on the complexity that can be dealt with in this work.

2.2 Requirements that the adapted method must satisfy

A clarification of the mission is needed at this point. Having explored the literature on the proposed tools and representation schemes in the preceding sub-section, focused consequent efforts are focused on proposing a modified Pahl and Beitz design method and including some of the design representations and tools in the method in order to design for some of the characteristics of the systems within the domain of applications that are the focus of this work. In the context of the validation square's first quadrant viz., theoretical structural validity, the first step in order to do so is compile the requirements that the process and the output should satisfy for the modified design method. Thus an effort is made to formalize the requirements that this design method must fulfill.

Must design for the environment

The information flow that needs to be designed for is dependent on the environment for which we are trying to design. A requirement of the primary function is to integrate the information that is gathered from the environment into knowledge about the environment. Thus, the design of any system will be dependent highly on the environment it is being designed for. As such, the design method must include certain steps which consider the influences of the particular environment the system is being used to measure or monitor. Some key questions to be asked while doing this are

What are the ways in which information can be gathered from the particular environment?

Do existing systems provide competent solutions in terms of accuracy, precision, safety, robustness, uncertainty to gather information from this environment?

What relevance does the history of the environment hold to our objective?

Specifically, in the task clarification phase, designers need to ask these questions when exploring and evaluating product ideas (Step 2, Task Clarification, Figure 4) Also, before the requirements list is set out, the environment specific needs and requirements ought to be focused upon. (Step 5, Task Clarification, Figure 4) Before the needs and requirements can be set out, the environment ought to be defined explicitly as part of the product proposal itself (Step 3, Task Clarification, Figure 4). All evaluations that are carried out in the later design phases ought to focus on environment specific requirements. This would reflect in the embodiment design phase when the form designs are specified (Step 10, Embodiment Phase, Figure 4) as well as in realizing customizable designs in the detailed design phase, since customizability would lend directly to effective functioning of the system in different environments.

Must build functions and concepts on a fundamental information flow and processing representation

The domain of applications that is being considered and the common functionality of systems within this domain impose on the designer to ensure an interactive and intelligent information flow schematic underlying the function of the system or product being designed. Thus, as an augmentation to existing systematic representations of a system's function structure, and the conceptual flow of information, matter and energy, the design method must include a bare bones representation of the information flow, without taking into explicit consideration geometric and other structural requirements initially. Specifically, in the conceptual design phase, the representation scheme offered by the function structure needs to be augmented (Step 3, Conceptual Design Phase, Figure 4). The function structure though is a valuable construct and doing away with it is not conducive to representing flow of matter and energy in addition to information. Thereby, an information flow representation will be integrated into the representation of the working structures (Step 5, Conceptual Design Phase, Figure 4).

Must design for the available technology with respect to input transducers (sensors)

One of the drives behind exploring a systematic design method for such networks is the advancement in the technology of sensing devices. However, there are still limitations with respect to what sensors can do by themselves, and the design of a network of sensors must take into account these limitations. A consideration of existing platforms for the system early on in the design process would aid in determining the best possible solutions . However, a tradeoff between defining these constraints early on and thus limiting the scope of applying multi-disciplinary solutions versus allowing too many options to be open and thereby, leading to a number of unnecessary uncertainties related with the thousands of possible solutions has to be carried out. Fortunately, the stepwise process from the abstract to the specific decisions in the Pahl and Beitz method (Figure 4) ensure this tradeoff is carried out in a balanced manner.

The Requirements List should include the following categories

A key aspect of designing an intelligent system is to incorporate the ability of the system to analyze, compare, evaluate and thereby make decisions. In order to do design these abilities into the system, a designer needs to make sure all the requirements that need to be fulfilled in order for the system to answer decision based questions are included in the requirements list of the particular system. One step towards ensuring this would be to identify the key requirement categories which must be included in the system's requirements list, thereby ensuring a thorough consideration of all aspects of the function that the system needs to carry out.

Output Knowledge

For designing any complex system, where the complexity maybe due to the large quantity of sensors, or multiple sources of information in the environment, or due to many events occurring at once, it is necessary that the design of the system is adapted for the particular need of the system in the situations that we can expect. Thereby, it must be very clearly defined what the output knowledge should be from the networked system. This may simply be the need for consensus amongst a bunch of temperature sensors, or it may be predicting health emergencies while monitoring a subject based on a large number of parameters (blood pressure, gait, heartbeat, facial expressions etc.). These requirements will help determine the answer to the question: what information does the system need now to fulfill its function?

Library

This category will cover requirements which enable the system to gauge whether the information it is collecting at a particular instant is adequate to create the requisite output knowledge about the environment. This library, in very sophisticated applications will also contain a self-learning ability. (For eg. the library should update itself to understand patterns in repeating behavior of the environment. This will allow the system to respond more efficiently and effectively to the environment's behavior.

Coverage

For the design of any network gathering information from the environment, one of the most important factors will be the coverage area of the network's effective function. Requirements in this category will include both spatial and functional coverage.

Communication

The gap between gathering disparate information from separate sources in the environment and combining them together to create knowledge that is to be outputted will require communication between the agents in the network. Requirements in this category will clearly define the level at which these communications need to occur, and the specific protocol that needs to be implemented to ensure proper integration of information. The requirements which have to do with the protocol that needs to be implemented will substantiate the logical links between information items which transform into output knowledge.

Resources and technology - Sensors

These requirements will help us select us the appropriate sensors for designing the system. The sensing functionality that we want to achieve with the networked system will be translated into requirements under this category. They will also help us identify the technological constraints that must be taken into account while selecting solutions for the particular sensor network, in terms of the actual sensors which can be used.

Note that these requirement categories are not exhaustive. In certain applications there maybe reclassification or addition of other categories required. For example, in an Ambient Intelligent System for targeted customer services, customer preferences such as visibility and intrusion are considered important requirement categories [6].

Function Structure must include an instance of each of the following general functions

In order to realize an intelligent system which interacts with its environment and users as part of its function, there are certain fundamental functions that it must carry out.

These are found to be irrespective of the application that we are designing the system for. The only assumption being made is that the system must convert information from the environment into knowledge about the environment in an intelligent manner.

These can be represented as:

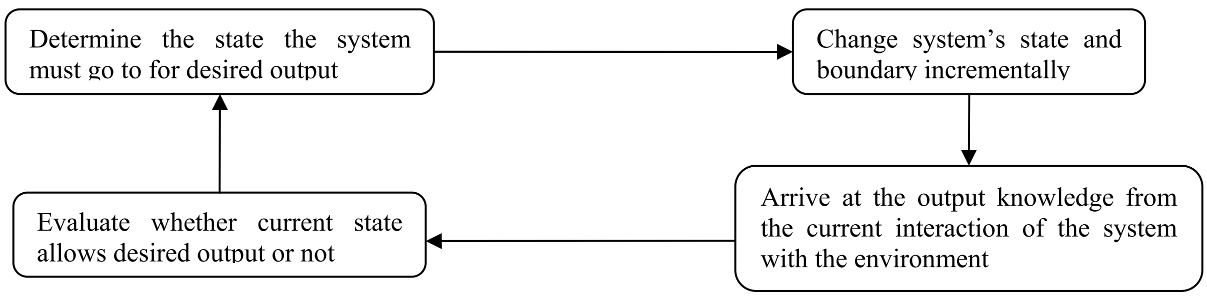


Figure 8: Essential functions of systems with intelligent and interactive information flow

By mapping these functions to the function structure (Step 3, Conceptual Design Phase, Figure 4) for a specific application of the design method, the designer is supported in subsequent decisions, as there is added assurance that functions associated with maintaining intelligence in the information flow have been considered. This will also lend to reduction in the iterations that the designer must go through in order to consider all the functions that the system must fulfill.

Must explore existing solutions as product ideas

As described in Section **Error! Reference source not found.**, a lot of work has been done in developing systems for particular types of application of sensor networks. These need to be explored for product ideas at an early stage. This will save time and perhaps allow for improvements to be made by leveraging upon existing solutions and combining them with either new technology or new architecture and protocol which might be better suited to the environment and application that the network is being designed for. Fortunately, this requirement is more than adequately fulfilled by the existing steps of the Pahl and Beitz design method in the search for product ideas (Step 3, Task Clarification Phase, Figure 4) as well as the search for working principles (Step 4, Conceptual Design Phase, Figure 4)

Must clarify the task with the help of requirements

For any systematic effort to be made towards designing a complex system with uncertainties involved, we must make use of all the information that we have about the system we want to design. These can be included into the design process through requirements. The list of requirements is referred to constantly, and is used as a constantly updated document in order to keep a record of all the assumptions and constraints that we are making in the design process. Once again, the Pahl and Beitz design method already fulfills this requirement with the aid of a working document as a requirements' list (Step 6, Task Clarification Phase, Figure 4), which acts as a core transformation between the first two phases of the design method. The requirements list is a great way to evaluate design decisions as well as the design activities being carried out.

Should categorize the requirements in a way that the categories are mutually exclusive and collectively exhaustive

Categorizing the requirements list will allow particularizing of the design process to a certain class of products. In this case, this class is sensor networks. Creating categories specific to sensor networks will allow the designer to create an exhaustive set of requirements based on reverse engineered knowledge that already exists about sensor networks and their design. These categories can be arrived at through reverse engineering the requirements list for examples of existing sensor networks. Some of the requirements categories which are a subset of such an intended set of categories are already outlined in another requirement for the modified method as shown on page 63.

Must proceed stepwise from the overall abstract of the task to the particulars of the design

This requirement is helpful in two ways. Firstly, it sets up the essential functions that the system must satisfy as the fundamental context within which all subsequent tangible design steps can be carried out, i.e. the designer is assured that the solutions he is looking for are for the correct problems. Secondly, it enables a way to manage the complexity of designing a system. Starting with the fundamental requirements, it compartmentalizes further design activity with the use of function diagrams. In this way a large and complex problem can be treated as modules of smaller problems connected with flows of basic entities such as information, energy or material. In the Pahl and Beitz systematic design method, this is ensured with the use of constructs such as function structures (Step 3, Conceptual Design Phase, Figure 4) and morphological matrices to search for working principles for the functions within the function structure (Step 4, Conceptual Design Phase, Figure 4).

The design method must facilitate milestones in the design timeline

The first reason why this is important is that it facilitates planning and time management for the designer. Secondly, these milestones allow iterations to occur without loss of information. If at a later stage in the design process, a mistake is discovered, it can be traced back to a particular milestone and then a particular design task or assumption made in getting to that milestone, which caused that mistake down the design timeline. The Pahl and Beitz method creates these milestones in the form of core transformations between the 4 different design phases. These are, the Requirements List, the preliminary layout of a principal solution, and then the detailed product documentation once the detailed design is done (Figure 4).

2.3 Synopsis

The requirements for the modified method have been proposed. The justifications provided for each of the requirements tie in to either the advantages or the limitations of the original Pahl and Beitz design method. Thereby, one part of the theoretical structural validity is established. The literature survey carried out for each of the proposed constructs prior to the requirements satisfies the other part of theoretical structural validity. However, to maintain logical consistency, a connection between the constructs and the requirements for modification need to be made.

An evaluation can be made on how these constructs, tools and objects satisfy the requirements that have been identified in Section 2.2. The evaluation is shown in Table 2, where a tick mark indicates a positive qualitative evaluation of whether the corresponding column's construct, method, tool or object satisfies the corresponding row's requirement. Note that the requirements for the design method throughout the thesis are distinguishable as inclined text as compared to other requirements that are discussed in this work.

Table 2: Satisfaction of Requirements for the design method

Requirements	Pahl and Beitz design method	Taxonomy of LST	Modeling and Simulation tools	Graph Theory	SysML
Must design for the environment	✗	✗	✓	✗	✓
Must build functions and concepts on a fundamental information flow and processing representation	✗	✓	✗	✓	✓
Must design for the available technology with respect to input transducers (sensors)	✗	✗	✓	✓	✗
The Requirements List should include the following categories	✓	✗	✗	✗	✓
Function Structure must include an instance of each of the following general functions	✓	✗	✗	✗	✓
Must explore existing solutions as product ideas	✓	✗	✓	✓	✗
Must clarify the task with the help of requirements	✓	✗	✗	✗	✓
Should categorize the requirements in a way that the categories are mutually exclusive and collectively exhaustive	✓	✗	✗	✗	✓

Table 2 continued

Requirements	Pahl and Beitz design method	Taxonomy of LST	Modeling and Simulation tools	Graph Theory	SysML
Must proceed stepwise from the overall abstract of the task to the particulars of the design	✓	✓	✗	✓	✓
The design method must facilitate milestones in the design timeline	✓	✓	✓	✗	✗

The gap within which to design a design method is thus established. Based on the evaluation of the proposed objects, tools, constructs and considering the limitations of my competencies in their application, and the scope of this project, some of them will be actually applied in the proposed design method, while the integration of the others into the design method are left as open research items, and are deliberated upon in the future work section.

Additionally, the theoretical structural validity is established at this point in the thesis. As described in Section 1.4.1, the two main requirements of TSV are the enumeration of requirements and the evaluation of the logical consistency of the proposed constructs, tools and modification in the proposed design method. As described in this synopsis, these requirements have been met.

CHAPTER 3

The Adapted Method

Now that the logical consistency of the structure of the framework has been established, the proposed design method is put forth with justifications for each of the modifications and adaptations made to the original Pahl and Beitz design method.

As described in Chapter 1, there are several steps in each of the design phases of the Pahl and Beitz design method (Figure 4) which the designer must go through to ensure a systematic flow of design activities from the abstract to the specific, to prevent design fixation, and to ensure that the most satisfactory working principles are selected. This flow of information through the design phases is marked by milestones which are considered to be core transformations in the design process. Specific to the chosen focus on systems with interactive and intelligent information flow and seamless integration with the environment, adaptations to the original Pahl and Beitz design method are proposed in this chapter.

In this context, the system is the product that we wish to design using an adapted form of the Pahl and Beitz product design method. The prime functions of this product are to collect information from the environment, and to integrate and store that information as knowledge. In this context, the adaptation of the Pahl and Beitz Design method involves some or all of the following in each of its phases:

- Adaptation/change of existing design steps
- Addition of new steps

- Modification of core transformations between design phases

Each of these is utilized to adapt the design process to better apply to design systems with sensing and interactive information flow between system and environment by satisfying one or more of the requirements that are described in Section 2.2. The modifications to the design steps are highlighted in italics in Figure 9.

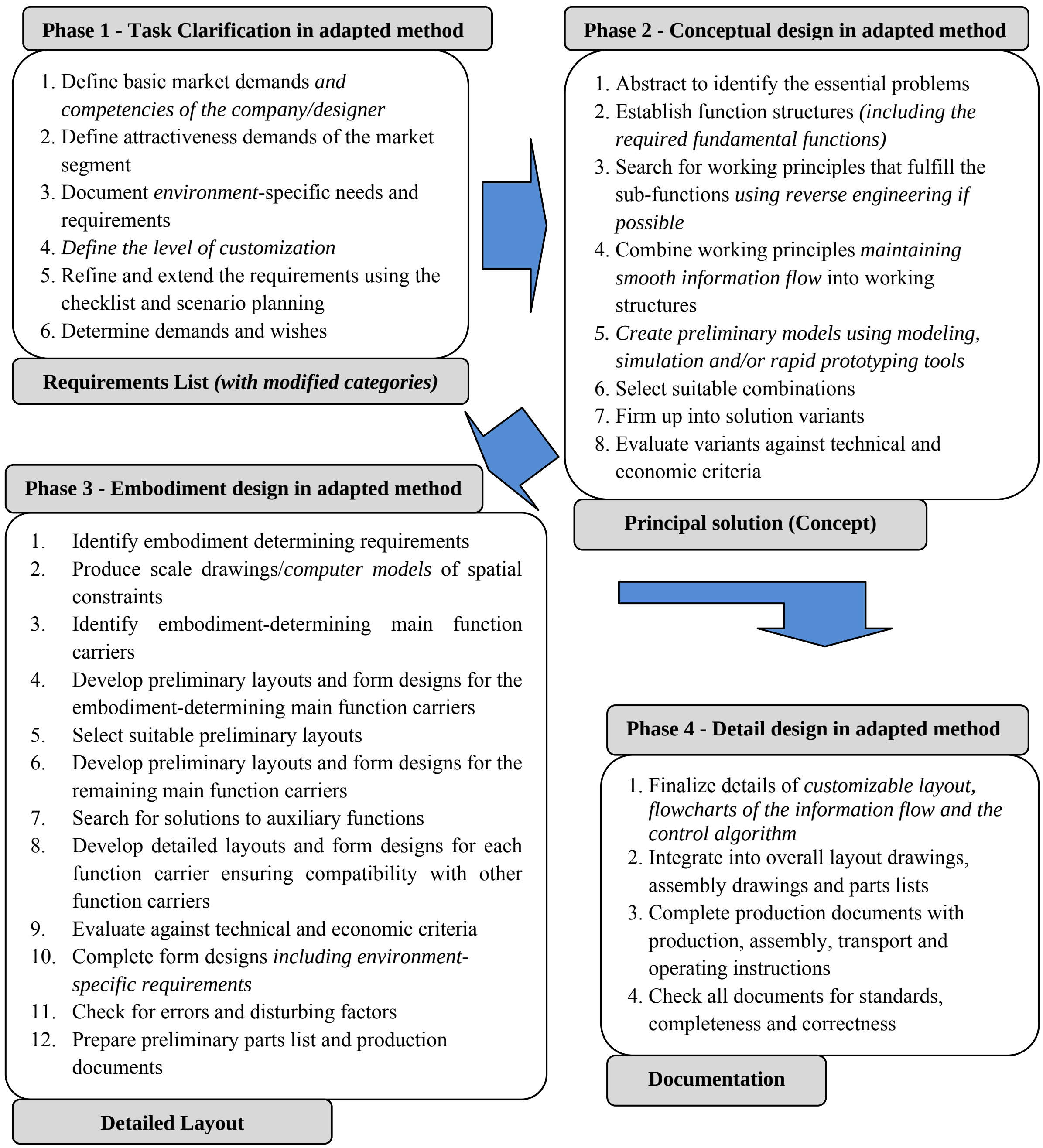


Figure 9: The modified Pahl and Beitz design method

3.1 Task Clarification

As show in Figure 10, there are two additions to existing steps, an additional step and an adaptation in the core transformation that results from this phase of the design viz. the requirements list. These changes are italicized in the figure.

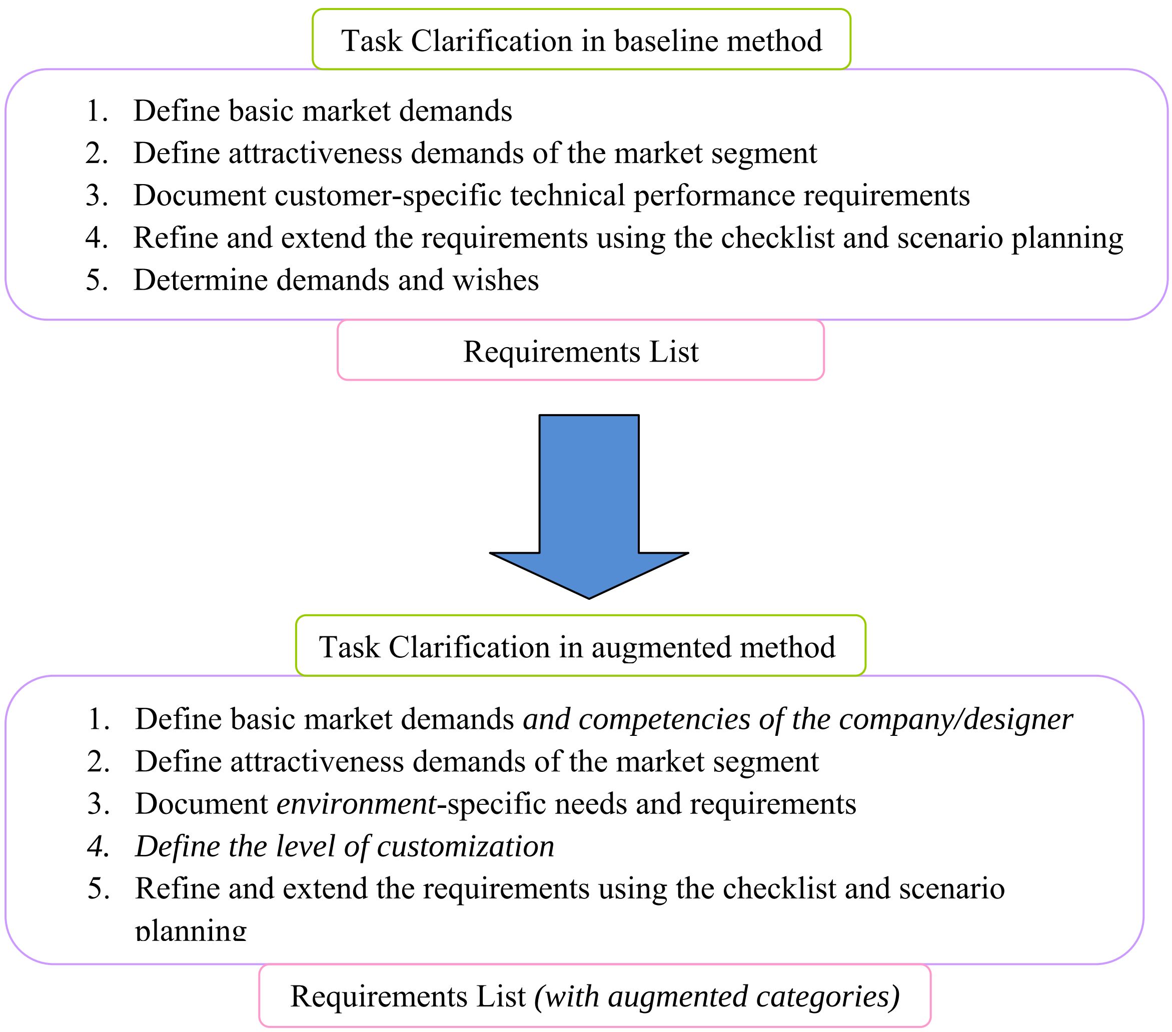


Figure 10: Augmentation of Task Clarification

Step 1: Define basic market demands and competencies of the company/designer: The demands for systems in intelligent applications of sensing and robotics have grown substantially in terms of the variety of disciplines of modern life and in terms of performance requirements [1]. It is impractical to conceive of a design method which can deal with all of them. The robustness of the design method to tackle different disciplines and different environments is greatly influenced by the competencies of the designer. Thereby, it is necessary to take into account what the designer/company can achieve right in the beginning in of the design method to prevent hasty cost cutting measures later on in the design process. In particular this applies to the domain of designing sensing and information capture devices in terms of the following ways:

- Knowledge base with respect to the environment we want to capture information from – A substantial part of the design of a system with the prime function of monitoring the environment would be to acquire parametric knowledge about the environment. In terms of engineering specifications this knowledge would translate directly to parameters and physical constants. It will be up to the designer to identify the parameters that will fit his/her model of the environment and vice-versa.
- Prior experience in design of systems with similar functional capabilities as the ones desired in the present system – This has direct implications in the design, as prior experience applied to a design would make it a variant or adaptive design where modifications or changes can be made to a pre-existing design and approach as opposed to an original design, where the approach has to be developed from scratch.
- Understanding of information flow in sensing functions involved in the particular environment of interest – This is of importance to search for solutions to satisfy

specific functional requirements better. For instance, Wi-Fi and Bluetooth™ communication can both be used to satisfy the requirement for interfacing devices with a computer. In the case of accessing high speed internet, Wi-Fi is a better solution principle, because of the accompanying technology developed which allow it to be usable in corporate and home networks. Bluetooth™ on the other hand offers better functionality for connecting devices and has in fact been demonstrated in the example shown in this work.

Step 3: Document environment-specific needs and requirements: For the specific domain of applications that we have in mind, the customer forms part of the environment. Most applications that are perceived to be of importance today and of continued interest involve human and computer interaction. Some of these applications (as pointed out in Chapter 1) are ergonomics in manufacturing environments [8], crash-test systems [2], ambient intelligence for the home and health monitoring of human subjects [6] etc. User-specific needs in these systems form a subset of the environment-specific needs and requirements. It is necessary to include other factors of the environment in systems involving sensing and information capture. These may be physical parameters such as temperature, pressure and atmosphere or intangible parameters such as level of intrusion, visibility, customizability etc. The change in this step from Step 3 of Conceptual Design Phase in Figure 4 is basically in the focus on the environment-specific needs and requirements.

Step 4: Define level of customization: Mass customization is a concept for which the marketing and manufacturing community is largely responsible[8]. Designers can no longer ignore the important ramifications it has on selection of product ideas and implementation of embodiment and detail design. Thereby, it is an important consideration that must be taken into account in the very beginning to have an effective part to play in the design of the product. Its merit in application to sensor networks and systems with information capture and integration cannot be overstated. The prime functions of such systems involve observation, monitoring and feedback amongst other forms of interaction with humans. Many of them have the primary objective of catering to individuals. Thus, it is essential that these systems be designed with the custom requirements of the individual in mind. During the earlier stages of design, we can define the level of customization we wish to achieve as an ambition in terms of satisfying a larger section of the global market, and to make our product relevant in a large number of applications and environments. This is an additional step in the task clarification phase and is not present in Figure 4. However, it is shown in the appropriate place in Figure 9.

Requirements List with augmented categories:

A key aspect of designing an intelligent system is to incorporate the ability to analyze, compare, evaluate and thereby make decisions into the system. In order to do design these abilities into the system, a designer needs to make sure all the requirements that need to be fulfilled in order for the system to answer decision based questions are included in the requirements list for the particular system. One step towards ensuring this would be to identify the key requirement categories which must be included in the

[8] http://en.wikipedia.org/wiki/Mass_customization

system's requirements list, thereby ensuring a thorough consideration of all aspects of the function that the system needs to carry out.

Note that these requirement categories are not exhaustive. In certain applications there maybe reclassification or addition of other categories required. For example, in an Ambient Intelligent System for targeted customer services, customer preferences such as visibility and intrusion will be important requirement categories. Thus this step does fulfill the requirement for including the abstracted categories from the general characteristics of systems with intelligent and interactive information flow, but does not fulfill the requirement of maintaining categories which are mutually exclusive and collectively exhaustive.

3.2 Conceptual Design

As show in Figure 11, the proposed changes are two additions to existing steps, and an additional step. These changes are italicized in the figure.

Conceptual design in baseline method

1. Abstract to identify the essential problems
2. Establish function structures
3. Search for working principles that fulfill the sub-functions
4. Combine working principles into working structures
5. Select suitable combinations
6. Firm up into solution variants
7. Evaluate variants against technical and economic criteria

Principle solution (Concept)

Conceptual design in adapted method

1. Abstract to identify the essential problems
2. Establish function structures *(including the required fundamental functions)*
3. Search for working principles that fulfill the sub-functions *using reverse engineering if possible*
4. Combine working principles into working structures
5. *Create preliminary models*
6. Select suitable combinations
7. Firm up into solution variants
8. Evaluate variants against technical and economic criteria

Principle solution (Concept)

Figure 11: Adaptation of Conceptual Design phase

<u>Step 2: Establish function structures (including the required fundamental functions):</u> Tying in to the discussion on the second research question (Section 1.2.1), there are certain fundamental questions that we identified that the designer must ask in order to make the system intelligent with respect to information flow. A discussion is also provided under the specific requirement for the modified method on page 66. Based on

that discussion this addition is made to Step 2 of the conceptual design phase as shown in Figure 9 and Figure 11. A careful abstraction of these questions reveals them as instances of application of cognitive skills pertaining to basic human intelligence. The skills are classified based on the cognitive Bloom's Taxonomy, which is a categorization of the domains of learning in human beings [68]. Bloom's Taxonomy identifies six basic categories of cognitive skills: knowledge, comprehension application, analysis, synthesis and evaluation. In the case of the function structure for intelligent systems, four of these skills are absolutely necessary. These skills are application, analysis, synthesis and evaluation. The system we design must possess instances of these skills identifiable as basic functions and are largely irrespective of the application that we are designing the system for. The only assumption being made is that the system must convert information from the environment into knowledge about the environment in an intelligent manner. The intelligence is implicit in that the functions are instances of application of skills that only an intelligent being is capable of. These are represented in Figure 12.

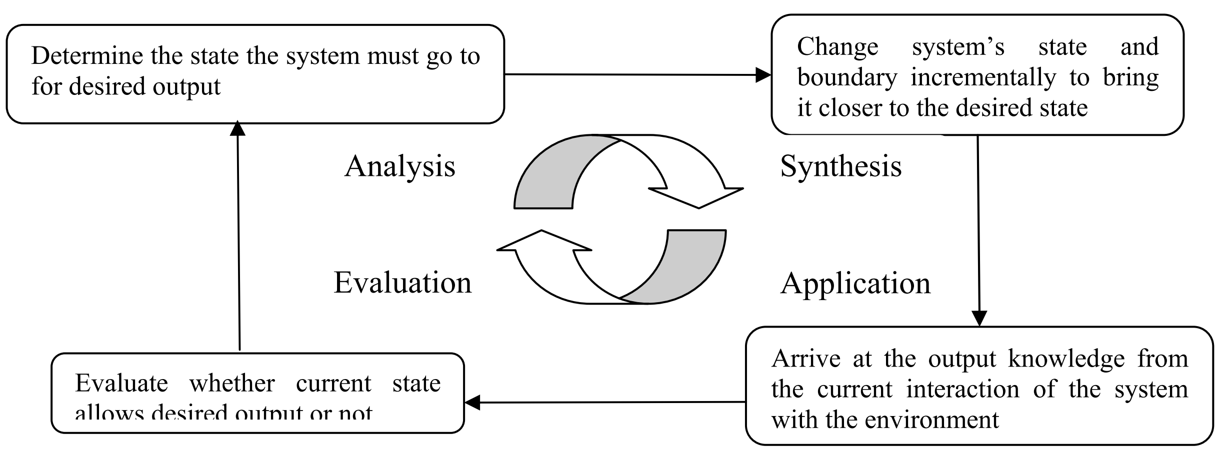


Figure 12: A mapping of intelligence to fundamental functions that the system must satisfy

A system which is exchanging information actively with its environment, must constantly update its state with respect to the parameters which determine how it will collect the information, where it will collect it from, and what information does it need to collect. The attribute of built in intelligence that is thus implicit in the functions above can be explained as follows:

Determine the state the system must go to for desired output: This function is in the top left box in Figure 12. For instance, in emergency and alarm systems with ambient intelligence, researchers are looking for solutions where vital functions like the pulse and blood pressure of human subjects are read out in short time intervals wirelessly. A strong deviation from standard values of these parameters is evaluated automatically, and prompts changes in the system's monitoring urgency, and its focus on what parameters to monitor and evaluate thence. In addition, the system must also automatically send an alarm signal to an emergency service station. [5, 7] An integral function in such a system would be to judge whether the subject being monitored is afflicted or not. An analysis of the vital parameters being monitored is thereby necessary to reach the desired "output" viz., the judgment whether the person is afflicted or not. In order to reach this output the system must determine the change or at the least the direction in which its state variables should move. These variables define the information it collects, the number and types of sensors it uses to collect the information and parameters such as the frequency and accuracy with which it must collect that information.

Change system's state and boundary incrementally to bring it closer to the desired state: This function is in the top right box in Figure 12. For a system whose primary function is to collect information from the environment and integrate it to create knowledge, the change in its state variables will require a change in the system's state and its boundary. A tangible way to consider this function is to consider sensors in physical space. We wish for these sensors to work mostly in a decentralized fashion with an intelligence in their network, which is able to decide upon factors such as which sensors need to be active at what time, and where should the sensors move (in the case of mobile sensors) to ensure complete coverage (spatial and functional). One way to model this functioning of the network is to consider different scenarios as different states with different boundaries. In one particular situation 'm' out of 'n' sensors can be functioning which may be considered as part of the system[9] and thus the boundary is defined between these 'm' sensors and the environment they are monitoring. In another scenario this number and the particular sensors making up the active number may differ. Thus, the boundary of the system will differ. In this manner, the problem can be made tangible at the design stage. In other control scenarios, event based or time based control [20-22] of boundaries is also a possibility, as discussed under the first research question. This change in the state and boundary follows as a result of the analysis that is carried out in the previous functional step. It involves a proposition in terms of where the system must go from its existing state based on the analysis. This action forms an instance of the higher order skill viz. synthesis.

Arrive at the output knowledge from the current interaction of the system with the environment: This function is in the bottom left box in Figure 12. The actual collection of information and its integration falls into this category. This is largely an instance of application of the functions that the sensors, the sensor network architecture and the

---

[9] Based on the definition of "system", "environment" and "boundary" given in the mission of this work

wireless network architecture can fulfill based on their technological and communication capability.

Evaluate whether current state allows desired output or not: This function is in the bottom right box in Figure 12. As mentioned earlier, the system must constantly update itself to ensure that the correct information is being collected in the best possible manner, and it is being integrated to provide the knowledge that is required of it. This update has to be done on the basis of an evaluation whether the system is fulfilling all its requirements for the desired output or not. Thus, the functional capacity of the system must include an evaluation of its present output state against its desired output state. In most cases, this can be visualized as a discrete time function where after small intervals of time, an evaluation is carried out against a library of requirements within the system. This is perhaps the strongest demand that is made in terms of intelligence of the system.

Implicitly, these functions will form the basis for the primary functions in the function structure for our systems.

Step 3: Search for working principles that fulfill the sub-functions using reverse engineering if possible: Working principles "reflect the physical effect needed for the fulfillment of a given function and also its geometric and material characteristics." [15] One of the key motivations for this research is to apply innovative and cross-disciplinary solutions to problems in intelligent sensor network designs. One way to make this happen is to identify working principles across disciplines which at the conceptual level satisfy similar functionality and are perhaps implicitly more effective in overcoming some of the drawbacks or problems that existing solutions in the domain of interest (sensor networks, information flow systems) are beset with. This process is an application of reverse engineering. **Reverse engineering** (RE) is defined as the process of discovering the technological principles of a device, object or system through analysis of its structure, function and operation (Wikipedia).

Reverse engineering can speed up the process of multi-disciplinary research. Often advances in one domain and the resulting solutions thereof are made applicable to problems in other disciplines. Graph theory itself is a perfect example. It sprung from the study of bridges, onto theoretical chemistry, to topology in general, and thereby was adapted for application in designing network algorithms.[53, 69-70] A key requirement for designing network algorithms was to make the interaction geometry between agents explicit, which was seen as a task too difficult to be worth the effort. An alternative view was adopted viz., to treat interactions as purely combinatorial. As shown in Section 2.1.3, graph theory turned out to be a very powerful working principle to match these requirements [53]. Thus, such a process can be captured as an assertive step in a design process by ensuring the reverse engineering of any solutions that seem to fulfill requirements of the design. In addition there are other advantages of reverse engineering such as interoperability, retrieval of lost documentation, product analysis, security auditing, and building competitive technical intelligence[10].

<u>Step 4: Combine working principles, maintaining smooth information flow, into working structures:</u> An addition is made to Step 4 of the conceptual design phase where working principles are combined to formulate working structure alternatives. This addition falls in line with the requirement that the design of the system must be based on a fundamental

[10] http://en.wikipedia.org/wiki/Reverse_engineering

information flow diagram. The justification for the same was provided in detail in Section 2.2. The working principles must be combined to ensure the physical and geometrical compatibility of the working principles to be combined, which in turn ensures the smooth flow of energy, materials and signals as indicated in the function diagram.[15] An important factor of compatibility in our system is the information flow. We need to ensure that the information flow is possible in real time, with the least amount of loss and with the least amount of effort in the form of external energy or material input from the environment to the system and then within the system to its memory or the processor.

In order to extract common approaches to systems which require the explicit consideration of information flow as one of the key factors determining compatibility amongst its working principles, we leverage the theory of living systems. As described in Section 2.1.1 the theory supports the use of generic subsystems based on the manipulation and transfer of matter, energy and information [18]. These generic subsystems can be used to represent the flow of information in systems which gather information from the environment and integrate this information to create knowledge about the environment. A symbolic representation developed by Shupe [24] is used for the information flow through the system (using the generic sub-systems proposed by Miller [19] is shown in Figure 13.

A flow diagram represents fundamental predictions on the way the information flow can be affected through systems which monitor the environment. Only those sub-systems are extracted from the entire taxonomy of sub-systems which are essential for input, transfer, processing and output of information. This is done to align the conceptual design of the system with the intended focus on the information flow. Information is expected to flow into the system from the environment through one or several input transducers. The processing units might yet require decoding of the information (e.g. into assembly language), which is done by the decoders.

The processing involves system learning (associator), decision-making (decider), storage (memory), and tracking of time steps if the information cycle is in the form of discrete time steps (timer). Thereafter, the information is encoded into other forms for easy interfacing with the user/designer. The encoded information is then outputted through the output transducer.

