CAREGIVER-MACHINE COLLABORATIVE MANIPULATION WITH AN ADVANCED HYDRAULICALLY ACTUATED PATIENT TRANSFER ASSIST DEVICE

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CAREGIVER-MACHINE COLLABORATIVE MANIPULATION WITH AN ADVANCED HYDRAULICALLY ACTUATED PATIENT TRANSFER ASSIST DEVICE

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To those who believe in me and encourage me to do better.

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SUMMARY

A significant need has been identified for an improved device to assist in transferring mobility limited patients, particularly those who are heavier or bariatric. Typical transfers include moving between a bed, wheelchair, chair/couch, toileting chair or toilet, car, or the floor. Currently, clinicians suffer more disabling workplace injuries than construction workers or firefighters, many of which are attributable to moving patients. A new, cost effective, hydraulically actuated prototype patient transfer assist device has been developed and fabricated; hydraulic actuation has advantages in terms of force density over electrical actuators that are typically used at this power scale. More generally, improved methods for control of machines that work collaboratively with humans, sharing a task and a workspace, were developed in this work. Furthermore, it investigates how hydraulic power, specifically electro-hydraulic pump controlled actuation, can be utilized in the human power scale. It also aims to overcome some of the control challenges with these actuation systems in this type of application, such as non-ideal characteristics of the low cost actuation systems and management of a machine with large force capability operating in a home or clinical environment with humans in its workspace.

A needs assessment has been performed, and the results indicate several needed improvements over current market patient lifts. The device needs a larger range of motion and better ability to maneuver around obstacles, lower required physical and metal workloads for the caregiver, force capability to maneuver up to 700 lbs., control that is smooth and safe, and management of external interaction forces. A new prototype mobile patient transfer assist device (PTAD) has been designed and fabricated, with four degrees of freedom (DOFs) fully functional. Each DOF is actuated by an electro-hydraulic pump control system, which includes a separate servo drive, reversible DC electric motor, bidirectional gear pump, and hydraulic actuator. A simple, intuitive caregiver interface has been implemented, which provides coordinated rate control using a force sensing handle mounted near

the patient for the operator input. The caregiver interacts directly with the patient, while simultaneously controlling the lift device. This machine enables the exploration of controls and operator interfaces that can transform healthcare.

With a powerful machine working in a relatively delicate environment, it is necessary for the controller to manage any external interaction forces, to keep them in a safe range, in addition to smoothly controlling motion. A significant challenge lies in implementation of interaction control with these electro-hydraulic pump controlled actuators, which are intrinsically stiff, have slow dynamics, and have many nonlinear or non-ideal features. An impedance control framework has been formulated and implemented, using redundant sensing of obstacles, with feedback of both external interaction forces and proximity.

Operator experiments were performed, using a mannequin representing the patient, including transfer operations between various locations in a simulated home/clinical environment. Some tests included obstacles to evaluate the control performance in unwanted collisions. Results indicate improvements over current market lifts in terms of operator ratings, even with this bulky, first generation prototype, and they show that comparable stages of the transfer operations can be performed considerably faster with a single operator using the PTAD than with the current market patient lift. Operator control experiment results show that the interaction control results in statistically significant reductions in collision forces by an average of 53%, and greater reductions in cases where the machine is moving faster, with greater momentum and subsequently larger collision forces; similar controlled experiments in hardware with software inputs result in reductions in collision forces of 87%. Overall, the results demonstrate that the new features of the patient transfer assist device make it easier, more efficient and safer to use, as compared with current market patient lifts. Beyond the patient transfer application, this project aims to make steps toward improving control in the broader application set of machines that work collaboratively with humans, sharing a task and a workspace; for example, in construction, manufacturing, or distribution.

CHAPTER I

INTRODUCTION

1.1 Introduction

In this research, a new type of hydraulic assist device is proposed for human-machine collaborative manipulation for moving mobility limited patients, or more generally, any complex, heavy payloads. It is intended to aid workers in moving heavy payloads through unstructured, cluttered environments that are relatively delicate, as compared to the forces involved in lifting the payloads. There is a recognized urgent need for an improved assist device of this type for patient transfers. Currently, clinicians are among the most common professions to suffer disabling work-related orthopedic injuries, even more than construction workers or firefighters, and a majority of those injuries result from transferring patients. This research is focused on methods to design and control an assist device to safely aid caregivers in moving patients and manage interaction forces through control, but the machine and its control can be modified for use in other applications. The focus of the research is on the control of motion and forces, with input from a human operator. The target user group for the patient transfer assist device (PTAD) includes patients who are unable to perform independent transfers, such as patients with high level spinal cord injuries, neuromuscular disorders, and the elderly, as well as their caregivers.

Beyond the patient lift application, this project aims to make steps toward improving control in the broader application set of useful machines that work collaboratively with humans, sharing a task and a workspace; for example, this could include applications in construction, manufacturing, or distribution. Furthermore, it aims to investigate how hydraulic power, specifically electro-hydraulic pump controlled actuation, known as direct drive actuation, can be utilized in the human power scale. Hydraulic actuation has significant advantages in terms of power density as compared with electrical actuators that are more commonly used in this power scale. In this type of machine, overall compactness is an important design requirement, and with the addition of multiple actuated degrees of freedom, the high power density of hydraulic actuation is an asset. While direct drive hydraulic actuation is used in industry, it has not been as widely studied in the research literature as applications using valve-based control. This actuation approach presents significant challenges in terms of control of motion and forces. It is necessary to solve problems related to patient lifts concurrently with solving the problems of hydraulics applied to patient lifts.

1.2 Motivation for an Improved Patient Transfer Assist Device (PTAD)

A significant need has been identified for an improved device to assist in transferring mobility limited patients. Typical transfers include moving between a bed, wheelchair, chair/couch, toileting chair or toilet, car, or the floor. Our needs assessment indicates that current market lifts are insufficient for current market need and do not take advantage of newer developments in robotics technology. The population with the greatest need for this type of device includes those who are unable to perform independent transfers, particularly heavier or bariatric patients. In this project, the aim is to develop an improved patient transfer assist device that is more intuitive, easy and safe to operate, powerful, and maneuverable than current market lifts. The needs assessment also revealed that heavier patients are particularly difficult to transfer, and that the current market lifts are insufficient for the needs of many patients and caregivers. The relevant patient population includes those with spinal cord injuries, neuromuscular disorders, and the elderly, most of whom are wheelchair users. Caregiver injuries from patient transfers are a growing concern in the healthcare industry. According to a recent series on National Public Radio titled "Injured Nurses", nurses suffer over 35,000 back and other orthopedic injuries that require missed work each year (56).

1.3 Vision for an Assist Device for Collaborative Manipulation of Heavy Payloads in Unstructured and Relatively Delicate Environments

This research presents tangible steps toward a vision of a new type of human-collaborative payload transfer assist device, using direct drive hydraulic actuation. The assist device is directly controlled by the human operator, by pushing on the machine in the desired payload motion vector. As the operator pushes harder, it moves faster, independent of the payload. The device lifts and maneuvers the primary weight of the payload, while the operator is able to manually fine tune the payload position and orientation with minimal applied force. This allows for the process to capitalize on the human's dexterity while also making use of the machine's high payload capacity, providing capability for complex maneuvers of the heavy payload in an unstructured and relatively delicate environment. An ideal version of the machine would sense any obstacles in close proximity or in contact, notify the operator of any impending collisions, and prevent any large collision or external contact forces, while still allowing for full utilization of the workspace and external contact, controlled forces in a safe range for a human when desired.

Figure 1: Concept for collaborative payload assist device

This interaction control approach can help to reduce the operator's mental workload by offloading the interaction control task, of preventing any potential damage or injury to anyone or anything in the environment, from being primarily the operator's responsibility to being primarily the machine's responsibility, allowing the operator to focus on the payload transfer task. This capability for obstacle avoidance is not only an important safety feature, but it has potential to significantly improve efficiency of operation.

When humans work in a cluttered environment, they sense any contact or interaction forces through skin and joints, and they can respond to any unwanted interaction forces in a compliant manner, even when their force generating capabilities are much greater than the forces involved in the unwanted contact. Ideally, the machine should do the same.

1.4 *Proposed Improvements Over Current Patient Transfer Assist Devices*

A prototype PTAD is developed in this research, and it demonstrates the concepts of multiple electro-hydraulically actuated degrees of freedom with coordinated control, as well as interaction control, applied to the patient transfer application. Some issues with patient lifts are directly improved with this prototype:

- Lower forces required from the operator
- Powered base motion
- Capability to perform transfers faster
- Larger range of motion (including the ability to reach the floor).

Key design concepts are proven through the testing, which are expected to lead to more significant performance improvements. First, the addition of multiple hydraulically actuated degrees of freedom with intuitive coordinated control can be expected to lead to the following, in later stages, after an optimized mechanical design is achieved:

- Improved maneuverability around obstacles and through tight spaces.
- Improved ability to lift patients from difficult-to-reach places.

Second, the addition of intuitive coordinated control, where the operator simply pushes on the machine in the desired direction of patient motion, can be expected to lead to reduced operator mental workload. Third, the addition of interaction control can be expected to result in the following improvements, once it is applied to all degrees of freedom:

- Improved safety for patients and others in the workspace
- Reduced operator mental workload
- Fewer incidences of damage to objects in the workspace
- Faster transfer operations.

Addition of more actuated degrees of freedom with coordinated, feedback controlled motion has considerable advantages in this application. But without the addition of interaction control, it would have potential to increase the possibility of injuries or damage resulting from collisions. For example, if a joint is controlled by an operator in open loop from a manual hydraulic input lever, then the operator can feel any significant increases in the force applied by the actuator. Adding feedback control of velocity or position can improve the machine dynamic response and enable coordinated control, but it reduces the operator's feel for the environment; when the machine encounters an obstacle, the feedback control increases the actuator command to achieve the desired motion, and the operator is less aware of the increase in forces applied to the environment than with open loop manual hydraulic control. Furthermore, the addition of more actuated degrees of freedom can result in higher collision force capabilities from some joints (e.g. the wheels, which are not actuated in the current market patient lift). The addition of various forms of interaction control typically provide the operator with even better haptic information about interaction forces than open loop control, and it allows for the controller to reduce the interaction forces. Additionally, like driving a car with ultrasonic backup sensors, if the machine can be trusted to warn the caregiver of any impending external interactions, and to minimize interaction forces, then the caregiver will be able to spend less time checking around the machine to avoid collisions while moving through the workspace, thereby reducing the caregiver's mental workload and improving the speed of operations.

1.5 Prototype Patient Transfer Assist Device

A fully functional four degree of freedom (DOF) patient transfer assist device has been designed, fully fabricated and tested in a human operator study. The prototype is actuated by direct drive hydraulic actuation, using a separate pump-controlled electro-hydraulic actuation system for each degree of freedom. It is controlled from an operator's force sensing handle mounted near the patient. Several types of control were tested, and a new form of control using an impedance control framework with feedback of external force and/or proximity was developed. One of the biggest challenges in this design is developing methods to obtain suitable smooth control of motion and external interaction forces with desirable dynamic response using the intrinsically stiff, relatively low bandwidth, low cost direct drive hydraulic actuators, as well as non-ideal off the shelf mechanism components, and to manage the nonlinear and non-ideal effects of real, cost effective components.