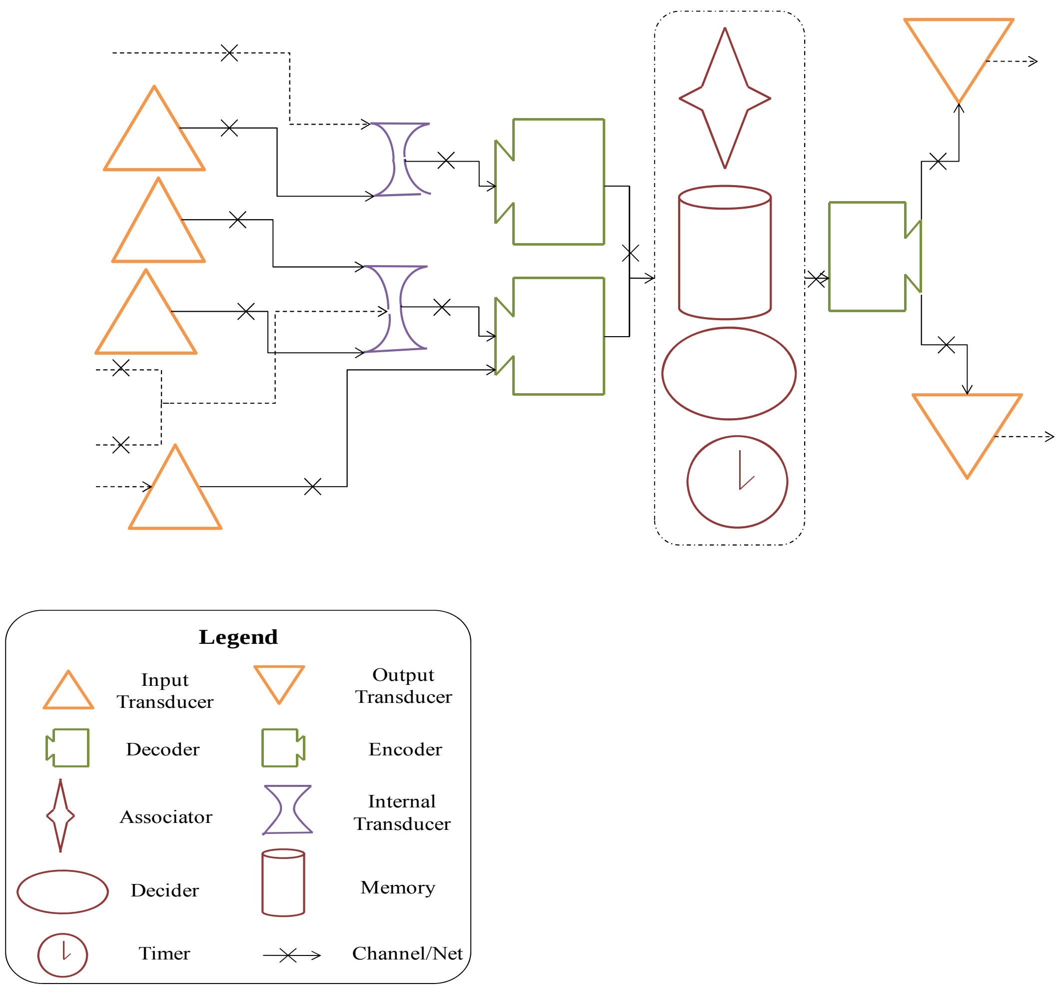


Figure 13: Generic information flow diagram using Shupe's symbolic representation [24]

The particular arrangement in the figure is merely an example which can be intuitively attributed to many sensor network systems. The actual arrangement can differ for the particular application in the following ways:

- Number of a type of generic sub-system
- Number of layers of the internal transducers, decoders and processing components

It is essential however that for the domain of applications that are the focus of this work, a layer of input transducers mark the flow of information from the environment to the system, and a layer of output transducers marks the opposite.

In order to ensure that further design steps are based on the fundamental layout of the information flow diagram, we should identify the decisions that need to be taken in order to complete our model or layout at discrete points in the information flow diagram. Each of these decisions will involve a design activity either in the form of optimization, simulation, or drawing solutions from literature, a database or the state of the art. For example:

- For the transmission of information through a channel between any two sub-systems, there are issues of maintaining accuracy, and minimizing error.
- The coverage aspect comes into play at the input transducer. Both the information flowing into it from the environment, and the information flowing out of it into internal transducers, will be checkpoints for coverage requirements.

Several other design activities might correspond to other specific points in the flow diagram, depending on the requirements and the function structure, and the information flow diagram itself. In this way, representing the working structures in the form of information flow diagrams will allow us to approach the modeling of physical components, and geometric relations in the context of maintaining the information flow, the way we want to.

Step 5: Create preliminary models: This is a new step that is added to the conceptual design phase and is shown in Figure 9 and Figure 11. In order to select a principle solution (concept), it is important that we construct preliminary models of our solution variants, or working structures. This is a step which is not included in the Pahl and Beitz design method, but is especially relevant given the sophisticated modeling and simulation tools that are available in design and engineering disciplines today. These will help us evaluate the solution variants with visual aid. They might help us identify obstacles to the field of vision of a sensor for example. If identified in the early design phases, a correspondingly wiser selection of the principle solution can prevent wasted effort in re-design during the later stages of the embodiment phase, or the detail design phase. Depending upon the detail described in the working principles, these can vary from a simple solid model to a complete finite element analysis of the geometry, to a simple prototype as well.

3.3 Embodiment Design

As show in Figure 14, the proposed changes are two additions to existing steps. These changes are italicized in the figure.

Embodiment design in baseline method

1. Identify embodiment determining requirements
2. Produce scale drawings of spatial constraints
3. Identify embodiment-determining main function carriers
4. Develop preliminary layouts and form designs for the embodiment-determining main function carriers
5. Select suitable preliminary layouts
6. Develop preliminary layouts and form designs for the remaining main function carriers
7. Search for solutions to auxiliary functions
8. Develop detailed layouts and form designs for each function carrier ensuring compatibility with other function carriers
9. Evaluate against technical and economic criteria
10. Optimize and complete form designs
11. Check for errors and disturbing factors

Definitive layout

↓

Embodiment design in adapted method

1. Identify embodiment determining requirements
2. Produce scale drawings/*computer models* of spatial constraints
3. Identify embodiment-determining main function carriers
4. Develop preliminary layouts and form designs for the embodiment-determining main function carriers
5. Select suitable preliminary layouts
6. Develop preliminary layouts and form designs for the remaining main function carriers
7. Search for solutions to auxiliary functions
8. Develop detailed layouts and form designs for each function carrier ensuring compatibility with other function carriers
9. Evaluate against technical and economic criteria
10. Optimize and complete form designs *including environment-specific requirements*

Definitive layout

Figure 14: Adaptation of the Embodiment Phase

Step 2: Produce scale drawings/computer models of spatial constraints: This is an addition to take advantage of solid modeling and computer aided design software which can be used for effective and efficient model creation. It is better to use computer models, as parameters can be changed easily to study different layouts. Parametric models of spatial constraints can be created with ease using modern solid modeling software. A characteristic of the dynamic systems in consideration in this work is that spatial constraints may be moving and evolving. Parameterization of models is even more crucial in such systems to predict their behavior and thereby evaluate them better.

An additional aspect of the design of networks is the constraints on the communications and the connections that are possible between the agents of the network. Mesbahi and Egerstedt [53] identify the common thread in a number of examples from distinct disciplines ranging from swarms of social animals, formations of unmanned aerial vehicles, sensor networks, nano systems etc. to be a set of fundamental system-theoretic attributes. In their work [53], they explore and propose ways to model and control these multiagent systems with graph theoretic methods. As pointed out in Section 2.1.3 algorithms can be created for the optimal and adaptive control of networks. Note that, though these algorithms may not directly represent spatial algorithms, but in a layout for a sensor network, or any collection of agents collecting information, system controls will need to be designed with the spatial constraints hard-coded or at the least integrated into the algorithms.

Step 10: Complete form designs including environment-specific requirements: The addition of environment-specific requirements has been included to reinforce that the designer must design for the environment. The systems which are our focus need to be geared for the environment they are built for. The environment dictates the functionalities that the system must fulfill, and the performance metrics of the system.

3.4 Detail Design

As show in Figure 15, the proposed change is additions to an existing step. The change is italicized in the figure.

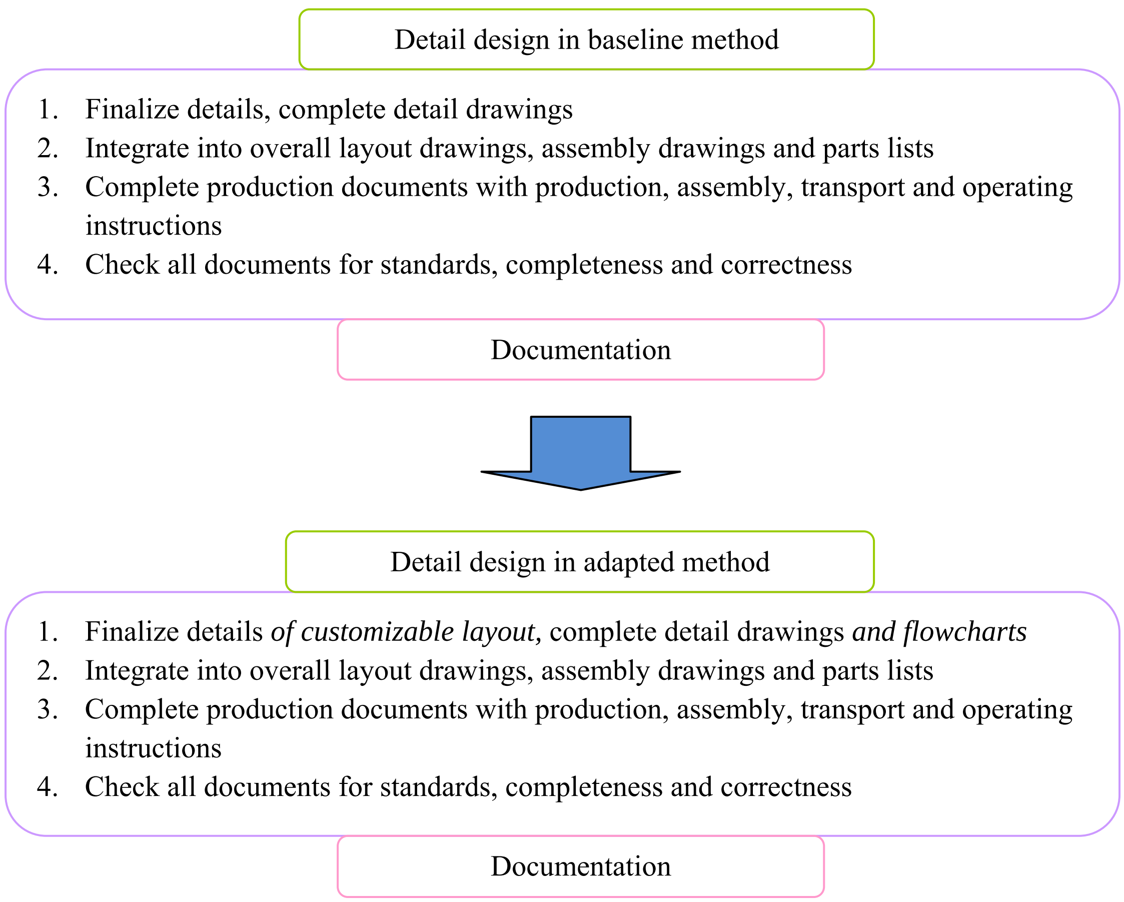


Figure 15: Adaptations in detail design

<u>Step 1: Finalize details of customizable layout, flowcharts of the information flow and the control algorithm:</u> The changes for this step are made in the first step of the detail design

phase. As pointed out in the task clarification phase, it is essential that these systems be designed with the custom requirements of the individual in mind. The customization built into the system must be reflected in the final details and layout diagrams. Moreover, since we are in the process of designing systems with sensors, perhaps robots, or any type of information gathering agents, we must design the control and network (if there are more than one of them) architecture as well. Thereby, a logic diagram, a flowchart, or an algorithmic representation needs to be included in the final layout and details of the product.

3.5 Synopsis

In this chapter a modified method has been proposed. The modifications were made in the context of the characteristics of the domain of applications in sensing, networks, and intelligent decision making systems and the proposed tools and ontological objects in this work. In the context of theoretical structural validity, both the research questions have been answered. Constructs have been proposed for adequate representation of systems with intelligent and interactive information flow at different levels of abstraction within the Pahl and Beitz design method. Each of the constructs were supported by a literature survey. Based on the requirements for the design method for design of systems with intelligent and interactive information flow, modifications were made to the Pahl and Beitz design method including the usage of these constructs. The modifications were justified with references to the requirements. At this point the hypotheses that were set out in Chapter 1 have been elaborated and justified with references and explanation. In the next chapter the validation of these hypotheses is carried out in the context of the validation square. The validation includes the design of an example system, i.e. the Nintendo Wii™ based motion capture system.

CHAPTER 4

Validation

A condensation of the validation context adopted in this work is now presented. Though several references have been made whenever a change or something new has been suggested, the proposed constructs and the modified design method need to be validated further. Thus, in order to validate the decisions made in this work, and the performance of the proposed design method, the validation square's quadrants will be described in context of this work and satisfaction of requirements within each will be detailed in this chapter. As identified in Section 1.4.1, the validation square is a rigorous framework that can be used for validating engineering design methods [29-30]. Though the supporting discussions and justifications for each of the quadrants of the validations square are distributed over this entire document, a condensed discussion with references to sections which support the claims of validation of each of the quadrants will be provided in this chapter.

Based on the discussions and research so far, the theoretical structural validity (quadrant 1 of the validation square, Figure 5) can be established. Before we can approach the empirical validity (Squares 2 and 3) however, the design example is presented with the step by step progression of the design phases of the proposed design method.

The adapted Pahl and Beitz design method is applied to the layout design of a motion capture system based on the Nintendo Wii Remote™ platform. The example problem chosen has to satisfy some key characteristics that form the context for this work. Some of the key characteristics and a preliminary discussion on how the chosen problem satisfies them are provided in Table 3.

Table 3: Appropriateness of the chosen problem based on the characteristics of systems with intelligent and interactive information flow

Characteristic	Discussion and justification
Lack of cost effective solutions	In general, motion capture devices for humans, and the wrist joints in this specific case already exist. The Wii Remote™ however offers the promise of a low cost and an accurate objective data capture system. With a simple attachment the Wii Remote™ can capture full 6 degree of freedom (DOF) data given 4 light emitting diode (LED) emitters [71]
Multiple interacting sensors	In the system proposed two distinct kinds of information need to be collected. One is the objective wrist angle data, and then there is the corresponding muscle activity resulting in the arm due to wrist motion. Thus there is a need for more than a single sensor. In addition to the Wii™, an Electromyography (EMG) unit needs to be integrated into the system for capturing muscle activity
Communication issues	The Wii™ is meant for use with the Nintendo console. However, the need for interfacing it with a computer is clearly felt in this project. Furthermore, the EMG data collection needs to be synchronized with the Wii™'s data collection. It is anticipated that these requirements and others that come up in further analysis will directly relate to communication issues and will require working principles in communication standards and software
Human- computer interaction	This is an obvious characteristic of the propose example problem, as the system will require a processor and a storage medium in the form of a computer, whereas the very environment that will be monitored is a human
Large amount of information generated	The Wii Remote™ sensor works at a 100Hz frequency. Given some processing time, the data generation is still going to be substantial for each subject. EMG data will abound as well. It is anticipated that after complete development, if successful, this system can be used to train workers, and create best practices in terms of wrist motions, knife grips and supports for workers in a poultry manufacturing plant. Thereby, data will be collected in quite abundance for each human subject that uses the system.

4.1 The example – Design of a motion capture system to facilitate reduction of wrist injury

Based on the preceding evaluation of the appropriateness of this problem in the context of validation, the example system will be designed step by step of the modified method. The validation square is shown again (Figure 16) in order to clearly define the contextual relationships between the constructs proposed in this work, the modified design method and the example problem chosen.

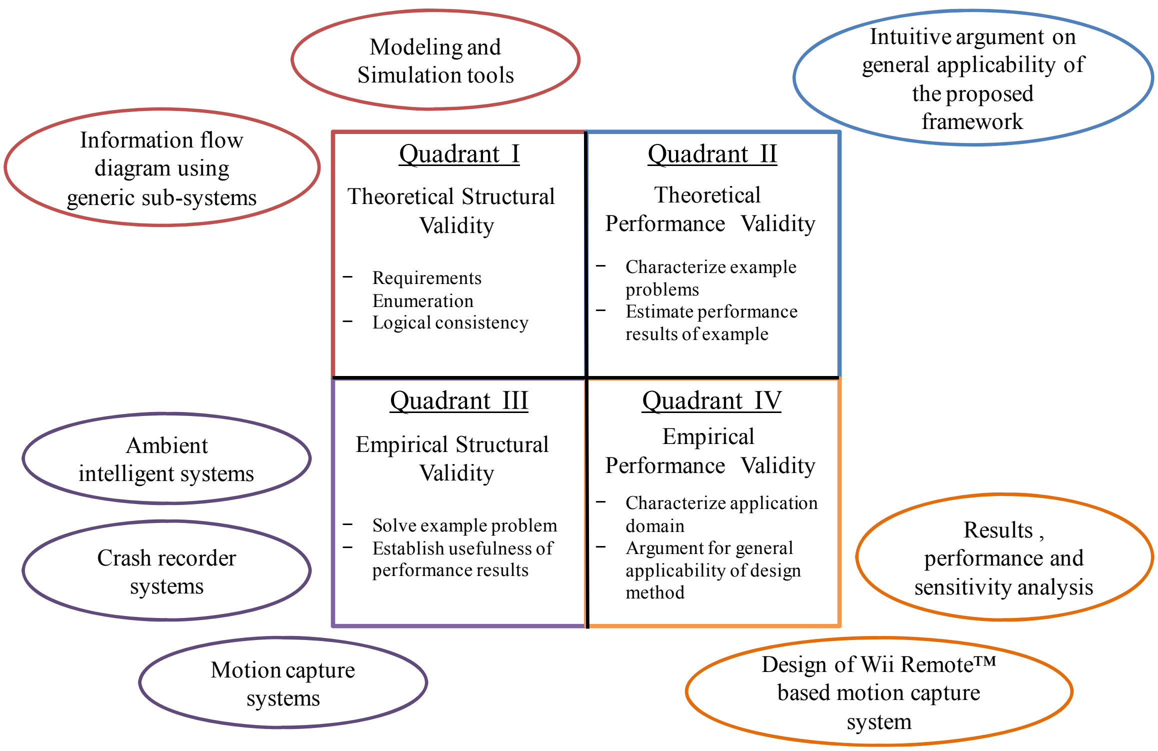


Figure 16: Contextual relationships - The validation square for the design of systems with intelligent and interactive information flow

This figure is a concise representation of all the propositions in this work and will be justified through the design example as well as intuitive arguments made at the end of this chapter in the context of the validation square. However, the visual relationships drawn in the figure will help maintain connectivity of reason and logic behind the arguments that are posed for empirical performance validity as well as theoretical performance validity. In the subsequent sub-sections, each of the design phases are carried out stepwise.

Some of the steps of the design method are augmented for the particular platform of the Wii Remote™ and the particular environment of wrist motion. Some steps have been precluded because in some cases, the complexity of the design to be tackled in the omitted steps is dealt with in prior steps. The information which the system is being designed to gather is objective wrist motion data in human subjects, in order to aid in designing risk reducing practices and training exercises for workers in the poultry manufacturing industry. In order to produce a complete implementation within the constraints of resources on this research work, the system chosen as an example is not as complex as a full blown AmI system with a large number of sensors, but a simpler system with a few interacting sensors, and information exchange between the environment and system.

4.1.1 Task Clarification

Step 1. Define important market demands and competencies of the WII Remote™ and how it can be adapted to these demands

Motion capture systems can be found in many types ranging from acoustic, magnetic, optical and prosthetic based systems [72] but many of these systems are prohibitively expensive. There is thus a demand for low cost motion capture systems. By leveraging the substantial capital already invested into market-pervasive gaming technologies like the Nintendo Wii™, it is now possible to provide realistic, agile, and timely assessments of human motion. This transformative power allows for the potential of greater collaboration possibilities, enriched 3-D modeling and simulation, and improved business processes while allowing for greater unobstructed hands-on involvement of the test subjects. The Wii™'s capabilities of 3-D motion capture can easily be integrated with other human motion quantifiers such as muscle activity, and nervous activity. This is facilitated by the ease of converting the data that the Wii™ captures through Bluetooth transmission to a computer. Muscle and nervous activity associated with motions that the Wii™ captures can be monitored using Electromyography (EMG) techniques. "Electromyography (EMG) is an experimental technique concerned with the development, recording and analysis of myoelectric signals. Myoelectric signals are formed by physiological variations in the state of muscle fiber membranes." [73] It is a way to measure performance of the muscles and make informed decisions in surgical operations, or training exercises for muscles, and has been used extensively in ergonomic studies. The EMG signal is based upon action potentials at the muscle fiber membrane resulting from depolarization and repolarization processes which are actuated by excitation in motor nerves induced by the central nervous system or reflex. Thus any motion that is voluntary or involuntary produces the action potential which can be picked up by EMG probes.

As compared to Step 1 of Task clarification in the original design method (Figure 4) this step has been modified to include a focus on a particular platform, viz. the Wii Remote™ and a consideration of the competencies of the designer in terms of what can be done with this platform at the present time. This is in line with requirements posed for the modified method, specifically the following:

- *Must design for the available technology with respect to input transducers (sensors)*
- *Must design for the environment*

<u>Step 2. Define attractiveness demands of the market segment</u>

The attractive demand of the Wii™ platform as a standalone motion capture system is the low cost and easy to use implementation of the system. There are products available which combine the ability to detect muscle movement, measure motion specifics and then use feedback offer training to the subject who is using it. These come in the portable form too and as such are convenient gadgets when training a single muscle movement at a time. However, these products are typically expensive. For example, the MyoTrac Portable Muscle Monitor costs nearly $500 [74]. In laboratory setups as well, the use of dynamometers, and a controlled actuation of the wrist motion make them unfit for application in the real world as a system. The data that the system is used to gather in such cases is useful, but the repeatability and real time usage of the system in order to create knowledge about the environment, viz. the wrist and the arm of the subject is limited. Instances are work done by Keir and co authors in [8, 12-13] and Morse and co authors in [75].

The Wii Remote™ typically costs less than $45. Expenses of the LEDs, the wiring and the rest of the setup to achieve similar functionality are expected to total to a maximum of $100. Note that this cost does not include development or testing cost. Thereby, its attractiveness lies in the possible low cost implementation. In addition, the Bluetooth functionality of the Wii™ makes it perfect for integrating with other detailed information on the muscle activity which can only be collected using an EMG unit. The ease of use, light weight and accuracy of the Wii™ allows for customizing the system to capture data from different joints and parts of the body. Muscle monitors in the market normally cater to a specific area of the body, and often pose a tradeoff between the weight and the functionality; prioritizing one normally leads to a compromise on the other.

This step corresponds to the original method itself, and no adaptation was required for this step. However, its relevance in this particular design is notable towards fulfilling the requirement that the design method must design for the available technology in the input transducer (sensors).

Step 3. Document environment-specific needs and requirements

The environment consists of human workers in a poultry manufacturing plant facing risks of wrist injuries due to repetitive and prolonged wrist motion. Specifically instances of Carpal Tunnel Syndrome (CTS) are particularly high. Carpal tunnel syndrome is associated by symptoms and signs, which are caused by compression of the median nerve traveling through the carpal tunnel[11]. Though specific causality between work related activity and CTS has not been established, a review by the National Institute for Occupational Safety and Health (NIOSH) indicated that job tasks that involve highly repetitive manual acts or specific wrist postures were associated with incidents of CTS. It

[11] Scott, K.R., Kothari, M.J., *Treatment of carpal tunnel syndrome*
http://www.uptodate.com/patients/content/topic.do?topicKey=~wx2xecoDuYz0gp&selectedTitle=1~107&source=search_result

affects individuals through pain, paresthesias, numbness and tingling sensations from the arm extending onto the shoulder and neck area. Addressing factors such as repetitive use of the arm have been found to improve comfort in some studies [76]. This problem affects 0.1% of the general population and as many as 15% of workers in high-risk industries [77]. To identify training and best practices, we require objective data capture of the wrist motion of these workers while they work, preferably over a large portion of their working hours.

There is thus a need for the system to be portable, so that it isn't necessary for them to move from their working place. Moreover, the system should be as little intrusive and lightweight as possible, thereby causing the least discomfort to the workers. We will have to design the system to capture relative motion between the arm and the wrist since the wrist angles are the physiological measures of interest. In addition to the wrist motion capture, the effect of repeated motion on the muscles in the human carpal tunnel needs to be monitored. In previous work [9] related to statistical study of CTS in floor cleaners, the authors have concluded that repetitive flexion, extension and circumflexion of the wrist and hand grip are possible reasons for developing CTS. Flexion and extension of the wrist are shown in Figure 17.

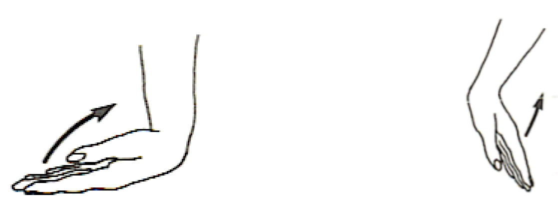


Figure 17: Left – Flexion; Right – Extension (*Courtesy: http://www.brianmac.co.uk/musrom.htm)*

In another study Bekkelund et al. reported a study of 42 floor cleaners and 41 controls (secretaries), wherein compared to the secretaries, the cleaners had larger sensory distal latencies and increased heat and cold threshold of the median-nerve. Distal latency[12] is the interval between the stimulation of a compound muscle and the observed response. Larger sensory distal latencies has been shown to indicate a characteristic in people suffering from CTS [78].These factors can be characterized with the aid of EMG probes on the arm of the human subject. Prior knowledge about the history of the environment which is the arm of the subject can be incorporated into this characterization with a comprehensive understanding of the effect of the workplace on a population in general. At the same time, every human arm would be different in its thickness, the latencies that the EMG can pick up, and the level of muscle activity that the probes can detect depending on fitness levels and other factors.

This step was modified to include a focus on the environment specific needs and requirements as can be seen from Figure 10, where the evolution in the steps of the task clarification are clearly shown. The requirement fulfilled in this case is that the design method must design for the environment. Its implications are clear in the fact that the EMG sensor is already identified as a working principle at this early stage of design. A realizable form of the design is made possible making the product's realization all the more possible.

Step 4. Define the level of customization

[12] http://medical-dictionary.thefreedictionary.com/distal+latency

The Wii™ platform as a platform for a motion capture device which can be used for training workers in the manufacturing environment is to be explored. However, there is an opportunity here to make the device capable of motion capture for any environment. The needs and requirements imposed by the environment are not restrictive of the functions that the platform can be used to fulfill provided the system is non-intrusive, low-cost and can be used to capture relative motion. These are requirements that are common to many applications of motion capture devices. In order for the system to be usable in other applications, it is desired that the design freedom be fixed only with respect to these fundamental requirements. For example, in ambient intelligence researchers are looking at wearable computers and smart clothes based on examples given in the ISTAG report "Scenarios for Ambient Intelligence in 2010" [5, 7]. Benini et al. observe trends in sensor networks based on the "disappearance" criterion where wireless sensor networks are moving from obtrusive, to symbiotic and bio-hybrid implementation [6]. Thus the applicability of a Wii™ based motion capture system to other environments is expected.

Within the environment and application of interest, a factor of customization is the human subject who will use the system. The motion capture must be possible for different people with the same system. Since the capture of the motion of the wrist is of interest, the system layout must be built in a way that it can be adapted to the person's upper limb's geometrical and muscular features.

The Wii™ remote itself offers a number of functionalities which can be taken advantage of in a modular fashion. A Nunchuk attachment to the Wii™ for instance, adds three degree of freedom data thereby making the augmented device a complete 6 DOF motion capture device. Moreover, since the Bluetooth™ data that the remote sends out can be easily manipulated, each button on the Wii™ can be used as a functional input, thereby enhancing the interaction between the user and the device and thereby the computer as well. In this effort however, the Nunchuk attachment is not used, since the requirement is for 3 DOF data in the form of the wrist angles.

A degree of customization can be incorporated at the point where the sensors' work is done, and the information is made accessible. The form of the information in which it is integrated into knowledge can be tailored to create different types of analyses. Sensitivity, accuracy and precision issues can be researched. For different scenarios, which can range from monitoring different joint motions to placing the EMG probes at different locations, the information can be converted to different forms to perform more meaningful analyses for the particular scenario in consideration.

This step is an addition to the original Pahl and Beitz design method and relates directly to the requirement that the method must design for the environment. Several factors of uncertainty such as the geometrical parameters and responsiveness of different individuals are clearly identified and have been matched to design options in the form of customization requirements. Thereby, the merit of including this requirement is demonstrated by including this step in the modified method.

<u>Step 5. Refine and extend the requirements using the checklist and scenario planning</u>

The Pahl and Beitz design process provides a comprehensive checklist in order to ensure that a large number of aspects can be considered during the planning stage of a design. This checklist provides categories of requirements for planning the design which have been abstracted from mechanical systems. However, they can be applied to any system in general.

In this work the focus is on aspects of the design which make the platform implementable and feasible. Thereby, the progress of each requirement category in the checklist from the abstract stage down to engineering specifications will not be traced. The key requirements that are addressed in this work have to do with the design layout, synchronization of information collection and integration and processing of the information.

In this example, it is required to obtain the wrist angle of an individual based on feedback from the Wii Remote™ that is mounted to the forearm of an individual. Relative placement of LEDs and the Wii Remote™ can be used to measure the relative motion of the wrist. Information must be transmitted from the LEDs to the Wii Remote™ and thereafter to a computer. We must locate the LEDs with respect to the WII remote™ in a manner which allows complete coverage of the wrist's motion while maintaining the maximum resolution possible. The motion angles information collection needs to be synchronized with the recording of muscle activity information. In this way we can draw comparisons and studies on how wrist angles affect the muscle activity and thus the risk of carpal tunnel syndrome. If possible, real time feedback should be facilitated to the user on the basis of the studies.

This step is taken from the original design method itself and is shown in the modified method as well (Figure 9). It serves to satisfy the following method requirements:

- *Must clarify the task with the help of requirements*
- *Must proceed stepwise from the overall abstract of the task to the particulars of the design*

<u>Step 6. Determine demands and wishes</u>

At this point a condensation can be made on the intent of the design. The primary focus of this design is a customizable layout and prototype which can be used by people with different geometrical features and can be used as a platform for a real time training system in the future.

In the context of this focus, as identified in the adaptation of the design method, the requirements for the design ought to be classified under specific categories. These are listed in a requirements list and are of two types. A demand (D) is a requirement which must be fulfilled absolutely, whereas a wish (W) is a requirement which we would like to fulfill, but maybe traded off against other wishes or a demand.

Table 4: Requirements List for Wii Remote™ system

D W	Requirements
	Output Knowledge
D	Must detect wrist motion relative to the arm in terms of wrist angles
D	Must capture muscle activity information at the moments when the wrist moves
	Library
D	Must convert LED positions that the sensor actually measures to the wrist angles.
D	Must include information about the user which customizes the suggested training
W	Must convert raw EMG signals to decisions related to training the subject to reduce strain on the carpal tunnel muscles
	Coverage
D	Must cover wrist positions from -30 to 10 (flexor/extensor) degrees and -30 to 40 degrees (adduction/abduction) with an accuracy of 1 degree [79].

Table 4 continued

D W	Requirements
D	Must maintain accuracy of 1^0 at accelerations of 1000 rad/s^2 *
D	Measurement of wrist motion must be adaptable to 95% of the population**
	Sensors
D	Sensor required to detect 3 DOF movement and muscle activity
W	Sensor installation should minimize intrusion and discomfort
	Feedback
W	Should facilitate automated feedback to user in the form of signals which define certain limits on the movement in order to train the worker for reduced injury risk

*The maximum acceleration value was estimated by capturing dynamic motions via high speed video on the wrist of researchers.

**Considered representative of almost all people

Most of these requirements are explained in the previous step of the task clarification phase. Some of the quantitative values that have been included are based on preliminary tests and assumptions.

This step is taken from the original design method itself and is shown in the modified method as well (Figure 9). It serves to satisfy the following method requirements:

- *Must clarify the task with the help of requirements*
- *The design method must facilitate milestones in the design timeline*

4.1.2 Conceptual Design

<u>Step 1. Abstract to identify the essential problems</u>

In their search for satisfactory solutions, designers, far from allowing themselves to be influenced by fixed or conventional ideas, must therefore examine very carefully whether novel and more suitable paths are open to them. In order to solve the problem of fixation and sticking with conventional ideas, *abstraction* is used. Essentially, the requirements are combined and generalized in order to provide us with a crux of the task. Keeping in mind that the method has been adapted to design systems with information flow as the focus, we fashion the crux of the task requirements to the end of facilitating the information flow to suit our prime requirements from the system Table 5.

Combining the generalized requirements, the crux of the task can be defined as: Design of a non-intrusive system which accurately and precisely measures and outputs the entire range of comfortable wrist motion in the form of angles for different users and synchronous EMG data representing muscle activity caused in the arm.

Table 5: Abstraction of requirements

Abstracted requirements
Output Knowledge Objective wrist motion data in the form of angles and synchronized EMG data ***Library*** Must transform all measured information to requisite knowledge in the form of wrist motion angles and related effect on the carpal tunnel ***Coverage*** Must achieve coverage of entire space of wrist movement for different people ***Sensors*** Non-intrusive sensors to detect 6 DOF movement and corresponding muscle activity ***Feedback*** Automated feedback for training purposes is desired

This step is taken from the original design method itself and is shown in the modified method as well (Figure 9). It serves to satisfy the following method requirements:

- *Must clarify the task with the help of requirements*
- *Must proceed stepwise from the overall abstract of the task to the particulars of the design*

Step 2. Establish function structures (including the required fundamental functions)

The function structure is shown in Figure 18, and the corresponding system and boundary description are provided below

System and boundary description

The function diagram is constructed with the primary mindset of tracking and designing the information flow from the environment to the system and then to a common memory in the system. The environment is basically the arm of the subject who uses the system. The system is comprised of four components – the LEDs, the WII Remote™, the EMG unit and a processor (computer) to which the information is communicated. There is some level of choice with respect to the boundary and its nature. The information transfer across the boundary is of prime interest to us. Based on the selection of working principles for affecting this transfer, the exact boundary description will be detailed in the following steps in the design process. Vaguely, the boundary can be described as the structural unit which will be mounted on the arm in order to support the LEDs and the Wii Remote™ and the interface between the skin of the subject's arm and the EMG surface probes.

The function structure

The function structure (Figure 18) consists of functions and sub-functions and the flow of information and energy between them. A boundary between the system and environment is provided as well. However, this boundary is not clearly defined as a physical boundary as described above. The functions are enclosed in red boxes, and the sub-functions in black ones. A justification and explanation for each of the functions is provided below the function structure, followed by a description and justification for the sub-functions. These explanations help provide the link between the conceptual representation of the function structure and the working principles which are ideated on in the next step of the conceptual design phase.

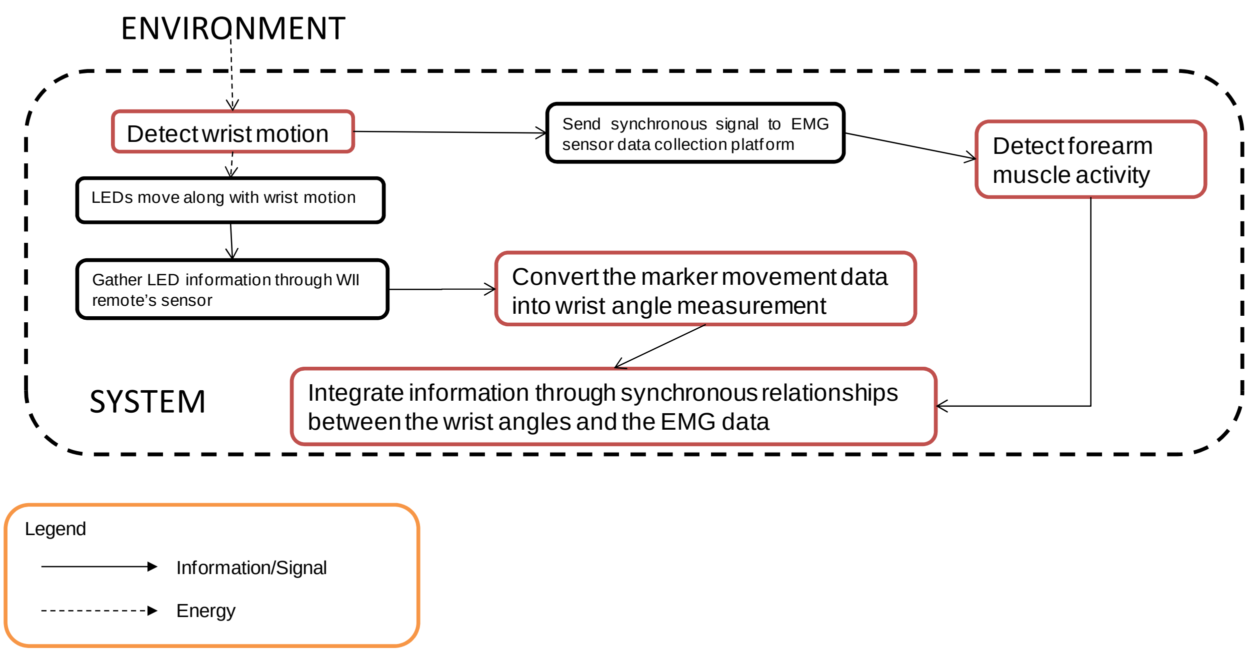


Figure 18: Function structure for motion capture system

Description of primary functions

Each function is meant to fulfill some of the requirements. They have been worded in as abstract a manner as possible, in order to prevent curtailing the design freedom, and the options that the designer has in selecting working principles for each of the functions and thereby a satisfying principal solution.

Function 1 - Detect wrist motion

The key output knowledge that is the aim of this design is to accurately measure wrist motion angles for workers in a repetitive stress situation in order to reduce the risk of CTS through muscle injury. We have also imposed the requirement that the system must work autonomously once installed correctly for each user. Thus, the system must be able to detect the wrist motion on its own. In other words, the system must possess an input transducer which transfers the motion of the wrist through markers into the system's boundary. Implicitly, we are defining the sensor and the markers it detects as the system, whereas, the human wrist in motion is the environment. The design activity will be determining the combination of the markers and the sensor in terms of placement and structure with respect to the environment.

In this system, the design decisions on what sensor and markers to use here have been narrowed down to a combination of the WII Remote™ and a LED beacon. In searching for working principles for this particular function of detecting the wrist motion, we are going to explore the possibilities of locating these in a way which makes for accurate and precise motion measurements.

A note on input transducers and internal transducers: In this design example, we assumed the use of the WII Remote™ as a sensor, and thereby are constrained to include markers as well. For the bare requirement of detecting motion for a binary scenario where the system only needs to know if there is motion, or no motion, we could use a basic camera. However, the requirement to detect objective 3 DOF data for this motion requires the use of markers, or at an abstract level, input transducers. In other words, the input transducers serve to preserve the objective detail of the motion information that the system is extracting from the environment.

Function 2 - Convert the marker movement data into wrist angle measurement

Once the motion of the wrist is detected, it is essential to harness it in terms of relevant information for satisfying output knowledge requirements of the system. The purpose for which the system is designed for is to serve to study the effect that wrist motion has on the muscles which lead to risk of CTS. The figure below is a solid model created to get a preliminary grasp on the environment that this system is being designed for.

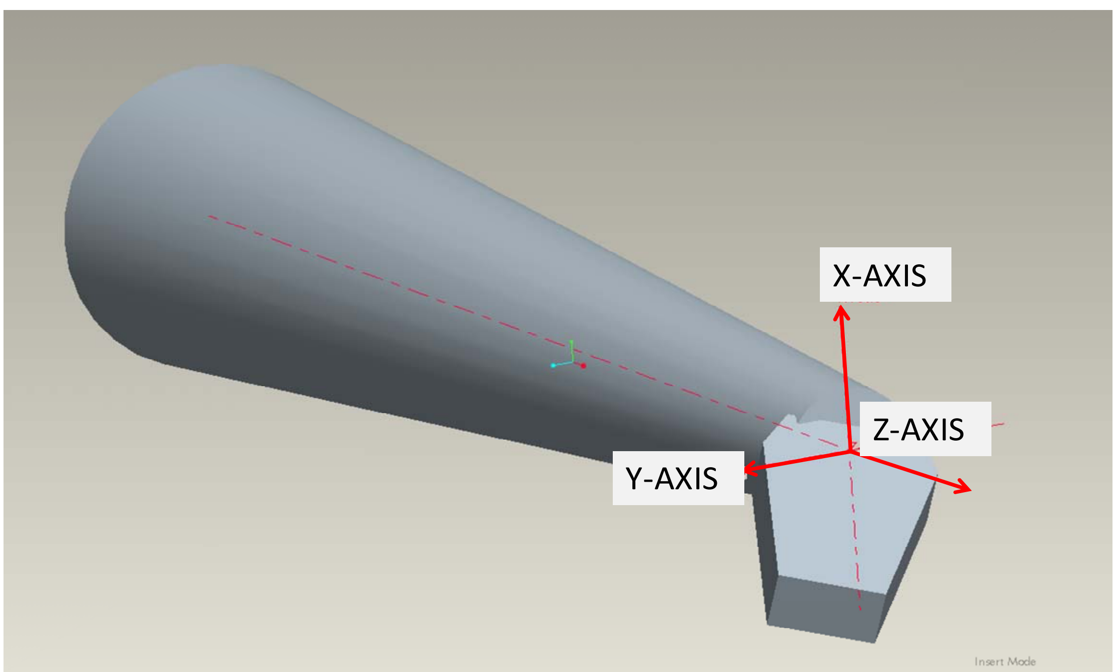


Figure 19: Solid model of the arm with wrist motion in 3 DOF (*Created in: PTC ProEngineer Wildfire 4.0)*

The Wii™ remote provides us with the 2-D coordinates of the images of LED sensors within its field of view. Provided we can interface the device with a computer to extract this information, this image data needs to be converted into corresponding 3-D angles. This will require the programming of a module which, based on the initial location of the LED markers, can track the 2-D image in order to back calculate the wrist angles based on the reverse engineered transformation and projection equations of the Wii™'s sensor relative to the wrist coordinate system.

Function 3 - Detect forearm muscle activity

As described earlier, the Carpal Tunnel Syndrome (CTS) is caused by pressure on the median nerve at the point where it passes through the wrist. The median nerve supplies sensation to the thumb side of the palm, and to the thumb, index finger, middle finger, and the thumb side of the ring finger. The area where the nerve enters the palm is called the carpal tunnel. Since the passageway is stiff, any swelling in this area can put pressure on the nerve. Injury to the wrist area can cause swelling of the tissues and thus CTS [80]. Thus, in order to quantify and suggest preventive measures for CTS, it is expected that the muscle activity during wrist motion may offer insight into what ranges of motions, or what kinds of motions are riskier than others. Issues of synchronizing data collected from the two sensors (the Wii™ and the EMG) will need to be dealt with.

Based on this evidence, it is logical for us to capture information on the muscle activity that repetitive motion of the wrist causes, in order to quantify the risk that it poses to CTS. Now, the muscles that surround the carpal tunnel and which we need to actively monitor during the motion of the wrist extend up into the arm and can be broadly classified under two categories, viz. the flexor muscles in the arm and the extensor muscles (Figure 20).

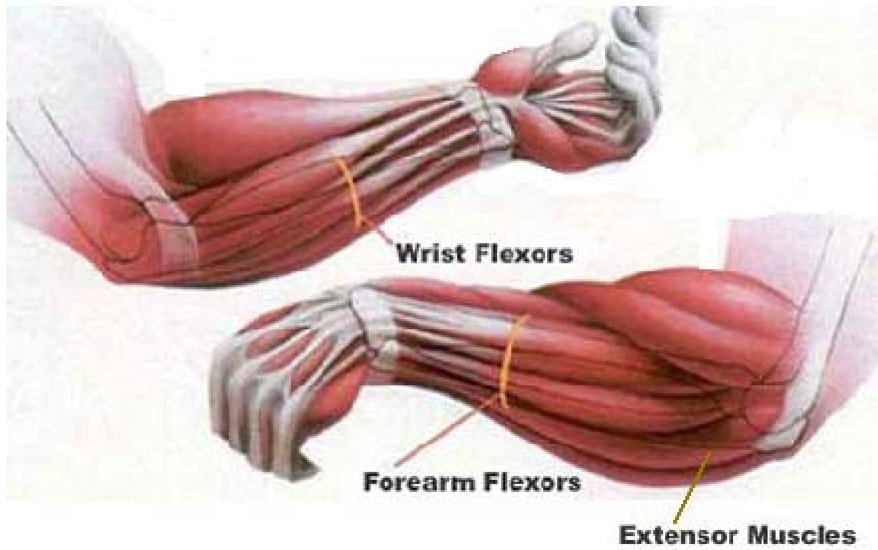


Figure 20: Flexor and Extensor Muscles (*Courtesy: www.forearmmuscle.com*)

Function 4 - Integrate information through synchronous relationships between the wrist angles and the EMG data

The common way to measure muscle activity is through electromyography (EMG), wherein the information is in the form of highly irregular, analog electric signals of low voltage and with a lot of noise. Through real-time or post processing, the relevant information eventually needs to be gleaned out of this information. Our objective is to gather this information and store it in a form which is easily understandable, can be easily processed and is synchronized with the corresponding wrist motion stored in the form of wrist angles. An extension of this design would be to use the collected information and create a feedback loop with real time processing of the information, to train workers autonomously in the workplace, without any interventions.

Description of sub-functions

Sub-function 1 - LEDs move along with wrist motion

The WII Remote™ with an attachment can gather objective 6 DOF data. For the environment in discussion, and the output knowledge that is required, only 3 DOF data is required, which are the three wrist angles. This is because the muscles in the carpal tunnel are only affected by wrist rotations. The wrist joint is assumed to be restricted in translation and thus only 3 DOF are required. The WII remote uses a built in IR camera which detects LEDs installed in a sensor bar in the WII console in order to determine its location and orientation completely in Cartesian space [81]. In other words, the WII remote acts as the interface between the environment (the player of the game) and the system. In this system, this role is given to the LEDs. The LEDs act as the interface or the input transducer for the system. They will act as the interface between the environment (the wrist) and the system. Thus, it is required for us to design a component comprising of the LEDs which can be fixed to the wrist in a comfortable and non-intrusive manner. Moreover, the relative locations of the WII remote and the LEDs should be designed in a way which ensures complete coverage of the wrist motion range.

Sub-function 2 - Gather LED information through Wii Remote™'s sensor

In order to create meaningful conclusions and interpretations from any information gathered from the environment, we will need to transfer the information to a processor. The Wii Remote™ acts as an internal transducer which converts the LED position information to wrist motion angle data.

Sub-function 3 - Convert incoming information into wrist angle measurements

The Wii Remote™ will typically use information coming from LEDs to detect motion in the wrist. Thereby, we can design a scenario where these LEDs are attached to the wrist. Thus, the wrist's motion is reflected in the LEDs motion. The change in position of these LEDs can be used to detect the angle of motion of the wrist in all directions. This sub-function will do exactly that. It is expected that a number of uncertainties will creep in for performing this function. An analytical transformation from the LEDs to the Wii™ could perhaps be achieved, if the system is located in a constrained manner with respect to the environment, which is the arm. For different people using the system, a number of factors are expected to creep in resulting in errors in the transformation equations. An elaboration on this function will be performed in later sections.

This step in the conceptual design phase is adapted from the original design method itself as indicated in Figure 11. It serves to satisfy the following design method requirements:

- *Must proceed stepwise from the overall abstract of the task to the particulars of the design*
- *Function structure must include an instance of the following general functions*

The second requirement's fulfillment is explicitly justified in Section 2.2 with a mapping between the general functions (Figure 8, Figure 12) and the function structure for this example system (Figure 18).

Step 3. Search for working principles through other applications and reverse engineering

Based on the function diagram, a partitioning of the design problem is achieved in the form of functions and sub-functions as show in Figure 18. This partitioning allows the designer to search for solutions, i.e. working principles, for each of these functions and sub-functions independently. The quotient of innovative and multi-disciplinary solutions is raised by approaching the design in this fashion. For this design problem, since the platform is already decided, i.e. the Wii™, the first step is to reverse engineer the Wii™ remote's capabilities that can be used to satisfy the functions above. A short description on the EMG sensors will follow suit.

Reverse engineering the Wii Remote™ [81]

The Wii Remote™ has a built-in IR camera mounted in the front of the case. This camera is connected to an integrated image analysis chip that can identify up to four IR light sources, and report their position on the camera CCD, and their (approximate) size and brightness. Since the camera is passive, it needs infrared light sources to work. The Wii gaming console comes with a "sensor bar", which simply emits infrared lights from two clusters of IR LEDs mounted at either end of the bar. Together with the sensor bar, many Wii games, and the console operating system itself, use the IR camera to measure yaw, the horizontal angle of rotation of the Wiimote with respect to the sensor bar.

The Wii Remote™ can track up to 4 light-emitting diodes (LEDs) at a frequency of 100 Hz. This ability to track the LEDs satisfies the primary function of the product that we are designing. Instead of the remote moving and the emitters lying in a sensor bar, we can have the emitters moving and the remote stationary with respect to them. Certain challenges are posed because of the choice of the Wii™ based platform. These are:

- Designing the system layout for complete coverage within the associated volume and field of view for the sensor for our application. This challenge is difficult to accomplish because of the large range of motion of the wrist, and the short distance between the Wii Remote™ and the volume available for a constellation of LEDs (LED beacon).
- Interfacing the WIi™ with a processor or computer to store and process information.
- Converting the 2-D image data collected from the Wii™ to meaningful wrist angles.

General test with the Wii Remote™

If the Wii Remote™ is to be used the accuracy of its readings must be evaluated. This will depend on the resolution that it offers. The Wii™'s image plane consists of 1024X768 pixels. The corresponding resolution in dimensions of inches or centimeters ought to be evaluated. It is anticipated at this point, that such a relationship would also help in developing transformation equations for conversion of LED marker data to wrist angles.

Additionally, it must be confirmed that no issues exist concerning barrel or pincushion effects that may occur when using circular or spherical optics on a rectangular shaped camera sensor. Due to this potential distortion, which exists for many cameras, a calibration routine is required to remove as much image distortion as possible. Nintendo performs this calibration within the Wii Remote™ in order to remove some of these effects, but it was necessary to confirm the level of the distortion removed. In order to answer this question, a simple test[13] was performed to validate the remote's output. Figure 21 shows the general setup for the validation test.

Figure 21: Wii Remote™ calibration test setup

[13] The test was carried out by Jonathan Holmes at the GTRI Food Research Building, Georgia Tech

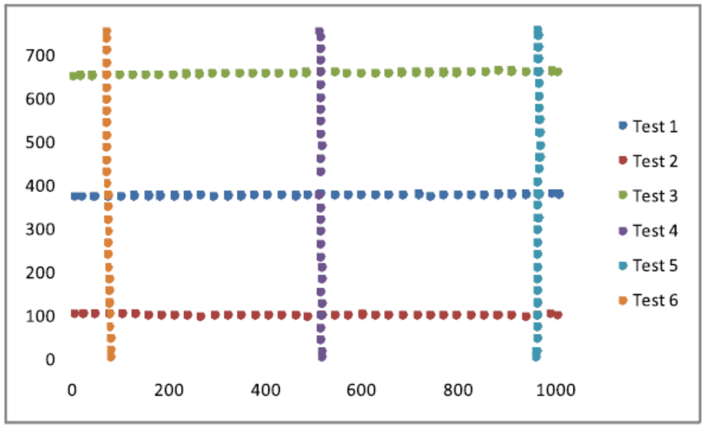


Figure 22: Calibration test data points

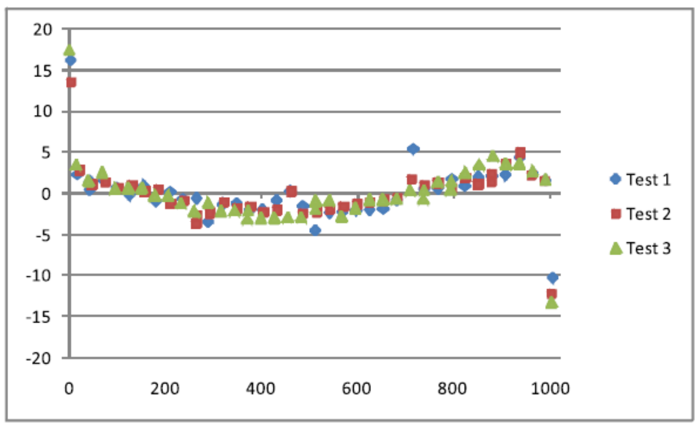


Figure 23: Horizontal position vs. error (in pixels)

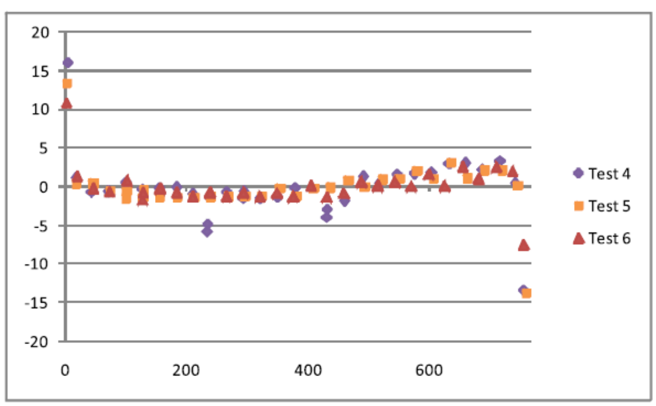


Figure 24: Vertical position vs. error (in pixels)

For this particular test, an IR LED was moved in a controlled fashion along two axes. This movement was controlled on the milling machine using a digital readout (DRO). The XYZ table of the milling machine allowed precise movements of the LED to any point within .001" accuracy. This provided the ability to move the fixture in a plane at a much higher precision than the Wii Remote™ could detect. The LED was set at a distance of 14" from the sensor, which is visible in Figure 2. Lastly, the Wii Remote™ was attached to a tripod allowing the readout of data via a nearby laptop directly from the Wii Remote™ when the LED was turned on. During the test, coordinates were recorded from the DRO as well as from the remote’s image sensor. The LED was swept independently across the x- and y-axes through the origin, as well as 2” above and below the origin. The resulting pixel positions measured by the image sensor are shown in Figures 3–5. Linear interpolation provided a relationship between the LED’s real-world position and the pixel value reported by the image sensor - this resulted in an R^2-value of 0.999. 94.5 pixels were found to correspond to one inch of motion along the x and y axes at a distance of 14 inches from the Wii Remote™ along the z – axis. However, we found that the accuracy of the sensor decreased near a narrow portion of the sensor’s margins, which meant the linear R^2-value could be increased to 0.9999 by windowing the image to exclude the outermost 20 pixels of the sensor area. Ultimately, this test helped to build the confidence that the results of Nintendo’s calibration of the camera would allow us to make accurate measurements using imaging sensor.

The EMG sensor

EMG sensors offer a way to "look" into the muscles and their activity. Key aspects of the Bagnoli™ Handheld EMG unit that will be used for this system are outlined below:

- The unit has six channels each of which can be used to collect data from an interface with the subject's body.
- Another channel exists for creating a reference signal. This is particularly important as EMG probes are extremely sensitive to small voltages. The actual nerve conduction signals are of really low voltage. Without a reference signal from the body, the probes are likely to pick up a lot of noise (eg. vibrations of the air conditioner from the walls)
- It consists of an amplifier which can be calibrated to output voltages within a specified range.
- The output is in the form of analog signals, which need to be sampled and converted to digital form to be collected on the computer.

The EMG unit provides functionality for capturing muscle activity in the forearm, but needs to be interfaced with the computer and the Wii™ in a fashion which allows for information exchange. The associated working principles will be highlighted later in the thesis.

The following morphological matrix in Table 6 illustrates the working principles or solutions that were considered for each of the functions in the function diagram. The above mentioned challenges are dealt with in one or more of the functions of the matrix.

Table 6: Morphological Matrix

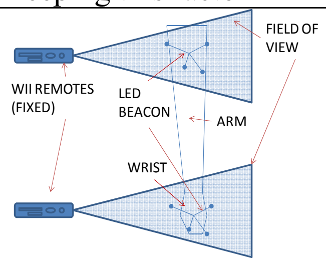
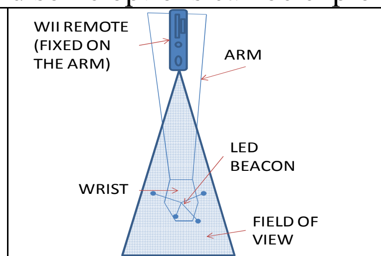
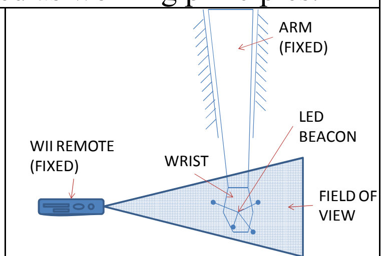
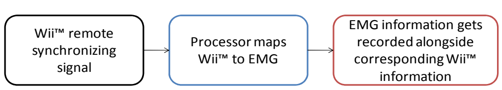
<table>
<tr><th>Function</th><th colspan="6">Description of function and working principles suggested</th></tr>
<tr><td rowspan="3">Detect wrist motion</td><td colspan="6">This is the key measure of interest for the system. The Wii Remote™ is normally the part of the system to move with respect to the emitters which lie still in the Nintendo Wii gaming console. However, we are required to detect the wrist motion relative to the arm, i.e. the measurements should not be affected by arm movement. Keeping this factor in mind some options can be explored as working principles.</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">By using two Wii Remotes™ and LEDs installed onto the arm, we can arrive at the relative motion of the wrist with respect to the arm</td><td colspan="2">If a single Wii Remote™ is installed onto the arm, and the LEDs onto the wrist, since both move along with the arm, the arm's motion is negated out of the measurements and we are left with the relative motion of the wrist</td><td colspan="2">Another option would be to fix or clamp the arm so that it doesn't move and thereby, the remote can be placed anywhere with the LEDs on the back of the wrist in its field of view</td></tr>
<tr><td rowspan="2">LEDs move along with wrist motion</td><td colspan="6">There is only one possible avenue to make this happen, which is by installing the LEDs onto the back of the wrist. Design issues which arise are where should the LEDs be in 3 dimensional space, and what supports should be used to install them onto the wrist. Given that the LEDs are installed on the wrist, we must also ensure that power is supplied to them in a non-intrusive manner.</td></tr>
<tr><td colspan="3">We can use cylindrical supports made of Al which can be installed onto the LEDs circuit board which in turn is installed onto the back of the hand with regular tape</td><td colspan="3">We can use cylindrical and hollow supports in order to reduce the weight of the apparatus and also provide wire access to the LEDs through the hollow in the cylinder to power the LEDs.</td></tr>
<tr><td>Gather LED information through WII remote's™ sensor</td><td colspan="6">The working principle is that given the LEDs are within the field of view of the Wii Remote™, the sensor in the camera will gather the position data for all the LEDs. Therefore, a design constraint springs up to ensure the LEDs are always within the field of view of the Wii Remote™. Clearly, the best way to do this is through a solid model. If we are able to model a placement of the Wii™ and the LEDs, we can arrive at the volume within which the LEDs should lie so that under the usual wrist motion ranges, they lie within the Wii remote's™ field of view</td></tr>
<tr><td>Convert the marker movement to wrist angles</td><td colspan="6">The conversion of the LED markers' position data into corresponding wrist angle data requires a geometric model. This can be analytical or iterative. An evaluation for both the methods is provided below</td></tr>
</table>

Table 6 continued

<table>
<tr><th>Function</th><th colspan="2">Description of function and working principles suggested</th></tr>
<tr><td>Convert the marker movement to wrist angles</td><td>The analytical model will require geometric manipulation of the LEDs' modeled positions in 3-D space. By tracking their projections on a plane located somewhere in the middle of the subject's arm, the angles through which the wrist has moved with respect to the initial calibrated position can be calculated. Placing the plane on which the LED images are projected somewhere in the middle of the arm precludes the possibility of multiple angles accounting for the same image coordinates due to the LEDs crossing the plane of projection during motion.</td><td>An iterative procedure involving an optimization algorithm can be used to arrive at the angles of wrist motion from the LED marker position data. The Levenberg – Marquardt method is just such an existing method which is used for the very purpose. The algorithm for this method already exists, and is easily implementable. However, it does increase the processing time for this functional step, thereby resulting in fewer data points collected for the wrist motion, if the algorithm is applied in real time.</td></tr>
<tr><td>Send synchronous signal to EMG sensor data collection platform</td><td>Since the Wii™ remote is connected to the computer via Bluetooth, and the EMG unit will be connected to the same computer as well, an obvious solution to this sub-function is to mark the data packets the Wii™ remote sends to the computer with a time signature. This time signature will then be applied by the processor to the information coming in from the EMG unit, and thereby the synchronization is done at the point when data is recorded.


</td><td>A simpler way is made possible with the Wii™'s rumble functionality. The Wii™ remote contains a small motor with a 3.5V input which provides it the rumble used to enhance user experience in gaming. By removing the motor, and connecting the leads to an interface with the raw EMG signal collector, the information collection from the EMG can be controlled using the rumble signal which can be programmed to operate on a user given signal, either based on a motion, or simply by pressing a button on the Wii™ remote.

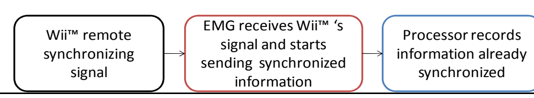

</td></tr>
<tr><td>Detect forearm muscle activity</td><td colspan="2">The only way to capture muscle activity in a non-intrusive fashion, which is one of the fundamental requirements of pursuing this design, is by using surface electrodes of an EMG unit. A handheld, battery operated 6 channel EMG system with by Bagnoli™ is selected to satisfy this function. Though the unit possesses 6 channels, only two probes are required; one on the flexor and the other on the extensor muscle in the forearm. The uncertainty is with respect to where exactly to place these probes on the arm. This is established by gauging the maximum effect that can be perceived by the eye and by touching the person's arm as the arm is flexed and extended.</td></tr>
</table>

Table 6 continued

Function	Description of function and working principles suggested
Integrate information through synchronous relationships between the wrist angles and the EMG data	It is foreseen, that the device will be used for purposes of physical training, diagnosis of injuries, and profiling of workers to ensure worker safety and health. Thus, the information that is gathered must be transferred to a computer so that we are able to ensure storage and further manipulation of data with a ready to use graphical user interface. Processing of the information can be done in various ways to output some knowledge about how the EMG data and wrist angles map together for predicting training techniques and best practices for the targeted beneficiaries of this design. Keir and co authors for instance, perform an analysis of how motion at wrist angles cause pressure on the carpal tunnel muscles [12]. Thresholds of these pressure values classify the safe and unsafe zones of wrist motion for the subject. Since our design problem is to capture the motion parameters required to facilitate such studies, it is outside the scope of this problem to suggest training methods. It is important to note however, that the system is designed with the ultimate aim in mind of training and monitoring health and safety in a customizable fashion for any human.

This step is adapted from the original method and the addition of reverse engineering as a construct is utilized as was indicated in Figure 11. The addition of reverse engineering to the step helped satisfy the following requirements for the design method:

- *Must design for the available technology with respect to input transducers (sensors)*
- *Must explore existing solutions as product ideas*

Step 4. Combine working principles maintaining smooth information flow into working structures

The combination of these principles is outlined in an information flow diagram as shown in Figure 25. In this example, enough is already known about the functionalities and the requirements of the system and the working principles so that a single information flow diagram can be easily chosen. In a more general case, it is anticipated that a number of combinations of the objects of the taxonomy of LST can be made possible to affect the required information flow and integration. The alternatives thus generated would each account for a number of different working structures in the next design step.

A: LED Beacon – The LEDs and their attachments, will act as the input transducer. They are the markers bearing information which are transforming the wrist motion into the changing positions of the LEDs.

B: Wii remote™ sensor – The Wii Remote's™ sensor captures information about the LEDs position and captures the information in the form of point coordinates on its image plane. The optical signal is converted into an electric signal, which is distributed into Bluetooth™ packets and thereafter sent through the Bluetooth™ channel to a computer. Again, one Wii Remote™ if installed onto the arm is good enough for our purposes.

C: Timer – Some sort of synchronizing signal needs to be transmitted from the Wii™ remote to the EMG unit to indicate the start of motion and thus actuate the collection of EMG information. In this design, the rumble motor of the Wii™ remote acts as the physical representation of the timer. A communication between the processor of the computer and the Wii™ leads to a small voltage being sent to the timer or the rumble motor, which can be picked up to synchronize data collection between the Wii™ and the EMG.

D: EMG Probes – These act an input transducer bearing or picking up electronic voltages in the nerves which cause muscle activation in the arm's muscles. They transform the muscle activity information into an analog signal consisting of varying voltages.

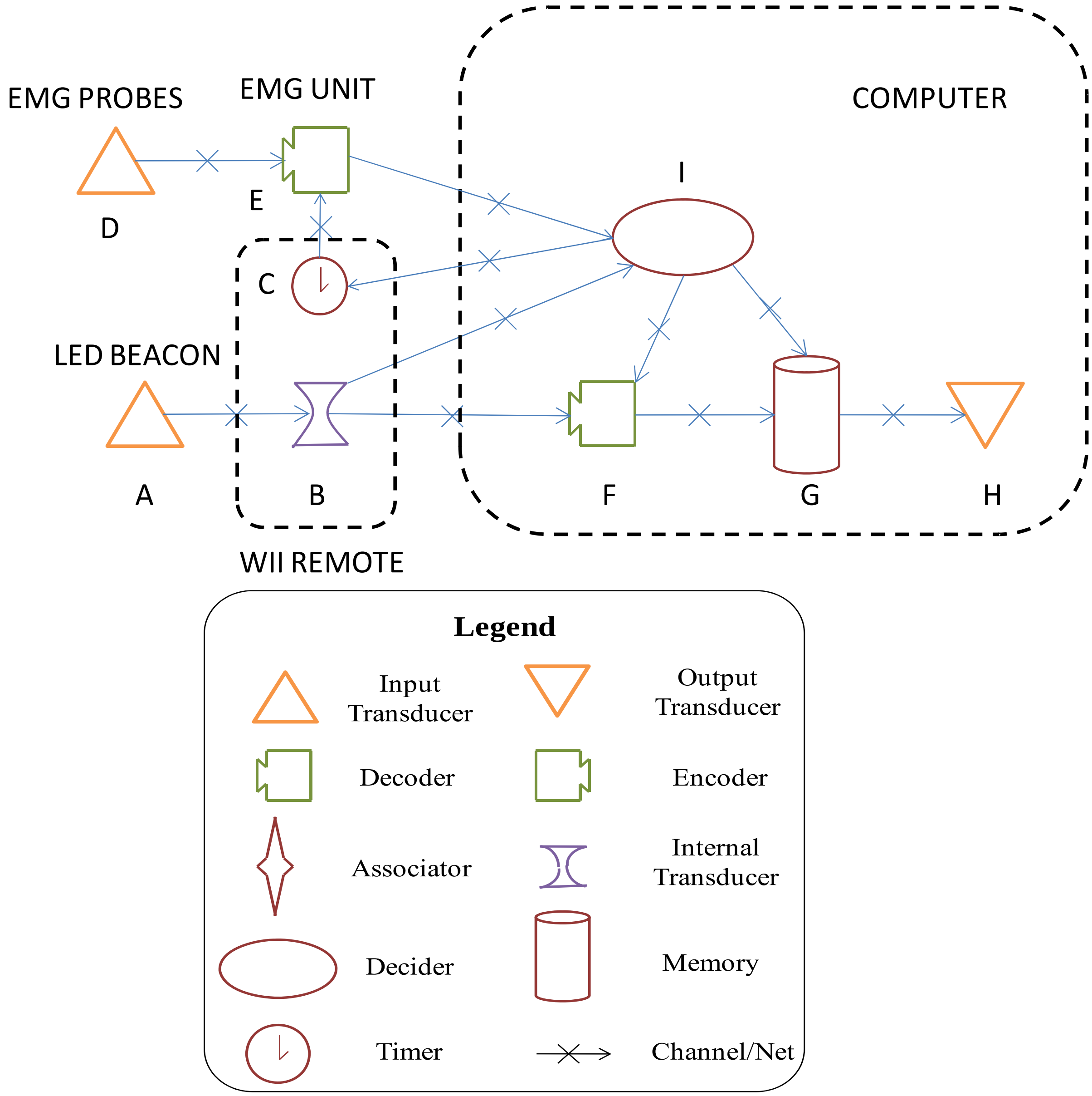


Figure 25: Information flow diagram for Wii remote™ based motion capture system

E: EMG Unit – This consists of the filter, and a modem sort of unit which convert the voltage information from the EMG probes into readable information in the form of discrete voltage signals which are recorded later in the computer. This unit also takes the timer input to synchronize the information collection procedure of the EMG with the Wii™

F: Angle Solver – An analytical model or a regression model will act as a decoder subsystem. The code transformation is from the LED image coordinates to the wrist angles.

G: Memory – Any storage of the information for post-processing or even real time processing for training workers based on the wrist angle and muscle activity data can be done within the computer using database tools and the computer's primary memory, and RAM. These act as the generic memory sub-system.

H: Output Transducer – In the case of our design, we are merely making the system capable of motion capture and thereby the display of objective 3 DOF data on wrist motion. Thus the output is limited to display on the computer, which thus acts as the output transducer. However, if we are to extend the design of the system, we can achieve feedback to the user of the system through the vibratory function of the Wii Remote™ as well.

I: Decider – The processor acts as the decider. This processor is programmed to make decisions involving the conversion of 2-D image data to the wrist angles, receiving and processing the Wii™'s data packets being sent in, and actuation of rumble in the Wii™ based on a preset synchronizing condition and storage of information. If we select the working principle with two sets of sensors and LED beacons, then the decider has the added task of calculating the relative motion of the wrist with respect to the arm.

An example of existing alternatives in the combination of the objects of the taxonomy of LST into an information flow diagram is the placement of the timer and the inputs and outputs to and from the timer. Should the information flow from the Wii

Remote™'s transducer to the timer, which would mean the synchronization in the data collection is real time and not based on recording of time packets, or should the information flow to the processor from both the tranducers, the Wii™ and the EMG sensor, along with an additional information packet, which would be a recording of the time at the moment of information collection? In the latter case, the resulting data recorded could be synchronized based on the additional information recorded. The prior has been chosen, since it satisfies the requirement of maintaining real time functionality in the system.

Each sub-system in the information flow diagram (Figure 25) need not correspond to a separate physical entity. The sub-systems are an embodiment of a particular type of function that is being carried out by the system, related to manipulation or transfer of information. For instance, all of I, F, G and H together form the computer in physical reality, whereas, A is the LED beacon, B and Care the Wii Remote™ and so on.

This step was modified from the original method as shown in Figure 11. The representation of varying working structures with a single information flow diagram at a high level served to satisfy the requirement that the design method must build functions and concepts on a fundamental information flow and processing representation. Specifically, the hypothesis to research question 1 is tested at this point. The representation used at this conceptual level of abstraction serves to incorporate a number of variants with a single diagram, and defines the system components, the boundary and the environment clearly for design purposes. Thus the hypothesis stands established as far as the conceptual representation is concerned.

Step 5. Evaluate variants against technical and economic criteria

Preliminary solid models of the variants though revealing in some aspects of advantages one variant has on another, provides little addition in the way of a decisive comparison which cannot already be inferred from our description of the working principles. Thus, an explicit step for preliminary solid models has been omitted from this example system.

However, an evaluation of the working structures needs to be carried out against the requirements that were set out to fulfill for this design. This will help in the selection of the principal solution (concept). The EMG sensors possess almost a ready module and offer little choice in way of their physical integration with the system. One particular decision regarding the working principle of interfacing the Wii Remote™ with the EMG sensor is to synchronize their data collection procedures.

Table 7: Evaluation of variant against the requirement categories

Category	**Number of sensors and LEDs – One vs. two**	**Structure of LED supports – Hollow vs. Solid**	**Analytical vs. Regression model to calculate angles**
Output Knowledge	Both the variants satisfy the requirements	Both the variants satisfy the requirements	Intuitively, an analytical model should provide higher accuracy in the results than a regression fit. However, in this example, there are a number of uncertainties which act as sources of error in making an analytical transformation from the 2-D image data of the LEDs to the 3 DOF wrist angles. Thus, the regression model is thus found to be a better fit.