This prototype also served as a testbed for the NSF Engineering Research Center for

Compact and Efficient Fluid Power (CCEFP), which was focused on improving efficiency, effectiveness and compactness of fluid power technology. Projects within the CCEFP range from fundamental research to component level research to fully functional prototype testbed systems. Fundamental research projects are designed to feed into new component designs, which can then be validated in new types of circuits and systems within the testbeds. The PTAD was a testbed for the CCEFP, so it was necessary to make the design modular, and to leave physical space for testing new components and circuits.

1.6 Research Objectives

Objective 1: Develop guidelines for design of an improved marketable patient transfer assist device

A needs assessment for an improved patient lift has been performed, based on input from a wide range of stakeholders in the patient lift industry. That information has been compiled into a set of guidelines for design of a new patient transfer assist device, and it has been used to guide the development of the first prototype.

Objective 2: Develop prototype to validate concept patient transfer assist device design, actuation system and control approach, using low cost direct drive hydraulic actuation

A new prototype patient transfer assist device with four actuated degrees of freedom has been fully designed, fabricated and tested. It utilizes low cost electro-hydraulic pump controlled actuators for all four degrees of freedom, and it is controlled from human operator input force.

Objective 3: Formulate control algorithms for a collaborative manipulation assist device

Control algorithms have been developed to obtain smooth motion control and manage undesirable external interaction forces, using low cost direct drive hydraulic actuation. The controllers also mitigate undesirable effects of the significant nonlinearities and non-ideal features of the system, complex kinematics, and intrinsic stiffness and slow dynamics, through feedback control.

- *Sub-objective 3a:* Formulate and implement a control strategy to manage any unintentional external interaction forces, using low cost direct drive hydraulic actuation

An impedance control framework has been developed to manage any unintentional external interaction forces, using feedback of measured (or potentially estimated) external interaction forces, measured proximity, and position. The control architecture includes a virtual force feedback term that is computed based on the proximity to an obstacle, as well as any external force; results show that it can significantly reduce external interaction forces using either or both forms of feedback. Preliminary tests were also performed on several other forms of interaction control.

- *Sub-objective 3b:* Develop operator interface that provides intuitive, simple, coordinated control from a force sensing handle, with dynamic response suitable for a human operator

  The implemented control architecture uses an operator input force on the machine as input for coordinated control. The operator pushes on a handle on the machine in the desired direction of patient motion; the controller generates a patient velocity approximately proportional to that force vector, so as the operator pushes harder, it moves faster.

Objective 4: Validate control of unintentional external interaction forces through controlled experiments with software inputs

A set of hardware experiments was performed to validate the performance of the controller in terms of tracking a desired motion trajectory and controlling external interaction forces.

Objective 5: Evaluate and analyze patient transfer collaborative manipulation assist device concept through human operator studies

A set of human operator studies was performed, to evaluate and analyze the patient transfer assist device machine design and control. The performance was compared with a benchmark study using a current market lift. Metrics included a time study and an operator survey.

Objective 6: Evaluate and analyze control strategy to control external interaction forces through human operator studies

The human operator study was also used to evaluate and analyze the impedance-based control framework used to control external interaction forces, with a human operator input.

Performance in unexpected collisions was compared with and without compensation for interaction. Metrics included motion tracking performance and interaction forces, and statistical analyses of the results were performed using ANOVAs.

1.6.1 Additional Research Contributions

Through the process of developing solutions for the primary research objectives, several additional new ideas and contributions were also cultivated.

1: Impedance control with force feedback was implemented using low cost direct drive hydraulic actuation, using low level pressure control. Low level force control was approximated, using low level pressure control of the hydraulic actuators.

2: Proximity measurements were added to a traditional impedance control framework as a virtual force term, which was computed based on momentum.

3: A successful hydraulic circuit based solution to pressure oscillations resulting from an overrunning load condition was developed and implemented.

1.7 Organization of the Dissertation

The dissertation is organized into seven chapters, as follows.

Chapter 1: Introduction

Chapter 2: Previous Research

Previous related research is discussed, including earlier work on patient transfer devices, a subset of the vast amount of literature on various forms of interaction control, and various forms of force-assist control with human operators.

Chapter 3: Needs Assessment and Functional Requirements

A needs assessment was performed to investigate specific needs of an improved patient transfer assist device. The assessment includes input from a wide range of stakeholders in the current market patient lift industry, including patients and caregivers. It also includes a benchmark operator study using a current market patient lift. The results are assembled into a set of guidelines and recommendations for a new patient transfer assist device design.

Chapter 4: Machine Design and Modeling

The design and fabrication of the prototype patient transfer assist device are described, including the design process and component selection. It also describes modeling of the hydraulic actuation system and mechanics.

Chapter 5: Operator Interface and Control Approach for Collaborative Manipulation

The development of control algorithms to obtain desirable control of motion from the operator input force are described, while managing external interaction forces. The primary control implementation and analysis is based on an impedance control framework with external force feedback, as well as feedback of a virtual force term based on a proximity measurement. Preliminary experiments were performed on several other forms of interaction control, as well.

Chapter 6: Human Operator Testing

A set of human operator experiments on the PTAD with 19 participants is described. The experiments were divided into two main parts. First, operators performed a set of typical patient transfer operations, with a time study, and results were compared with those from the earlier benchmark study with a current market patient lift. Second, a set of experiments was performed to evaluate the controller performance in unexpected, undesirable collisions with obstacles.

Chapter 7: Conclusions and Future Work

Conclusions from this research are discussed, as well as a set of suggested future work, both in terms of developing a marketable patient transfer assist device, and in terms of further developing the interaction control strategy.

CHAPTER II

PREVIOUS RESEARCH

2.1 Previous Research Overview

From the needs assessment, we learned that the patient transfer assist device (PTAD) will need to maneuver in tight spaces, such as bathrooms, garages, and small hospital rooms. The device not only has a patient and a caregiver in its workspace, but it is also likely to inadvertently run into furnishings, walls, and other obstacles. In both cases of possible environmental interactions, it would be beneficial for the machine to provide some management of external forces. Several forms of interaction control have been developed for such purposes, in order to provide compliance in interaction with obstacles and low output impedance (or force divided by velocity).

2.1.1 Patient Transfer

Caregiver injuries from patient transfers are a growing concern in the healthcare industry. According to a recent series on National Public Radio titled "Injured Nurses", nurses suffer over 35,000 back and other orthopedic injuries that require missed work each year (56). In (55) and (35), low back forces in caregivers are analyzed when performing various types of manual and machine assisted patient transfers. They show that even the best manual techniques result in low back loads at unsafe levels. The US population of adults aged 65 and over is estimated to grow from 40 million in 2010 to 55 million in 2020 (20). As a result of a high incidence of orthopedic injuries to caregivers resulting from manual transfer operations without a lift device, healthcare institutions are implementing “no lift” policies, which require caregivers to use lift devices for all patient transfers, rather than lifting patients manually. The Veterans Health Administration also issued a directive for safe patient handling (44), which describes a set of safer procedures for moving patients. Similarly, the Occupational Health and Safety Administration has created a guideline for nursing homes for prevention of musculoskeletal injuries, which includes patient transfers (22). Another set of ergonomics and injury prevention guidelines is defined in (39). A number of other research studies have investigated low back loads and other forms of injury risks in patient transfer operations, including (12) and (47). Our needs assessment indicates that current market lifts are insufficient for current market need and do not take advantage of newer developments in robotics technology. In this project, the aim is to develop an improved patient transfer assist device that is more intuitive, easy and safe to operate, powerful, and maneuverable than current market lifts.

While considerable research has investigated ergonomics of patient transfer operations, only a few published studies involve development of actual patient transfer assist devices. The original patent by Hoyer describes a lift device very similar to those on the market today, consisting of a U-shaped base with casters, a vertical post, and a lifting boom actuated by a hydraulic cylinder (23). In (30) and (53), a new type of patient lift called the Strong Arm is developed, which mounts to the base of a power wheelchair. It is also controlled from an operator input force and uses a sling. The device is powered by electric motors and travels with the patient on the power chair. However, difficulties with this design include significant lifting power limitations and tipping stability. In (38), design of a humanoid-style nursing assistant robot is developed, which is intended to perform patient lifting and moving tasks. The robot is led by the caregiver through tactile guidance. Patient comfort is an issue with this design. The National Institute for Standards and Technology also developed a new type of patient transfer device, which is also intended for rehabilitation by allowing the patient to walk with part of the body weight supported; however, while this device has a wide range of functionality, it is not a convenient transfer aid (6). The mechanical and actuation systems for the patient transfer assist device developed in this research are described in detail in (26).

2.1.2 Interaction Control

Many robots and heavy machines are designed to perform their duties without physical human interaction in the workspace, including most industrial robots, excavators, cranes and other heavy machinery. However, some machines are designed for collaborative manipulation, or physical human-robot interaction. Examples include some types of assembly robots, manufacturing robots that learn from teach-playback, and interactive humanoid robots (4). In this patient transfer assist device, it is desirable to manage interaction forces at two interaction ports, the machine-environment port and the operator-machine port.

The issue of improving safety in physical human-machine interaction has been receiving increasing attention as more of these types of machines are being developed, leading to new ISO standards, e.g. (1). Considerable research involving determination of safety criteria for robots in operation with human operators has been studied, but no consensus has been reached on suitable standards. Collision forces required to cause pain or injury vary widely depending on a number of factors, including where the impact occurs on the body, the time of impact, and whether or not the body is pinned or free. The ISO standards list a maximum threshold force of 150 N, but other researchers claim that this threshold is too high (21). In the comprehensive Robotics Handbook (49), a chapter is devoted to research on safety in physical human-robot interaction, and it includes a function to rate severity of injury based on impact duration. Haddadin has made a number of contributions in the area of safety in physical human-robot interaction, e.g. (21); he often uses one of the most common measures of human safety in robot interaction, the Head Injury Criterion (HIC), which is based on acceleration and time of impact. Park cites a lower maximum collision force target of 50 N in (41). All of the recognized metrics for safety in human robot interaction are noted in literature to have significant limitations, and there is no consensus on a maximum acceptable collision force.

As for interactions between the machine and the environment, the concept of robot control design for environmental interaction and motion, rather than pure motion control, has been an active area of research for over three decades, resulting in a substantial volume of publications. Applications of interaction include human interactions, walking, machining, excavation and teleoperation with haptic feedback. A considerable amount of research in the 1980's involved hybrid force/position control, or a switching control between position control in free space and force control in contact, e.g. (45). A seminal set of papers was

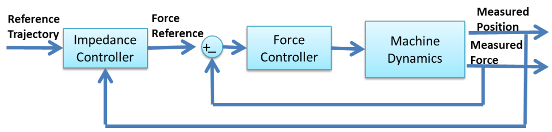


Figure 2: Basic "impedance" or "force-based impedance" control framework

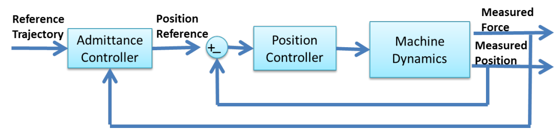


Figure 3: Basic "admittance" or "position-based impedance" control framework

published by Hogan in the late 1980's ((24),(25)), who developed and analyzed an *impedance control*; in this scheme, rather than controlling force or position, the controller aims to attain a desired output impedance transfer function $Z(s) = \frac{F(s)}{V(s)}$, or force divided by velocity. In this case of examining the impedance of a point of mechanical interaction between two bodies, the machine and the interacting body in the environment, $F(s)$ corresponds to an external interaction force, and $V(s)$ corresponds to the motion of the interaction point, or how it differs from the machine speed if there was no interaction force. If there is no external interaction force, then the controller drives the machine to the reference trajectory.