Table 7 continued

Category	Number of sensors and LEDs – One vs. two	Structure of LED supports – Hollow vs. Solid	Analytical vs. Regression model to calculate angles
Library	Both the variants satisfy the requirements	Both the variants satisfy the requirements	The algorithm chosen would form part of the library. Maintaining a speedy real time library would be better facilitated by the analytical solution. However, the regression solution, provides for easier implementation and future changes.
Coverage	With two sets, we can get better coverage. With one set we will have to model the constraint imposed by the field of view of the Wii Remote™	Both the variants satisfy the requirements	Both the variants do not affect the requirements
Sensors	In the case of two sets of sensors, their errors and inaccuracy will compound as their measurements need to be integrated to get the output knowledge desired	The jitter in the data will be higher due to the hollow cylinders as the solid supports will be more rigid. However, the sensors need to be powered and thus the hollow cylinders will prove more useful	To take advantage of a higher data capture rate of the sensors being used, the analytical solution is better, since it reduces the time taken in the angle calculation module
Feedback	In the variant with two sets, we cannot provide feedback using the Wii Remote™	Both the variants do not affect the requirements	Both the algorithms can be used to provide adequate feedback given a range of angles within which operations can be assumed

Though not explicitly included in the requirements, user comfort is an important factor in this design. We are designing this system with the ultimate aim of providing a training device for workers, athletes, trainees etc. Thereby, the device will be in use for long periods of time for each user. Thus, the variant of hollow cylinders provides an advantage in that it is a lightweight option and provides greater comfort to the user. Though the variant with two sets of sensors and LEDs provides greater comfort, because the Wii Remotes™ are off the arm, it involves installing another set of LEDs onto the arm in addition to the one on the wrist.

Clearly, in tasks which involve more wrist motion the difference in weight on the upper portion of the arm may not be big a concern. Moreover, two sets of sensors and LEDs have the disadvantage of increased cost. Thus we select the concept to be a single Wii Remote™ installed on the arm with the LEDs supported by hollow cylindrical supports.

Thus the concept can be visualized as shown in Figure 26.

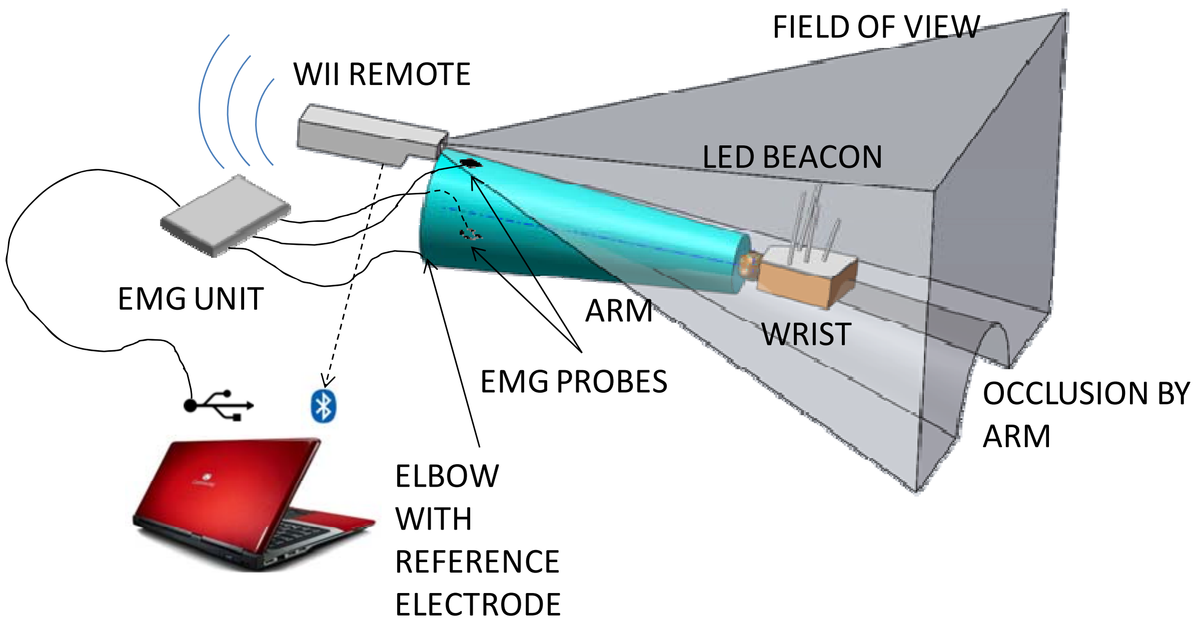


Figure 26: The solution principle or concept

This step is taken from the original design method (Figure 4) and serves to satisfy the requirement that the design method must fulfill milestones in the design timeline.

4.1.3 Embodiment Design

The primary focus of this design with respect to embodiment is the design of a customizable layout and a prototype which can be used by people with different geometrical features and can be used as a platform for a real time training system in the future. Based on this focus, the steps of the design method are carried out for the embodiment phase.

Step 1. Identify embodiment determining requirements

In order to identify these requirements, we refer back to the information flow diagram (Figure 25). At each sub-system and at each transmission channel coming into or going out of the sub-system, we can identify design decisions with respect to the embodiment that require consideration (Table 8). In the following table, against each of the sub-systems from Figure 25, the inputs and outputs are defined and in order to facilitate them, the design decisions that result are highlighted. Overall design decisions that need to be considered are highlighted for each sub-system as a whole as well.

Table 8: Design decisions associated with every node in the information flow diagram

	Sub-System	Input	Output
A	Input Transducer – LED Beacon. Design decisions: Where to place them in 3-D space	Wrist motion from the environment is the input. Design decisions: How to fix LED beacon onto the wrist? What supports to use for transmission of information to the beacon?	The light from the LEDs is the output. Design decisions: Where should the light be coming from in 3-D space relative to where it has to be received?
B	Internal Transducer – The Wii Remote™ sensor. Design decisions – Where should it be placed?	The light from the LEDs is the input. Design decisions: What resolution to maintain, and thereby, where to place relative to the beacon?	The Bluetooth communicated LED position data is the output. Design decision: None
C	Timer – The Wii™ remote's motor signal. Design decisions – How to synchronize the Wii™ and the EMG?	A signal from the processor is the input. Design decisions: When should this signal be sent, and how should it be actuated?	A voltage signal to the EMG unit is the output. Design decisions: How should this signal be interfaced with the EMG data collection unit, and thus used to control the output of the EMG unit?

Table 8 continued

	Sub-System	Input	Output
D	Input Transducer – EMG Probes. Design decisions – How many probes to use and where to place them?	Voltages picked up due to muscle activity. Design decisions – How to ensure minimal loss between the actual activity and the probes?	Analog signal consisting of noisy voltages form the output. Design decisions – None
E	Decoder – EMG Unit. Design decisions – How to sample the incoming analog data to ultimately record in the computer and how to synchronize the EMG data with the wrist motion?	Analog signal consisting of noisy voltages from the probes are the input and synchronizing signal from the timer in the form of a voltage. Design decisions – How to capture the synchronization?	Filtered and sampled EMG data synchronized with the wrist motion forms the output. Design decisions – How to interface the EMG unit with the computer?
F	Decoder – The algorithm which converts the sensor information collected. Design decisions – What algorithm to use to convert input data to requisite knowledge?	LED position data is the input. Design decisions – How to facilitate real time or post processing and conversion of the input data to facilitate?	LED position data in the form of angles form the output. Design decisions – None
G	Memory – This is basically the memory of the computer. Design decisions – What form should the information be stored in?	Wrist motion angles form the input. Design decisions – None	Wrist motion angles will form the output. Design decisions – None
H	Output transducer – This is basically the computer's output. Design decisions – None	The input is wrist motion angles and the EMG voltages. Design decisions – None	The output again is the wrist motion angles and the EMG voltages. Design decisions – None

Table 8 continued

	Sub-System	Input	Output
I	Decider – This is the processor of the computer. Design decisions – What platforms and operating systems should be used?	The inputs vary and are implicitly decided by algorithms we use. Design decisions – None	The outputs vary and are implicitly decided by the algorithms we use. Design decisions – None

Corresponding to these decisions the requirements that need to be met can be identified. Based on the design decisions identified, the embodiment determining requirements can be described under three basic categories, viz. vision, structure and process.

Vision: We need to obtain the wrist angle of an individual based on feedback from the Wii Remote™ that is mounted to the forearm of an individual. By placing IR LEDs on the wrist of the subject, the wrist angle can be tracked by measuring the X and Y coordinates from the IR camera and translating that into 3-D space. There are two requirements for implementing such a system. First, we must translate pixel coordinates from the IR camera into 3-D coordinates. Second, we must locate the LEDs with respect to the WII Remote™ in a manner which allows complete coverage of the wrist's motion while maintaining maximum resolution possible.

Structure: The cylindrical supports used to hold the LEDs in position so that they move with the wrist form the apparatus which is required to be as rigid as possible to prevent jitter in the data, but also needs to be lightweight to prevent undue stress on the individuals being monitored by the system. The decisions with respect to the EMG unit and probes are taken with the requirements in mind of monitoring the flexor and extensor muscles on the forearm, which extend to the carpal tunnel in the wrist. Thus, two probes need to be placed and a third probe is required as a reference voltage, and this is placed on the elbow of the subject, where the muscle activity is minimum. This reference electrode is required because the EMG probes are very sensitive, and the voltages it picks up from muscle activity are miniscule (range from +/- 5000 microvolts [82]), thereby leading to a lot of noise being picked up and spoiling the signal (for instance, the air conditioning vibration frequency).

Process: The system's processor or computer needs to be interfaced with the Wii™. This can be done using Bluetooth™ functionality of the Wii Remote™. Furthermore, the application or software used to interface must be tweaked to be able to create a feedback to the Wii™ in order to actuate the timer signal through the motor in the Wii™. An algorithm needs to be developed for converting the 2-D image data into 3-D wrist angles. The processing algorithms and platforms should be expandable for real time processing as well.

This step is taken from the original design method as it is. However, the implementation of the step involves the use of the information flow diagram that was formulated in Step 4 of the conceptual design phase from the adapted method (Figure 9). This adaptation in conjunction with the original step serves to satisfy the following requirements:

- *Must build functions and concepts on a fundamental information flow and processing representation*
- *Must proceed stepwise from the overall abstract of the task to the particulars of the design*

<u>Step 2. Produce scale drawings/computer models of spatial constraints</u>

The vision constraint in the concept is imposed due to the limited field of view of the Wii Remote™, compounded by the fact that it is kept at a short distance from the LEDs. Using Solidworks™, a solid model of the system is designed which clearly outlines the constraints on the volume within which the LEDs must be placed. The constraints are:

- They must exist in the camera's field of view: Modeled as a pyramid since the sensor plane which is a cross-section of the volume of the field of view is rectangular. (Figure 26)
- They must not be occluded by the arm: This was subtracted from the field of view of the Wii Remote™. (Figure 26)
- They must conform to comfortable wrist angles of motion: Angles of +10, -30 degrees from the horizontal (flexor/extensor) and +40, -30 degrees from the vertical (abduction/abduction) were assumed to be a comfortable zone of motion for repetitive motion by workers in a poultry manufacturing environment based on literature [8] (Figure 27). The motion of the wrist about the z-axis relative to the Wii Remote™ is minimal. Rotations are considered only about the x- and y-axes. (Figure 28)

- The intersection of the corresponding arbitrarily large volumes in a solid model form resulted in a convex and bounded volume. (Figure 29)

The portion of the volume of comfortable wrist motion lying within the camera's field of view (excluding the portion occluded by the arm) is the resulting feasible volume in 3-D space within which the LEDs must lie for complete coverage of comfortable wrist motion (Figure 29). The corner point coordinates for the feasible volume are listed in Table 9.

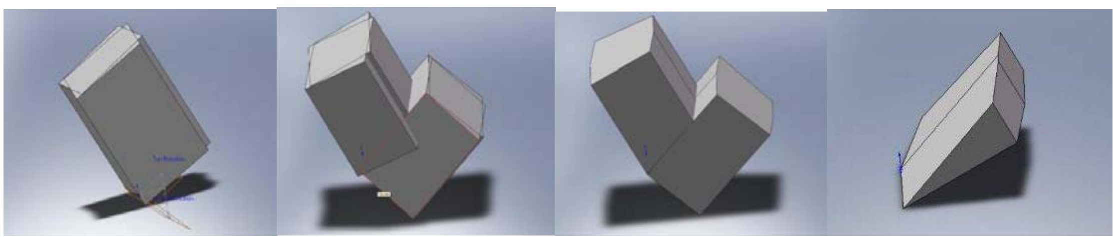


Figure 27: Union of horizontal wrist extremes (top left), union of horizontal and vertical wrist extremes (top right), union of intersections in both dimensions (bottom left), intersection of all four extremes (bottom right)

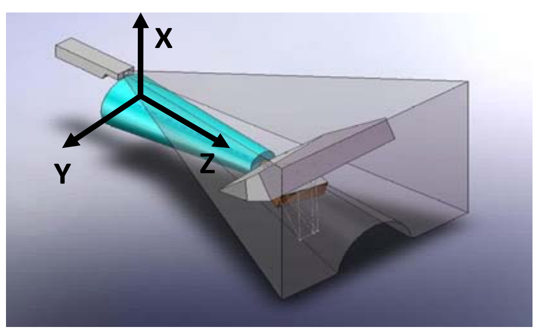


Figure 28: Axis system for the Wii Remote™

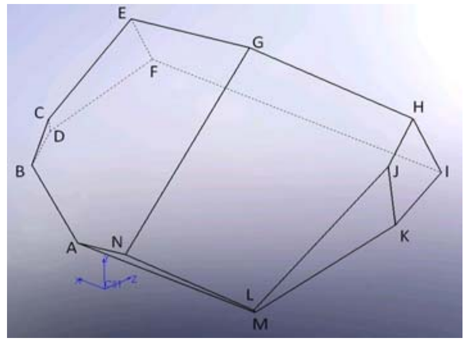


Figure 29: Modeling the spatial constraints in terms of the feasible volume within which LEDs must lie.

Table 9: Coordinates of the corners of the feasible volume for an arm length of 11.54 inches and height of Wii Remote™ = 2.54 inches

Point designation	X coordinate (inches)	Y coordinate (inches)	Z coordinate (inches)
A	0.422	1.805	0.906
B	1.136	4.854	2.427
C	2.026	5.213	3.422
D	1.628	5.238	3.492
E	4.449	4.474	5.648
F	2.958	4.474	6.344
G	5.267	0.000	5.267
H	4.941	-5.463	5.419
I	2.958	-5.463	6.344
J	3.918	-5.570	4.405
K	2.119	-5.621	4.544
L	0.496	-4.284	0.871
M	0.422	-4.297	0.906
N	0.752	0.000	0.752

Step 3. Select suitable preliminary layouts

With respect to the vision requirements, with the aid of a solid modeling environment, we can clearly define the spatial constraints, and thereby define a volume within which the LEDs ought to lie for them to be visible by the Wii Remote™ at all times. This volume is also defined by the range of motion of the wrist, as identified in the last step. Now, suitable layouts exist for any and every location of the LEDs within the feasible volume (Figure 29). The placement of the Wii Remote™ should be as far as possible up the arm to allow for a bigger range of view. At the same time, it should be closer to the LED beacon to allow for minimum occlusion by the arm.

Based on the process requirements, the layout consists of a selection of an operating system, a programming language, and a coded solution in that language that can be used to read data from the Wii™ and actuate its motor signal when required. In addition, a module is required to convert the image coordinates obtained from the Wii™ into 3-D wrist position angles. For this purpose the following solution is chosen,

Operating System: Windows XP

Programming Languages: C# and MATLAB

Solution: A Wii Remote™ Whiteboard solution created by Johnny Chung Lee[14] built upon a managed library created by Brian Peek[15]. A module for conversion of image data into wrist angles was created in MATLAB and is elaborated upon in subsequent design steps.

Step 4. Complete form designs including environment-specific requirements

Some of the steps of embodiment design have been skipped as per the original Pahl and Beitz design method, and our adapted design method. This is because there is a higher degree of specificity already achieved in our description of the system, than is expected before these steps are carried out.

[14] http://johnnylee.net/projects/wii/
[15] http://blogs.msdn.com/coding4fun/archive/2007/03/14/1879033.aspx

<u>Component design – Wii Remote™</u>

The form design for our system requires a robust placement of the LEDs in 3-D space which manages uncertainty in the jerk in support wires, and keeps the LEDs within the field of view of the Wii™. The decision can be modeled with a baseline formulation [83]. Thereafter it is solved using an exhaustive search algorithm. In order to preserve customization, the formulation is made generic in terms of parameters which vary from one user to the next. In the results section, the model is simulated for a particular set of parameters.

<u>*Given:*</u> The Wii Remote's™ infrared (IR) camera can detect and track up to four infrared light sources. The camera has a built-in image processor that analyzes the raw camera image, identifies bright spots, and computes their (x, y) positions and approximate radius on the camera's image plane. With a customizable IR beacon with four LEDs at known positions (in a non-planar arrangement, i.e., a tetrahedron), it is possible to derive the camera's—and hence the Wii Remote's™ position and orientation relative to the beacon based on the (x, y) positions of the beacon's LEDs on the camera's image plane. Since the position of the camera is fixed, the beacon's position relative to the camera can be found as well. The 4 LEDs on the beacon are attached on the wrist of a person and the Wii Remote™ is attached on the arm of the person. Therefore, the wrist angles can be measured. Some assumptions made are:

- Neglecting spherical aberration, the pixel size is the same for the entire image plane.
- The support wires are to be hollow cylinders as per the concept we selected

Constraints: The field of vision of the sensor restricts the design space for the LEDs. The wrist motion is limited within some angles of rotation about each of the x- and z-axes. The deflection of the LEDs must be constrained to achieve the image's desired precision. Explicit consideration of resulting volume constraints were discussed in Step 2 of the embodiment design phase.

Find: The design variables are the 3-D locations of the 4 LEDs which determine the resolution of the Wii Remote™ and the accuracy which can be quantified by the deflection in the LEDs due to acceleration of the wrist. These would affect the precision of the readings of the Wii Remote™ in identifying the wrist angles. The overall objective of this task is to maximize precision in the system.

Key assumptions: Some assumptions which were made during the LED placement decision, and are thus highlighted below

- Angular acceleration used for calculations is the maximum acceleration of the wrist. The maximum angular acceleration was found to be approximately 1,000 rad/s^s from crude laboratory experiments using a high speed camera. Therefore, this was also included in the requirements list.
- An angle of -30, +10 degrees from the horizontal (flexor/extensor), and -30, +40 degrees (adduction/abduction) from the vertical were used for the range of the wrist. For the initial decision formulation, this was deemed appropriate by researchers due to the high risk of repetition involved in meat processing applications [79]
- Changes in intensity of IR LEDs are irrelevant. The Wii Remote™ not only detects the X, Y coordinates of the LED, but also a spot size. It is suspected the spot size can

affect the accuracy of the sensor. Due to the difficulty in modeling the change in spot size as a function of distance from the sensor as well as the emission cone of the LED, this was ignored. However, this error is expected to be small.

- Worst case deflection is used as the boundary condition. The deflection will have a frequency associated with the natural frequency of the LED support and will continually change in magnitude as the dynamics of the system change. The worst case, i.e. maximum deflection was chosen as working conditions in the calculations.
- The optimal resolution will be proportional to the area between the projected points on the sensor plane. This holds true because the greater the area of the sensor that is used (in pixels), the greater the saturation of this area. This means that the pixel resolution for any given angle will be maximized. In summary, the farther the LEDs are apart, the greater the resolution will be.
- For transformation of the 3-D LED coordinates to the Wii Remote™'s image plane, it is assumed the Wii Remote™ is aligned with the arm and the wrist when the wrist is in the original position with all angles equal to zero.

It is expected that this placement is dependent on environment specific parameters. These are the arm length of the user, and the height of the Wii Remote™ lens from the origin of the wrist coordinate frame. The solid model is parameterized with respect to these parameters so that the spatial constraints are generated automatically by feeding in the parameter values.

Search Algorithm

The baseline formulation needs to be implemented in a simulation in order to reach a solution for the placement of the LEDs. This solution must also be customizable to the parameters chosen to represent differences in users.

The algorithm written in MATLAB is included the Appendix. The spatial constraint is modeled by entering in the coordinates of the volume within which the LEDs must lie. At each increment of the design variables the position of each of the LEDs is checked. If a LED lies outside the constraint volume then that set of design variables is not considered. Furthermore, at each increment the length from the LED to the center of rotation of the wrist is evaluated. If this length is greater than the length calculated as per Equation 8, then that set of design variables is discarded. An exhaustive search across a cube which encompasses the constraint volume is carried out and the LED locations providing the best resolution are determined.

The mathematical formulation of the constraints and the objective function are presented below. The assumptions from the list above are incorporated into this formulation explicitly, and are referred to accordingly.

Mathematical Formulation

- *Objective Function*

The objective function is the resolution of the image that the LED beacon projects onto the image plane of the Wii Remote™'s IR camera. The other objective i.e. accuracy is dependent on the support wires that are used for the LEDs as well as how far the LEDs are from the center of the wrist. A jerk resulting in a deviation of less than a degree for each LED within one second is assumed to be negligible considering the fact that the Wii

Remote™ records up to 100 data sets per second. Thus, this objective is hard coded as a constraint and its mathematical formulation is shown later.

In order to calculate the resolution, as mentioned in the assumptions, the area of the quadrilateral formed by the images of the 4 LEDs needs to be calculated. For determining this area, the transformation from the 3D LED coordinates to the image plane needs to be established. This transformation is modeled according to Figure 30.

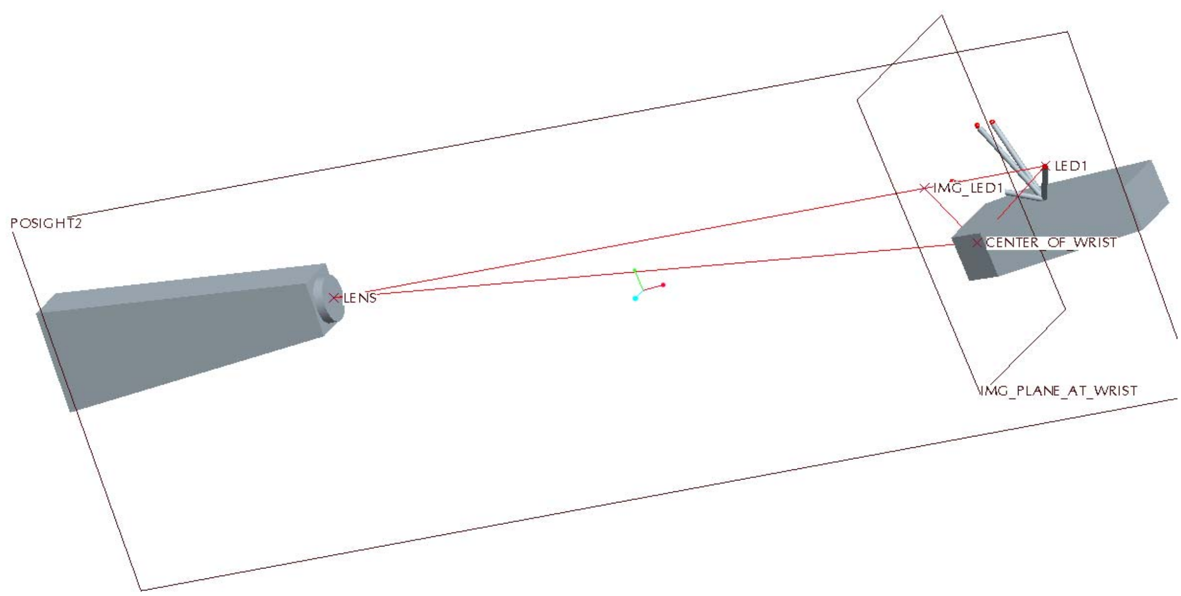


Figure 30: Model of the geometric transformation between the 3-D LED coordinate and the 2-D IR image

It is assumed that the Wii Remote™ is only translated with respect to the center of the wrist, and not rotated. Furthermore, it is assumed to be in line with the arm, and thus translated backwards along an axis stretching along the arm from the wrist, and then up on the arm's surface along a perpendicular axis. Triangles can be drawn with the three vertices formed by, the center of the Wii Remote™'s lens, the center of the wrist and each of the LEDs in the beacon. In Figure 31, this triangle is shown with one of the LEDs mounted on the wrist. A second project triangle is shown in the same figure. The transformations can now be carried out on the resulting triangles for each of the LEDs.

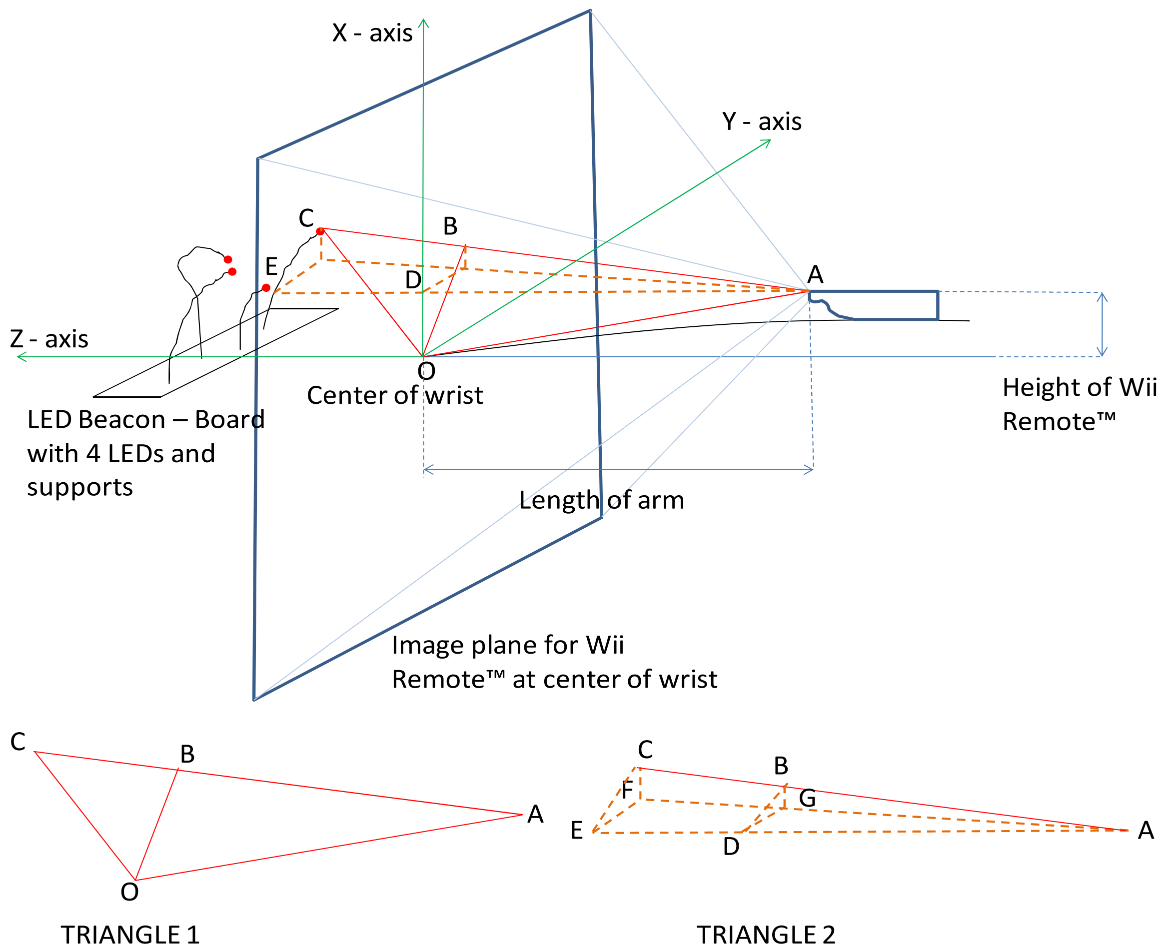


Figure 31: Transformation of LED coordinates to 2-D images on an image plane at the wrist

$$AE = AD + DE = Length\ of\ arm + X\ coordinate\ of\ LED\ at\ C$$

Equation 1

$$EC = \sqrt{EF^2 + FC^2}$$

$$= \sqrt{(Z\ coordinate\ of\ LED\ at\ C)^2 + \left((Y\ coordinate\ of\ LED\ at\ C) - Height\ of\ Wii\ Remote\right)^2}$$

Equation 2

$$DB = EC \times \frac{AD}{AE} \quad , since\ \Delta ABD \approx \Delta ACE$$

Equation 3

$$AB = \sqrt{AD^2 + DB^2}$$

Equation 4

$$\therefore \ \overrightarrow{OB} = \overrightarrow{OA} + \overrightarrow{AB} = \overrightarrow{OA} + \frac{\overrightarrow{AC}}{|AC|}|AB|$$

Equation 5

Given the coordinates of C and A in the assumed coordinate frame with origin at O, vectors OA and AC can be calculated easily.

Thus, the coordinates of B are known from the vector OB. This vector lies on the given y-z plane and corresponds to the projection of the LED along the line of sight with the lens of the Wii Remote™.

An important constant that is used to affect the mathematical transformation is the variation of resolution of the Wii Remote™ with distance from it. As shown in the general test with the Wii™ in Step 3 of the conceptual design phase (the reverse engineering of working principles) this constant is 94.5 pixels/inch for a distance of 14 inches from the Wii Remote™.

Thus, the coordinates of the point B can be calculated in pixels with respect to a plane which has its origin at the left and bottom corner of the image plane spanning the field of view of the Wii Remote™,

$$\therefore \quad yp = c(Y\ coordinate\ of\ B - Height\ of\ Wii) + 384$$

$$and, \quad zp = c(Z\ coordinate\ of\ B) + 512$$

$$,where\ \ c = \frac{94.5 \times 14}{Length\ of\ arm}\ \ pixels/inch$$

Equation 6

Thereafter, the resolution objective is calculated as the area of the quadrilateral projected by the four LEDs onto the same plane,

$$R = .5 \times ((yp(1) \times zp(2) - yp(2) \times zp(1)) + (yp(2) \times zp(3) - yp(3) \times zp(2)) + (yp(3) \times zp(4) - yp(4) \times zp(3)) + (yp(4) \times zp(1) - yp(1) * zp(4)))$$

Equation 7

- *Constraints*

There are two constraints which are used in this formulation. The first constraint is the one imposed by the field of view of the Wii Remote™ and the obstruction caused in the field of view by the arm of the person wearing it. The second is imposed by the accuracy to 1 pixel/second.

The first constraint is modeled using a Solidworks model, which helps us to easily extract the coordinates of the corner points of the constraint volume. This task has already been explained and an example has been carried out for an arm length of 11.54 inches and height of Wii Remote™ = 2.54 inches (Step 2 of Embodiment Design, Figure 29, Table 9).

The second constraint is with regard to maintaining accuracy based on the rigidity of the supports and the acceleration imparted to the LEDs at the tip due to the jerks and high acceleration of the wrist. As outlined in the assumptions, this acceleration is assumed to be the maximum possible which were determined based on experiments carried out on the researchers using a high speed camera. Thereby, an angular acceleration of 1000 rad/s^2 is assumed for determining the constraint on the location of the LEDs. If an accuracy of 1 pixel is to be maintained, the stretch of each LED from the center of rotation of the wrist can be restricted so as to allow only that much rotation per second for the LED for an acceleration of 1000 rad/s^2 as would result in a change in a pixel on the image plane. This quantity of length will be dependent on the length of the arm as well.

$$length = (((3 \times Ess \times \max\_def) \times (D^\wedge 2 + d^\wedge 2))/(5 \times ang\_accel))^\wedge.2$$

$$where, \quad \max\_\mathrm{def} = \frac{Length\ of\ arm}{94.5 \times 14}\, inches/pixel$$

$$D = outer\ diameter\ of\ hollow\ support; d = inner\ diameter\ of\ support$$

$$ang\_accel = 1000\, rad/s^2$$

$$Ess = Young's\ modulus\ of\ the\ support\ wire\ material$$

$$= assumed\ to\ be\ 193 \times 10^{11} for\ steel\ SS304$$

Equation 8

In the search algorithm the spatial constraint is modeled by entering in the coordinates of the volume within which the LEDs must lie. At each increment of the design variables the position of each of the LEDs is checked. If a LED lies outside the constraint volume then that set of design variables is not considered. Furthermore, at each increment the length from the LED to the center of rotation of the wrist is evaluated. If this length is greater than the length calculated as per Equation 8, then that set of design variables is discarded. An exhaustive search across a cube which encompasses the constraint volume is carried out and the LED locations providing the best resolution are determined.

Component design –EMG unit and probes

The EMG probes chosen are non intrusive, in that they stick to the surface of the skin as against the needle type probes, which penetrate the skin. The location of the EMG probes is determined by locating spots on the flexor and extensor muscles in the forearm where a considerable amount of flexing and extending of the muscle respectively is felt.

The EMG unit chosen is the Bagnoli™ handheld 6 channel system. In order to synchronize the data capture with the Wii Remote™'s data capture, and to transmit the information from the EMG to the computer, an interfacing controller is required.

Component design –Microcontroller

The Arduino micro-controller was selected to satisfy this purpose. An Arduino is a single-board microcontroller and a software suite for programming it. It is a device made for controlling student-built interaction design projects [84] . The analog input from the EMG is fed into the Arduino. The Wii Remote™'s voltage input from the motor which causes the rumble in the remote is also fed into the Arduino. The software suite that comes with the Arduino is very easily accessible and understandable. The Arduino

IDE[16] comes with a C/C++ library called "Wiring", which makes many common input/output operations much easier. The code is adapted to activate the data collection from the EMG only after the Arduino receives a signal from the Wii Remote™. Thus, the information capture is synchronized. The rate of sampling by the Arduino can also be customized to match the rate of capture by the Wii Remote™.

This step in the embodiment design phase is taken from the original method, but is augmented with the use of modeling tools (Figure 30) in the form a solid model. The requirements that are fulfilled through this step are:

- *Must design for the environment*
- *Must proceed from the overall abstract of the task to the particulars of the design*

The specific fulfillment of the second requirement is explicitly dealt with in Section 4.2.3.

Step 5. Check for errors and disturbing factors

In order to evaluate the decisions made in the design process, and the performance of the selected components, calibrated experiments were carried out. Ten subjects were recruited for a research study intended to gather ergonomic data of the wrist. A feasibility study was carried out on the use of the Wii-based motion capture device for ergonomics assessments (IRB Protocol H10050 approved by the Georgia Institute of Technology Institutional Review Board on 3/15/2010). Figure 32 is an image of the test setup used for the experiment. The details of the experiments are outlined below.

[16] "Project Homepage", Arduino project

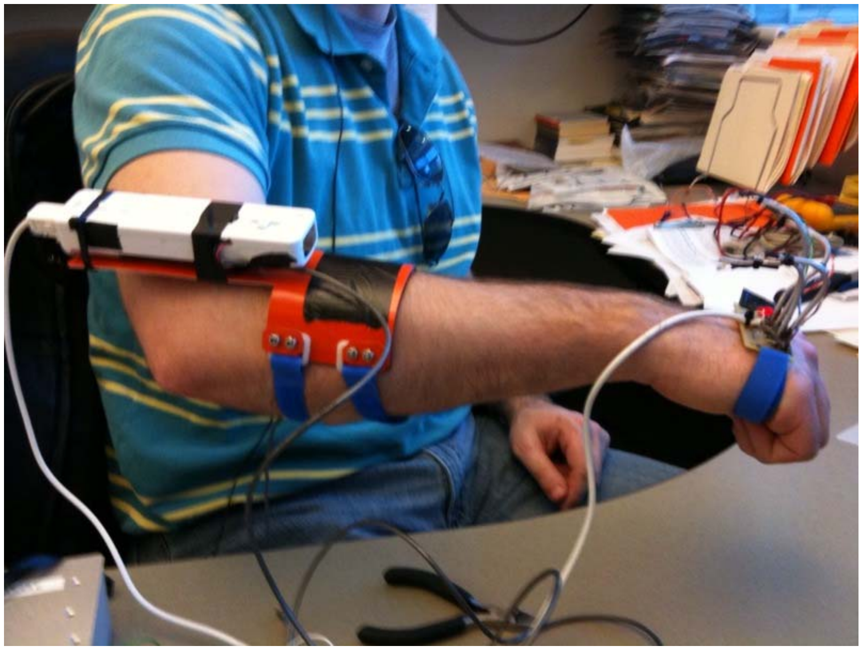


Figure 32: Working design of the motion capture system

<u>Feasibility study of WII Remote motion capture and EMG sensor system</u>

This is a description of the experiments that were carried out under Protocol H10050 in the Food Research Technology Division of the Georgia Tech Research Institute.

<u>Aim</u>

Two sensors used to synchronize the motion of the wrist through different angles, velocities and accelerations to the corresponding muscle activity experienced in the same wrist. Through these experiments, the objective is to test the effectiveness of the system in achieving integration of these information items Specifically, data was collected from wrist motion of the subjects and at the instance of motion, EMG data was recorded from the corresponding muscle activity in the wrist, to build a platform which could be used to quantify the effect of the motion in the wrist on the muscles of the carpal tunnel in the wrist in the future.

Apparatus

Data on the wrist motion will be collected using a WII Remote™ and 4 infra-red marker Light Emitting Diodes (LEDs). The Wii Remote™ was strapped onto the arm of the test subject and the LED arrangement was fixed on the back of the palm of the same arm of the subject, as shown in Figure 32. A Delsys EMG sensor system (Figure 33) was used to detect muscle activity from the flexor and extensor muscles in the arm of the subject. An Arduino microcontroller (Figure 34) was used to sample the EMG data, as well as synchronize the Wii Remote™'s data collection with the EMG data collection.