For this most common type of interaction control, termed impedance control, feedback of both position (or rate) and external force are used. There are two main forms. First is a force-based form, which uses an inner force control loop, shown in Fig. 2, and aims to control the interaction port impedance $Z(s) = \frac{F(s)}{V(s)}$. The second is a position-based form, also called *admittance control* which uses an inner position control loop and aims to control the interaction port admittance $Y(s) = \frac{V(s)}{F(s)}$, or the inverse of impedance, Fig. 3.

Many variations on these forms of impedance and admittance control have been published. In the original paper by Hogan (24), the impedance control is expanded to a multiple degree of freedom arm. It uses a basic proportional-derivative control to act as a virtual spring in the robot task space (also described in (32)). A very informative and thorough investigation on impedance control is described in a dissertation by Buerger (7). He investigates stability and performance of the simple impedance control and a different admittance control form called *natural admittance control*, further described in (40). He also describes an optimization method for determining optimal gains for an impedance controller. And he investigates different types of actuators, high- and low-stiffness, high- and low-inertia, hydraulic and electric actuators, and he discusses tradeoffs in the control design. He points out that for high-stiffness high-inertia actuators, position-based control tends to produce better low-output-impedance results. This form of force-based impedance control was implemented on the boom actuator of the patient transfer assist device, and some preliminary experiments with physical human interaction were performed, described in detail in (29). It was extended to include redundant sensing of obstacles through proximity measurements, with an added proximity based virtual force term, in (27). In the multiple-DOF formulation of simple impedance control, as described by Hogan and Buerger, the mapping between external forces and resulting actuator forces is based on a quasi-static assumption; in (36), dynamic compensation is added to improve performance.

A variety of other forms of interaction controllers have been developed and implemented, other than those based on Hogan's impedance control. In 1999, Chiaverini and Siciliano wrote a survey of interaction control schemes, implemented them on an industrial manipulator, and compared the performance in free space and contact (8). The authors note the importance of managing joint friction and claim that it is advantageous to have an inner position control loop. Gonzalez developed a variation on impedance control that aims to obtain improved performance in the presence of hard nonlinearities such as stick-slip friction and coarse discretization (19). Newman developed a different form of interaction controller called the *natural admittance* controller, based on theoretical performance limits on stable interaction controllers (40). This form is particularly suited for rejection of Coulomb friction, and it was later used by Buerger in (7). Impedance and admittance control are also used for control of haptic display devices, as in (18). Colgate proposed the concept of the Z-width as a measure of impedance related performance (9), and he proposed a set of criteria to analyze stability of a force feedback system in contact with any arbitrary passive environment in (11).

Several studies have applied interaction control to hydraulic or pneumatic systems. In (5), a model-based impedance control scheme for improved performance in hydraulic joints for the SARCOS hydraulic humanoid is developed. In (46), a position-based impedance control is developed for a mini-excavator and provide details on the controller development for a single hydraulic cylinder. In this and other papers, they investigate force estimates from pressure measurements. The same authors also implemented the impedance control on a bilateral teleoperation system for all four degrees of freedom of the excavator, with a matched-impedance scheme, in (51).

In (54), an impedance control algorithm was developed for a pneumatic cylinder which used an inner pressure control loop, using acceleration measurements rather than force as feedback. They note advantages of using actuators with high open loop compliance. In (52), an impedance control algorithm for a series elastic actuator is developed, which includes three loops, an outer impedance control loop, a middle torque control loop, and an inner rate velocity loop, with simulated variations in components, but no experiments were performed on hardware. In Love's dissertation (34), he developed an adaptive impedance control that varies the target impedance based on an estimate of the environment admittance. He discusses two different structures for impedance control, a target model reference control, and a computed torque method, which uses a model to compute the torque required to overcome the robot's natural dynamics, plus additional compensation to produce the desired impedance at the end-effector.

Impedance control is a form of indirect force control; many studies have also investigated direct force control (50); some of these results are relevant to the force-based impedance control. In (15), Seering and Eppinger point out that instabilities with increasing controller gains are often not captured in linear models in these systems; they also discuss a variety of non-ideal characteristics. The authors suggest force controllers which provide phase lead, such as derivative control, to raise closed loop bandwidth; however, signal noise can be problematic in such implementations. Alleyne also performed some investigations on direct force control in hydraulic systems. In (3), he starts with an adaptive Lyapunov-based control algorithm for force tracking of a valve-controlled hydraulic cylinder, then simplifies the controller in two stages, and shows that the simpler algorithm performs well at somewhat lower bandwidth. In (2), the authors investigate fundamental limitations in force tracking of servovalve controlled hydraulic actuators, resulting from the feedback of cylinder piston velocity to actuator pressure.

Another appropriate control approach for this collaborative manipulation approach is the passivity-based human power amplifier, which aims to make the machine act as a passive mechanical tool, amplifying the human input force. This approach inherently includes management of interaction forces between the human and the machine, as well as those between the machine and the environment. Recent work in this area has been spearheaded by Li. In (33), he applies the controller to a device consisting of a hydraulically actuated mechanical oar with a force-sensing handle, intended to amplify the human force, and he demonstrates stable controlled amplification of the human applied force, as well as tracking of an associated computed reference velocity. In (13) and (14), this approach is expanded to a bilateral teleoperation system with hydraulic and pneumatic hardware. This power amplifier approach with a force sensing handle was applied to an earlier pre-prototype patient transfer assist device, using a hydraulic cylinder for lifting the patient payload in (28). The approach is promising in that it provides an intuitive way to amplify the human force, it provides some haptic feedback to the operator, and it allows for good control of velocity in free space and force in contact, with a smooth transition between the two; however, the substantially varying payload can be problematic.

Another relevant aspect of the previous literature involves the concept of collaborative manipulation, control methods that allow a human operator to control the machine to assist in manipulating the same workpiece or payload. One well known design is that of the Cobot, which provides an operator with assistance by imposing virtual boundaries to constrain and guide motion; cobots are intrinsically passive devices and do not amplify human applied force ((10), (43)). A number of studies were published in the late 1980's and early 1990's on using robot assistive devices to aid in maneuvering and supporting weight of heavy objects in manual assembly tasks. In (31), a strategy is developed where the robot supports the weight of an object and moves it in the direction of the intentional force applied by the operator, with the operator pushing on the workpiece itself. Velocity and acceleration control algorithms based on an estimate of the operator's intentional force are developed and compared. In the patient transfer assist device, the payload is a human rather than a simple mass, who is able to move and exert forces on the machine, so the operator's intentional applied force must be measured rather than estimated. In (17), another control algorithm for assisting the operator in handling heavy objects is developed. The manipulator has two force sensors near the end-effector, one in a handle for sensing the operator input, and one for measuring environment interaction forces. This application is very similar to the patient transfer assist device. In this control development, they obtain the desired force augmentation and position tracking using two impedance controllers, one for managing human-machine interaction, and one for managing machine-environment interaction. In (48) development of a PowerMate robot assistant for handling and assembly tasks is discussed. Several operation modes and levels of interaction are discussed, as well as methods for safety, such as light curtains, laser scanners, and an enable switch.

For the patient transfer assist device, a collaborative manipulation architecture which utilizes measured operator force is needed. Other challenges include implementing interaction control with the slow dynamics and highly nonlinear friction of the direct drive hydraulic system, a complex mechanism, and a widely varying payload.

CHAPTER III

NEEDS ASSESSMENT AND FUNCTIONAL REQUIREMENTS

3.1 Needs Assessment Overview

At the start of this project, a needs assessment was performed to determine what are the most important features and requirements for a new marketable patient transfer assist device. The assessment included a review of current market transfer aids and lifts, a set of interviews with a range of stakeholders, a focus group with spinal cord injury patients and their home caregivers, and a benchmark operator study using current market patient lifts.

The target patient population for this project includes those who require assistance for transfers, particularly bariatric patients. It is most applicable to patients who are unable to perform independent transfers. The population includes those with spinal cord injuries, neurological disorders, the elderly, and patients who are weakened by other issues. In general, clinicians advise patients who are able to transfer independently as much as they can, to exercise and gain independence, but many patients do not have that ability.

3.2 Current Devices

A wide range of patient lift and transfer devices have been developed, ranging from simple boards to powerful multiple degree of freedom humanoid robots. In this review, they are divided into devices that are widely used, those that are commercially available but rarely used, and those that are in the experimental/development phase. Simple mechanical transfer aids, such as slider sheets, draw sheets, and slider boards, can be used to reduce friction when sliding transfers are possible. The term “patient lift” generally refers to simple actuated devices that lift the weight of the patient.

3.2.1 Current Market Patient Lifts

Several types of patient lifts are currently available on the market; these are actuated devices that lift the weight of the patient, most often with the patient suspended from a sling. The most commmonly used patient lift style is based very closely on the original design by Hoyer (23). An example is shown in Fig. 4.

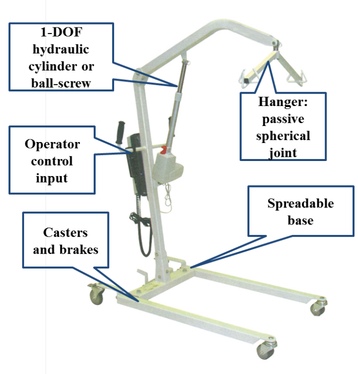


Figure 4: Most commonly used current market patient lift [www.phc-online.com]

Bariatric versions of these lifts are also available; they are mechanically similar, but they are typically capable of lifting up to 1000 lbs. The patient lifts are typically mounted on four wheels, either two or four casters, with brakes. The base is adjustable from a U-shape (sides parallel) to a V-shape (wider), using a mechanism with a handle mounted at the back. Only one degree of freedom is powered, the lifting arm shoulder joint. Most commonly, the joint is powered hydraulically by a hand pump, but in some machines it is powered by an electric motor. Electrically actuated units are battery powered and driven by up/down pushbuttons.

The patient rests in a sling that is attached to a hanger bar at the end of the arm; this is the industry standard for several types of lifts. The hanger bar swivels with a small range of motion in three degrees of freedom, as a spherical joint. Slings have three or more straps to attach to hooks on the hanger bar. Strap length is adjustable using various attachment loops, but it is not adjustable on-the-fly.

A few other types of transfer devices are also used often, comprising considerable market share. One type is often called a Sit-to-Stand or Stand-Assist lift (Fig. 5), among other brand names. This style of lift supports the patient in moving from a sitting to standing position, and it transports the patient in a standing position, rolling on casters. For a transfer, first, a seated patient straps a small sling behind the back and places the feet on a wheeled platform. The lift raises the patient to a standing position on the platform, with the knees against a brace and the back supported. The lifting mechanism may be powered by the caregiver, utilizing the mechanical advantage, or it may be powered by an electric motor. At the destination, the patient is returned to a seated position. This type of lift requires some lower body strength and good balance from the patient; many patients lack the strength and stability necessary to use a stand assist lift.