Figure 33: Bagnoli™ Delsys surface probes *(Courtesy:www.delsys.com)*

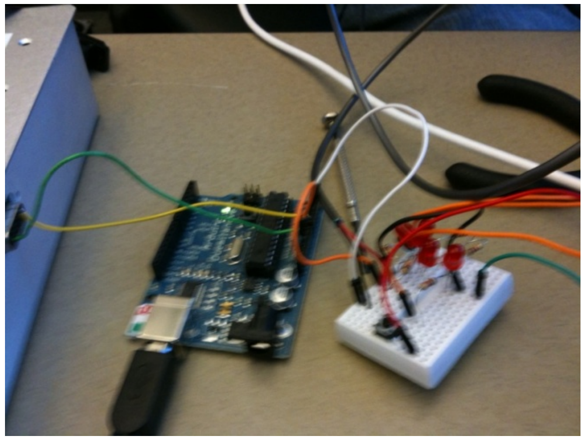


Figure 34: Arduino board with attachments

A schematic of the experiment is shown through a flowchart in Figure 35. This figure corresponds to a more specific form of the information flow diagram that was designed in the conceptual design phase using the taxonomy for sub-systems in LST. The causalities set in that diagram (Figure 25) are preserved throughout the design phases down to the experiments and the prototype.

The boxes within the red dotted box form the system, and the green dotted box forms the environment. The other boxes represent the optimization routine outlined in previous sections for the layout parameters. Note that, for the prototype, a single configuration of the LEDs was used for all the subjects. This is primarily because, the prototype was built in a previous iteration of the design for this system, and the need for locating the LEDs in an optimal fashion became an evident need based on that design. Due to constraint on resources, a more compliant LED beacon could not be built in time for this thesis. Efforts are ongoing to develop a better prototype for this purpose.

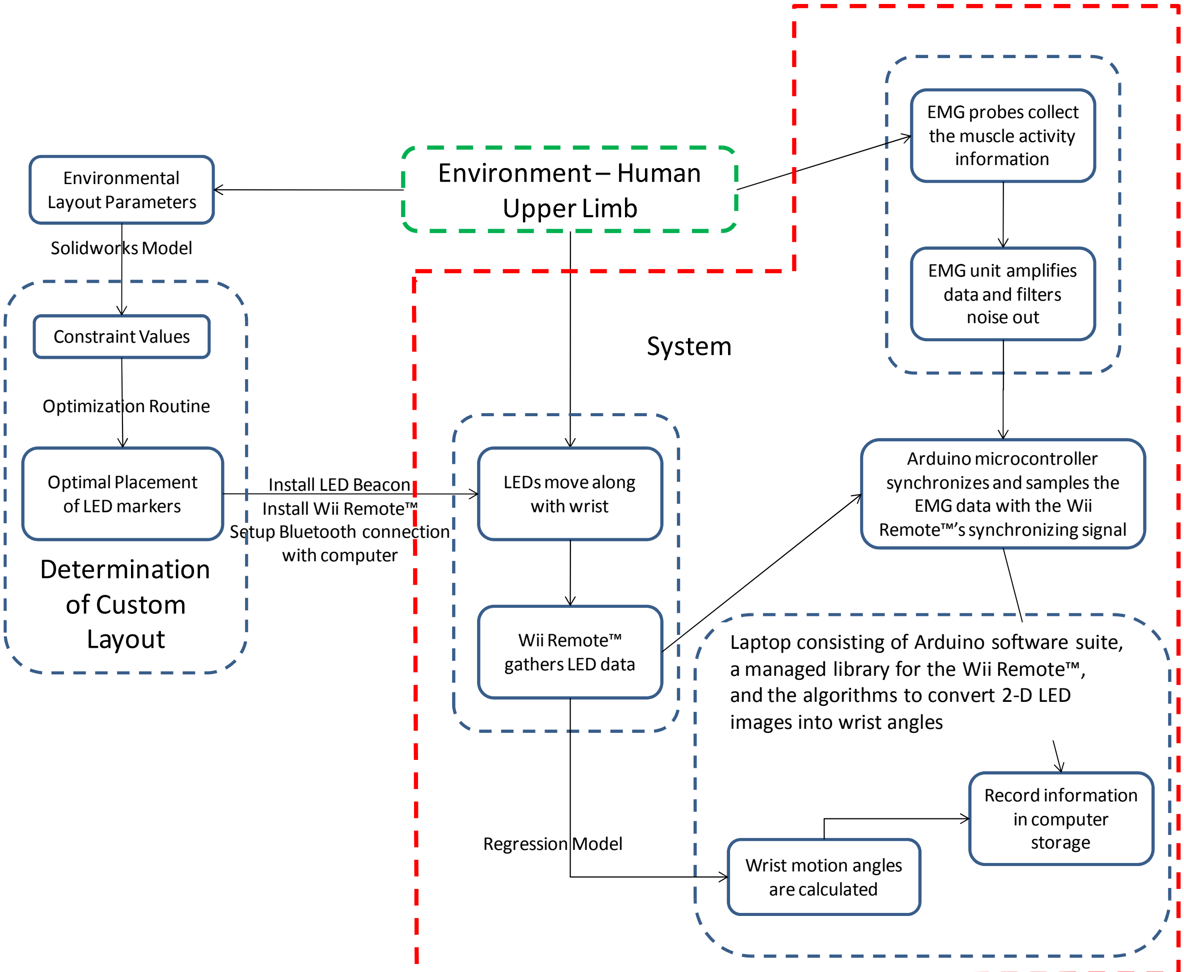


Figure 35: Information flow layout for experiments

Subjects

The system was to be tested only in terms of efficacy of data collection. Therefore, any human could be used as a subject for this test. Georgia Tech students were used as the test subjects. For this experiment, 6 volunteers were chosen to ensure a spectrum of physical conditions.

Procedures

- Installation of the EMG sensor

1. Preparation of the Skin

This needs to be done to improve the input impedance to the electrodes in order to ensure better amplification of the low voltage signals from the muscle activity without introducing too much noise into the received signal. A little bit of alcohol was rubbed onto the skin with some cotton for this purpose.

2. Placing the Probes

The EMG surface electrodes were placed on the forearm muscles. The key areas that were covered are the flexor and extensor muscles on the forearm.

3. Other EMG gear

The probes lead into the EMG system's amplifier, from where the signal is transmitted through a low pass filter to a computer. These units were kept comfortably out of the way of the participant to avoid intrusion during cutting tasks.

- Installation of the WII Remote™ and the LEDs

1. The subject was asked to strap on the Wii Remote™ onto the upper arm.
2. The LED beacon was fixed onto the back of the palm of the same arm of the subject.

- Rotation of the Wrist

1. A number of iterations resulted in convergence on a calibration routine which was used to model a regression approach towards the calculation of wrist angles based

on the 2-D image data from the Wii Remote™ sensor. The subject was asked to perform this calibration routine through 42 sets of data as follows.

Calibration procedure

The setup that was used is shown in Figure 36.

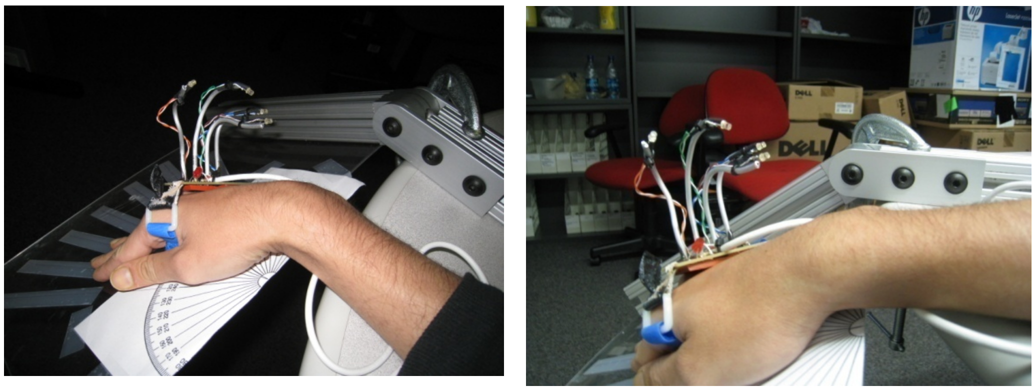


Figure 36: Calibration setup

As shown in the figures, the setup consists of a rotating aluminum arm with a plexi-glass board attached to it on which a protractor is pasted. The objective of the setup is to facilitate a rotation of the wrist through prescribed angles about the X and Y axes by γ and β respectively to achieve the required adduction/abduction and flexion/extension respectively. The X-axis is perpendicular to the arm, and points upwards away from the arm. The Y-axis is perpendicular to the arm and points right away from the arm.

The aluminum arm shown in is rotated through each of the angles of the range of -30 to 30 degrees about the Y-axis i.e. from flexion to extension. At each angle, the subject is asked to rotate the wrist to align with each of the angles from -30 to 20 degrees about the X-axis in increments of 10 degrees. Thus, at each angle of flexion/extension, six different positions of adduction/abduction are recorded. This results in 42 readings of the four LEDs on the LED beacon. This data is then used to create a regression mapping between the image coordinates and the two angles of rotation.

2. After calibration, the subject was asked to simulate the movements associated with cutting poultry while wearing the Wii™-based motion capture device and the EMG sensors. They were asked to hold a knife (sharp edges were covered appropriately), and perform incisions on the shoulder of an artificial mold of a chicken. The act involved a pierce and slice operation which was repeated five times, after which the subject was asked to simulate the sharpening of the knife on an imaginary grinding wheel by rubbing the knife against it twice.

The data collected from the Wii Remote™ when plotted as it is show a distinct pattern which seems to match with the actions that were carried out in the chicken cutting exercises. The data for the left most LED on the LED beacon (from the user's point of view) is plotted in Figure 37.

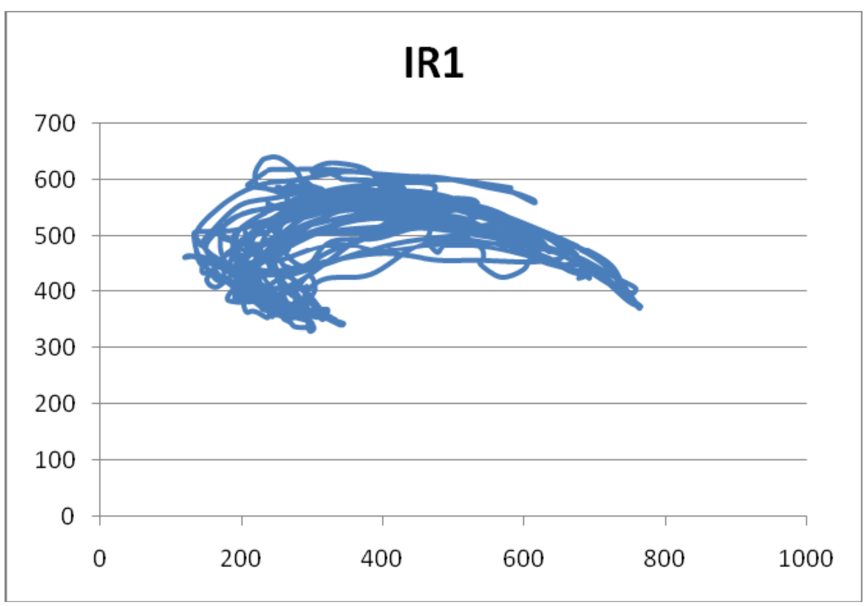


Figure 37: Motion of left most LED as seen on the image plane of the Wii Remote™

An analysis of the performance of the entire system is carried out in Section 4.2.

4.1.4 Detail Design

The detailed design phase of the design process is currently under development. Results from human subject testing are being evaluated and examined so they can be used primarily to characterize the performance of the proposed system better. Some iteration is required before a production documents can be created and a bill of materials is finalized. Much of the efforts in this design have been leveraged based upon open source software. Some of the software used possesses additional abilities, but creates inefficiencies in the lag they introduce in data capture. These can be simplified for better efficiency. The EMG data collected requires analysis, and further processing in order for it to indicate particular trends in muscle activity. The mapping of the EMG information and the wrist angle information has been done as far as information collection is concerned. Though a certain level of transformation to knowledge is affected by converting the LED image data to wrist angles, the integration of the two information types (i.e. EMG and wrist angles) has been carried out as far as synchronization. In order to facilitate training of muscles and other possible uses of this system, further integration is required. A constraint on the resources has limited efforts towards that direction. Further work is deliberated upon in the future work section.

4.2 Results of example problem

In the context of this work, the intent of pursuing the design of the Wii Remote™ based motion capture system was laid out in the context of the validation square. The example problem chosen was shown to satisfy certain characteristics which make it a suitable example for the domain of applications in systems with intelligent and interactive information flow. Now, the performance of the design is evaluate in terms of the performance parameters of the designed system and the extent to which the design method used satisfies the requirements set out for the adapted method in Section 2.2. There are 3 aspects of this performance that need to be evaluated.

- Customization of the system with respect to the length of the user's arm and the height of the Wii Remote™ above the wrist of the person
- Synchronization of the information collected from the Wii Remote™ and the EMG sensor
- Requirements for the modified method (Section 2.2) that were satisfied by the implementation of the modified method for this system

4.2.1 Selection and customization of layout parameters

As described in the conceptual design phase, the primary focus of the design is a customizable layout which can be used by people with different geometrical features and can be used as a platform for a real time muscle training system in the future.

For given parameters in terms of length of arm and height of Wii Remote™, the resulting maximum length of LED supports that can be used while maintaining an accuracy of 1 pixel is calculated. Based on the parameters, the mathematical coordinate transformations to represent the LED coordinates in the Wii Remote's™ coordinate frame can be calculated quantitatively. An exhaustive search is carried out on all possible locations of the LEDs within the determined spatial constraint volume. This algorithm provides us with the best possible locations for the 4 LEDs for highest resolution data.

For an arm length of 11.5 inches and height of 2.15 inches (parameters corresponding to one of the researchers) the results from the optimizer are shown in Table 10.

Table 10: Optimizer results for LED locations in 3-D space for arm length = 11.5 inches, and Wii Remote™ height = 2.15 inches

LED	X-coordinate (inches)	Y-coordinate (inches)	Z-coordinate (inches)
1	4.75	-2.23	2.42
2	4.75	.77	4.58
3	2.75	.77	2.42
4	4.75	3.77	2.42

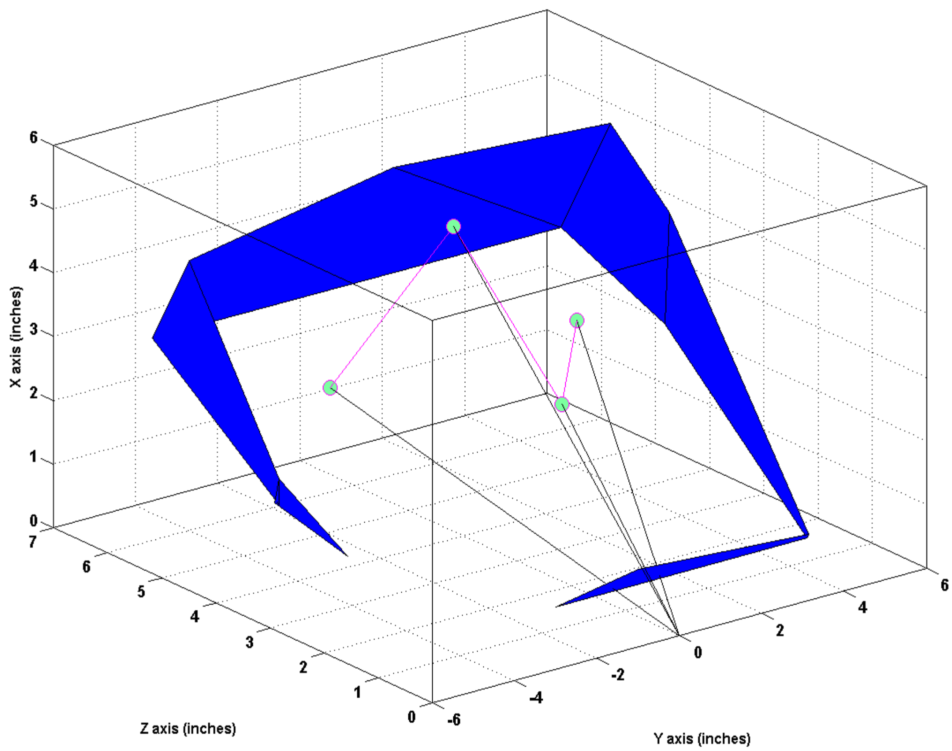


Figure 38: Optimizer results for LED locations in 3-D space for arm length = 11.5 inches, and Wii Remote™ height = 2.15 inches.

In Figure 38, the optimal locations of the 4 LEDs are shown. The blue surfaces represent the bounding constraint volume. The top and bottom surfaces have been removed in this figure in order to see these point locations better. Table 10 lists the coordinates of the LEDs achieved after applying the LED placement decision algorithm. The resolution corresponding to these LED locations was, represented by the area of the corresponding quadrilateral on the image plane. One would expect that the maximum resolution would be at the corners of the feasible space. However, this is not the case due to the constraining condition imposed by the maximum allowable support length for each LED, which is restricted based on the maximum deflection we will tolerate.

Another reason the LEDs are not at the maximum allowable space is because they must go through several rotations along with the wrist and still exist in the field of view. As a means of validation, the sources of error and their effect on the algorithm's output on the LED positions and the resulting resolution is examined. The following section describes the sensitivity analysis carried out for this purpose.

Sensitivity Analysis

In order to fulfill the requirement of maintaining customization in the final design of the system, the algorithm for LED location is parameterized for individualized factors. As mentioned before, these are the arm length of the user and the height of the Wii Remote™ from the wrist of the user. However, both these measurements are difficult to measure with accuracy. It is expected then that the location of the LEDs that is decided upon for a particular set of parameters maybe erroneous depending on these measurements. Thus, a sensitivity analysis is carried out assuming an error in these measurements, as follows. The implementation algorithm for the same is included in the Appendix.

For the arm length of 11.54 inches and a Wii Remote™ height of 2.54 inches, an error of 20% was introduced in both the measurements. It is expected that any change in these values due to movement of the arm in realistic conditions, or due to error in their measurement will be well within the tolerance of +/-20%. The resulting positions of LEDs and the corresponding maximum resolution values are shown in Table 11. The resolution is plotted as a surface for the matrix of length and height values corresponding to the length and height values.

Table 11: Resolution as a function of error in length and height measurements

Resolution ($X10^5$ pixels^2)		Percentage of Length of arm (11.54 inches)								
		80%	85%	90%	95%	100%	105%	110%	115%	120%
Percentage of Height of Wii Remote™ (2.54 inches)	80%	1.17	1.16	1.16	1.15	1.14	1.13	1.12	1.11	1.10
	85%	0.98	0.97	0.96	0.95	0.95	0.94	0.93	0.92	0.92
	90%	0.82	0.82	0.81	0.81	0.80	0.79	0.79	0.78	0.78
	95%	0.70	0.70	0.69	0.69	0.68	0.68	0.68	0.67	0.67
	100%	0.61	0.60	0.60	0.60	0.59	0.59	0.58	0.58	0.58
	105%	0.53	0.53	0.52	0.52	0.52	0.51	0.51	0.51	0.50
	110%	0.47	0.46	0.46	0.46	0.46	0.45	0.45	0.45	0.44
	115%	0.41	0.41	0.41	0.41	0.40	0.40	0.40	0.40	0.39
	120%	0.37	0.37	0.36	0.36	0.36	0.36	0.36	0.35	0.35

The LED locations show no change within the 20% error and are the same as in Table 10. Though surprising at first glance, a careful look at the constraints reveal that the space within which the LED locations must lie is quite constricting. The constraint imposed based on the accuracy factor of 1 pixel per second, eliminates some of the space of the shown constraint volume from consideration.

Also, based on the assumption that the Wii Remote™ is in line with the arm, so that its line of view is parallel to the Z-axis and displaced only along the X-axis (refer to Figure 28), it is expected that the quadrilateral projection of the 4 LEDs onto the Wii™'s image plane does not change considerably with the length of the arm. The variation in the length of the arm changes the 'c' value of 94.5 pixels per inch (which is the resolution of a pixel at 14 inches away from the Wii Remote™). Along with a slight change in the area of the quadrilateral, this results in a small decrease in the resolution due to increase in the length as can be seen in Figure 39 along the y-axis.

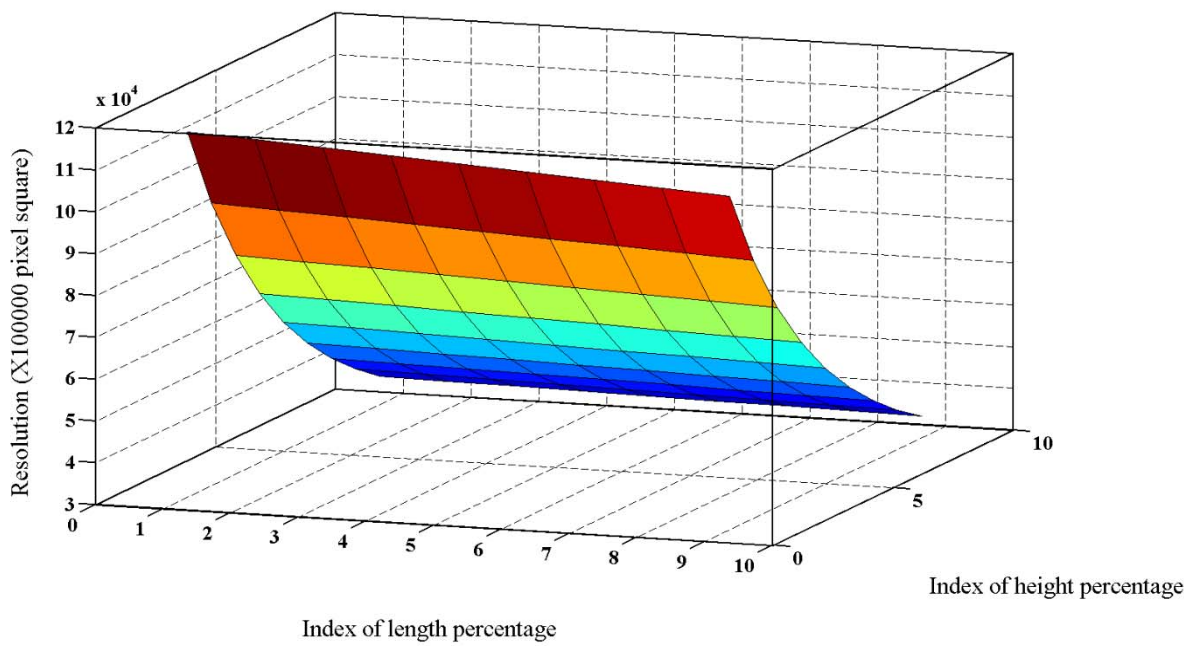


Figure 39: Variation of resolution in pixels^2 with error in measurement of height and percentage (Refer to Table 11 for order of length and height percentage)

The increase in height of the Wii Remote™ results in a larger change in the resolution. A different height of the Wii Remote™ leads to a larger change in the projected quadrilateral, since it changes the line of sight between a LED and the Wii

Remote™ considerably as opposed to a change in the length of the arm. This is depicted in Figure 39 with the curving decline along the x-axis.

Thus, the variation in resolution for the same location of the LEDs is quite high if the error is in the height measurement of the Wii Remote™ as compared to when it is in the length of the arm. At the same time, the lowest resolution is $.35X10^5$ $pixels^2$, which still provides enough resolution for us to record LED position data from the Wii Remote™ which can be used to determine wrist angles. However, these results do offer cause for concern since a mere 5% error in the height measurement results in a 15% change in resolution. This seems to be a bit high, and might be a problem when calculating wrist angles using the image data from the Wii Remote™.

For the design method used, these results would translate to a change in the process adopted in the installation of the device on the arm of the person. In addition to the design of the information flow and subsequent component design, a deliberation on the installation of the device ought to be considered. This would form part of the detail design phase. As such, these results serve to perform part of the detail design phase. They indicate that the measurements taken for a particular person in terms of the arm length and the height of the Wii Remote™ should be taken conservatively so that if error is in the negative side of the actual values, the resulting resolution is only higher than expected and not lower. These results serve to tie in to research question 2 which addresses the issue of the overall design of systems with interactive and intelligent information flow. Some of the aspects mentioned in the elaboration of the research question (Section 1.2.1) are clearly being addressed here, including the number of sensors, the placement of sensors, the information to be collected, along with issues of accuracy and precision of the information.

4.2.2 Performance based on precision

The calculation of wrist angles is one of the final outputs of the designed system. To evaluate the performance of the system with respect to the output experiments are carried out with the aid of volunteers as per the IRB Protocol H10050 approved by the Georgia Institute of Technology Institutional Review Board on 3/15/2010 as described in Step 5 of the embodiment design phase.

The prototype and the setup that was used are shown in Figure 32 and were described along with the experiment in Step 5 of the embodiment design phase. In Figure 35, the elements of this prototype and the connections between them have been represented using a flowchart.

The EMG unit is a 6 channel system from Bagnoli™. The sensors are surface probes as shown in Figure 33. The Arduino board with the attachments is shown in Figure 34.

<u>Post processing of Experimental data</u>

One of the wishes in the requirements' list was to have real time feedback from the system to the user, in order to facilitate training exercises. Though the system's components were chosen to fulfill this requirement, the software which processes the information to create knowledge, needs to be developed to a much greater extent before the system performs this function in real time.

This was anticipated, as the efforts behind performing real time feedback include the following tasks, which were identified as beyond the scope of this work:

- Convert raw EMG data into meaningful graphs of muscle activity with processing to indicate when muscles are over tensed.
- Perform calibration of muscle activity based on factors such as maximum grip force, torque of the wrist, resting position, rotation of the wrist to extremes about each of the 3 axes and others.
- Relate the muscle activity to the wrist angles based on a individualized algorithm, which adapts itself to different users.

Thus, processing, and creation of knowledge from the information collected has been carried out in an offline manner. The following discussion elaborates on the post processing algorithm which was used to determine the wrist angles from the data that was collected from the Wii Remote™. The justification is provided, and then the implementation

<u>Regression model for determination of wrist angles</u>

Some assumptions which were made in the layout design activities were found to be invalid in a real world scenario. The alignment of the Wii Remote™ with the arm is not a reliable assumption. Thus the image plane cannot be assumed to be coplanar with a plane passing through the center of rotation of the wrist and perpendicular to the Z-axis along the arm. An additional inaccuracy in the analytical transformation between the LEDs and the Wii Remote™'s image plane creeps in because of the uncertain positioning of the LED beacon fixture which is tied onto the back of the palm of the subject. Since one of the prime requirements of exploring this platform, and the need is for a low cost system which is robust for motion capture and training applications in the work environment, controlled and structured experiments or a rigid and intrusive system was out of the question. Thereby, an analytical model was discarded for calculating the wrist angles from the LED image data. Instead, a regression model is used for the same purpose. Further explanation on the barriers to an analytical model is provided in the closure section, and some ideas are put forth for future implementation.

A multivariate regression is setup in MATLAB using the stepwisefit() function. The dependent variables are the two angles of rotation, i.e. flexion/extension (β), and abduction/adduction (γ). The independent variables are the coordinates of the images of the four LEDs (x_i,y_i) which were collected for predesigned ranges of angles of rotation of the wrist as described in the experiment description in Step 5 of the embodiment design phase.

As mentioned earlier prior work in the capture of wrist motions have involved mostly a controlled and expensive setup [8, 12-13, 75]. In a study of the effect of wrist angle and other factors, i.e. gender, exertion direction and angular velocity on maximal dynamic grip force and wrist torque, the authors have collected objective motion data from the wrist and arm motion and performed a regression analysis using MANOVA (Multivariate Analysis of Variance). However, the "isokinetic dynamometer" apparatus developed in their work consists of several components, and involves controlling the wrist's motion with the aid of a servo motor. The regression model that they have developed is thus only effective when working in the laboratory with a similar setup. An attempt is being made in this example system to design a non-intrusive, easy to use and low cost system which can be customized for use by different individuals in a work environment. Thus, the laboratory section of data collection for this system is limited to a calibration routine, which is designed in a manner so that it is hoped that the user's motion characteristics are captured in the regression model. Thereafter poultry cutting tasks are simulated to validate the ability of the system to collect data in a synchronous manner from the environment.

Regression is performed on the following variables:

- Independent variables – 2-D coordinates of the LEDs collected from the Wii Remote™'s Bluetooth packets
- Dependent variables – Wrist angles for flexion/extension (β) and abduction/adduction (γ)

A regression model which uses MANOVA requires positive definite covariance[17] between the dependent variables. In this case, it is not possible to determine a positive definite covariance between the dependent variables in this case because the calibration data, which is the data that is used to build the regression model, is collected for a matrix constructed by a range of β vs. a range of γ. This means that a multivariate regression model was not a possibility for these dependent variables since in the data collected there really was no correlation between them. Thus, for each angle, a quadratic regression model was developed using the other angle as an independent variable. In this way, if any dependence was to be included, the analysis of variance would include a considerable

[17] http://en.wikipedia.org/wiki/Multivariate_analysis_of_variance

weightage for the other angle in the model for one. The implementation algorithm for the regression model developed is included in the Appendix.

The coefficients and corresponding P-values for a typical test are shown in Table 12 and Table 13. The quadratic regression model consisted of all one degree terms (amounting to 9 including the other angle's term) and second degree terms of the type x_i^2, $x_i y_j$ and y_j^2, where (x_i, y_j) are the coordinates of the LEDs (i,j = 1, 2, 3, 4).

Table 12: Regression results for γ (adduction/abduction) for Subject 1

Term	Coeff'	'Std.Err.'	'P'
β	-4.50E-01	3.39E-02	1.93E-15
x1*y4	2.63E-04	4.23E-05	3.48E-07
x2*y2	3.17E-04	8.12E-05	3.92E-04
y2*x3	6.48E-04	1.30E-04	1.57E-05
y2*y4	-7.82E-04	7.63E-05	3.22E-12

Table 13: Regression results for β (flexion/extension) for Subject 1

Term	Coeff'	'Std.Err.'	'P'
x1*y2	-1.00E-03	2.33E-04	6.50E-05
x1*y3	6.88E-04	2.52E-04	9.50E-03
y1*x4	3.38E-04	3.12E-05	3.29E-13

The terms that were included in the regression model differed greatly from one subject to another. This was expected, as the custom dimensions, and fit of the system on the subject were very different, and would result in different ways in which the LEDs would move along with the wrist.

The calibration data itself is used to calculate errors induced due to regression. The errors induced for a typical subject are shown in Figure 40-Figure 43. Error in degrees is calculated as the difference between the actual angle γ or β that was used during calibration (measured from the protractor on the plexi-glass board and the angle formed by the rotating aluminum arm, Figure 22) and the corresponding angle that was calculated from the regression fit for γ or β respectively.

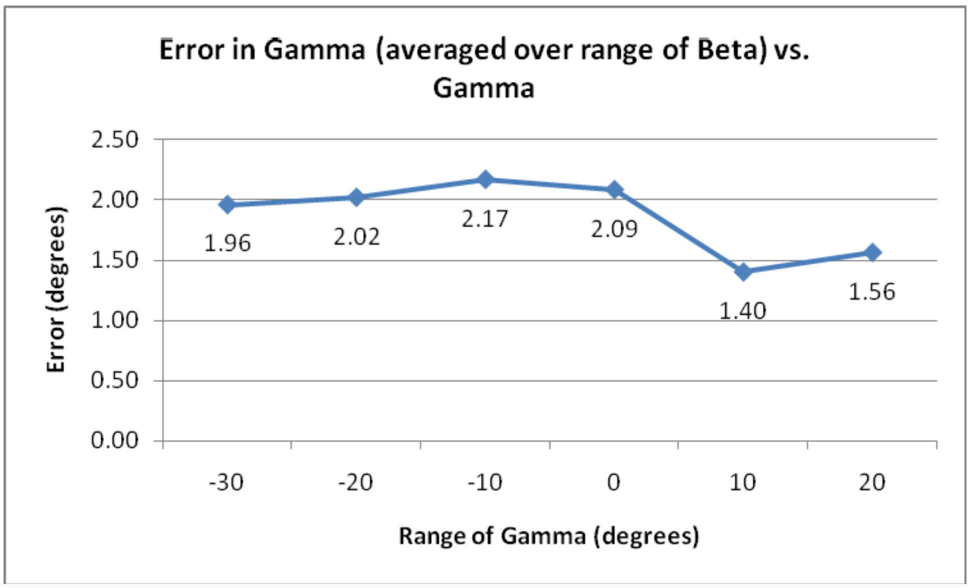


Figure 40: Error in calculated angle of adduction/abduction from regression model averaged over the range of flexion/extension for Subject 1 vs. the range of angle of adduction/abduction

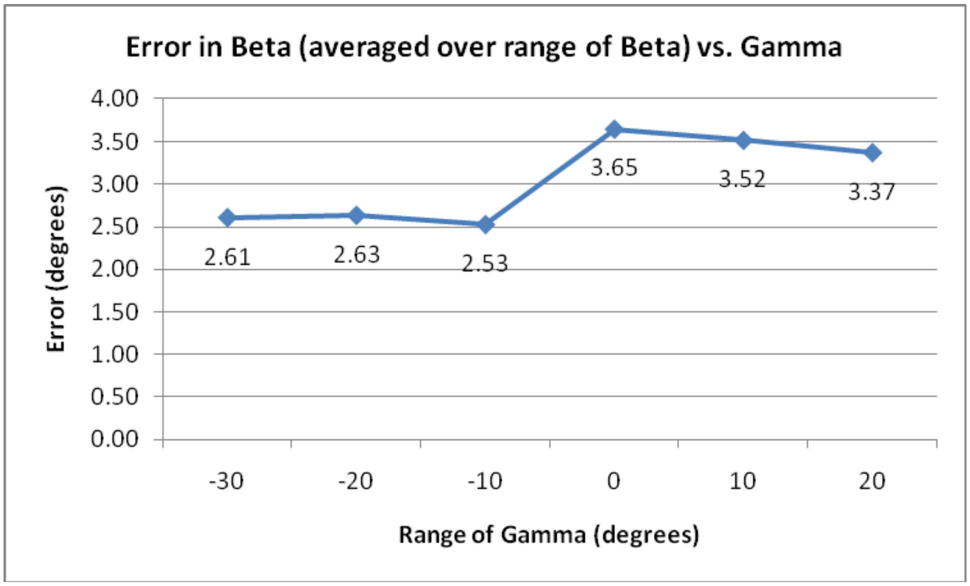


Figure 41: Error in calculated angle of flexion/extension from regression model averaged over the range of flexion/extension for Subject 1, vs. the range of angle of adduction/abduction

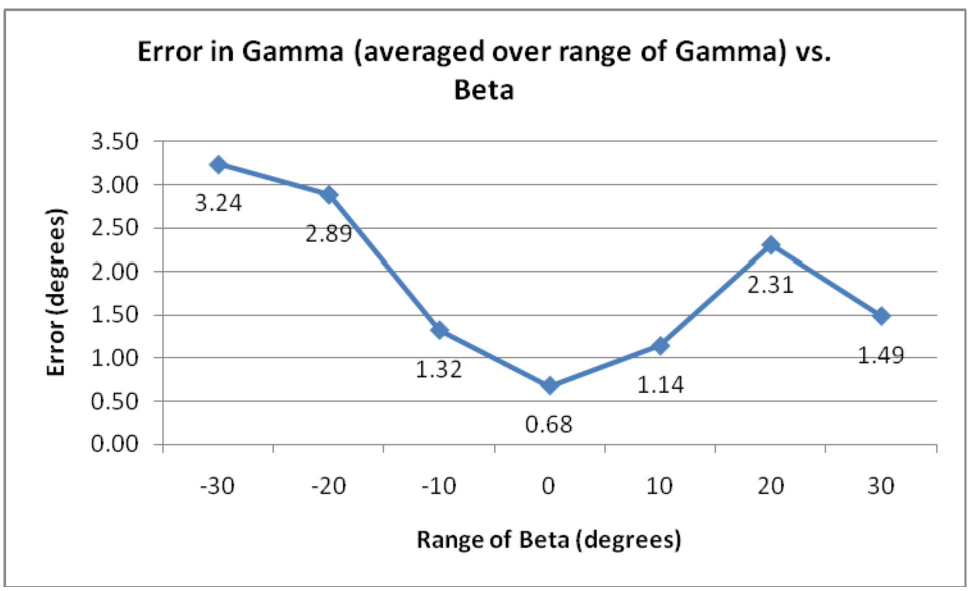


Figure 42: Error in calculated angle of adduction/abduction from regression model averaged over the range of prescribed adduction/abduction for Subject 1, vs. the angle of flexion/extension

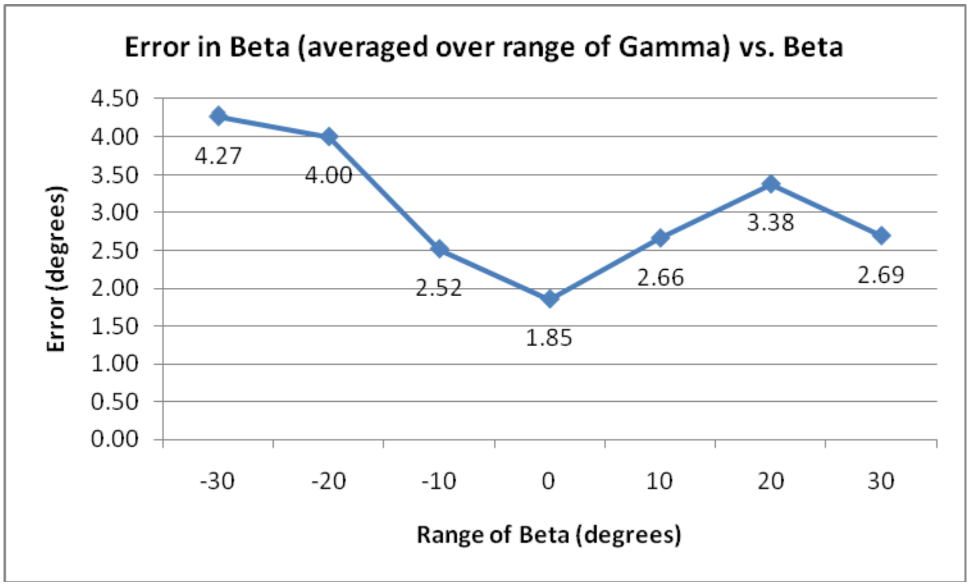


Figure 43: Error in calculated angle of flexion/extension from regression model averaged over the range of prescribed adduction/abduction for Subject 1, vs. the angle of flexion/extension

For subject 1, the figures above have been shown to depict the error in the regression model's output for LED images fed in for prescribed angles. These LED image measurements are the same as taken during the calibration for the corresponding angles. The calibration procedure which was followed characterizes the angles γ and β as described on page 154 . This characterization can be assumed to be quite accurate at β being closer to zero. This was expected from a visual perspective of the calibration being carried out. When the flexion/extension angle is closer to zero, the subsequent adduction or abduction that the subject imposes is considerably with ease, and the angles chosen are easy enough to reach for most subjects. However, at higher angles of flexion and extension, the twisting for adduction or abduction is considerably restrained in the wrist. There are pronounced vibrations in the palm and subjects found it perceptibly more difficult to cover the range of angles with ease. Most importantly, the wrist is restricted, and it is the fingers that bend outward away from the wrist, leading to higher inaccuracies. Thus, at lesser degree of flexion and extension, the errors are lesser as can be seen from Figure 42 and Figure 43.

The average errors with respect to the calibration data in the regression model are shown in Table for the 6 subjects that were tested.

Table 14: Average errors of calibrated wrist angle calculation

	Average Error (degrees)		Percentage Error	
Subject #	Gamma	Beta	Gamma	Beta
1	1.87	3.05	3.74%	6.10%
2	2.55	2.02	5.09%	4.03%
3	0.34	0.37	0.69%	0.74%
4	1.19	1.60	2.37%	3.20%
5	2.08	1.97	4.16%	3.93%
6	1.14	1.38	2.29%	2.75%
Overall Averages	1.53	1.73	3.06%	3.46%
	1.63		**3.26%**	

As shown in Table 14, the average errors that the regression model output are quite low. From a simulation point of view, in robotics, this percentage of error may not be a very promising prospect. However, the purpose of this design is to capture motion, not for simulation of precise control tasks, but to aid in customized feedback for crude tasks with a high range of variation possible. Most design efforts have been towards modeling the human joints in order to perform inverse and forward kinematics on the model. In [85], the authors present a motion capture system using magnetic sensors which models the human skeleton as a number of joints. The authors conclude that their model performs for human subjects but with errors up to 10 cm in the inter-joint distances. In a motion range of 70^0 this would result in an error of greater than 2^0 .Thus, the results shown in Table 14 are better than the state of the art for measuring joint motion in humans. The motion capture systems thus used have been for the sole purpose of determining the joint parameters and thereafter input the parameters into an analytical model. Thus, in non controlled surroundings, such as those around a worker in a poultry manufacturing plant, where, intrusive sensors, or constraints are not a feasible option for training, these results hold the promise of a very useful system.

As described before, after the calibration routine each individual was asked to mimic poultry manufacturing workers with chicken cutting tasks holding a knife with edges well covered with thick tape.

It is evident from a visual standpoint (Figure 44) itself that synchronization of information collection between the Wii Remote™ and the EMG unit seems to have been achieved. This was expected, since there was no room left for error in that design objective. Certain trends as demarcated by the red lines in the figure can be observed. The intervals on the time axis are different for the muscle response and the angles due to difference in sampling rates of the Wii Remote™ and the EMG unit in series with the Arduino microcontroller. The first column from the left marked by two red lines on either side of it is believed to represent the piercing and slicing exercise carried out on the mold chicken. The second column is probably when the subject holds the knife against the grinding wheel, since the motion is considerably low in that case as is seen from the EMG response. A similar pattern of change in the angles with time can be seen in the third column as in the first, which suggests the second set of piercing and slicing exercises carried out by the subject.

The chicken cutting exercise reveals a number of insights regarding the model that has been adopted, and serves to validate some of the key findings and assumptions in the design. Towards the merit of these exercises, certain trends can be observed in Figure 44, which correspond to the prescribed tasks in the chicken cutting exercises and thus serve to validate the process of information capture designed for the system, in terms of the Wii Remote™'s IR sensor and its capture of 2D image data. Furthermore, since the regression model was used to output these trends, they build confidence in the use of regression as a working principle for a real world scenario usage of the system.

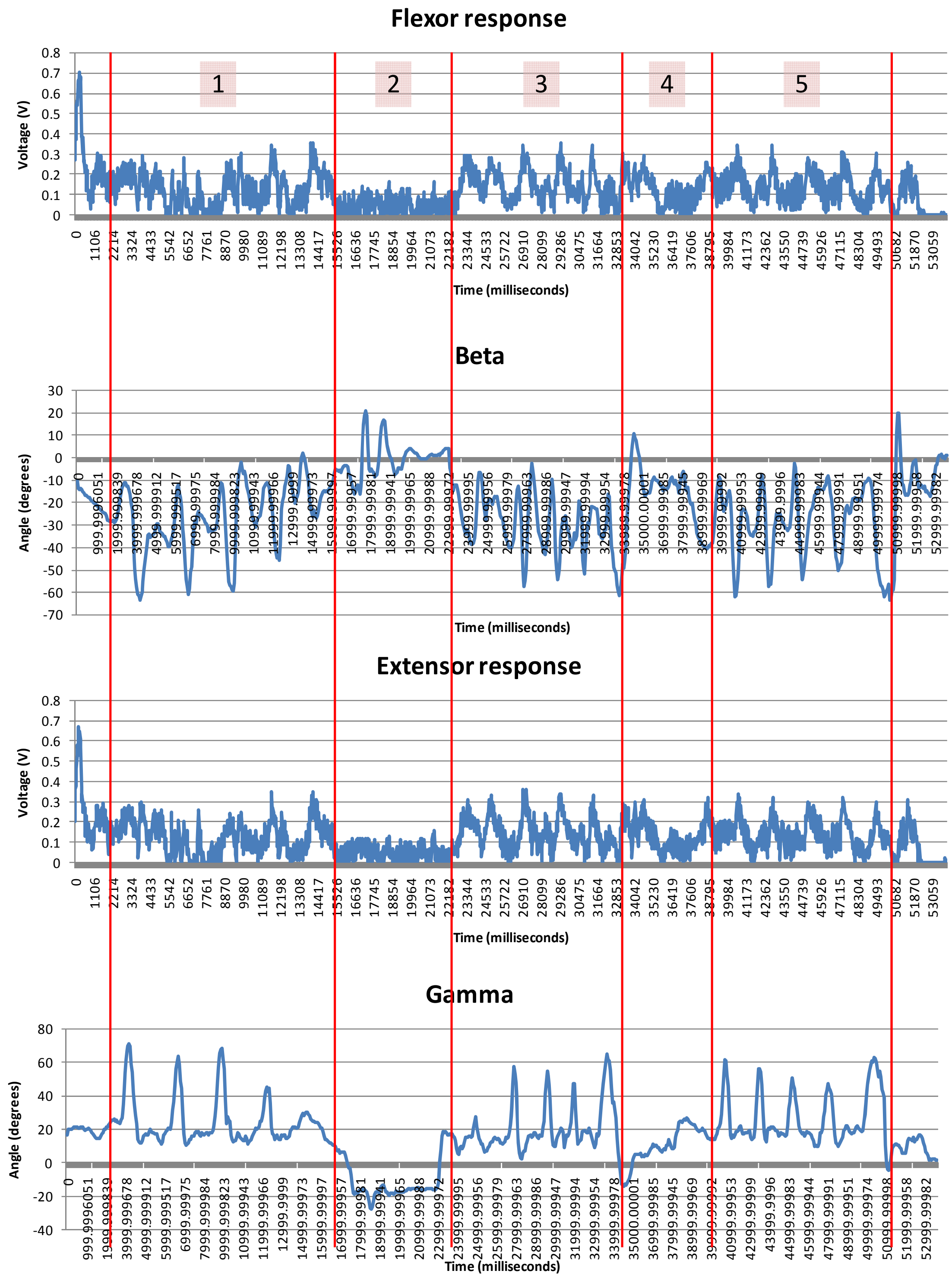


Figure 44: Response functions synchronized with calculated wrist angles

In some cases however, the exercises indicate the need for removing certain assumptions made in this work. Primary amongst these are:

- The rotation about the z-axis (roll), which is actually a rotation of the elbow joint, for the purpose of poultry manufacturing, was neglected. The unexpected values for γ (yaw) and β (pitch) calculated through the regression model for the chicken cutting exercises suggest that this assumption needs to be removed. The most important consequence of this realization is that, a different working principle for attaching the Wii Remote™ or/and the LED beacon needs to be considered. The present layout design will not be able to capture the motion of the wrist about the z-axis effectively. This is because, as the roll occurs, a high chance of all the LEDs disappearing out of the field of view of the Wii Remote™ is introduced.
- The LED beacon needs to be customizable for different users, as is modeled using the optimization routine described in Section 4.1.3 with the results in Section 4.2.1. This customization must ensure that the LEDs stay within the field of view of the Wii Remote™ unhindered by the motion of the wrist or the arm. Certain discontinuities are noticed in the responses of the wrist angles, which were easily traceable to 2-D image data from the Wii Remote™ wherein the coordinates of the LEDs were (1023,1023), clearly indicating that the LED was out of the field of view of the Wii Remote™'s 1024X768 camera. It also brings to highlight the inability of the software packages used to distinguish the resolution in height and breadth once the LED has left the field of view. Thus, LEDs which leave the field of view, are not traceable with the last image data either. Thereby, it is crucial for either the supports to be compliant, so that they can be bent to locations determined by the optimization

routine, or to have a customizable assembly in place of the supports. This brings in the consideration of a design decision which was hitherto condoned. The prototype was developed[18] before the constraint imposed by asserting custom requirements of different individuals' parameters, and therefore resulted in a flawed design. This limitation will entail an iteration of design activity at Step 1 of the embodiment design phase.

- Though trends were observed in the response and wrist angle graphs (Figure 44) for each subject that was tested, these trends varied widely, and in most cases included inconsistencies as well. Keeping in mind that the subjects chosen for the experiments were Georgia Tech students with absolutely no training or real world experience of chicken cutting, these inconsistencies are not surprising. A more effective way to test the motion capture prototype and the algorithms used for processing the Wii™ image data would be to test real workers in a poultry manufacturing plant.

Note that the limitations that were found with the aid of the experiments are very much part of the design process, and call for iterations of the process. The credit goes to Pahl and Beitz for organizing design information and workflow in a manner, where it becomes easy for us to identify which design decision needs to be change in order to fix the limitation, as is indicated for each of the limitations in the list above.

4.2.3 Requirements fulfilled for modified Pahl and Beitz method

A key aspect of validating the chosen example problem and the design process employed is to evaluate the extent to which the requirements that were set out in Section

[18] The prototype was developed at the Food Processing Technology Division at GTRI

2.2 were fulfilled in our design example. Each of the requirements and justifications of their fulfillment have been laid out below.

Must design for the environment

The proposed method includes several constructs and systematic steps to maintain the relevance and traceability of the environment specific needs and requirements down to the detailed design layouts. Some of the key questions that were laid out with respect to the environment are implicitly made into design decisions in the proposed method. These are:

What are the ways in which information can be gathered from the particular environment?

Do existing systems provide competent solutions in terms of accuracy, precision, safety, robustness, uncertainty to gather information from this environment?

What relevance does the history of the environment hold to our objective?

The task clarification phase provides a general enough approach towards understanding the environment, and the boundary that would define it either physically or functionally as against the system. In the example, the relevance of these questions to a designer is evident in our design from our analysis of the market, and the competencies of the designer in the task clarification phase. They serve to identify requirements, working principles and criteria to evaluate working principles and structures. This consideration, is also evident from the detail design phase wherein the experiments set out for evaluating the feasibility of the Wii™ platform and the proposed system as a whole for motion capture, are described. Six students from Georgia Tech were selected with no bias towards a particular body structure, or state of health. As such, the environment, though varying does not affect the efficiency or the effectiveness of objective motion capture.

Must build functions and concepts on a fundamental information flow and processing representation

This requirement was clearly satisfied with the aid of the taxonomy of LST that was employed to integrate working principles into a working structure. The concept was thus based on a fundamental representation of the information flow and processing, and the entities that are responsible for the same. Thereafter, embodiment determining requirements were drawn out from this fundamental representation, by a systematic consideration of every node in the information flow diagram, and the input and output for each of these nodes.

Must design for the available technology with respect to input transducers (sensors)

The example employed was based on a particular platform which is the Nintedo Wii™ remote, based on an ongoing analysis of motion capture systems and the requisite functionalities from such systems, in a particular environment, i.e., a manufacturing facility for poultry processing with manual workers employed for repetitive wrist motion tasks leading to higher risks of sustaining injuries such as the carpal tunnel syndrome. The selection of the Wii™ was accompanied with a complete reverse engineering of its functions, and its capabilities, and a constant matching of what the Wii™ remote can do to what the requirements are for the system ensured that the design was made with its limitations and advantages in mind. The function structure construct of the Pahl and Beitz method followed by a reverse engineering of the Wii™ in context of the functions required to be fulfilled in the system specifically, ensures the satisfaction of this requirement.

With respect to the EMG sensors and the EMG amplifier, the limitation that was posed was the lack of a ready synchronizing mechanism or an inlet for a synchronizing signal. This necessitated the use of an Arduino board in order to multiplex a signal from the Wii Remote™ and the EMG signal, thereby actuating EMG signals only when the subject and the investigators were ready to begin based on a user input through the Wii Remote™'s "1" button.

The Requirements List should include the following categories

Another look at the requirements list, and the subsequent identification of essential problems for the system makes it evident that the example problem does indeed include the suggested categories. The value of these categories is achieved later in the design timeline, during the evaluation of working principles. The general requirements and trends that are embodied by asserting these categories in the requirements list (as explained in Section 2.2) will thus be satisfied in any system that is designed using the proposed method, since all the working principles within the system's function are evaluated against these categories.

Function Structure must include an instance of each of the following general functions

This requirement in particular requires the designer to keep the fundamental functions in mind when formulating the function structure. An explicit evaluation of the function structure against the fundamental functions need not be a part of the design method, and is thus not included in the design method. However, for the example motion capture system, loose associations between the generalized intelligence functions and the specific functions and sub-functions for the system can be made as shown in Figure 45.

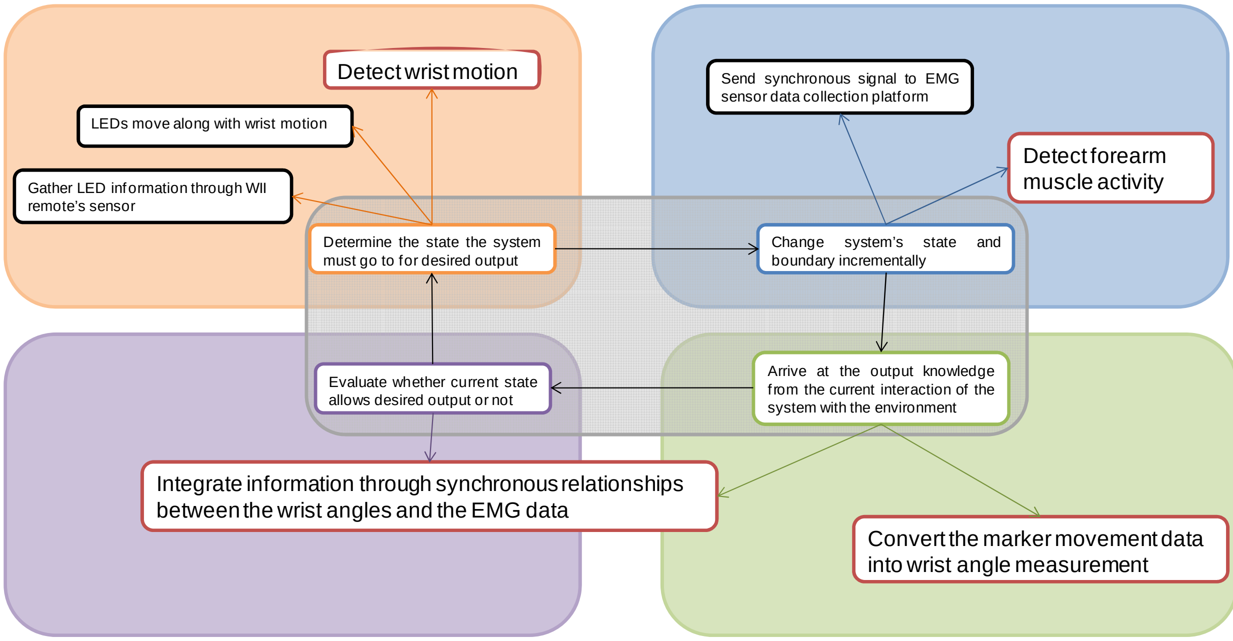


Figure 45: Mapping of fundamental functions to the functions structure for the Wii™ based motion capture system

In this system, the information capture tasks are marked by a specific beginning point and a specific end point. However, for a system such as an ambient intelligence system, the concept of marked points in time is largely replaced by events. An event based system would lend itself very well to the four basic functions identified. At the same time, the time based function that the example system can be mapped to them as well.

The wrist motion detection is the start of the procedure to gather information from the environment. It is at this point the system evaluates that to gather the output knowledge i.e. synchronized muscle activity data with wrist angle data, it needs to buzz the EMG unit or the computer, to start recording EMG data, as indicated by the top left region in Figure 45. The decision on what the system needs to do for affecting this change is trivial in this case, since in the design of the system, this has been hard coded as a single working principle, which is to send a rumble signal to the Wii™ remote which is then transmitted to an interfacing Arduino board where it activates the EMG signal.

The detection of forearm muscle activity in principle changes the system boundary to include the interface between the EMG probes and the skin of the subject's arm as shown in the top right region of Figure 45.

The conversion of marker data from the Wii™ along with the recording of the EMG data satisfies the third fundamental function, i.e., to arrive at the output knowledge for which the system was designed as shown in the bottom right region of Figure 45.

The evaluation step is trivial in our example as well, for the next requisite bit of information from the environment is the same as in the last time step in the case of this system. Thereby, it is merely an increase in the time step in the algorithm at a pre-designated frequency as shown in the bottom left region of Figure 45.

<u>Must explore existing solutions as product ideas</u>

This requirement is satisfied in the initial stages of the Pahl and Beitz design method during the analysis of the market and the competencies of the designer. Additionally, while extracting the requirements for the system's function, existing state of the art products are referred to (such as the MyoTrac Portable Muscle Monitor in the example). In the conceptual design phase, the morphological matrix employed helps the designer to partition the system's functions and search for working principles from existing products which satisfy particular functions.

The overall design in the motion capture example in fact is based on this requirement ratified by the fact, that the Wii™ platform, a solution in the gaming industry is adopted to perform ergonomic motion capture.

Must clarify the task with the help of requirements

The Pahl and Beitz design method already provides a well structured and systematic approach towards building the requirements list as a working document which can be referred to and changed iteratively during the design timeline.

Should categorize the requirements in a way that the categories are mutually exclusive and collectively exhaustive

The categories chosen for our domain of applications as shown in the example satisfy this requirement. Each category has specific requirements in the example system, and all of them together fulfill the needs and requirements that are identified in the task clarification phase at the analysis stage.

Must proceed stepwise from the overall abstract of the task to the particulars of the design

Again, the Pahl and Beitz method already provides a stepwise, systematic process where genericity and abstraction are high in the earlier phases, and eventually, every detailed aspect of the system being designed is taken care of in the later phases. The adoption of a high level representation of the information flow in the case of systems with intelligent and interactive information flow is also conducive to the fulfillment of this requirement. The adoption of this construct results in a systematic flow of design activity from an abstract representation to the design of particular physical components for the motion capture system in the following manner (Figure 46).

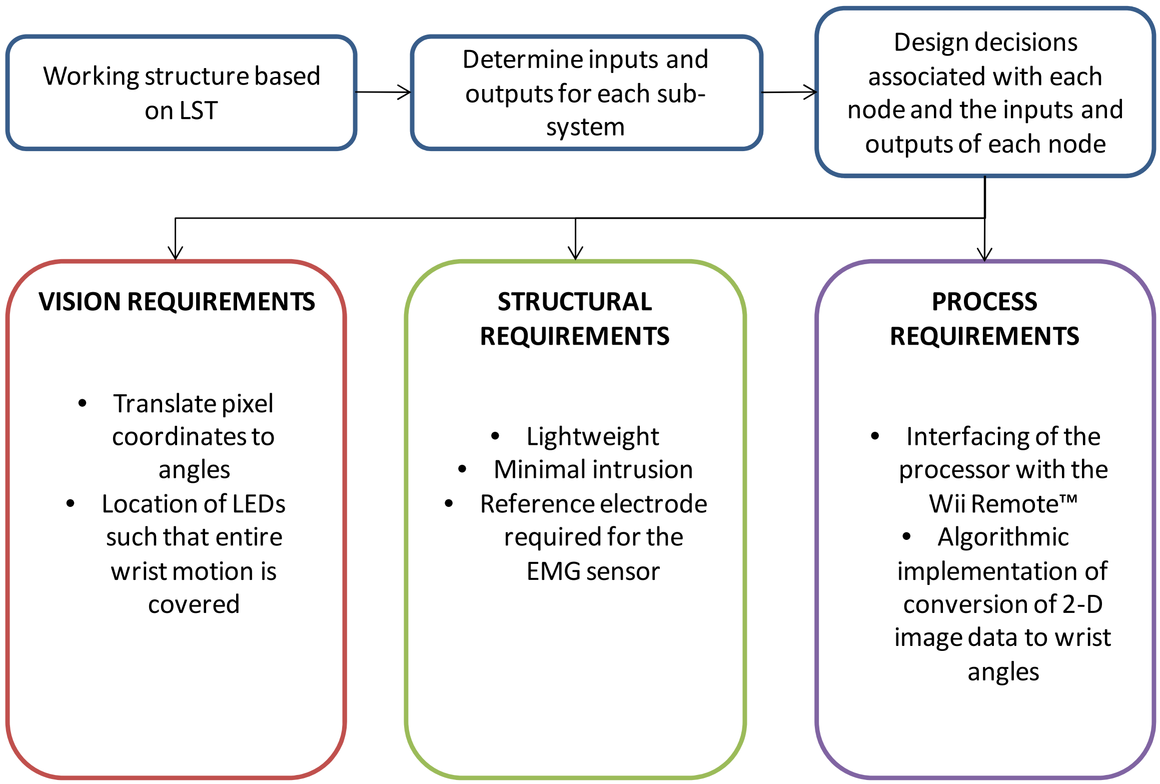


Figure 46: Flow of design activity from the abstract to the specific

The design method must facilitate milestones in the design timeline

This is another advantage of the Pahl and Beitz method. It provides for the requirements list, the working structure or concept, the layout and the final design, all milestones acting as core transformations which are standalone descriptions of the system that is being designed but at different levels of abstraction.

4.3 Evaluation of adapted method – The Validation Square

As described in Section 1.4.1, this work has been presented with the context of the validation square in mind. It was the guide for this thesis (Section 1.4.2, Figure 6). Each of the quadrants of the validation square must be referred to, and the proposed design method must be validated with respect to the requirements posed within each quadrant as described in Section 1.4.1. These have been laid out in the following sub-sections.

4.3.1 Theoretical Structural Validity

The first quadrant is theoretical structural validity (Figure 5). As pointed out in Section 1.4.1, the primary consideration is the logical consistency of the proposed design method. In order to demonstrate the theoretical structural validity of the proposed method, certain steps need to be followed. These are explained in Section 1.4.1. The fulfillment of each of these steps and the accompanying requirements to satisfy the TSV is done throughout the thesis in a systematic manner, and is outlined in the table below.

Table 15: Theoretical Structural Validity

Requisite steps	Section or sub-section where step is fulfilled
Determine the requirements for the outcomes of the method and for the process	Section 2.2
Search the technical literature related to each parent construct being used in the proposed design method	Section 2.1
A logical flow, showing adequate inputs and outputs from the design steps	CHAPTER 3
Evaluate usefulness of ontological constructs and theories	Section 2.3
Represent the procedure of proposing and evaluating all the constructs and the tasks carried out to incorporate them for the vision of the thesis	Figure 47

In Section 3.5, as a synopsis to the proposed modified design method, the theoretical structural validity is shown to be satisfied with a subjective argument which relates to Table 15 directly.

In Figure 47, the framework which is the mission of the thesis is presented. It doubles as a logical understanding and justification of how the research questions posed in the thesis translate to the particulars, including the tasks carried out in the thesis. The interrelationships show how the requirements posed for the design method are connected to the library of design solutions and categories. Thus, a logical flow of reason and a consistent context are demonstrated, which in addition to the validation steps checked out in Table 15 provide proof of theoretical structural validity.

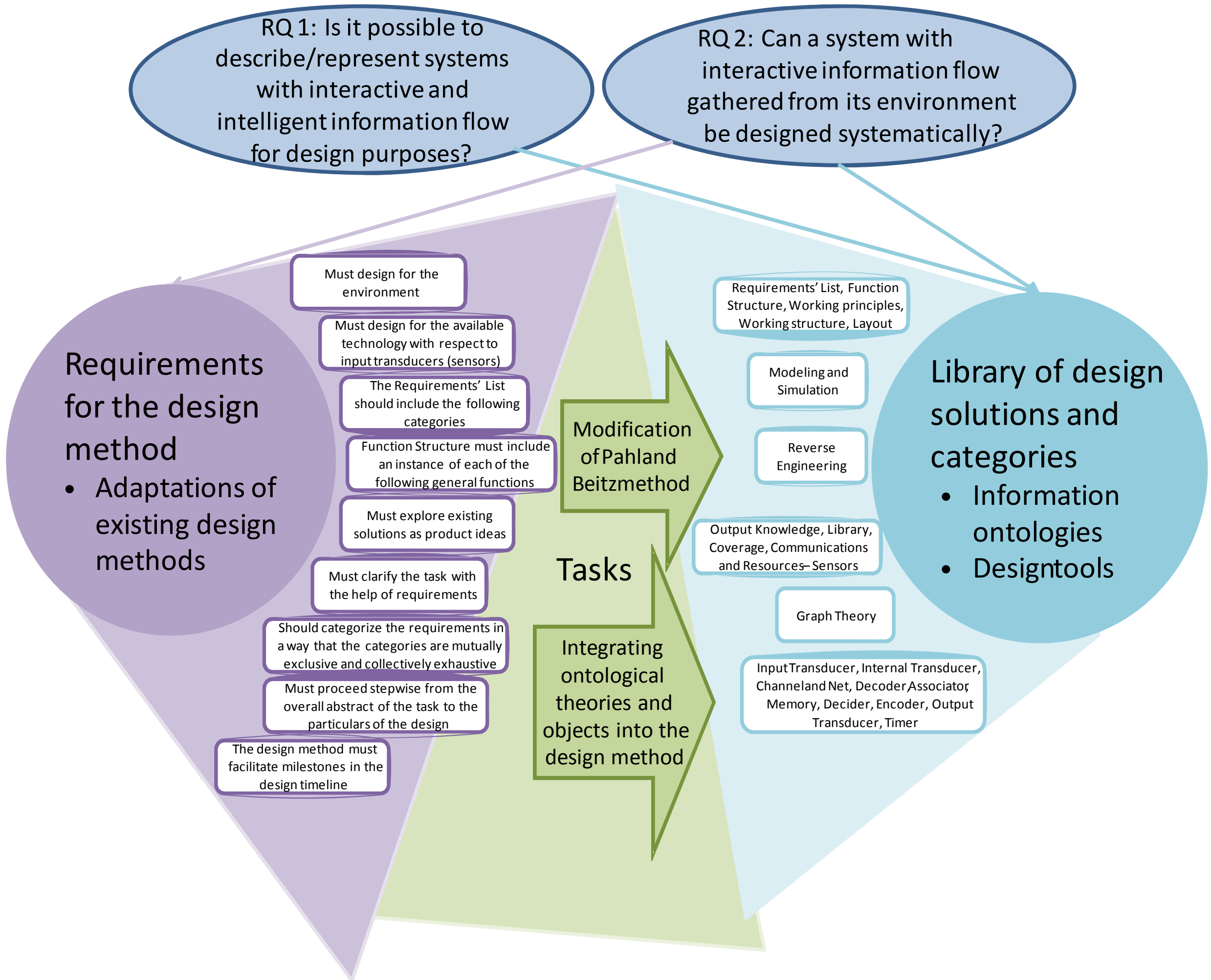


Figure 47: Representation of the framework mapping the requirements, tasks and the library to answer the research questions

4.3.2 Empirical Structural Validity

The empirical structural validity (ESV) is the second quadrant of Figure 5. The primary requirement to demonstrate ESV is to identify suitable examples to verify the performance of the proposed design method. The focus of this work is on a domain of applications which share some common characteristics. Thereby, in providing the vision for this work, specific instances in this domain of application have been implicitly identified and explained. The gap analysis clarifies the characteristics that are crucial design considerations in the applications suggested. Some of these applications and the characteristics they require are shown in the Table 16. These are a broad class of problems which can be characterized largely by the nature of the equipment, i.e. sensors and the necessary human-computer interaction as part of their functional requirement. The next step is to evaluate whether data that can be collected in the example problems could support conclusions with respect to the performance of the design method. The simplifying assumptions that are made in these problems need to be identified explicitly, in order to verify that these problems are actual and representative of real world problems. In the thesis, this will be carried out with a literature survey and the corresponding match with design parameters under consideration.

Table 16: Mapping of example problems with characteristics of domain of applications

	Lack of cost effective solutions	Multiple interacting sensors	Communication issues	Human-computer interaction	Large amount of information generated
Motion capture systems	✓	✓	✓	✓	✓
Health and safety monitoring systems	✓	✓	✓	✓	✓
Crash recording systems	✓	✓	✓	✓	✓
Multi-agent robotics	✓	✓	✓	✓	✓
Mobile sensing networks	✓	✓	✓	✓	✓

4.3.3 Empirical Performance Validity

The empirical performance validity (EPV) is the third quadrant in Figure 5. The primary requirement of EPV is to utilize the proposed design method to design an example system and verify design method in terms of performance metrics of the example system and the fulfillment of the requirements posed off the design method.

A representative problem has been used to evaluate the results of applying the proposed design method in terms of the design method requirements documented in the first quadrant. The design of a Wii™-based motion capture system was carried out with the proposed design method, and with the use of some of the proposed tools, and ontological objects. The performance of the designed system, and the approach adapted to design it has been evaluated in depth in Section 4.2. Performance measures related to accuracy and precision are evaluated with simulated and experiment results, thereby providing confidence in the process effectiveness of the design method. Key figures and tables that evaluate the performance and the limitations are highlighted below.

Table 17: Reference to items which evaluate performance of the system

Index of figure or table	What was evaluated
Figure 22, Figure 23, Figure 24	The barrel or pincushion effects that may occur when using circular or spherical optics on a rectangular shaped camera sensor are proven to be negligible
Figure 38, Table 10	A solution which satisfies the constraints of the Wii Remote™'s field of view and an accuracy of 1 pixel is ensured with for the custom requirements of each user of the system
Figure 39, Table 11	Resolution is maintained near the maximum possible within the spatial constraints with 20% error accounted for in measurements
Figure 40, Figure 41, Figure 42, Figure 43, Table 14	Regression model use to calculate the wrist angles is proven to be accurate within a 3% error provided only pitch and yaw are considered. Scope for improvements in the system accompanied by the particular changes in design decisions are identified

Table 17 continued

Index of figure or table	What was evaluated
Figure 44	The synchronization of EMG and Wii™ information is ensured, and thus the platform is proven to be a feasible one for real time integration of information into knowledge

In addition to the performance of the example system designed, the application of the proposed design method must be evaluated as well. The metrics for this evaluation are the requirements that were set out for the design method in Section 2.2. The justification behind the satisfaction of these requirements is provided in detail in Section 4.2.3. Thus, EPV is achieved with the aid of the example system.

4.3.4 Theoretical Performance Validity

The requirements proposed for the design method in this work are application independent. They are based on an evaluation of the general characteristics of systems with intelligent and interactive information flow. Some of the requirements do draw from examples or specific applications, but this is done only to show the thought flow which led me to consider the specific requirement. The confidence in these requirements is thus justified as far as their applicability to systems independent of the example domain (motion capture systems) is considered.

The adaptations to the Pahl and Beitz design method are made with these requirements and the proposed tools and representation schemes in mind. There is no bias towards the example system in any of the proposed modifications to the original method. This lends to the confidence that the proposed modifications are to adapt the method for designing systems with intelligent and interactive information flow in general, and are not restricted to motion capture systems.

The constructs proposed in this work are application independent as well. Most of these constructs are very general and have been applied to several disciplines. LST for instance has been developed to integrate the findings of system theorists and scientists in biology, physiology, neurology, the social sciences, economics and management. Modeling and simulation tools are applied practically in every domain of engineering, science and humanities. The only thread that ties these tools to this work is an understanding of the general characteristics and requirements of systems with intelligent and interactive information flow, and the subsequent mapping of these by functionality offered by the tools and objects proposed.

Thus, none of the aspects of the proposed framework tailor specifically to the example chosen to validate this work. Thereby, it is safe to take the leap of faith and look for future domains and application problems where this framework can be applied to. Note that the approach taken to build this framework and the proposed design method allows for further addition and adaptation. More requirements can be added and certain steps can be evolved. These would be driven largely by technology, and the competency of the designer or the researcher. Thus, this work offers a platform for future researchers and designers to employ the suggested framework in aiding their design activities for systems with intelligent and interactive information flow.

CHAPTER 5

Closure

In this chapter a stock is taken of what has been accomplished. This evaluation is done with respect to the research questions and the hypotheses posed in the thesis earlier. Thereafter, advantages of this work are identified. Limitations and related future work are described to complete the document.

The hypothesis of RQ1 is tested in this work, by integrating the generic sub-systems and the taxonomy of LST into the Pahl and Beitz design method. The objects drawn from LST are use as ontological objects which represent a generic class of devices, software, connections and communications in a system with intelligent and interactive information flow. By generalizing the system's functions to the basic consideration of information flow through it, a systematic approach towards designing complex systems has been proposed. Furthermore, other tools and objects that can be used have been identified in Section 2.1. Graph theory and SysML in particular are identifiable as important constructs which can be integrated into a systematic design method towards the representation and design of complex and interactive systems.

The hypothesis of RQ2 is tested in this work, by modifying the Pahl and Beitz design method in the context of designing systems with intelligent and interactive information flow. The modifications are made so as to demonstrate a logical consistency of reason for making each modification. This is ensured by making use of the validation square. The first quadrant, i.e. theoretical structural validity is used to maintain structural and logical consistency of all the claims made in the thesis. Thus, requirements which the modified method must fulfill are proposed first, and then the adaptations are made. The modified method is then tested by designing an example system. The characteristics that prove the system an appropriate example for this work have been highlighted in Section 4.3.3. The design is carried out stepwise as Pahl and Beitz suggest. Thereafter, the performance of the resulting platform and prototype designed is evaluated. The performance includes issues on resolution, customization, synchronization, and accuracy of output knowledge. High performance of some components of the designed system is highlighted. Where the performance leaves something to be desired, appropriate iteration of the design is made, or suggestions and plans for future work are made if resources posed a constraint. Lastly, the validation square is used to evaluate, verify and condense arguments made in this thesis, and evaluate their worth. The fourth quadrant, i.e. theoretical performance validity helps build confidence in the proposed constructs and approaches in this thesis.