Figure 5: Stand assist lift [www.phc-online.com]

A second common form of patient lift is a ceiling track mounted lift (Fig. 6). These are commonly used in rehabilitation centers, and in some homes, and in other places where transfers occur frequently. However, transfers are limited to locations where the ceiling track is installed, and installation costs are high. Ceiling track mount lifts use motorized pulleys, similar to some overhead gantry cranes. A hanger bar is attached at the end of the cable, and a sling is attached to the hanger bar. The sling and hanger bar are very similar to the Hoyer-style lift. The caregiver operates the overhead lift using pushbuttons (up/down and forward/back along the track). Some freestanding portable overhead lifts are available (for example, http://www.norco-inc.com/content/patient-lifts-ceiling-tracks-and-freestanding), but they are not used as often because of space and setup requirements.

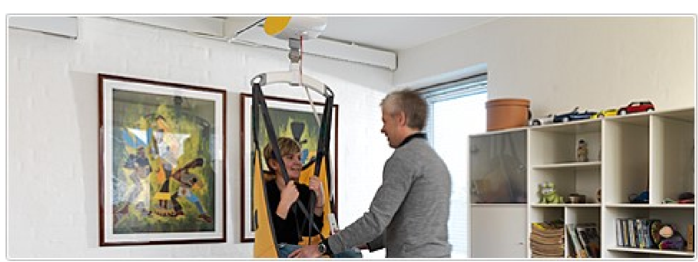


Figure 6: Ceiling track mount lift [www.guldmann.com]

The Maxi Move floor lift by Arjo Huntleigh is one of the most advanced current market patient lifts. It is electrically powered, with several feature options. Options include a powered seat rotation and weight capacities of ∼300∼700 lbs. It has a few other design features that the stakeholders requested, such as a horizontal beam (to enable car transfers) and a large vertical range of motion. The current retail price for the Arjo lifts is around ∼ \$4,000 ∼ \$7,000, depending on features.

Figure 7: Current market Arjo Huntleigh Maxi Move Floor Lift [www.arjohuntleigh.com]

3.2.2 Slings

Most types of patient lifts require some form of sling to hold the patient during transfers. Many different types of slings are available. For transfers to or from a seated position, a U-style sling is used, like the one shown in Fig. 8. Getting a patient into a sling can be one of the most challenging aspects of the process for the caregiver, though experienced caregivers gain efficiency. Because of skin related problems, it is not recommended to leave a sling under a patient; the sling must be applied and removed for each transfer. To apply a sling for a patient in a seated position, first, the wider part of the U-shaped sling is placed behind the patient's back. Then, the smaller parts, or the wings, are crossed under the patient's legs so that the patient cannot slide out of the sling. If a patient is moving between two flat surfaces in a supine posture, a different type of sling that is shaped like a flat sheet can be used; this also requires an appropriate larger hanger bar. If a patient is in a supine position, the sling is applied by first rolling the patient to one side, placing the sling under that side, then rolling the patient the opposite direction onto the sling, and smoothing the sling under the patient; this process is termed "log rolling". A different type of small sling is used with the Sit-to-Stand lifts (5); this sling is used to hold the patient's

Figure 8: Hoyer style patient lift [www.rehabmart.com]

back close to the lift, as the patient is lifted and held in a standing position.

In response to the difficulty of getting a sling under a patient in a supine position, several devices similar to the one shown in Fig. 9 have been developed, using a set of opposing belts to roll under a patient, so that the caregiver does not have to "log roll" the patient. In the stakeholder interviews, none of the participants mentioned using any such powered devices to go under patients.

Figure 9: Powered transfer board [http://www.maxonmotor.com/]

3.2.3 Manual Transfer Aids and Friction-Reducing Aids

A number of other types of simple mechanical aids are available and often used. Draw sheets and slider sheets are used to slide a patient in a supine position between two flat surfaces, such as a bed, gurney, or operating table. They are made of low friction materials, typically plastics, and they often have handles for the caregivers. Similarly, higher functioning patients with good upper body strength and balance can use transfer or slider boards (Fig. 10) and swivel boards to aid in transferring or rotating. With a slider board, the patient pulls the wheelchair beside another surface, such as a car seat, chair, or couch, places the two ends of the board on the two surfaces, and uses his hands to scoot across the board. However, users report that it is common for transfer boards to slip, often causing patients to fall to the floor. Physical therapists and clinicians usually advise patients to transfer independently as much as possible, in order to exercise and maintain strength.

Figure 10: Bariatric slider board [www.allegromedical.com]

3.2.4 Experimental Patient Lifts

Many researchers, in both industry and academia, have tackled the problem of patient lift design. This section discusses a few types of experimental patient transfer devices. One well documented experimental patient lift device is the Home Lift Position and Rehabilitation Chair (HLPR), developed by NIST (6). This device is intended to serve multiple purposes, as a powered wheelchair, transfer device, and rehabilitation aid. Transfers are similar to other patient lifts, using a sling as a seat; it is also intended to function as a powered wheelchair by having a powered base. Additionally, it provides a way for a patient to walk with part of the body weight supported by the machine. The machine is controlled by the patient from a joystick, and it is intended to provide improved independence by allowing for independent machine-assisted transfers. A number of users and clinicians agreed that there are some patients for whom it would be beneficial to have the ability to perform machine-assisted independent transfers. However, many patients would be unable to use such a device, such as those with higher level spinal cord injuries and various neurological disorders. The patient population who could benefit is fairly small, since it would be only those wheelchair users who are unable to perform independent transfers using only their upper body, or with simple mechanical transfer aids, but who are sufficiently high functioning to use such a device safely without assistance. Experts claim that the HLPR chair is capable of performing many functions, but it does not perform any function as well as a more specialized device.

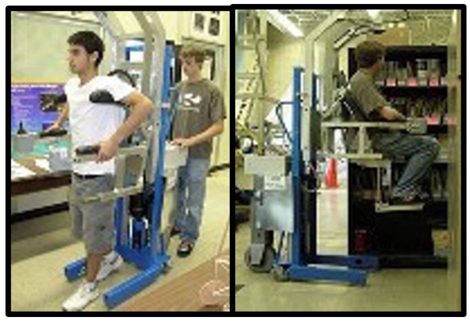


Figure 11: NIST Home Lift Position and Rehabilitation (HLPR) chair

A number of patents have been filed for new patient transfer device designs. Fig. 12 ((16)) illustrates the concept of a rotation of the sling, to help in moving a patient between a supine position and a sitting position. This sling rotation concept has been proposed to users and clinicians as a potential feature for this new patient transfer assist device design. Some caregivers thought a powered sling rotation would substantially aid the ease of transfer operations. Others expressed concern that patients who do not have good trunk control could pitch forward and fall out of the sling if rotated too far forward.

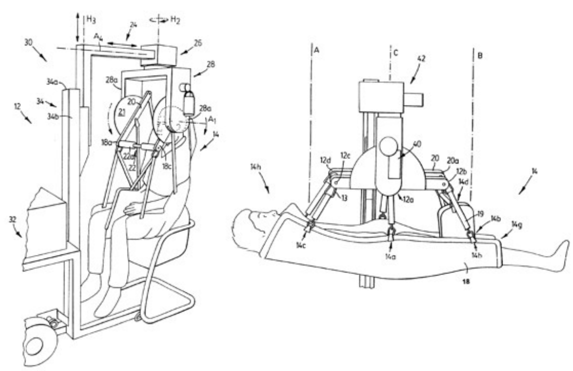


Figure 12: Patent for patient lift with rotating sling angle [(16)]

Figure 13 shows a concept wheelchair for transporting patients. It is non-powered, and it uses the friction reducing concept of a slider board to aid in transfers. It is only for transferring patients between locations in a seated position. The seat slides between the patient and the patient's seat, with the patient straddling the device, riding facing the caregiver. The usefulness of this concept device is limited to only certain transfers, and to patients with good trunk control and balance.

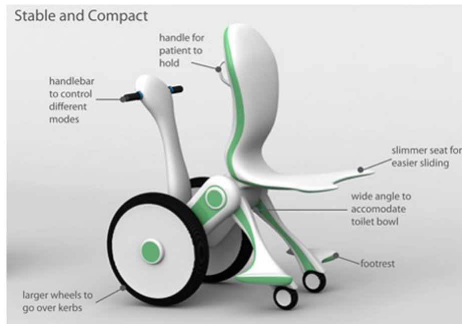


Figure 13: Concept wheelchair for transporting; patient sits facing handle bar, reverse from traditional wheelchairs [www.medgadget.com]

Figure 14 shows a device developed by the NSF Quality of Life Technology Engineering Research Center. This device is intended for higher functioning patients who use power wheelchairs. It is electrically actuated, with four degrees of freedom and sufficient force capability to lift an average sized patient, up to 250 lbs, and it mounts to a power wheelchair. The patient rests in a sling, similar to other transfer devices. It uses a force sensing handle for the operator input, which provides coordinated control. A switch is used to manage the kinematic redundancy. There are two key unique aspects of this device. The first is that it is controlled by the patient from a force sensing handle mounted at the end of the lift device. The second is that it mounts to a power wheelchair. The base is mounted on a rack that allows the lift to rotate to the back of the chair when not in use. While this design has significant advantages in terms of compactness, redundant degrees of freedom, and portability, the limited weight capacity and tipping stability are significant problems, analyzed in (53).

Figure 15 shows another concept transfer device developed by Toyota. This concept is similar to the concept wheelchair shown in Fig. 13, but the device is powered.

On the more conceptual end of the spectrum is a set of humanoid style robots (Fig. 16) that some researchers have tried using for patient transfer purposes. Humanoids have a number of problems in this application. They do not provide comfortable patient interfaces, and they generally have issues with tipping stability. It is difficult to control and power so

Figure 14: UPitt/QoLT Strong Arm power chair mounted patient transfer assist device [(30)]

Figure 15: Toyota patient transfer device [http://www.amsvans.com/blog/tag/patient-transfer-assist/]

many degrees of freedom, particularly in an unstructured environment, performing variable tasks.

3.3 Input from Stakeholders and Users in the Current Market Patient Lift Industry

In order to obtain information from users, three different forms of sessions were hosted for stakeholders to provide input about what is needed from a new patient transfer assist device design, and on the use of current Hoyer-style patient lifts. First, a small set of interviews was held with a range of stakeholders in the current patient lift industry. Then a focus group was hosted, consisting of spinal cord injury patients, as well as their home caregivers and physical therapists. Finally, a benchmark operator experiment was performed, using a current market Hoyer-style patient lift, specifically an Invacare model 9805 lift, to transfer a 250 lb. mannequin between various locations. This information was collected according to Georgia Tech IRB protocol H12421.

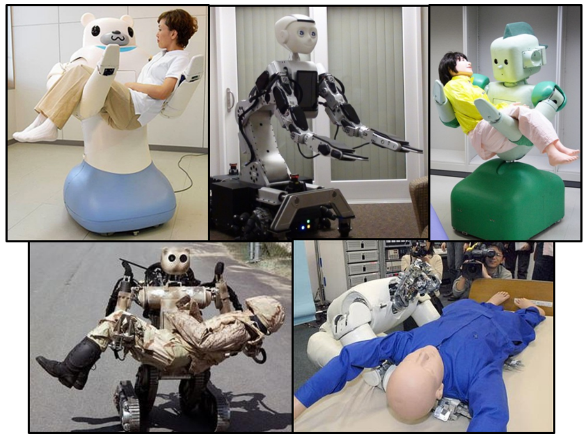


Figure 16: Humanoid style patient transfer robots

3.3.1 Interviews

Six interviews were performed, with one or two participants in each interview. The participants were as follows: (1) the wife and son of a bariatric paraplegic patient, (2) a nurse in Emory Hospital, (3) two clinicians in the Shepherd Center for Spinal Cord Injury and Rehabilitation, (4) a clinician and a manager with Wesley Woods Assisted Living Center, (5) two sales personnel with a local patient lift distributor, and (6) an experienced engineer in the current patient lift industry. Interview discussion topics were focused on how patient lifts are used, what features in a new device would be beneficial, and what are the main issues and limitations with current lifts. The interviews were performed early in the project, and they were informal but semi-structured, including a scripted set of questions. The questions were different for different types of stakeholders. Interview participants were recruited via email, and no compensation was provided for participation.