5.1 Advantages

In the context of the tools, design methods, ontological objects, and the systematic approach based on the validation square, there are several advantages of the proposed framework and the design method in this work. The merit and advantages can be classified into three broad categories:

Customizability – As justified in Section 2.1, a formalization or methodological development of ontology for our domain of systems is avoided since the focus in this thesis is not to develop ontologies for representation of a generic system, but rather on proposing a framework within which designers can use the objects, tools and semantics offered by existing ontologies to satisfy requirements of intelligent and interactive systems in the established domain of applications. Similarly, any standardization which may lead to a fixation in the adaptability of the design method, or the proposed library of tools has been actively avoided in the thesis. This has provided both the proposed framework and the approach towards modifying the Pahl and Beitz design method for design of intelligent systems, with a high level of customizability, based on the competencies and familiarity of the designer with the system in question, as well as on subsequent identification or adaptation of other multi-disciplinary technologies, and solutions which were not within the scope of this work given my competencies.

Context – The domain of applications or the context of this work was established through a careful balance between keeping the scope large enough to apply to a large class of systems with intelligent and interactive information flow, but at the same time was supported with a number of examples and citations to demonstrate the need for systematic design approaches to fill the gap between higher demands of complexity, knowledge, computing, and interfacing being made on such systems and the large pool of interdisciplinary research and products already existing in the domain of sensing and robotics. Thereby, there is value in the thesis as a standalone document of relevant research as well as in the applicability of the proposed methods and objects in this work to further research in similar and other domains.

Systematic – From the point of view of the design method, some of the key requirements which were considered in this work were based on maintaining systematic procedures towards moving from the abstract to the specific, and towards maintaining design history and accountability. The Pahl and Beitz method's most important characteristic is its systematic approach. As identified in the gap analysis (Section 1.1.2), the lack of systematic approaches for the design of systems with intelligent and interactive information flow is the prime motivator for this work. By conforming to the overall structure of the Pahl and Beitz method, it has been ensured that applications of this framework, and subsequent build ups on this work (if any) are systematic and repeatable.

5.2 Limitations and Future Work

This thesis provides only a first step towards defining a framework for representing and designing systems with intelligent and interactive information flow. Therefore, many of the limitations of the current work serve as a basis for future work in addition to the existing open research questions for this work.

An attempt was made to include diverse examples which fall under the category of systems with intelligent and interactive information flow. However, with a notable lack of literature adopting a similar viewpoint towards such systems, with the definition of information and systems adopted in this work, clearly many more systems can be studied to both, extract more basic functions and requirements of these systems, and strengthen the case for the ones that have been identified in this work. Future work in this regard, would involve looking up systems in applications such as holistic security systems and intelligent robotic systems.

With regard to the tools and ontological aspects, clearly some of the identified tools could be implemented beyond the discussion and evaluation carried out in this work towards the design framework proposed. Future work in this regard could focus on the implementation of SysML at various stages in the proposed design method. A more focused study on the value of model based systems engineering in general, in the design of such systems is also in order.

Graph theory is an important super theory for ontological representation [14], whose value to the design of systems with intelligent and interactive information flow, is hinted at, but not utilized in this work. A single example was chosen for this work and the design was carried out right down to details. However, the complexity of the problem chosen is limited in terms of the number of interacting agents and thus does not warrant the application of graph theory which is more useful for applications with a larger number of sensors or agents. Future work can be done on a more complex problem such as the ambient intelligence problem, where graph theory can be shown to be an invaluable tool to enable the design of control algorithms and the representation and design of the physical system as well. Some concepts and ideas for application of graph theory have been compiled in order to facilitate a starting point for future research.

In the example chosen, a number of tasks need to be carried out towards seeing the technology transfer to real world application. The first step is to integrate the two pieces of knowledge, i.e., the wrist angles and the EMG data to come up with suggestions on practices which would help reduce the risk of wrist injuries. A study of EMG data and its processing to output more meaningful knowledge is required for this transformation. Secondly, the LED beacon employed in our tests and the detail design need to incorporate supports which are in some way compliant to allow for optimal location based on the geometrical parameters of the person using the system. As of now, the system that was tested is a prototype with hard supports that cannot be easily shifted around. However, the ground work for implementing a customizable LED beacon is in place, with the module on satisfaction of precision and accuracy objectives already implemented based on a 3-D model which is parameterized to take inputs of arm length and Wii™ remote height for a particular subject. In the context of customization, this system is designed to be applicable for motion capture in general, and can be used for various kinds of body motions. However, the supports for the Wii™, the LEDs and details such as wiring need to be tailored for the particular joints or kinds of motion that need to be studied. Requirements pertaining strictly to the information flow that needs to be facilitated have been satisfied, but requirements from the geometry and structure can be refined to affect this customization. A number of challenging but intelligent problems can be foreseen if in future work considerations of weight, geometry and placement of structures were also to be included in the requirements list.

In conclusion, the "Framework for the Design of Systems with Intelligent and Interactive Information Flow" provides a customizable process and tools to link multi-disciplinary solutions to problems and design issues that need to be solved for intelligent sensing systems.

5.3 Critical Evaluation

In this section I will round up and evaluate the work in terms of the efforts that I have specifically put in into this thesis. What I have accomplished and what I have laid the foundation for can be put forth in bullet points at this stage.

What I have accomplished

- The definition of a complex set of problems arising from the demand for complex systems with functions of monitoring and collecting data to make sense of the environment. This problem definition is centered from the point of view of a designer who is tasked with designing these systems with the requirement to consider conflicting requirements associated with the demand

- An understanding of what the Pahl and Beitz method offers and what it doesn't for the designer in order to design systems from the point of view of information flow
- The adoption of the taxonomy of Living Systems Theory to adequately and completely represent the flow of information through the system from the environment for the Pahl and Beitz design method
- Ideas on how graph theory and SysML can be used for adequate representation of systems with intelligent and interactive information flow in embodiment and detail design phases
- A new, modified and customizable design method better suited for the design of systems with intelligent and interactive information flow than the original Pahl and Beitz design method
- The validation of the logic and consistency of all proposed modifications in the method with the help of a requirements list for the new method
- The design of a motion capture system based on the Nintendo Wii Remote™ to perform empirical performance validity of the proposed design method

What I have laid the foundation for

- Representation of systems with intelligent and interactive information flow for complex systems with a large number of interacting agents including sensors, humans and computers
- A state of the art motion capture system ready to use as a training device
- Integration of SysML and graph theory into the design method for representation of the system and its function at varying levels of abstraction
- A solution for designers to design a complex system with intelligent and interactive information flow

In conclusion, the most valuable pitch in this work is to view complex and interactive systems as the means to facilitate information flow and integration between several agents, and thus simplify the problem of designing those systems in the context of the adopted view.

APPENDIX

Exhaust search algorithm (Section 4.1.3 – Embodiment Design phase)

```
function [Xmax, max_res] = exhaust_search(length, height)

init_rot=[-1 0 0;0 0 1;0 1 0]; % Rotate
% dimensional limits from SolidWorks
dim_lim(1,:) = [5.44,1.27,2.73];
dim_lim(2,:) = [4.47, 4.45, 5.65];
dim_lim(3,:) = [0.00, 5.27, 5.27];
dim_lim(4,:) = [-5.46, 4.94, 5.42];
dim_lim(5,:) = [-5.46, 2.96, 6.34];
dim_lim(6,:) = [-5.93, 0.45, 0.97];
dim_lim(7,:) = [-5.53, 0.42, 0.91];
dim_lim(8,:) = [4.47,2.96,6.34];
dim_lim(9,:) = [1.81, .42, 0.91];
dim_lim(10,:) = [0.00, 0.75, 0.75];
dim_lim = .0254 * dim_lim;

dim_lim_new(1,:) = [4.85, 1.14, 2.44];
dim_lim_new(2,:) = [5.21, 2.03, 3.42];
dim_lim_new(3,:) = [5.23, 1.63, 3.49];
dim_lim_new(4,:) = [-5.57, 3.92, 4.41];
dim_lim_new(5,:) = [-5.62, 2.12, 4.54];
dim_lim_new(6,:) = [-4.28, .50, .87];
dim_lim_new(7,:) = [-4.30, .42, .91];
dim_lim_new = .0254 * dim_lim_new;

% rotate coordinates using init_rot
for i = 1:size(dim_lim,1);
    dim_lim(i,:) = dim_lim(i,:) * init_rot';
end

for i = 1:size(dim_lim_new, 1)
    dim_lim_new(i,:) = dim_lim_new(i,:) * init_rot';
end
c=0;
for i = 1:size(dim_lim,1)
    if i==6 || i==7 || i==1
        continue
    else
        c=c+1;
        dimlim(c,:) = dim_lim(i,:);
    end
end

for i = 1:size(dim_lim_new,1)
    c=c+1;
    dimlim(c,:) = dim_lim_new(i,:);
end

% Definition of the 7 planes and their normal vectors
% Plane 1 - Pts. 1,2,3
```

```
A1=[ 1 dim_lim(1,2) dim_lim(1,3);1 dim_lim(2,2) dim_lim(2,3);1
dim_lim(3,2) dim_lim(3,3)];
B1=[ dim_lim(1,1) 1 dim_lim(1,3);dim_lim(2,1) 1
dim_lim(2,3);dim_lim(3,1) 1 dim_lim(3,3)];
C1=[ dim_lim(1,1) dim_lim(1,2) 1;dim_lim(2,1) dim_lim(2,2)
1;dim_lim(3,1) dim_lim(3,2) 1];
D1=[ dim_lim(1,1) dim_lim(1,2) dim_lim(1,3); dim_lim(2,1) dim_lim(2,2)
dim_lim(2,3);dim_lim(3,1) dim_lim(3,2) dim_lim(3,3)];
% Plane 2 - Pts. 2,3,4
A2=[ 1 dim_lim(2,2) dim_lim(2,3);1 dim_lim(3,2) dim_lim(3,3);1
dim_lim(4,2) dim_lim(4,3)];
B2=[ dim_lim(2,1) 1 dim_lim(2,3);dim_lim(3,1) 1
dim_lim(3,3);dim_lim(4,1) 1 dim_lim(4,3)];
C2=[ dim_lim(2,1) dim_lim(2,2) 1;dim_lim(3,1) dim_lim(3,2)
1;dim_lim(4,1) dim_lim(4,2) 1];
D2=[ dim_lim(2,1) dim_lim(2,2) dim_lim(2,3); dim_lim(3,1) dim_lim(3,2)
dim_lim(3,3);dim_lim(4,1) dim_lim(4,2) dim_lim(4,3)];
% Plane 3 - Pts. 4,5,6
A3=[ 1 dim_lim(4,2) dim_lim(4,3);1 dim_lim(5,2) dim_lim(5,3);1
dim_lim(6,2) dim_lim(6,3)];
B3=[ dim_lim(4,1) 1 dim_lim(4,3);dim_lim(5,1) 1
dim_lim(5,3);dim_lim(6,1) 1 dim_lim(6,3)];
C3=[ dim_lim(4,1) dim_lim(4,2) 1;dim_lim(5,1) dim_lim(5,2)
1;dim_lim(6,1) dim_lim(6,2) 1];
D3=[ dim_lim(4,1) dim_lim(4,2) dim_lim(4,3); dim_lim(5,1) dim_lim(5,2)
dim_lim(5,3);dim_lim(6,1) dim_lim(6,2) dim_lim(6,3)];
% Plane 4 - Pts. 4,6,7
A4=[ 1 dim_lim(4,2) dim_lim(4,3);1 dim_lim(6,2) dim_lim(6,3);1
dim_lim(7,2) dim_lim(7,3)];
B4=[ dim_lim(4,1) 1 dim_lim(4,3);dim_lim(6,1) 1
dim_lim(6,3);dim_lim(7,1) 1 dim_lim(7,3)];
C4=[ dim_lim(4,1) dim_lim(4,2) 1;dim_lim(6,1) dim_lim(6,2)
1;dim_lim(7,1) dim_lim(7,2) 1];
D4=[ dim_lim(4,1) dim_lim(4,2) dim_lim(4,3); dim_lim(6,1) dim_lim(6,2)
dim_lim(6,3);dim_lim(7,1) dim_lim(7,2) dim_lim(7,3)];
% Plane 5 - Pts. 7,9,10
A5=[ 1 dim_lim_new(7,2) dim_lim_new(7,3);1 dim_lim(9,2) dim_lim(9,3);1
dim_lim(10,2) dim_lim(10,3)];
B5=[ dim_lim_new(7,1) 1 dim_lim_new(7,3);dim_lim(9,1) 1
dim_lim(9,3);dim_lim(10,1) 1 dim_lim(10,3)];
C5=[ dim_lim_new(7,1) dim_lim_new(7,2) 1;dim_lim(9,1) dim_lim(9,2)
1;dim_lim(10,1) dim_lim(10,2) 1];
D5=[ dim_lim_new(7,1) dim_lim_new(7,2) dim_lim_new(7,3); dim_lim(9,1)
dim_lim(9,2) dim_lim(9,3);dim_lim(10,1) dim_lim(10,2) dim_lim(10,3)];
% Plane 6 - Pts. 1,2,8
A6=[ 1 dim_lim(1,2) dim_lim(1,3);1 dim_lim(2,2) dim_lim(2,3);1
dim_lim(8,2) dim_lim(8,3)];
B6=[ dim_lim(1,1) 1 dim_lim(1,3);dim_lim(2,1) 1
dim_lim(2,3);dim_lim(8,1) 1 dim_lim(8,3)];
C6=[ dim_lim(1,1) dim_lim(1,2) 1;dim_lim(2,1) dim_lim(2,2)
1;dim_lim(8,1) dim_lim(8,2) 1];
D6=[ dim_lim(1,1) dim_lim(1,2) dim_lim(1,3); dim_lim(2,1) dim_lim(2,2)
dim_lim(2,3);dim_lim(8,1) dim_lim(8,2) dim_lim(8,3)];
% Plane 7 - Pts. 8,5,6
A7=[ 1 dim_lim(8,2) dim_lim(8,3);1 dim_lim(5,2) dim_lim(5,3);1
dim_lim(6,2) dim_lim(6,3)];
```

```
B7=[ dim_lim(8,1) 1 dim_lim(8,3);dim_lim(5,1) 1
dim_lim(5,3);dim_lim(6,1) 1 dim_lim(6,3)];
C7=[ dim_lim(8,1) dim_lim(8,2) 1;dim_lim(5,1) dim_lim(5,2)
1;dim_lim(6,1) dim_lim(6,2) 1];
D7=[ dim_lim(8,1) dim_lim(8,2) dim_lim(8,3); dim_lim(5,1) dim_lim(5,2)
dim_lim(5,3);dim_lim(6,1) dim_lim(6,2) dim_lim(6,3)];
% Plane 8 - Pts. 1,2,3 of dim_lim_new
A8=[ 1 dim_lim_new(1,2) dim_lim_new(1,3);1 dim_lim_new(2,2)
dim_lim_new(2,3);1 dim_lim_new(3,2) dim_lim_new(3,3)];
B8=[ dim_lim_new(1,1) 1 dim_lim_new(1,3);dim_lim_new(2,1) 1
dim_lim_new(2,3);dim_lim_new(3,1) 1 dim_lim_new(3,3)];
C8=[ dim_lim_new(1,1) dim_lim_new(1,2) 1;dim_lim_new(2,1)
dim_lim_new(2,2) 1;dim_lim_new(3,1) dim_lim_new(3,2) 1];
D8=[ dim_lim_new(1,1) dim_lim_new(1,2) dim_lim_new(1,3);
dim_lim_new(2,1) dim_lim_new(2,2) dim_lim_new(2,3);dim_lim_new(3,1)
dim_lim_new(3,2) dim_lim_new(3,3)];
% Plane 9 - Pts. 4,5,6 of dim_lim_new
A9=[ 1 dim_lim_new(4,2) dim_lim_new(4,3);1 dim_lim_new(5,2)
dim_lim_new(5,3);1 dim_lim_new(6,2) dim_lim_new(6,3)];
B9=[ dim_lim_new(4,1) 1 dim_lim_new(4,3);dim_lim_new(5,1) 1
dim_lim_new(5,3);dim_lim_new(6,1) 1 dim_lim_new(6,3)];
C9=[ dim_lim_new(4,1) dim_lim_new(4,2) 1;dim_lim_new(5,1)
dim_lim_new(5,2) 1;dim_lim_new(6,1) dim_lim_new(6,2) 1];
D9=[ dim_lim_new(4,1) dim_lim_new(4,2) dim_lim_new(4,3);
dim_lim_new(5,1) dim_lim_new(5,2) dim_lim_new(5,3);dim_lim_new(6,1)
dim_lim_new(6,2) dim_lim_new(6,3)];


% Determinant of each
A(1)=det(A1); B(1)=det(B1); C(1)=det(C1); D(1)=-det(D1);
A(2)=det(A2); B(2)=det(B2); C(2)=det(C2); D(2)=-det(D2);
A(3)=det(A3); B(3)=det(B3); C(3)=det(C3); D(3)=-det(D3);
A(4)=det(A4); B(4)=det(B4); C(4)=det(C4); D(4)=-det(D4);
A(5)=det(A5); B(5)=det(B5); C(5)=det(C5); D(5)=-det(D5);
A(6)=det(A6); B(6)=det(B6); C(6)=det(C6); D(6)=-det(D6);
A(7)=det(A7); B(7)=det(B7); C(7)=det(C7); D(7)=-det(D7);
A(8)=det(A8); B(8)=det(B8); C(8)=det(C8); D(8)=-det(D8);
A(9)=det(A9); B(9)=det(B9); C(9)=det(C9); D(9)=-det(D9);

centroid(1)=sum(dimlim(:,1))/14;
centroid(2)=sum(dimlim(:,2))/14;
centroid(3)=sum(dimlim(:,3))/14;


for l = 1:9
    subs1(l) = A(l)*centroid(1)+ B(l)*centroid(2) + C(l)*centroid(3) +
D(l);
end

max_x = max(dimlim(:,1));
max_y = max(dimlim(:,2));
max_z = max(dimlim(:,3));
min_x = min(dimlim(:,1));
min_y = min(dimlim(:,2));
min_z = min(dimlim(:,3));
```

```
max_l_def = 0.2248; % Maximum length for LED supports based on an
acceleration of 1000 rad/s^2
area = 0;
max_res = 0;

count=0;
for a = min_x:2*.0254:max_x
    for b = min_y:2*.0254:max_y
        for c = min_z:.0254:max_z
            X(1:3) = [ a b c];
            for d = min_x:2*.0254:max_x
                for e = min_y:2*.0254:max_y
                    for f = min_z:.0254:max_z
                        X(4:6) = [ d e f];
                        for g = min_x:2*.0254:max_x
                            for h = min_y:2*.0254:max_y
                                for i = min_z:.0254:max_z
                                    X(7:9) = [ g h i];
                                    for j = min_x:2*.0254:max_x
                                        for k = min_y:2*.0254:max_y
                                            for m = min_z:.0254:max_z
                                                X(10:12) = [ j k m];
                                                flag = 0;

                                                for l= 1:9

                                                    for n = 0:3
                                                        subs2 =
A(l)*X(3*n+1) + B(l)*X(3*n+2) + C(l)*X(3*n+3) + D(l);
                                                        if
subs2*subs1(l) < 0
                                                            flag = 1;

count=count+1;

                                                            break;
                                                        end
                                                    end
                                                    if flag == 1
                                                        break
                                                    end
                                                end
                                                if flag == 0
                                                    for p = [1,4,7,10];
                                                        if ((X(p)^2 +
X(p+1)^2 + X(p+2)^2)^.5)> max_l_def;
                                                            flag=1;
                                                            disp('Max
length violated by LED')
                                                            disp(p);
                                                            break
                                                        end
                                                    end
                                                end
                                                if flag == 0
```

```
                                                    area = 
abs(obj_fun2(X,length,height));

                                                end
                                                if area>max_res
                                                    max_res = area;
                                                    Xmax = X;
                                                end
                                            end
                                        end
                                    end
                                end
                            end
                        end
                    end
                end
            end
        end
    end
end


xlabel('Y axis (inches)');ylabel('Z axis (inches)');zlabel('X axis 
(inches)');
plot3(XX,YY,ZZ,'-mo', 'MarkerFaceColor',[.49 1 .63],'MarkerSize',12);
hold on
or(2,:)=Xmax(1:3)/.0254;
plot3(or(:,1),or(:,2),or(:,3),'-k')
hold on
or(2,:)=Xmax(4:6)/.0254;
plot3(or(:,1),or(:,2),or(:,3),'-k')
hold on
or(2,:)=Xmax(7:9)/.0254;
plot3(or(:,1),or(:,2),or(:,3),'-k')
hold on
or(2,:)=Xmax(10:12)/.0254;
plot3(or(:,1),or(:,2),or(:,3),'-k')
hold on
end
```

Calculation of objective function

```
function [area] = obj_fun(X,length,height)

% Calculate OB vector or projection of LEDs onto image plane at the
center
% of rotation of the wrist
for i = 1:4
    AE = length + X(3*i-2);
    AD = length;
    EC = sqrt(X(3*i)^2 + (X(3*i-1)-height)^2);
    DB = EC*AD/AE;
    AB = sqrt(AD^2 + DB^2);
    OAv = [-length, height, 0];
    OCv = [X(3*i-2),X(3*i-1), X(3*i)];
    ACv = OCv - OAv;
    AC = norm(ACv);
    OBv = OAv + ACv*AB/AC;
    zp(i) = OBv(3);
    yp(i) = OBv(2);
end
c = 94.5*14/length;     % Scale from pixels to inches
yp = yp - height;       % Translate origin to line of sight of Wii
Remote(TM)
yp = yp*c;
zp = zp*c;
yp = yp + 384;          % Translate origin to the lower left corner of
the image plane of the Wii Remote(TM)
zp = zp + 512;

% Area of quadrilateral = Resolution
area = .5*((yp(1)*zp(2)-yp(2)*zp(1)) + (yp(2)*zp(3)-yp(3)*zp(2)) +
(yp(3)*zp(4) - yp(4)*zp(3)) + (yp(4)*zp(1) - yp(1)*zp(4)));
end
```

Sensitivity Analysis

```
function main()
clear all
close all
init_rot=[-1 0 0;0 0 1;0 1 0]; % Rotate
% dimensional limits from SolidWorks
dim_lim(1,:) = [5.44,1.27,2.73];
dim_lim(2,:) = [4.47, 4.45, 5.65];
dim_lim(3,:) = [0.00, 5.27, 5.27];
dim_lim(4,:) = [-5.46, 4.94, 5.42];
dim_lim(5,:) = [-5.46, 2.96, 6.34];
dim_lim(6,:) = [-5.93, 0.45, 0.97];
dim_lim(7,:) = [-5.53, 0.42, 0.91];
dim_lim(8,:) = [4.47,2.96,6.34];
dim_lim(9,:) = [1.81, .42, 0.91];
dim_lim(10,:) = [0.00, 0.75, 0.75];
dim_lim = .0254 * dim_lim; % Conversion to meters

dim_lim_new(1,:) = [4.85, 1.14, 2.44];
dim_lim_new(2,:) = [5.21, 2.03, 3.42];
dim_lim_new(3,:) = [5.23, 1.63, 3.49];
dim_lim_new(4,:) = [-5.57, 3.92, 4.41];
dim_lim_new(5,:) = [-5.62, 2.12, 4.54];
dim_lim_new(6,:) = [-4.28, .50, .87];
dim_lim_new(7,:) = [-4.30, .42, .91];
dim_lim_new = .0254 * dim_lim_new;

% rotate coordinates using init_rot
for i = 1:size(dim_lim,1);
    dim_lim(i,:) = dim_lim(i,:) * init_rot';
end

for i = 1:size(dim_lim_new, 1)
    dim_lim_new(i,:) = dim_lim_new(i,:) * init_rot';
end
c=0;
for i = 1:size(dim_lim,1)
    if i==6 || i==7 || i==1
        continue
    else
        c=c+1;
        dimlim(c,:) = dim_lim(i,:);
    end
end

for i = 1:size(dim_lim_new,1)
    c=c+1;
    dimlim(c,:) = dim_lim_new(i,:);
end

% Definition of the 7 planes and their normal vectors
```

```
% Plane 1 - Pts. 1,2,3
A1=[ 1 dim_lim(1,2) dim_lim(1,3);1 dim_lim(2,2) dim_lim(2,3);1
dim_lim(3,2) dim_lim(3,3)];
B1=[ dim_lim(1,1) 1 dim_lim(1,3);dim_lim(2,1) 1
dim_lim(2,3);dim_lim(3,1) 1 dim_lim(3,3)];
C1=[ dim_lim(1,1) dim_lim(1,2) 1;dim_lim(2,1) dim_lim(2,2)
1;dim_lim(3,1) dim_lim(3,2) 1];
D1=[ dim_lim(1,1) dim_lim(1,2) dim_lim(1,3); dim_lim(2,1) dim_lim(2,2)
dim_lim(2,3);dim_lim(3,1) dim_lim(3,2) dim_lim(3,3)];
% Plane 2 - Pts. 2,3,4
A2=[ 1 dim_lim(2,2) dim_lim(2,3);1 dim_lim(3,2) dim_lim(3,3);1
dim_lim(4,2) dim_lim(4,3)];
B2=[ dim_lim(2,1) 1 dim_lim(2,3);dim_lim(3,1) 1
dim_lim(3,3);dim_lim(4,1) 1 dim_lim(4,3)];
C2=[ dim_lim(2,1) dim_lim(2,2) 1;dim_lim(3,1) dim_lim(3,2)
1;dim_lim(4,1) dim_lim(4,2) 1];
D2=[ dim_lim(2,1) dim_lim(2,2) dim_lim(2,3); dim_lim(3,1) dim_lim(3,2)
dim_lim(3,3);dim_lim(4,1) dim_lim(4,2) dim_lim(4,3)];
% Plane 3 - Pts. 4,5,6
A3=[ 1 dim_lim(4,2) dim_lim(4,3);1 dim_lim(5,2) dim_lim(5,3);1
dim_lim(6,2) dim_lim(6,3)];
B3=[ dim_lim(4,1) 1 dim_lim(4,3);dim_lim(5,1) 1
dim_lim(5,3);dim_lim(6,1) 1 dim_lim(6,3)];
C3=[ dim_lim(4,1) dim_lim(4,2) 1;dim_lim(5,1) dim_lim(5,2)
1;dim_lim(6,1) dim_lim(6,2) 1];
D3=[ dim_lim(4,1) dim_lim(4,2) dim_lim(4,3); dim_lim(5,1) dim_lim(5,2)
dim_lim(5,3);dim_lim(6,1) dim_lim(6,2) dim_lim(6,3)];
% Plane 4 - Pts. 4,6,7
A4=[ 1 dim_lim(4,2) dim_lim(4,3);1 dim_lim(6,2) dim_lim(6,3);1
dim_lim(7,2) dim_lim(7,3)];
B4=[ dim_lim(4,1) 1 dim_lim(4,3);dim_lim(6,1) 1
dim_lim(6,3);dim_lim(7,1) 1 dim_lim(7,3)];
C4=[ dim_lim(4,1) dim_lim(4,2) 1;dim_lim(6,1) dim_lim(6,2)
1;dim_lim(7,1) dim_lim(7,2) 1];
D4=[ dim_lim(4,1) dim_lim(4,2) dim_lim(4,3); dim_lim(6,1) dim_lim(6,2)
dim_lim(6,3);dim_lim(7,1) dim_lim(7,2) dim_lim(7,3)];
% Plane 5 - Pts. 7,9,10
A5=[ 1 dim_lim_new(7,2) dim_lim_new(7,3);1 dim_lim(9,2) dim_lim(9,3);1
dim_lim(10,2) dim_lim(10,3)];
B5=[ dim_lim_new(7,1) 1 dim_lim_new(7,3);dim_lim(9,1) 1
dim_lim(9,3);dim_lim(10,1) 1 dim_lim(10,3)];
C5=[ dim_lim_new(7,1) dim_lim_new(7,2) 1;dim_lim(9,1) dim_lim(9,2)
1;dim_lim(10,1) dim_lim(10,2) 1];
D5=[ dim_lim_new(7,1) dim_lim_new(7,2) dim_lim_new(7,3); dim_lim(9,1)
dim_lim(9,2) dim_lim(9,3);dim_lim(10,1) dim_lim(10,2) dim_lim(10,3)];
% Plane 6 - Pts. 1,2,8
A6=[ 1 dim_lim(1,2) dim_lim(1,3);1 dim_lim(2,2) dim_lim(2,3);1
dim_lim(8,2) dim_lim(8,3)];
B6=[ dim_lim(1,1) 1 dim_lim(1,3);dim_lim(2,1) 1
dim_lim(2,3);dim_lim(8,1) 1 dim_lim(8,3)];
C6=[ dim_lim(1,1) dim_lim(1,2) 1;dim_lim(2,1) dim_lim(2,2)
1;dim_lim(8,1) dim_lim(8,2) 1];
D6=[ dim_lim(1,1) dim_lim(1,2) dim_lim(1,3); dim_lim(2,1) dim_lim(2,2)
dim_lim(2,3);dim_lim(8,1) dim_lim(8,2) dim_lim(8,3)];
% Plane 7 - Pts. 8,5,6
A7=[ 1 dim_lim(8,2) dim_lim(8,3);1 dim_lim(5,2) dim_lim(5,3);1
dim_lim(6,2) dim_lim(6,3)];
```

```
B7=[ dim_lim(8,1) 1 dim_lim(8,3);dim_lim(5,1) 1
dim_lim(5,3);dim_lim(6,1) 1 dim_lim(6,3)];
C7=[ dim_lim(8,1) dim_lim(8,2) 1;dim_lim(5,1) dim_lim(5,2)
1;dim_lim(6,1) dim_lim(6,2) 1];
D7=[ dim_lim(8,1) dim_lim(8,2) dim_lim(8,3); dim_lim(5,1) dim_lim(5,2)
dim_lim(5,3);dim_lim(6,1) dim_lim(6,2) dim_lim(6,3)];
% Plane 8 - Pts. 1,2,3 of dim_lim_new
A8=[ 1 dim_lim_new(1,2) dim_lim_new(1,3);1 dim_lim_new(2,2)
dim_lim_new(2,3);1 dim_lim_new(3,2) dim_lim_new(3,3)];
B8=[ dim_lim_new(1,1) 1 dim_lim_new(1,3);dim_lim_new(2,1) 1
dim_lim_new(2,3);dim_lim_new(3,1) 1 dim_lim_new(3,3)];
C8=[ dim_lim_new(1,1) dim_lim_new(1,2) 1;dim_lim_new(2,1)
dim_lim_new(2,2) 1;dim_lim_new(3,1) dim_lim_new(3,2) 1];
D8=[ dim_lim_new(1,1) dim_lim_new(1,2) dim_lim_new(1,3);
dim_lim_new(2,1) dim_lim_new(2,2) dim_lim_new(2,3);dim_lim_new(3,1)
dim_lim_new(3,2) dim_lim_new(3,3)];
% Plane 9 - Pts. 4,5,6 of dim_lim_new
A9=[ 1 dim_lim_new(4,2) dim_lim_new(4,3);1 dim_lim_new(5,2)
dim_lim_new(5,3);1 dim_lim_new(6,2) dim_lim_new(6,3)];
B9=[ dim_lim_new(4,1) 1 dim_lim_new(4,3);dim_lim_new(5,1) 1
dim_lim_new(5,3);dim_lim_new(6,1) 1 dim_lim_new(6,3)];
C9=[ dim_lim_new(4,1) dim_lim_new(4,2) 1;dim_lim_new(5,1)
dim_lim_new(5,2) 1;dim_lim_new(6,1) dim_lim_new(6,2) 1];
D9=[ dim_lim_new(4,1) dim_lim_new(4,2) dim_lim_new(4,3);
dim_lim_new(5,1) dim_lim_new(5,2) dim_lim_new(5,3);dim_lim_new(6,1)
dim_lim_new(6,2) dim_lim_new(6,3)];


% Determinant of each
A(1)=det(A1); B(1)=det(B1); C(1)=det(C1); D(1)=-det(D1);
A(2)=det(A2); B(2)=det(B2); C(2)=det(C2); D(2)=-det(D2);
A(3)=det(A3); B(3)=det(B3); C(3)=det(C3); D(3)=-det(D3);
A(4)=det(A4); B(4)=det(B4); C(4)=det(C4); D(4)=-det(D4);
A(5)=det(A5); B(5)=det(B5); C(5)=det(C5); D(5)=-det(D5);
A(6)=det(A6); B(6)=det(B6); C(6)=det(C6); D(6)=-det(D6);
A(7)=det(A7); B(7)=det(B7); C(7)=det(C7); D(7)=-det(D7);
A(8)=det(A8); B(8)=det(B8); C(8)=det(C8); D(8)=-det(D8);
A(9)=det(A9); B(9)=det(B9); C(9)=det(C9); D(9)=-det(D9);


centroid(1)=sum(dimlim(:,1))/14;
centroid(2)=sum(dimlim(:,2))/14;
centroid(3)=sum(dimlim(:,3))/14;


X_surf(1)=dim_lim_new(2,1);
X_surf(2)=dim_lim_new(3,1);
X_surf(3)=dim_lim(8,1);
X_surf(4)=dim_lim(2,1);
X_surf(5)=dim_lim(3,1);
X_surf(6)=dim_lim(4,1);
X_surf(7)=dim_lim(5,1);
X_surf(8)=dim_lim_new(5,1);
X_surf(9)=dim_lim_new(4,1);
X_surf(10)=dim_lim_new(6,1);
X_surf(11)=dim_lim_new(7,1);
```

```
X_surf(12)=dim_lim(9,1);
X_surf(13)=dim_lim(10,1);
X_surf(14)=dim_lim(9,1);
X_surf(15)=dim_lim_new(1,1);
X_surf(16)=dim_lim_new(2,1);
X_surf(17)=dim_lim(2,1);
X_surf(18)=dim_lim(3,1);
X_surf(19)=dim_lim(10,1);
X_surf(20)=dim_lim_new(6,1);
X_surf(21)=dim_lim_new(4,1);
X_surf(22)=dim_lim(4,1);


Y_surf(1)=dim_lim_new(2,2);
Y_surf(2)=dim_lim_new(2,2);
Y_surf(3)=dim_lim(8,2);
Y_surf(4)=dim_lim(2,2);
Y_surf(5)=dim_lim(3,2);
Y_surf(6)=dim_lim(4,2);
Y_surf(7)=dim_lim(5,2);
Y_surf(8)=dim_lim_new(5,2);
Y_surf(9)=dim_lim_new(4,2);
Y_surf(10)=dim_lim_new(6,2);
Y_surf(11)=dim_lim_new(7,2);
Y_surf(12)=dim_lim(9,2);
Y_surf(13)=dim_lim(10,2);
Y_surf(14)=dim_lim(9,2);
Y_surf(15)=dim_lim_new(1,2);
Y_surf(16)=dim_lim_new(2,2);
Y_surf(17)=dim_lim(2,2);
Y_surf(18)=dim_lim(3,2);
Y_surf(19)=dim_lim(10,2);
Y_surf(20)=dim_lim_new(6,2);
Y_surf(21)=dim_lim_new(4,2);
Y_surf(22)=dim_lim(4,2);

Z_surf(1)=dim_lim_new(2,3);
Z_surf(2)=dim_lim_new(3,3);
Z_surf(3)=dim_lim(8,3);
Z_surf(4)=dim_lim(2,3);
Z_surf(5)=dim_lim(3,3);
Z_surf(6)=dim_lim(4,3);
Z_surf(7)=dim_lim(5,3);
Z_surf(8)=dim_lim_new(5,3);
Z_surf(9)=dim_lim_new(4,3);
Z_surf(10)=dim_lim_new(6,3);
Z_surf(11)=dim_lim_new(7,3);
Z_surf(12)=dim_lim(9,3);
Z_surf(13)=dim_lim(10,3);
Z_surf(14)=dim_lim(9,3);
Z_surf(15)=dim_lim_new(1,3);
Z_surf(16)=dim_lim_new(2,3);
Z_surf(17)=dim_lim(2,3);
Z_surf(18)=dim_lim(3,3);
Z_surf(19)=dim_lim(10,3);
Z_surf(20)=dim_lim_new(6,3);
```

```
Z_surf(21)=dim_lim_new(4,3);
Z_surf(22)=dim_lim(4,3);


X_surf = X_surf/.0254;
Y_surf = Y_surf/.0254;
Z_surf = Z_surf/.0254;
dim_lim_new = dim_lim_new/.0254;
xlabel('X axis (m)');ylabel('Y axis (m)');zlabel('Z axis (m)');
fill3(dim_lim_new(1:3,1),dim_lim_new(1:3,2),dim_lim_new(1:3,3), 'b');
hold on
fill3(X_surf(8:11),Y_surf(8:11),Z_surf(8:11), 'b');
hold on
fill3(X_surf(1:4),Y_surf(1:4),Z_surf(1:4),'b');
hold on
fill3(X_surf(3:7),Y_surf(3:7),Z_surf(3:7),'b');
hold on
fill3(X_surf(5:7),Y_surf(5:7),Z_surf(5:7),'b');
hold on
fill3(X_surf(6:9),Y_surf(6:9),Z_surf(6:9),'b');
hold on
fill3(X_surf(10:13),Y_surf(10:13),Z_surf(10:13),'b');
hold on
X_surf = X_surf*.0254;
Y_surf = Y_surf*.0254;
Z_surf = Z_surf*.0254;
dim_lim_new = dim_lim_new*.0254;


length = 11.5*.0254;
height = 2.15*.0254;
k = 1;


for i = .8*length:.05*length:1.2*length
    l = 1;
    lparam(k) = i;
    for j = .8*height:.05*height:1.2*height
        [Xmax,max_res(k,l)] = exhaust_search(i,j);
        hparam(l) = j;
%         c(1:3) = (l+5)*.01;
        l = l + 1;
        for m = 1:4
            X_X(m) = Xmax(3*m-2);
            Y_Y(m) = Xmax(3*m-1);
            Z_Z(m) = Xmax(3*m);
        end

    end
    k = k + 1;
end

end
```

Regression model for calculation of wrist angles and errors (Section 4.1.3 – Embodiment Design phase)

```
function main()

% STEPWISE FIT REGRESSION

close all
clear all

gamma = [ 0, 10, 20, -10, -20, -30];
beta = [ -30, -20, -10, 0, 10, 20, 30];

% TAKE OUT CALIBRATION DATA

% ROW = -30 degrees
fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row-30.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1; % Count of points taken in
z=1; % Count of angle
for i = 2: size(C{1},1)
    if strcmp(C{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                Xi = temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C{j+1}(i));
            ext(k) = z;
        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
```

```
        end
    end
    Xi = Xi_temp;


    % Xgamma = [Xgamma;[Xi,pbeta(7:12)]];
% BUILT THE X FOR GAMMA
%     g = size(Xgamma,1);
    for i = 1:size(Xi,1)
        Xgamma(i,:) = [Xi(i,:),-30];
% BUILT THE X FOR GAMMA
        pgamma(i) = gamma(ext(i));
        pbeta(i) = -30;
    end
end


clear Xi
clear Xi_temp
clear ext
clear temp


% ROW = -20 degrees




fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row-20.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1;
z=1; % Count of angle
for i = 2: size(C{1},1)
    if strcmp(C{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                Xi = temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
```

```
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    g = size(Xgamma,1);
    for i = 1:size(Xi,1)
        Xgamma(g+i,:) = [Xi(i,:),-20];
% BUILT THE X FOR GAMMA
        pgamma(g+i) = gamma(ext(i));
        pbeta(g+i) = -20;
    end
end
clear Xi
clear Xi_temp
clear ext
clear temp



% ROW = -10 degrees


fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row-10.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1;
z=1; % Count of angle
for i = 2: size(C{1},1)
    if strcmp(C{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                Xi = temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
```

```
            end
            Xi(k,j) = str2double(C{j+1}(i));
            ext(k) = z;
        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    g = size(Xgamma,1);
    for i = 1:size(Xi,1)
        Xgamma(g+i,:) = [Xi(i,:),-10];
% BUILT THE X FOR GAMMA
        pgamma(g+i) = gamma(ext(i));
        pbeta(g+i) = -10;
    end
end
clear Xi
clear Xi_temp
clear ext
clear temp



% ROW = 0 degrees



fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 0.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1;
z=1; % Count of angle
for i = 2: size(C{1},1)
    if strcmp(C{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
```

```
                clear Xi;
            Xi = temp;
            else
                clear Xi;
            end
            k = k-1;
            break;
        end
        Xi(k,j) = str2double(C{j+1}(i));
        ext(k) = z;

    end
    z=z+1;
    k=k+1;
  end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    g = size(Xgamma,1);
    for i = 1:size(Xi,1)
        Xgamma(g+i,:) = [Xi(i,:),0];
% BUILT THE X FOR GAMMA
        pgamma(g+i) = gamma(ext(i));
        pbeta(g+i) = 0;
    end
end
clear Xi
clear Xi_temp
clear ext
clear temp



% ROW = 10 degrees



fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 10.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1;
z=1; % Count of angle
```

```
for i = 2: size(C{1},1)
    if strcmp(C{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                Xi = temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    g = size(Xgamma,1);
    for i = 1:size(Xi,1)
        Xgamma(g+i,:) = [Xi(i,:),10];
% BUILT THE X FOR GAMMA
        pgamma(g+i) = gamma(ext(i));
        pbeta(g+i) = 10;
    end
end
clear Xi
clear Xi_temp
clear ext
clear temp


% ROW = 20 degrees
```

```
fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 20.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1;
z=1; % Count of angle
for i = 2: size(C{1},1)
    if strcmp(C{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                Xi = temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    g = size(Xgamma,1);
    for i = 1:size(Xi,1)
        Xgamma(g+i,:) = [Xi(i,:),20];
% BUILT THE X FOR GAMMA
        pgamma(g+i) = gamma(ext(i));
        pbeta(g+i) = 20;
    end
end
clear Xi
clear Xi_temp
clear ext
```

```
clear temp



% ROW = 30 degrees



fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 30.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1;
z=1; % Count of angle
for i = 2: size(C{1},1)
    if strcmp(C{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                Xi = temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    g = size(Xgamma,1);
    for i = 1:size(Xi,1)
```

```
        Xgamma(g+i,:) = [Xi(i,:),30];
% BUILT THE X FOR GAMMA
        pgamma(g+i) = gamma(ext(i));
        pbeta(g+i) = 30;
    end
end
clear Xi
clear Xi_temp
clear ext
clear temp

% BUILD THE X FOR BETA (WITH LINEAR COORDINATES AND GAMMA
pgamma = pgamma';
Xbeta = [Xgamma(:,1:8),pgamma];

pbeta = pbeta';

% AUGMENT X MATRICES WITH SECOND DEGREE TERMS FOR IMAGE COORDINATES
for i = 1:8
    Xgamma = [Xgamma,Xgamma(:,i).^2];
    Xbeta = [Xbeta,Xbeta(:,i).^2];
    for j = i+1:8
        Xgamma = [Xgamma,Xgamma(:,i).*Xgamma(:,j)];
        Xbeta = [Xbeta,Xbeta(:,i).*Xbeta(:,j)];
    end
end

% RUN REGRESSION FOR BOTH ANGLES
[bgamma,seg,pvalg,inmodelg,statsg] =
Stepwisefit(Xgamma,pgamma,'penter',0.05);
[bbeta,seb,pvalb,inmodelb,statsb] =
Stepwisefit(Xbeta,pbeta,'penter',0.05);

% INTERCEPT VALUES FOR THE REGRESSION MODELS
constantg = statsg.intercept;
constantb = statsb.intercept;


% MAKE THE CONSTANTS 0 IF THE P_VALUE IS <.05
% FOR GAMMA
for i = 1:size(bgamma)
%     if i == 9
%         continue
%     end
    if (statsg.PVAL(i) < .05)
        continue
    else
        bgamma(i) = 0;
    end
end

% FOR BETA
for i = 1:size(bbeta)
%     if i == 9
%         continue
```

```
%     end
    if (statsb.PVAL(i) < .05)
        continue
    else
        bbeta(i) = 0;
    end
end




% CALCULATE THE ANGLES AT EACH OF THE DATA POINTS
% INPUT THE TEST FILE
fid = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\bandeh.csv');
C = textscan (fid,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid);
k=1;
for i = 2: size(C{1},1)
    %     if strcmp(C{1}(i), 'Next angle')
    %         i=i+4;
    %         continue
    %     else
    for j = 1:8
        if str2double(C{j+1}(i)) == 1023
            if(exist('Xi','var'))
                if(size(Xi,1)>1)
                    %                  Xi
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
            else
                k = k-1;
                break
            end

            k = k-1;
            break;
        end
        Xi(k,j) = str2double(C{j+1}(i));

    end
    k=k+1;
end


% Sort
Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
[Xs_sort,IX] = sort(Xs);

for i = 1:size(Xi,1)
```

```
    for j = 1:4
        Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
        Xi_temp(i,2*j) = Xi(i,2*IX(j));
    end
end
Xi = Xi_temp;

% AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi, Xi^2
and Yi^2
for k = 1:8
    Xi = [Xi,Xi(:,k).^2];
    for j = k+1:8
        Xi = [Xi,Xi(:,k).*Xi(:,j)];
    end
end

% angles0 = [0,0];
fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Result.csv','w+');
for i = 1:size(Xi,1)

    % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING TERMS
AND
    % THEIR ADDITION
    val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
    val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

    val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
    val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

    val_xys_g = val_xys_g + constantg;
    val_xys_b = val_xys_b + constantb;

    gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1- bgamma(9)*bbeta(9));
    bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1- bgamma(9)*bbeta(9));
    fprintf (fid2, '%f,%f\n',gamm,bet);
end
fclose(fid2);

clear Xi
clear Xi_temp
clear ext



% CALCULATE ERRORS FROM KNOWN CALIBRATION DATA-1




fid3 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 0.csv');
C2 = textscan (fid3,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid3);
```

```
k=1;
z=1;
for i = 2: size(C2{1},1)
    if strcmp(C2{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C2{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C2{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    % AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi,
Xi^2 and Yi^2
    for k = 1:8
        Xi = [Xi,Xi(:,k).^2];
        for j = k+1:8
            Xi = [Xi,Xi(:,k).*Xi(:,j)];
        end
    end

    fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Error0.csv','w+');
    size(Xi,1)
    for i = 1:size(Xi,1)
```

```
        % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING
TERMS AND THEIR ADDITION
        val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
        val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

        val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
        val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

        val_xys_g = val_xys_g + constantg;
        val_xys_b = val_xys_b + constantb;

        gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1-
bgamma(9)*bbeta(9));
        bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1-
bgamma(9)*bbeta(9));

        fprintf (fid2, '%f,%f,%f\n',gamma(ext(i)),gamma(ext(i)) -
gamm,0 - bet);
    end
    fclose(fid2);
end

clear Xi
clear Xi_temp
clear ext
clear C2


% CALCULATE ERRORS FROM KNOWN CALIBRATION DATA - 2


fid3 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 10.csv');
C2 = textscan (fid3,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid3);

k=1;
z=1;
for i = 2: size(C2{1},1)
    if strcmp(C2{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C2{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
```

```
            Xi(k,j) = str2double(C2{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    % AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi,
Xi^2 and Yi^2
    for k = 1:8
        Xi = [Xi,Xi(:,k).^2];
        for j = k+1:8
            Xi = [Xi,Xi(:,k).*Xi(:,j)];
        end
    end

    fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Error10.csv','w+');
    size(Xi,1)
    for i = 1:size(Xi,1)

        % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING
TERMS AND THEIR ADDITION
        val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
        val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

        val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
        val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

        val_xys_g = val_xys_g + constantg;
        val_xys_b = val_xys_b + constantb;

        gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1-
bgamma(9)*bbeta(9));
        bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1-
bgamma(9)*bbeta(9));

        fprintf (fid2, '%f,%f,%f\n',gamma(ext(i)),gamma(ext(i)) -
gamm,10 - bet);
    end
```

```
    fclose(fid2);
end
clear Xi
clear Xi_temp
clear ext
clear C2



% CALCULATE ERRORS FROM KNOWN CALIBRATION DATA - 3


fid3 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 20.csv');
C2 = textscan (fid3,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid3);

k=1;
z=1;
for i = 2: size(C2{1},1)
    if strcmp(C2{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C2{j+1}(i)) == 1023
                if(size(Xi,1)>1)

                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C2{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
```

```
        end
    end
    Xi = Xi_temp;

    % AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi,
Xi^2 and Yi^2
    for k = 1:8
        Xi = [Xi,Xi(:,k).^2];
        for j = k+1:8
            Xi = [Xi,Xi(:,k).*Xi(:,j)];
        end
    end

    fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Error20.csv','w+');
    size(Xi,1)
    for i = 1:size(Xi,1)

        % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING
TERMS AND THEIR ADDITION
        val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
        val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

        val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
        val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

        val_xys_g = val_xys_g + constantg;
        val_xys_b = val_xys_b + constantb;

        gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1-
bgamma(9)*bbeta(9));
        bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1-
bgamma(9)*bbeta(9));

        fprintf (fid2, '%f,%f,%f\n',gamma(ext(i)),gamma(ext(i)) -
gamm,20 - bet);
    end
    fclose(fid2);
end
clear Xi
clear Xi_temp
clear ext
clear C2


% CALCULATE ERRORS FROM KNOWN CALIBRATION DATA-4




fid3 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row 30.csv');
C2 = textscan (fid3,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid3);
```

```
k=1;
z=1;
for i = 2: size(C2{1},1)
    if strcmp(C2{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C2{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C2{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    % AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi,
Xi^2 and Yi^2
    for k = 1:8
        Xi = [Xi,Xi(:,k).^2];
        for j = k+1:8
            Xi = [Xi,Xi(:,k).*Xi(:,j)];
        end
    end

    fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Error30.csv','w+');
    size(Xi,1)
    for i = 1:size(Xi,1)
```

```
        % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING
TERMS AND THEIR ADDITION
        val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
        val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

        val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
        val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

        val_xys_g = val_xys_g + constantg;
        val_xys_b = val_xys_b + constantb;

        gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1-
bgamma(9)*bbeta(9));
        bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1-
bgamma(9)*bbeta(9));

        fprintf (fid2, '%f,%f,%f\n',gamma(ext(i)),gamma(ext(i)) - gamm,
30 - bet);
    end
    fclose(fid2);
end
clear Xi
clear Xi_temp
clear ext
clear C2
% CALCULATE ERRORS FROM KNOWN CALIBRATION DATA-5




fid3 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row-10.csv');
C2 = textscan (fid3,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid3);

k=1;
z=1;
for i = 2: size(C2{1},1)
    if strcmp(C2{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C2{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
```

```
            Xi(k,j) = str2double(C2{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    % AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi,
Xi^2 and Yi^2
    for k = 1:8
        Xi = [Xi,Xi(:,k).^2];
        for j = k+1:8
            Xi = [Xi,Xi(:,k).*Xi(:,j)];
        end
    end

    fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Error-10.csv','w+');
    size(Xi,1)
    for i = 1:size(Xi,1)

        % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING
TERMS AND THEIR ADDITION
        val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
        val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

        val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
        val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

        val_xys_g = val_xys_g + constantg;
        val_xys_b = val_xys_b + constantb;

        gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1-
bgamma(9)*bbeta(9));
        bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1-
bgamma(9)*bbeta(9));

        fprintf (fid2, '%f,%f,%f\n',gamma(ext(i)),gamma(ext(i)) -
gamm,-10 - bet);
    end
```

```
    fclose(fid2);
end
clear Xi
clear Xi_temp
clear ext
clear C2

% CALCULATE ERRORS FROM KNOWN CALIBRATION DATA-6




fid3 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row-20.csv');
C2 = textscan (fid3,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid3);

k=1;
z=1;
for i = 2: size(C2{1},1)
    if strcmp(C2{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C2{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C2{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
```

```
    end
    Xi = Xi_temp;

    % AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi,
Xi^2 and Yi^2
    for k = 1:8
        Xi = [Xi,Xi(:,k).^2];
        for j = k+1:8
            Xi = [Xi,Xi(:,k).*Xi(:,j)];
        end
    end

    fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Error-20.csv','w+');
    size(Xi,1)
    for i = 1:size(Xi,1)

        % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING
TERMS AND THEIR ADDITION
        val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
        val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

        val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
        val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

        val_xys_g = val_xys_g + constantg;
        val_xys_b = val_xys_b + constantb;

        gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1-
bgamma(9)*bbeta(9));
        bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1-
bgamma(9)*bbeta(9));

        fprintf (fid2, '%f,%f,%f\n',gamma(ext(i)),gamma(ext(i)) -
gamm,-20 - bet);
    end
    fclose(fid2);
end
clear Xi
clear Xi_temp
clear ext
clear C2
% CALCULATE ERRORS FROM KNOWN CALIBRATION DATA-7




fid3 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\row-30.csv');
C2 = textscan (fid3,'%s %s %s %s %s %s %s %s %s','delimiter',',');
fclose (fid3);

k=1;
z=1;
```

```
for i = 2: size(C2{1},1)
    if strcmp(C2{1}(i), 'Next angle')
        continue
    else
        for j = 1:8
            if str2double(C2{j+1}(i)) == 1023
                if(size(Xi,1)>1)
                    temp(:,:) = Xi(1:k-1,:);
                    clear Xi;
                    Xi = temp;
                    clear temp;
                else
                    clear Xi;
                end
                k = k-1;
                break;
            end
            Xi(k,j) = str2double(C2{j+1}(i));
            ext(k) = z;

        end
        z=z+1;
        k=k+1;
    end
end

% Sort
if (exist('Xi','var'))
    Xs = [ Xi(1,1), Xi(1,3), Xi(1,5), Xi(1,7)];
    [Xs_sort,IX] = sort(Xs);

    for i = 1:size(Xi,1)
        for j = 1:4
            Xi_temp(i,2*j-1) = Xi(i,2*IX(j)-1);
            Xi_temp(i,2*j) = Xi(i,2*IX(j));
        end
    end
    Xi = Xi_temp;

    % AUGMENT THE TEST DATA MATRIX WITH SECOND DEGREE TERMS OF XiYi,
Xi^2 and Yi^2
    for k = 1:8
        Xi = [Xi,Xi(:,k).^2];
        for j = k+1:8
            Xi = [Xi,Xi(:,k).*Xi(:,j)];
        end
    end

    fid2 = fopen ('C:\Documents and Settings\msinghee3\My
Documents\Downloads\Linearangle\Linearangle\Error-30.csv','w+');
    size(Xi,1)
    for i = 1:size(Xi,1)

        % CALCULATION OF CONSTANTS MULTIPLIED BY THE CORREPSONDING
TERMS AND THEIR ADDITION
        val_xys_g = dot(bgamma(1:8),Xi(i,1:8));
```

```
        val_xys_b = dot(bbeta(1:8),Xi(i,1:8));

        val_xys_g = val_xys_g + dot(bgamma(10:45),Xi(i,9:44));
        val_xys_b = val_xys_b + dot(bbeta(10:45),Xi(i,9:44));

        val_xys_g = val_xys_g + constantg;
        val_xys_b = val_xys_b + constantb;

        gamm = (val_xys_g + bgamma(9)*val_xys_b)/( 1-
bgamma(9)*bbeta(9));
        bet = (val_xys_b + bbeta(9)*val_xys_g)/( 1-
bgamma(9)*bbeta(9));

        fprintf (fid2, '%f,%f,%f\n',gamma(ext(i)),gamma(ext(i)) - gamm
,-30 - bet);
    end
    fclose(fid2);
end
clear Xi
clear Xi_temp
clear ext
clear C2



end
```

REFERENCES

1. Georgia Tech, U., John Hopkins Univ., UPenn, UCB, RPI, Univ. of Massachusetts, Amherst, U. of Utah, CMU, Tech Collab. (2009) "A roadmap for US robotics: From internet to robotics". URL: http://www.us-robotics.us/reports/CCCReport.pdf Accessed: Aug., 2009
2. Kullgren, A., Krafft, M., Tingvall, C., Lie, A., "Combining crash recorder and paired comparison technique: Injury risk functions in frontal and rear impacts with special reference to neck injuries". Accident Reconstruction Newsletter, 2008. **10**(94).
3. Davidsson, J., Svensson, M.Y., Flogard, A., Haland, Y., Jacobsson L., Linder, A., Lovsund, P., Wiklund, K. , "BioRID - A New Biofidelic Rear Impact Dummy". Proc. IRCOBI Conference on Biomechanics, Göteborg, Sweden, 1998.
4. Linder, A., Svensson, M.Y., "BioRID, a crash test dummy for rear impact: A review of development, validation and evaluation". Proc. of IRCOBI Conference on Biomechanics of Impacts, Göteborg, Sweden, 2001.
5. Abascal, J. "Ambient intelligence for people with disabilities and elderly people". Laboratory of HCI for Special Needs, URL: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.92.8860&rep=rep1&type=pdf Accessed: Oct. 2008
6. Benini, L., Farella, E., Guiducci, C., "Wireless sensor networks: Enabling technology for ambient intelligence". Microelectronics Journal, 2006. **37**: p. 1639-1649.
7. Ducatel, K., Bogdanowicz, M., Scapolo, F., Leijten, J., Burgelman, J-C. (2001) "Scenarios for ambient intelligence in 2010". URL: ftp://ftp.cordis.europa.eu/pub/ist/docs/istagscenarios2010.pdf Accessed: Oct., 2008
8. Mogk, J.P.M., Keir, P.J., "The effects of posture on forearm muscle loading during gripping". Ergonomics, 2003. **46**(9): p. 956-975.
9. M. Mondelli, A.G., M. Mariani, A. Baldasseroni, R. Ansuini, M.Ballerini, C. Bandinelli, M. Graziani, F. Luongo, R. Mancini, P. Manescalchi, S. Pellegrini, C. Sgarrella, F. Giannini, "Carpal tunnel syndrome and ulnar neuropathy at the elbow in floor cleaners". Clinical Neurophysiology, 2006. **36**(4): p. 245-253.
10. AAEM Quality Assurance Committee Charles K. Jablecki, M.T.A., Yuen T. So, Dennis E. Wilkins, Faren H. Williams, "Literature review of the usefulness of nerve conduction studies and electromyography for the evaluation of patients with carpal tunnel syndrome". Muscle & Nerve, 1993. **16**(12): p. 1392 - 1414.
11. William E. Daniell, D.F.-K., Lisa A. Chiou, Gary M. Franklin, "Work-related carpal tunnel syndrome in washington state workers' compensation: temporal trends, clinical practices and disability". American Journal of Industrial Medicine, 2005. **48**: p. 259-269.

12. Keir, P.J., Bach, J.M., Hudes, M., Rempel, D.M., "Guidelines for wrist posture based on carpal tunnel pressure thresholds". Human Factors, 2007. **49**(1): p. 88-99.
13. Au, A.K., Keir, P.J., "Interfering effects of multitasking on muscle activity in the upper extremity". Journal of Electromyography and Kinesiology, 2006. **17**(5): p. 578-586.
14. Borst, P., Akkermans, H., "Engineering ontologies". International Journal of Human-Computer Studies, 1997. **46**: p. 365-406.
15. Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H., "Engineering Design". Springer-Verlag London Limited, 2007.
16. McGuiness, D.L., Harmelen, F.v. (2009) "OWL Web Ontology Language Overview". W3C Recommendation, URL: http://www.w3.org/TR/owl-features/ Accessed:
17. Patil, L., Dutta, D., Sriram, R., "Ontology formalization of product semantics for Product Lifecycle Management". National Institute of Standards and Technology, 2005. **7274**: p. 1-7.
18. Mistree, F., Bras, B.A., Smith, W.F., Allen, J.K., "Modeling design processes: A conceptual , decision-based perspective". International Journal of Engineering Design and Automation, 1996. **1**(4): p. 209-221.
19. Miller, J.G., "Living systems". McGraw-Hill Book Company, New York, 1978.
20. Marti, P., Velasco, M., Bini, E., "The optimal boundary and regulator design problem for event-driven controllers". Book Chapter - Hybrid Systems: Computation and Control, 2009: p. 441-444.
21. Tabuada, P., "Event-triggered real-time scheduling of stabilizing control tasks". IEEE Transactions on Automatic Control, 2007. **52**(9): p. 1680-1685.
22. Velasco, M., Marti, P., Bini, E., "Control-driven tasks: Modeling and analysis". 29th IEEE Real-Time Systems Symposium, Barcelona, Spain, 2008.
23. Grimes, C.A., Dickey, E. C., Pishko, M. V., "Encyclopedia of Sensors". American Scientific Publishers. Vol. 1. 2005. 8000.
24. Shupe, J.A., "Decision-based design: Taxonomy and implementation". PhD. Dissertation, Department of Mechanical Engineering, University of Houston, Houston, Texas, 1988.
25. Bischoff, W., Hanse, F., "Rationelles Konstruieren Konstruktionsbucher Bd. 5". VEB Verlag Technik, 1953. **5**.
26. Bock, A., "Konstruktionssystematic - die Methode der ordnenden Gesichtspunkte". Feingeratetechnik, 1955. **4**(4).
27. Hansen, F., "Konstruktionssystematik 2". Aufl. Berlin: VEB-Verlag Technik, 1965.
28. Rodenacker, W.G., "Neue Gedanken zur Knostruktionsmethodik". Konstruktion 43, 1991: p. 330-334.
29. Seepersad, C.C., Pedersen, K., Emblesvåg, J. Bailey, R.R., Allen, J.K., Mistree, F., "The Validation Square: How does one validate design methods?". Decision-Based Design: Making Effective Decisions in Product and Systems Design (W. Chen, K. Lewis and L. Schmidt, Eds.), 2006: p. 305-326.

30. Pedersen, K., Emblemsvåg, J., Bailey, R., Allen, J.K., Mistree, F., "Validating design methods & research: The validation square". ASME Design ENgineering Technical Conferences, 2000(September): p. 10-14.
31. Guarino, N., "Formal ontology and information systems". Proceedings of FOIS, 1998. **6-8**: p. 3-15.
32. Lopez, M.F., Perez, A.G., "Overview and analysis of methodologies for building ontologies". The Knowledge Engineering Review, 2002. **17**(2): p. 129-156.
33. Ashburner, M., Ball, C. A., Blake, J. A., Botstein, D., Butler, H., Cherry, J. M., Davis, A. P., Dolinski, K., Dwight, S. S., Eppig, J. T., Harris, M. A., Hill, D. P., Issel-Tarver, L., Kasarskis, A., Lewis, S., Matese, J. C., Richardson, J. E., Ringwald, M., Rubin, G. M., Sherlock, G., "Gene ontology: tool for the unification of biology. The Gene Ontology Consortium". Nature Genetics, 2000. **25**(1): p. 25:29.
34. Al-Shahrour, F., Diaz-Uriarte, R., Dopazo, J., "FatiGO: a web tool for finding associations of Gene Ontology terms with group of genes". Bioinformatics Advance Access Publication, 2004. **20**: p. 578-580.
35. Harris MA, C.J., Ireland A, Lomax J, Ashburner M, Foulger R, Eilbeck K, Lewis S, Marshall B, Mungall C, Richter J, Rubin GM, Blake JA, Bult C, Dolan M, Drabkin H, Eppig JT, Hill DP, Ni L, Ringwald M, Balakrishnan R, Cherry JM, Christie KR, Costanzo MC, Dwight SS, Engel S, Fisk DG, Hirschman JE, Hong EL, Nash RS, Sethuraman A, Theesfeld CL, Botstein D, Dolinski K, Feierbach B, Berardini T, Mundodi S, Rhee SY, Apweiler R, Barrell D, Camon E, Dimmer E, Lee V, Chisholm R, Gaudet P, Kibbe W, Kishore R, Schwarz EM, Sternberg P, Gwinn M, Hannick L, Wortman J, Berriman M, Wood V, de la Cruz N, Tonellato P, Jaiswal P, Seigfried T, White R;, "The Gene Ontology (GO) database and informatics resource". Nucleic Acids Research, 2004. **32**: p. 258-261.
36. Belkin, N.J., Croft, B.W., "Information filtering and information retrieval: Two sides of the same coin?", in Communications of the ACM. 1992. p. 29-38.
37. Kim, W., Seo, J., "Classifying schematic and data heterogeinity in multidabase systems". IEEE Computer, 1991. **24**(12): p. 12-18.
38. Kashyap, V., Sheth, A., "Schematic and semantic similarities between database objects: A context-based approach". The International Journal on Very Large Data Bases, 1996. **5**(4): p. 276-304.
39. Wache, H., Vögele, T., Visser, U., Stuckenschmidt, H., Schuster, G., Neumann, H., Hübner, S. . "Ontology-based integration of information - A survey of existing approaches". in Proceedings of IJCAI-01 Workshop: Ontologies and Information Sharing. 2001. Seattle, WA.
40. Miller, J.G., "Living systems II. The cell". Currents in Modern Biology, 1971. **4**: p. 78-206.
41. Miller, J.G., "Living systems. III. The organ". Currents in Modern Biology, 1971. **4**: p. 207-254.
42. Miller, J.G., "Living systems: The group". Behavioral Sciences, 1971. **16**: p. 302-398.
43. Miller, J.G., "Living systems: The organization". Behavioral Science, 2007. **17**(1): p. 1-182.

44. Huang, J.M., Black, J.T., "An evaluation of chip separation criteria for the FEM simulation of machining". Journal of Manufacturing Science and Engineering, 1996. **118**(4): p. 545-554.
45. Fortin, M., Fortin, A., "A new approach for the FEM simulation of viscoelastic flows". Journal of Non-Newtonian Fluid Mechanics, 1989. **32**(3): p. 295-310.
46. Singhee, M., McDowell, D., Allen, J.K., Ghosh, S., "A decision -based framework for robust systems design of Mg alloys", in Mechanical Engineering. 2008, Indian Institute of Technology, Kharagpur: Kharagpur. p. 35.
47. Sun, W., Nam, S.J., Darling, A., "Bio-CAD modeling and its applications in computer-aided tissue engineering". Computer-Aided Design, 2005. **37**(11): p. 1097-1114.
48. Sachs, E., Cima, M., Cornie, J., "Three-dimensional printing: Rapid tooling and prototypes directly from a CAD model". CIRP Annals - Manufacturing Technology, 1990. **29**(1): p. 201-204.
49. Sinha, R., Liang, V.C., Paredis, C.J.J., Khosla, P.K., "Modeling and simulation methods for design of engineering systems". Journal of Computing and Information Science in Engineering, 2001. **1**: p. 84-91.
50. Zeigler, B.P., Praehofer, H., Kim, T.G., "Theory of modeling and simulation". 2000: Academic Press.
51. Abelha, A., Analide, C., Machado, J., Neves, J., Santos, M., Novais, P., "Ambient intelligence and simulation in helath care virtual scenarios". IFIP Establishing the Foundation of Collaborative Networks, 2007. **243/2007**: p. 461-468.
52. Couzin, I.D., Krause, J., Franks, N.R., Levin, S.A., "Effective leadership and decision-making in animal groups on the move". Nature, 2005. **443**(February).
53. Mesbahi, M., Egerstedt, M., "Graph theoretic methods in multiagent networks". Princeton University Press, 2009: p. 1-34.
54. Wu, Z., Leahy, R., "An optimal grapth theoretic approach to data clustering: Theory and its application to image segmentation". IEEE Transactions in Pattern Analysis and Machine Intelligence, 1993. **15**(11): p. 1101-1113.
55. Rajagopalan, R., Batra, J.L., "Design of cellular production systems: A graph theoretic approach". International Journal of Production Research, 1975. **13**(6): p. 567-579.
56. Krackhardt, D., "Graph theoretical dimensions of informal organizations", in Computational Organizational Theory, K.M. Carley, Prietula, M.J., Editor. 1994, Lawrence Erlbraum Associates, Inc., Publishers.
57. Meguerdichian, S., Koushanfar, F., Potkonjak, M., Srivastava, M.B., "Coverage problems in wireless ad-hoc sensor networks", in IEEE Infocom. 2001. p. 1380-1387.
58. Megerian, S., Koushanfar, F., Potkonjak, M., Srivastava, M.B. "Worst and best case coverage in sensor networks". in IEEE Transactions on Mobile Computing. 2005.
59. Moore, D., Leonard, J., Rus, D., Teller, S. "Robust distributed network localization with noisy range measurements". in Conference on Embedded Networked Sensor Systems. 2004. Baltimore, MD, USA.
60. Kuhn, F., Nieberg, T., Moscibroda, T., Wattenhofer, R. "Local approximation schemes for ad hoc and sensor networks". in Workshop on Discrete Algorithms

and Methods for Mobile Computing and Communications. 2005. Cologne, Germany.

61. Kofod-Petersen, A., "A case-based approach to realising ambient intelligence among agents", in Department of Computer and Information Science. 2007, Norwegian University of Science and Technology: Trondheim. p. 322.
62. Barralon, N., Coutaz, J., "Coupling interaction resources in ambient spaces:There is more than meets the eye!", in Engineering Interactive Systems. 2008, Springer Berlin/Heidelberg.
63. Friedenthal, S., Moore, A., Steiner, R., "A practical guide to SysML". The MK/OMG Press, 2008.
64. Goknil, A., Kurtev, I., Berg, K.v.d., "A metamodeling approach for reasoning about requirements". Model Driven Architecture - Foundations and Applications, 2008. **5095/2008**: p. 310-325.
65. Soares, M.d.S., Vrancken, J., "Model-driven user requirements specification using SysML". Journal of Software, 2008. **3**(6): p. 57-68.
66. Winkler, S., Pilgrim, J.v., "A survey of traceability in requirements engineering and model-driven development". Software and Systems Modeling, 2009.
67. Karban, R., Zamparelli, M., Bauvir, B., Koehler, B., Noethe, L., Balestra, A. "Exploring model based engineering for large telescopes - Getting started with descriptive models". in Proceedings of SPIE Astronomical Telescopes and Instrumentation. 2008: SPIE, Bellinghma, Washington, ETAS-UNIS.
68. Anderson, L.W., Krathwoh, D.R., Airasian, P.W., Cruishank, K.A., Mayer, R.E., Pintrich, P.R., Raths, J., Wittrock, M.C., "A taxonomy for learning, teaching and assessing: A revision of bloom's taxonomy of educational objectives, abridged edition". Allyn & Bacon, Inc., 2000.
69. Gibbons, A., "Algorithmic graph theory". Cambridge University Press, 1985.
70. Biggs, N., Lloyd, E., Wilson, R., "Graph theory". Oxford University Press, 1986: p. 1736-1936.
71. STMicroelectronics (2006) "STMicroelectronics Drives Gaming Revolution with Nintendo's Wii™". URL: http://www.st.com/stonline/stappl/cms/press/news/year2006/t2031.htm Accessed: Oct., 2009
72. Liverman, M., "Then animator's motion capture guide". Charles River Media, 2004.
73. Basmajian, J.V., Luca, C.J.D., "Muscles alive". 1985, Baltimore: Williams Wilkins.
74. LifeMatters-ToolsforStresslessLiving, "http://www.lifematters.com/myotrac_emg.asp".
75. Morse, J.L., Jung, M-C., Bashford, G.R., Hallbeck, M.S., "Maximal dynamic grip force and wrist torque: The effects of gender, exertion direction, angular velocity, and wrist angle". Applied Ergonomics, 2006. **37**(6): p. 737-742.
76. Cole D., H.-J.S., Manno M., Ibrahim S., Wells R., Ferrier S., "Reducing musculoskeletal burden through ergonomic program implementation in a large newspaper". International Archives of Occupational and Environmental Health, 2006. **80**(2): p. 98-108.

77. Katz, J.N., Larson, M.G.,Sabra, A., Krarup, C., Stirrat, C.R., Sethi, R., Eaton, H.M., Fossel, A.H., Liang, M.H., "The Carpal Tunnel Syndrome: Diagnostic Utility of the History and Physical Examination Findings". Annals of Internal Medicine, 1990. **112**: p. 321-346.
78. J. Thomas Megerian, X.K., Shai N. Gozani, "Utility of nerve conduction studies for carpal tunnel syndrome by family medicine, primary care, and internal medicine physicians". Journal of the American Board of Family Medicine, 2007. **20**(1): p. 60-64.
79. NIOSH, "Musculoskeletal disorders and workplace factors", in NIOSH Publication, B.P. Bernard, Editor. 1997. p. 97-141.
80. Jefferey N. Katz, M.G., Larson, Amin Sabra, Christian Krarup, Craig R. Stirrat, Rajesh Sethi, Holly M. Eaton, Anne H. Fossel, Matthew H. Liang, "The Carpal Tunnel Syndrome: Diagnostic Utility of the History and Physical Examination Findings". Annals of Internal Medicine, 1990. **112**: p. 26.
81. Kreylos, O. "Wiimote Hacking - Technology". URL: http://idav.ucdavis.edu/~okreylos/ResDev/Wiimote/Technology.html Accessed: Sep., 2008
82. Konrad, P., "The ABC of EMG - A practical introduction to kinesiological Electromyography". 2005.
83. Mistree, F., Hughes, O.F., Bras, B., "Compromise decision support problem and the adaptive linear programming algorithm". In Structural Optimization, M.P. Kamat, ed., AIAA, 1993: p. 251-290.
84. Thompson, C., "Build it. Share it. Profit. Can open source hardware work?", in Wired. 2008.
85. O'Brien, J.F., Bodenheimer, R.E., Jr., Brostow, G.J., Hodgins, J.K. "Automatic joint paremeter estimation from magnetic motion capture data". in Proceedings of Graphics Interface. 2000.