From the interviews, different perspectives were gained from patient lift users operating in different environments. For instance, the family of one bariatric patient with a low level spinal cord injury was interviewed. For patients with these types of injuries, it can be possible to transfer using slider boards or other simple mechanical aids, but they need assistance in certain situations or whenever the slider board slips and they fall onto the floor. In those cases, there are a number of places where current patient lifts cannot access a patient, for instance, inside a bathroom or in a tight garage space. In helping a bariatric patient maneuver inside a home environment, it can be very difficult to put a sling on the patient, especially after a fall in a difficult position, and the operation often requires more than one caregiver.

In a hospital or nursing home setting, one of the major limitations on lift usage is availability and ease of use. Nurses report that oftentimes the hospital will have only one patient lift per floor. To use a lift, the nurse has to walk down the hall to find the lift, make sure the batteries are charged if it is electrically powered, choose an appropriate sling, return to the patient's room, perform the transfer operation, and return the lift and its accessories. They report that oftentimes the lift is in use by someone else, or the batteries are weak, or the slings are missing. Hospital patients' needs are often urgent, and the nurses stay very busy. Sometimes, with smaller patients, nurses feel that they cannot spare the time required to use a lift, and they choose to transfer the patient unassisted. Also, a few elderly patients do not trust the machines, and they ask to be transferred without machine assistance. Also, particularly in nursing homes and assisted living centers, patient dignity is a significant concern; as a result, the time that patients spend in patient lifts is minimized, and transfers usually occur inside patient rooms. However, in home settings, it is not uncommon for a caregiver to roll a patient between rooms in a patient lift; sometimes transporting the patient in the lift is easier than transferring from the starting location to a wheelchair, then transferring again out of the wheelchair. It is our hope that the next generation PTAD will be faster and easier to use, thereby motivating clinicians to use the assist device.

3.3.2 Focus Group

The focus group consisted of people who use patient lifts on a daily basis. The group included three spinal cord injury patients, their home caregivers, and their physical therapists, plus one additional patient, for a total of 10 participants. During the meeting, the discussion started with a brief overview presentation on the project and the information sought from the focus group. The main part of the meeting was a guided group discussion on general input on how the participants use their lifts, what are the main limitations and issues with current lifts and what works well. Also, participants were asked for their ideas on features in a new patient transfer assist device. A few feature ideas were proposed to the group, and their input was requested. In response to questions about difficulties with current patient lifts and the transfer process, participants had a number of complaints. Participants were compensated with lunch.

Overall, the majority of the information from the focus group was gained through a guided group discussion, based on a set of discussion topics and questions. The researchers took notes on the discussion, and an audio recording was made of the entire session, which was later reviewed again by the research team. Most of the participants' comments were agreed upon by other members of the group; no significant differences in opinions between group members were recorded.

Participants for the focus group were recruited through physical therapists at the Shepherd Spinal Cord & Brain Injury Rehabilitation & Research Center. The therapists' roles include not only physical therapy, but also teaching the patients and their home caregivers about best practices for home care, about available assist devices, and how to properly use them. The focus group session was held at the Shepherd Center, and it included physical therapists, spinal cord injury patients, and their home caregivers. The focus group was held in one session, for one hour. In the beginning, a presentation was given to the group by the researchers about the proposed PTAD project and goals. A structured group discussion session followed the presentation, based on a set of open ended questions and proposed device features. Participants' responses were recorded in the researchers' notes and in audio recordings, and they were reviewed later by the research team. It is important to note that the input from the focus group is limited to spinal cord injury patients; they are only a subset of people who use lifts on a daily basis. Perspectives from different user groups were included through the individual interviews with clinicians in different types of facilities and other stakeholders.

3.3.2.1 Moving around obstacles

When asked, "If you needed to transfer and a lift was available, what is the most likely reason you would choose not to use one?", participants cited insufficient space available to use a lift. Similarly, when an engineer in the patient lift industry was asked his opinion on what are the biggest difficulties in lift design, he also said, "Space is the biggest issue" in patient lift design. For instance, car transfers are particularly difficult. In order to transfer a patient from a wheelchair into a car seat, you have to fit the wheelchair, lift, patient, and caregiver in a small space by an open car door. Furthermore, most patient lifts have an arched upper beam, while one model (Sunrise CLA-M) has a straight beam; the arched beams hit the top of the car and do not allow enough space to lift the patient above the car seat. Participants estimated the time required to load a patient, wheelchair and lift in a vehicle at around 25 minutes for an experienced caregiver; *the transfer operations in and out of a car can add as much as an hour round trip.* Wheelchair accessible vans are better solutions for spinal cord injury patients, but they are cost prohibitive for many.

Many other obstacles obstruct the use of patient lifts. The feet of the device encounter chair legs, bed feet, walls, and other furnishings. The caregiver's attention is focused on the patient, and it is difficult to keep track of all potential obstacles for all parts of the machine. In the benchmark operator experiments with the current market lift, caregivers were rarely able to navigate around the bed without the base making unwanted contact. Bathrooms rarely have enough space to perform transfers; usually, patients transfer to toileting chairs outside the bathroom.

There is a class of obstacles, including low couches, large low chairs, recliners, hotel beds (with boxed in frames to block items from being lost under the bed), and bathtubs, where the feet of a patient lift cannot move under the obstacle. In order to move a patient to any of these locations, the patient would have to move outside the footprint of the patient lift. Preventing tipping while performing those transfers with a patient lift would require either an alternate form of bracing against a wall other rigid surface, or a counterweight, which would have to be very heavy for some situations. Additionally, with the high mental workload required for caregivers in transfer operations, the safety of the patient is a concern, particularly in case of any inadvertent commands to the machine.

3.3.2.2 Dynamics & oscillation

Participants noted a few concerns related to machine dynamics. One is patient swinging\oscillation, which occurs primarily when the base rolls over something, such as a cord for a hospital bed. Caregivers report that in lifting and lowering, the current machines move sufficiently fast; these aspects are a small portion of the time required for a transfer operation. Patients complained of occasional instances of the machine moving down too fast, in cases with inexperienced caregivers; this indicates that the speed of motion should be limited.

3.3.2.3 Operator interface

Caregivers point out that patient transfers, "have a lot of steps and require a lot of planning." They also say that it requires a lot of multitasking, particularly when trying to fine tune the patient position in a seat or bed, while simultaneously maneuvering the lift device. When asked how they would like to control the device, caregivers suggested controlling some degrees of freedom with their feet (and noted that with current devices, they often move the base with their feet while guiding the patient with their hands), or getting the device started, then having it automatically keep going until they stopped it. These two suggestions have some safety issues, but they do point out an important point, that the caregiver is overtasked. If we can make the device easy to maneuver with one hand and minimal forces, and get better cooperation from the machine as a team member, then the transfers can be performed more efficiently. Particularly in a home environment, usually only one caregiver is available. It is necessary that a new PTAD is easily operable by a single caregiver, with one hand, in a simple and intuitive manner. It would be beneficial for the machine to aid the caregiver in maneuvering through tight workspaces by alerting the operator of any obstacles around the machine and minimize any potential collision or interaction forces with them.

3.3.2.4 Special patient groups

Participants pointed out that many people who require a patient lift also have other complicating factors; they may be on a ventilator, have spasticity, have had a recent surgery or injury, or have very brittle bones if they are not load bearing. In the cases of patients with spinal cord injuries and neurological disorders, spasticity is very common; according to clinicians, it is difficult to hold a patient still during an episode of spasticity, while also holding the patient lift. Many patients also have issues with blood pressure, and any fast motions can cause dizziness or fainting.

3.3.2.5 Slings

Patient slings are the industry standard in patient interfaces, and they have evolved over the years to maximize their ease of use and effectiveness. Putting a patient in a sling can require substantial forces from a caregiver, particularly in a supine position where the caregiver has to roll the patient's entire body. And if the patient is in an inconvenient position, such as after a fall, it can be even more difficult. However, primary caregivers become efficient with slings after some time. Some alternative sling concepts were proposed, but clinicians expressed concern with skin problems in immobile patients. For these reasons, it is never recommended to leave a sling under a patient between transfers. They also note that there is a lot of variation in sling position, which can cause unsafe conditions if placed improperly. If a patient without good trunk control is not properly aligned and pushed to the back of a chair, they can slide out of the seat.

3.3.2.6 Lift mechanics

Participants had several ideas for improvements to the lift mechanism design. Many current market lifts do not reach floor level; patients want to be able to sit on the floor to play with their children, or be lifted off the floor if they fall. Also, they would like to have a lift that folds into a small, lightweight package that fits in a car trunk. In terms of size, this may be possible with some version of a lift design, but there is a design tradeoff; the additional actuated degrees of freedom and capability to handle bariatric patients add

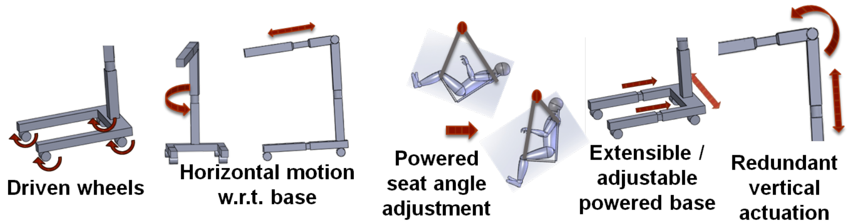


Figure 17: Example Feature Ideas Provided to Focus Group

significant weight, which make the machine too heavy for a single caregiver to safely lift into a car. Participants also suggested actuation to make the U-shaped base wider\narrower and longer\shorter.

3.3.2.7 Design ideas and tradeoffs

After obtaining the participants' ideas for additional design features and discussing issues with current market patient lifts, several of the researchers' ideas were presented to the group, and their input was requested. Figure 17 illustrates some of the design features that were proposed to focus group participants. The ideas were presented in the form of images, as shown in Fig. 17. They were provided not only to obtain feedback on these specific device features, but to encourage participants to think outside the box and provide more of their own ideas.

- *Actuated rotation of hanger bar - sitting posture to supine posture:* An additional actuated degree of freedom was proposed to allow for rotating patients on-the-fly, between a sitting posture and a supine posture. Some caregivers thought it would be very helpful, while others expressed concern about the possibility of patients without good trunk control pitching forward out of the sling.
- *Dockable mobile design:* The general concept of an added mechanism to allow the lift to dock to another sturdy object, such as a wall or heavy power chair to allow for patients to transfer outside the base of the lift without tipping. For example, if the lift could dock to a wall inside a bathroom, then it could transfer a patient into a tub. Participants only expressed concern that it would be to complicated and expensive to implement a docking feature.

- *Horizontal motion with respect to the base:* Additional degrees of freedom were proposed to allow the patient to move horizontally small amount, left/right and fore/aft, within limits to prevent tipping. Participants agreed that such motion would be helpful in cases where the base encounters an obstacle near the patient, such as chair legs.
- *Actuated wheels:* Two differential drive wheels were proposed, in addition to the casters. They aid the operator in propelling and turning the machine and provide for side-to-side motion of the patient. Participants agreed that powered wheels would be very helpful.
- *Extensible/adjustable powered base:* Actuation to adjust the spread and length of the feet was suggested. Participants thought these additional two degrees of freedom could be helpful in moving around chairs, wheelchairs, and other obstacles, as long as they are easy to access and operate.
- *Sling alternatives:* Several alternatives to the current slings were discussed. However, because of complex issues related to skin problems, supporting weak bone structures, and other physiological considerations, the sling design was determined to be outside the scope of this project.

Several design tradeoffs were also discussed, including tradeoffs between speed of motion and patient swing/oscillation, and between speed of motion and mechanical stability. In general, caregivers appreciate that the current devices are quite stable, and they did not request a faster moving machine. In the later design review meeting, specific required speeds were specified for the actuators. A more complicated tradeoff was that between maneuverability in tight spaces and mechanical stability, recognizing that adding any additional degrees of freedom that allow the patient to move with respect to the base will reduce the tipping stability.

3.4 Benchmark Operator Study

As a final step in the needs assessment, a benchmark operator study was performed using a current market patient lift, with human volunteers serving as caregivers and a

250 lb mannequin representing the patient, under Georgia Tech IRB protocol H13288. The benchmark study included twelve participants and is intended to serve three purposes. First, it provides additional information to support the new device design. Second, it provides some benchmark data for a baseline comparison for the new device experiments. Third, it provided an opportunity to perform a small pilot operator study on patient transfers, to practice and refine the experimental procedures for the final testing. The participants were primarily recruited via flyers and social media posts on Georgia Tech campus and websites. None of the participants were experienced patient lift users nor had experience using patient lifts in clinical settings, but a few participants had used patient lifts a few times prior to the experiment to transfer elderly family members.

Participants performed all tests with the current market lift (Invacare 9805) in one session, lasting approximately 45 minutes. They were compensated $20 upon completion of the experiments. After signing consent forms, they were given oral instructions on how to operate the lift, and they were asked to perform a small set of practice transfers to learn how to efficiently operate the device. Then they performed a specified set of transfers, and time study data was recorded, as well as video.

The participants performed several different mannequin transfers, using a current market patient lift similar to the one shown in Figure 4. First, they moved the lift into place and attached the sling to the lift. Then they lifted the patient from the wheelchair, drove around to the other side of the bed and over a rug, and transferred the patient onto a bed. Then they lifted the patient from the bed and transferred to a chair (Fig. 19). Walls were placed around the test area to simulate the limited space in a home, such as a bedroom. An area rug was placed in the route around the bed, to test performance in rolling and steering over carpet. Figure 18 shows an image from the benchmark operator testing.

The experiment data included three main components. A time study was performed, based on a task analysis developed by our human factors reasearch collaborator Brittney Jimerson with North Carolina A&T University. After the experiment, the participants filled out a survey, providing ratings on the device performance. The survey was compiled along with our human factors research collaborator. Also, most tests were recorded on video.

Figure 18: Photo from benchmark operator experiment

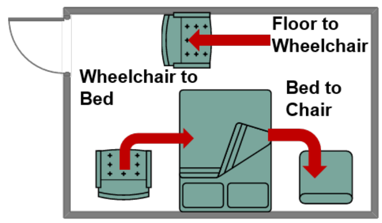


Figure 19: Transfers performed in benchmark operator experiments

3.4.1 Operator Performance

Figure 20 shows the results from the time study for two patient transfers, from the wheelchair to the bed (going around the bed to the opposite side), then from the bed to a chair. Because this project is not focused on sling design, the participants were not required to put the patient in the sling. The experiment started with the mannequin sitting on the sling in the wheelchair, and it ended with the mannequin sitting on the sling in a chair.

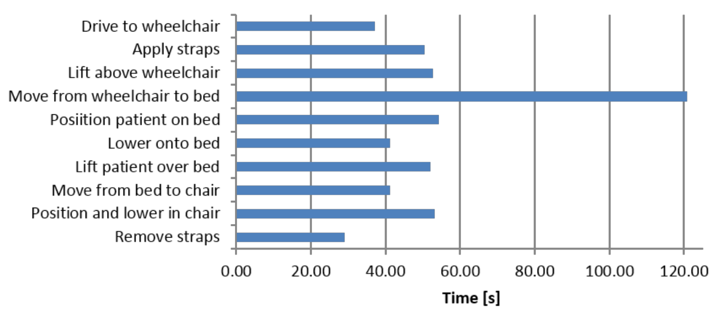


Figure 20: Time study results

While lifting and lowering the patient are key aspects of the transfer operation, these results reiterate users' comments that they are small components of the overall time requirement. It took an average of about two minutes for the caregiver to drive the lift around the bed with the patient attached; it was difficult for operators to move the lift around the bed, walls and other obstacles in the environment. The operators often ran into obstacles, such as walls or bed legs, then had to back up and steer around them. The simulated environment may have been a bit more constrained than a typical bedroom or other common space for transfers, more like a typical bathroom or garage. The subtasks called "drive to wheelchair" and "move from bed to chair" include the additional step of spreading or narrowing the base of the lift. The combined steps of lowering and positioning the mannequin on the bed also take over a minute and a half. Users note that it is challenging for the caregiver to manually fine tune the position of the patient and place limbs appropriately, while simultaneously controlling the device. By making it easier for the caregiver to precisely guide the motion of the device, providing various forms of obstacle avoidance, the time required for the transfer operations is expected to improve.

3.4.2 Operator Survey

The operator survey was divided into sections, corresponding to various aspects of the high level transfer task. The survey was designed to be used with both the current market lift and the newly developed patient transfer assist device, so that results can be compared. Some questions, particularly those related to the control, are more appropriate for the new device. Also, since the experiment was set up to test a constrained space, the survey results are likely somewhat skewed toward emphasizing that issue. Figure 21 shows results for the overall performance section of the survey. More details on survey results are given in Chapter 6 on Human Operator Testing.

Seven of the listed performance characteristics had median ratings of "poor" or "very poor": overall device maneuverability, ability to maneuver in tight spaces, ease of changing directions, overall controllability of the machine, control accuracy of the base, speed of response of the base, and smoothness of machine motion of the base. Note that most of these are related to motion control and can be improved using advanced feedback control with multiple DOFs. However, note that reducing the size of the machine footprint is not the only way to make it easier to maneuver the machine through a cluttered environment;

Operator Survey Data [Very Poor: 1, Excellent: 6]

Performance Characteristic		Median Rating
Controller		
a	Overall controllability of the machine	3
b	Accuracy – of the lifting arm	4
c	Speed of response – of the lifting arm	4
d	Smoothness of machine motion – of the lifting arm	4
e	Accuracy – of the base	2
f	Speed of response – of the base	2
g	Smoothness of machine motion – of the base	2
h	Minimization of patient swing/oscillation	3
i	Stability of the machine (in terms of tipping)	5
Prep/Completion		
a	Ease of use of sling loading/attachment	4
b	Ease of positioning the device for lifting	3
Lifting/Lowering		
a	Ease of positioning the device for lifting	3.5
b	Ease of fine tuning position of the patient	3.5
c	Ease of orienting the patient, or getting the patient into an appropriate posture	4

Performance Characteristic		Median Rating
Transfer		
a	Force/torque required to maneuver the device	3
b	Ease of obstacle avoidance	2
c	Ability to transfer quickly	3
d	Management of patient oscillation	3
e	Ease of positioning the device	3
f	Ease of changing directions	1
Overall		
a	Ability to perform the transfer operations alone	4
b	Ability to maneuver in tight spaces / ease of obstacle avoidance	2
c	Location/accessibility of device controls	4
d	Ability to transfer quickly	3
e	Overall device maneuverability	2.5
f	Rate your own overall performance	4
g	Your comfort level on your first experiment	3
h	Your comfort level on your last experiment	4.5

Figure 21: Results from benchmark operator survey with current market lift

there is a basic design tradeoff between footprint size and tipping stability. However, if more actuated degrees of freedom are used, allowing some small variation in the patient position relative to the base (and potentially allowing for some variation in the base size/shape), then it can be easier to maneuver the patient around some obstacles. The only machine performance characteristic with a median rating of "good" was the tipping stability of the machine. The ISO standard for these devices requires testing of stability on various inclined surfaces; these experiments were performed on a horizontal floor, so caregivers felt that the device was stable.

3.5 Functional Requirements

Based on the needs assessment, a small set of high level functional requirements was compiled. Design specifications were created based on the functional requirements for the device, which are described in the next chapter. At a high level, a marketable PTAD must be able to perform all typical transfers in a home or clinical environment, work within space constraints of a typical home or clinical environment, and have adequate lift capacity (at least 500 lb) in any configuration with a compact device. It also requires a simple, intuitive control strategy with smooth, stable motion, and it needs to enable to a single caregiver to simultaneously maneuver both the device and the patient.

Patient Transfer Device Requirements

Must-Have Machine Requirements

- Capability to perform most typical transfers within a home or institution (e.g. between a wheelchair, floor, toilet, bed, chair or car seat)
- Provide lift capacity equivalent to current market electrically actuated lifts (500 lb.) in any useable kinematic configuration
- Run all day on a single battery charge, typically ∼8∼12 transfers
- Have sufficient range of motion for performing typical patient transfers
  - Fit comfortably through 32 in. door (maximum base width ∼29 in.)
  - Lift patient above bed in a semisupine position (beam height ∼72 in.)
  - Comfortably reach floor height (beam height ∼22 in.)
  - Reach middle of a double bed (beam length ∼33 in. + ∼6 in. clearance = ∼39 in.)
  - Legs fit around typical toilet, bariatric wheelchairs chairs up to 35 in., and recliners up to 37 in.
- Compact design to work within the space constraints of a typical home or clinical environment
  - Navigate through typical bathroom, from wheelchair to toilet
  - Legs fit around typical toilet, bariatric wheelchairs chairs up to 35 in., and recliners up to 37 in.
  - Compact design to fit and maneuver inside a home garage
- Steerable, powered base
- Speeds up to 9 in/s (from experiments)
- Transfer operations should be completed in less time than with a typical Hoyer lift

Nice-to-Have Machine Features

- Capability to perform less common transfers within a home (e.g. if a patient falls in an difficult to access space, for example, between a toilet and a tub)
- Provide lift capacity equivalent to current market electrically actuated bariatric lifts (1000lb) in any useable kinematic configuration
- Lightweight, stowable, transportable design (to fit inside an SUV or hatchback, e.g. BMW 335 coupe: 38 in.x37 in.x17 in.)
- Powered, steerable, omnidirectional base
- Assisted patient seat angle adjustment
- Moveable base/outriggers to go around common seating locations, such as chair legs
- Capability to extend base or outriggers under low couches or beds
- Horizontal motion with respect to the base in two axes, within tipping stability limits
- Ability to change patient posture on-the-fly

Must-Have Control Design & Interface Requirements

- Safe under all conditions, particularly direct contact with humans
- Easily operable by a single caregiver
- Ability to control machine with one hand while simultaneously fine-tuning and orienting the patient with the other hand
- Capability to lift, orient and achieve appropriate posture of patient, via caregiver/machine team
- Smooth, stable control in all operating conditions
- Sufficient dynamic response for a range of patient weights
- Require minimal force applied by operator

Nice-to-Have Control Design & Interface Features

- Minimal swing and oscillation
- Smooth, stable control in all operating conditions
- Controller capability to prevent motion which could cause tipping, to allow for an extended the range of motion
- Same desirable dynamic response for a wide range of patient weights

3.6 Project Goals and Focus

While the needs assessment was an informative and revealing part of the design process, the main focus for this research is not on the traditional product development process. The focus of the research involves investigation of a collaborative manipulation assist device, with control to manage any unwanted external interaction forces, as well as application of hydraulic actuation and its associated control challenges, in an area that is atypical for hydraulics. While the work should provide foundational work for certain features and ideas for a new marketable patient transfer assist device with multiple actuated degrees of freedom, the end result of the research will not be a marketable device. Also, the technology used must have the possibility to be of reasonable cost, although the experimental prototype components may not actually be inexpensive. The pump-controlled electro-hydraulic actuation has advantages in terms of power density and compactness, and this work explores how certain control and operator interface features can improve the performance in patient transfer assist device design. One set of challenges in working with hydraulic actuation in such an application with a relatively delicate, unstructured environment, are the intrinsic stiffness and high force capability of the actuators. One goal of the research is to develop controller based features to manage any undesirable external forces. A functional prototype patient transfer assist device has been fabricated to match the desired functional requirements as closely as possible within a reasonable scope; much of the optimization of the device and some features that are less relevant to this research but are desirable in a marketable device are topics for future work.

CHAPTER IV

DESIGN REQUIREMENTS, MACHINE DESIGN, AND MODELING

4.1 Machine Design and Modeling Overview

This chapter describes the design of the first prototype PTAD. The primary purpose of the prototype is to demonstrate feasiblity of this multiple-DOF force-assist machine concept for aiding human workers in lifting and manuevering heavy payloads, in unstructured and relatively delicate environments, using low cost electro-hydraulic actuation. In the previous chapter, a set of functional requirements for a new marketable PTAD was developed based on the needs assessment and preliminary experiments with a current market patient lift. Based on that information, a set of design requirements is given in this chapter. That set was then filtered down to the requirements most critical to demonstrating the key ideas in this research.

Cost is a major consideration in developing a marketable PTAD, and it was primary consideration for this prototype to demonstrate that it is feasible to obtain desired control of motion and forces using low cost, efficient pump controlled electro-hydraulic actuation systems, rather than expensive servo valves. A fully functional first generation prototype PTAD has been designed, fabricated and tested. It has four DOFs hydraulically actuated, and it is controlled from an operator input force sensing handle. The prototype has been tested in a variety of patient transfer operations.

4.2 Concept Design

Based on the needs assessment, the first step was to develop a very high level concept of a 'dream' patient transfer assist device, with all of the features that would be desirable. At the concept stage, cost of the ultimate components that would substitute for developmental components was considered, and an investigation was made into how many of the desirable features were feasible, what were the tradeoffs between them, and how they could work together in one machine. Various kinematic configurations were considered, as well as a variety of actuated degrees of freedom. Figure 22 shows an early illustration of a concept design. Some design requirements are necessary, such as having the necessary range of motion, speed and power capabilities to perform the transfers, and having control that ensures safety with humans in the workspace. Other features would be nice to have in a marketable design, such as a powered sling angle rotation or omnidirectional wheels to ease maneuvering in tight spaces. Key features of both the concept design and the prototype include a) a main vertical lifting DOF, b) powered, steerable drive wheels and c) an extendable horizontal boom to allow for positioning of the patient on a support structure (e.g. bed, chair, wheelchair, car seat or toilet) while avoiding the base of the support structure.

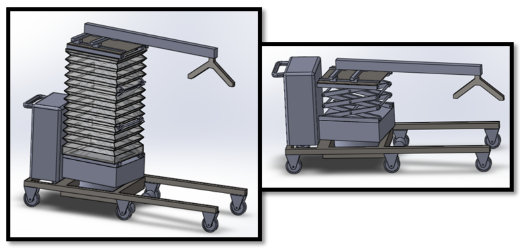


Figure 22: Early concept design for PTAD

A number of features have been proposed, including several additional degrees of freedom. A few of those proposed mechanical features are shown in Fig. 23. Features that would be nice to have include a foldable/stowable design, a structure lightweight and compactable enough to transport in a car (or at least a hatchback/SUV), moveable legs/outriggers to aid in avoiding obstacles or support structure bases, control to minimize patient oscillation, and control to inform caregivers of impending obstacles.

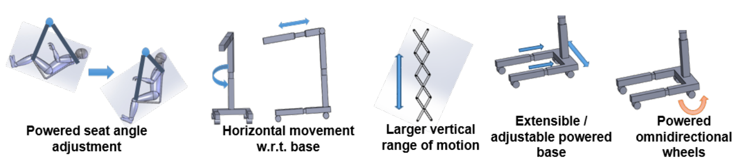


Figure 23: Concept features for a patient transfer assist device

4.3 Prototype Scope

At this stage it is important to emphasize the differences between the goals of this research prototype and the goals of an improved marketable patient transfer assist device.

The primary goals of this prototype are to demonstrate and validate feasibility of this concept of a force assist machine to aid workers in moving heavy, complex payloads through relatively delicate environments with humans in the workspace; the aim is to validate the operator interface and control approach, along with the use of low-cost hydraulic actuation with control of interaction forces.

This type of hydraulic operator assist device could be useful in a range of applications. The prototype is intended to demonstrate the concept, address any potential "show stoppers" in terms of the device design and control, answer the research questions, and show at a high level that the device is viable and has significant benefits for the operator. The aim is not to find the most optimal mechanisms for patient transfer operations within known space constraints, nor to optimize for the most compact package, nor to find optimal controller gains.

Controlling forces in a range that is suitable for humans in the workspace is critical. It is challenging to control forces in these types of non-ideal, intrinsically stiff actuation systems; these low cost pressure controlled actuators are not the industry standard, and it is an important research question to show that the capability to control interaction forces is not a show stopper. It is important to show that the operator interface and control strategy are effective at both generating the operator's desired motion response even with a heavy payload, and managing interaction forces to keep them in a safe range for humans in the workspace.

This prototype also served as a testbed for the NSF Engineering Research Center for Compact and Efficient Fluid Power (CCEFP). The structure of the various research projects and testbeds under the CCEFP includes fundamental research, new component designs, and novel systems and architectures. Fundamental research is tested in new components, and new component designs and architectures are tested within fully functional systems, or "testbeds". The PTAD was designed to serve as a testbed for the CCEFP, demonstrating fluid power technology at the human scale, using efficient low cost electro-hydraulic pump controlled actuation. Therefore, it was necessary to make the design modular, and to leave physical space for testing new components and circuits, such as new types of pumps or accumulators. This testbed requirement conflicts with the functional requirement for a patient transfer assist device to be as compact as possible. Also, it required implementation using low cost electro-hydraulic pump controlled actuators, and design of control strategies to compensate for their non-ideal features.

4.4 From Functional Requirements to Design Requirements

A set of functional requirements and features that would be beneficial in patient transfers was assembled based on the needs assessment. The following tables illustrate the mapping from those functional requirements to design requirements of a PTAD. The prototype developed in this work is focused only on certain aspects of the PTAD, so there are some requirements that it meets and some that it does not; some are recommended for a next generation design. Some of the key design considerations in this machine are challenging tradeoffs. It must be compact and highly maneuverable, yet it must have multiple actuated degrees of freedom and high force capability. And it must be powerful enough to lift and maneuver a payload up to at least 500 lb, preferably up to 1000 lb, in any configuration, yet it must not cause any damage or injury to any obstacle or human in the environment.

Table 1 lists a subset of the functional requirements from the needs assessment for the machine design that are relevant and needed for the proof of concept prototype, and table 2 lists requirements for the control system; the control and operator interface design is a thrust area for this research, so these requirements are listed separately. Each of those functional requirements maps directly to a specific design requirement. While not all of the design requirements are easily quantifiable, they do clearly define the relevant aspects of the design. The prototype meets all of this subset aside from one requirement. That is, the overall prototype dimensions are larger than what would be needed to perform transfer operations within a home; specifically, it is very long, and with the nonholonomic base, that makes it difficult to steer and move around obstacles. This in-house, off the shelf scissor mechanism was selected because design of a more suitable scissor mechanism is outside the realm of the scope of this project. Designing an effective scissor mechanism with high load capacity application can be nontrivial; while this off the shelf scissor mechanism is considerably larger than what would be ideal for this application, it does have the desired range of motion and provides capability to perform the transfers.

Table 1: Requirements for Prototype

Functional Requirement for Prototype & Marketable Device	**Design Requirement for Prototype & Marketable Device**	**Met With Prototype?**
Capability to perform most typical transfers within a home/institution	Range of motion & power capability for typical transfers	Yes
Lifting capacity equivalent to current market lifts	Lift capacity of at least 500 lb	Yes
Run all day untethered	Sufficient battery power for 12 transfers per day	Yes (Signals from wall power)
Compact design to work within space constraints of a typical home	Design to fit and easily operate in a typical bathroom, bedroom or garage	No
Necessary range of motion	Fit comfortably through 32" door	Yes
	Lift patient above bed, hanger bar height 72"	Yes
	Comfortably reach floor, hanger bar height 22"	Yes
	Reach middle of double bed, horizontal extension 39" clearance	Yes
Minimal operator force required for driving on carpet	Powered, steerable base	Yes
Capability to perform transfers efficiently	Capability to move payload with velocity $9\frac{in}{s}$ and acceleration $7\frac{in}{s^2}$	Yes
Stable, no tipping	Verified tipping stability in all kinematic configurations	Yes
Implementation with electro-hydraulic pump control (prototype only)	All degrees of freedom actuated by electro-hydraulic pump control	Yes
Modular design (prototype only)	Machine designed with accessibility & extra space for new components	Yes

Table 2 shows the operator interface and control requirements for the PTAD, divided into those that are relevant to the PTAD and those that can be added at a later stage, or would be nice to have but are not critical for performing the functions. The PTAD requires a control strategy that allows a single caregiver to control all of the degrees of freedom in an intuitive, safe and simple manner with one hand, while simultaneously fine-tuning the patient position and orientation with the other. The control to manage any potential unintentional external interaction forces is critical, particularly using electro-hydraulic pump control.

Table 2: Operator Interface & Control Requirements

Functional Requirement for Prototype & Marketable Device	**Design Requirement for Prototype & Marketable Device**	**Met In Prototype?**
Safe under all operating conditions, particularly direct contact with humans	*Control to manage any potential unintentional external interaction forces*	*Yes (Various approaches investigated)*
Capability to lift, orient and achieve appropriate posture of patient	Coordinated control of appropriate DOFs	Yes (though better options are available)
Easily operable by a single caregiver	Operator input handle and patient within reach	Yes
Ability to control machine (with one hand) while simultaneously fine-tuning/orienting patient (with the other hand)	Convenient location of input sensor; zero input when the operator lets go of the controls	Yes
Require minimal force from operator	Required operator input less than 15 lb	Yes (aside from overcoming casters)
Smooth, stable control	Prove stability under a range of operating conditions	Yes
Functional Requirement for Marketable Device	**Design Requirement for Marketable Device**	**Met In Prototype?**
Minimal swinging/oscillation	Control to cancel patient oscillation	No
Respond to operator input in the same way, independent of payload	Achieve desired dynamic response for a range of patient weights	Partially
Capability to rotate from seated to supine posture on the fly	Operator controlled, actuated sling rotation	No

Table 3 lists some useful design features that are not included in this prototype design. The requirements related to overall size are important, but in the prototype, they conflicted with the need for a modular design. Other features would be nice to have, but cost is a significant consideration.

Table 3: Required (or Nice to Have) Features for Next Generation PTAD

Functional Requirement for Marketable Device	**Design Requirement for Marketable Device**
Base motion in any direction	Omnidirectional wheels
Horizontal motion with respect to the base, side to side	Actuated swing with respect to base
Minimal oscillation	Payload swing compensation in control
Payload capacity to match current market bariatric lifts	1000lb payload capacity
Ability to change patient posture while lifted	Actuated sling angle rotation to adjust patient between seated and supine posture
Lightweight, stowable, transportable design	Compact, lightweight design that folds to fit in car (at least hatchback)
Capability to transfer patient into a car inside a garage	Compact design to fit & maneuver inside garage
Capability to transfer patient inside a small bathroom	Compact design to fit & maneuver inside small bathroom
Capability to move base/outriggers around common seating locations	Spreadable (and possibly extendable) base legs/outriggers that fit around a typical toilet, bariatric wheelchair (35") or recliner (37")
Capability to extend base or outriggers under low couches or beds	Low profile legs/outriggers

4.5 Prototype Design Process

Target force capabilities, speeds and accelerations were determined based on the needs assessment and preliminary experiments with the pre-prototype device. The required range of motion was determined based on measurements of a set of typical transfer operations (Fig. 24).

A set of actuated degrees of freedom was selected that has capability to produce the desired motion and forces using actuators that are currently available on the market. For each degree of freedom, a few different mechanisms, actuators, and electrical and hydraulic power supply combinations were considered, and preliminary calculations were performed to examine efficiency, complexity and power requirements for each option. For each selected mechanism and actuator combination, appropriate parameters for the associated hydraulic

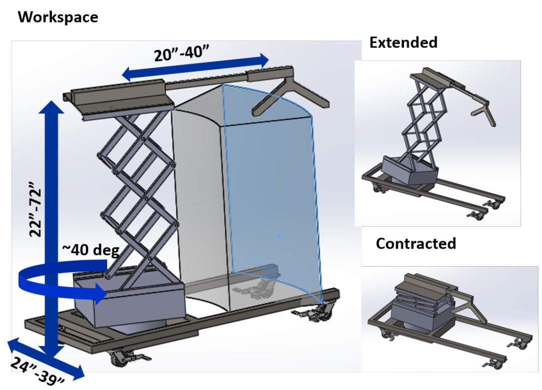


Figure 24: Required range of motion, determined from needs assessment

power supply were also determined. Figure 25 shows an example design process diagram for the lifting scissor, considering two types of mechanisms to achieve the large desired range of vertical motion.

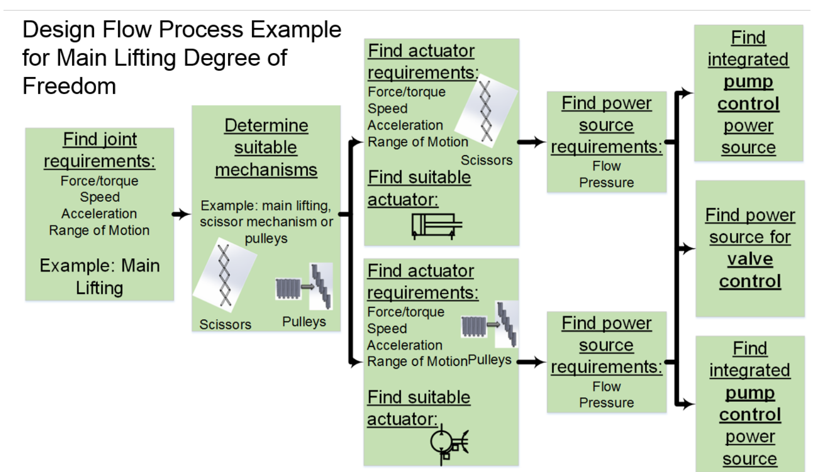


Figure 25: Design process flow for lifting DOF

There is a thrust within the CCEFP to move new systems toward pump control using electro-hydraulic actuators (EHAs), which consist of a separate DC motor and hydraulic pump for each DOF. The primary advantage of pump control over traditional valve control is that it can be considerably more efficient, by eliminating throttling losses. Electro-hydraulic pump controlled actuation was used for all degrees of freedom of the prototype PTAD.

4.5.1 Prototype Stages

The prototype design process was divided into stages, each with a different set of criteria. The first stage was a 2-DOF pre-prototype hydraulic lift device with valve controlled actuation, shown in Fig. 26, for the purpose of testing a few early concepts. This machine was modified from an earlier project. First, it was used to test the operator input from a force sensing handle, mapping to a velocity command, for use in transferring patients. Second, data from these simple patient transfer operations was used to determine requirements for speed, acceleration and force for the first generation prototype design. Third, it was used to test a passivity based human power amplifier controller, which is described in Chapter 5.

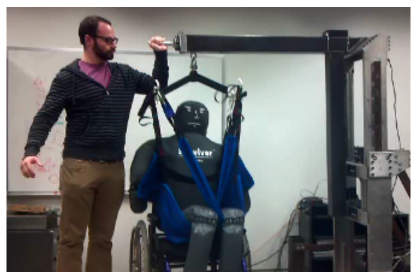


Figure 26: Required range of motion, determined from needs assessment

The second prototype stage (Fig. 27) was a completely new design and a step toward the final version of the prototype PTAD that was used for the control design, testing and operator experiments in this research. This version was actuated by pump controlled electro-hydraulic actuators (EHAs), and it was also controlled from a force sensing handle. It was divided into two separate machines, one with a vertical lifting scissor and horizontal boom extension, and another with two differential drive wheels. At this stage, the drive wheels were implemented on a separate small cart for the purpose of testing wheel controllers without risk of damaging the full machine. Complete actuation and control systems were implemented on both machines, including National Instruments controllers, servo drives, EHAs, battery power, and the operator input force sensing handle. Obstacle avoidance was implemented and tested on the wheels cart, using a set of twelve ultrasonic proximity sensors. In the third prototype stage, the wheels were integrated into the main machine.

The following sections describe this fully integrated PTAD prototype in detail.

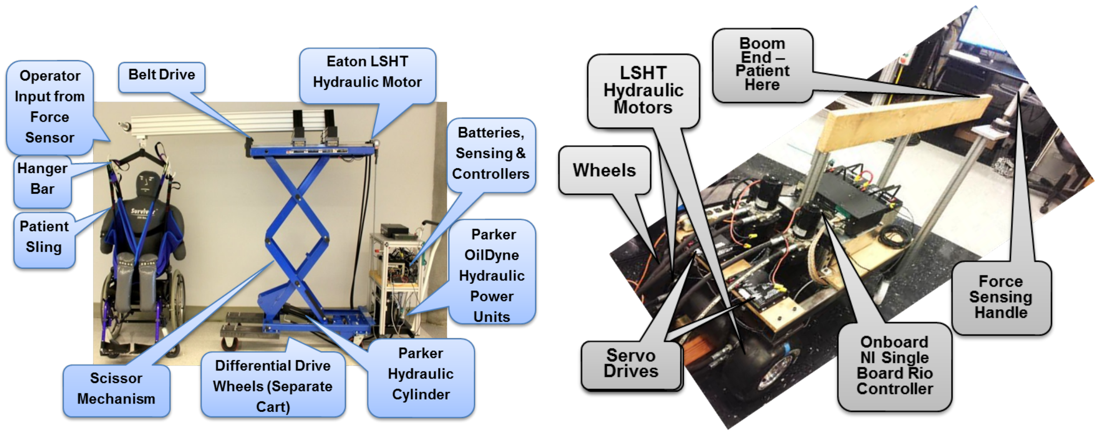


Figure 27: Left: first prototype components; right: wheel cart components

4.6 Current Prototype PTAD

A fully functional first generation prototype PTAD has been developed and fabricated, as shown in Fig. 28. It has four actuated degrees of freedom, each powered by its own EHA. All batteries, hydraulic power, actuators, electronics, amplifiers, sensing and controllers are onboard. The patient rests in a sling that is attached to a hanger bar at the end of the boom; this is the current industry standard. A force sensing handle is mounted near the patient at the end of the boom; this is the operator's control input, to be described in detail in later sections. The horizontal boom extension is driven by a belt drive mechanism and moves on a set of high load capacity linear bearings, and it is powered by a small low speed high torque (LSHT) geroler hydraulic motor. The vertical lifting consists of a scissor mechanism and actuated by a hydraulic cylinder. The wheels are actuated by larger LSHT hydraulic motors.

While this first prototype is considerably bulkier than desired, that extra size was needed for modularity and in order to use currently available mechanical components, in particular the scissor lift mechanism. Most of the design could easily be optimized to fit in a much more compact package; for example, using four scissor Xs rather than two would considerably decrease the outer dimensions of the scissor mechanism.

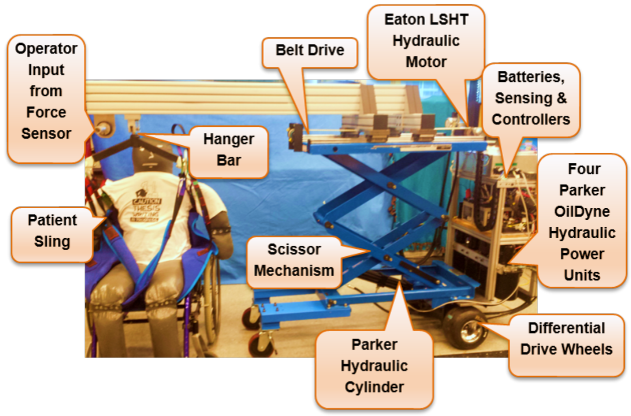


Figure 28: Four DOF prototype patient transfer assist device

4.6.1 Electro-Hydraulic Actuation System

The PTAD uses a form of electro-hydraulic pump control that allows for integration with onboard battery power and eliminates the need for expensive and inefficient servo valves, using a separate electro-hydraulic power unit for each actuator. As compared with traditional valve-controlled systems, in this electro-hydraulic actuator (EHA) architecture, the power unit only produces the pressure that is needed for operation, so there are no energy losses from throttling. An example schematic of these components, shown for the horizontal boom extension with a LSHT hydraulic motor and belt drive, is shown in Fig. 29.

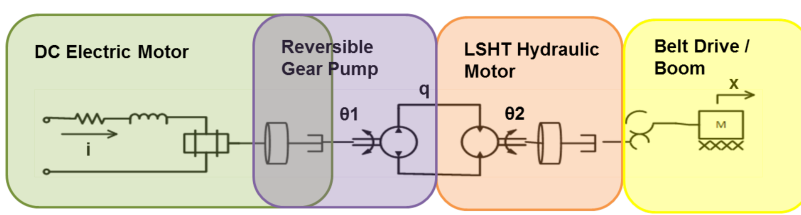


Figure 29: Actuation subsystem schematic for boom extension

Parker Hannifin's OilDyne division produces a line of small hydraulic power units (Series 108), which include a reversible DC motor (permanent magnet or series wound type), a very small bidirectional gear pump, check valves, and a reservoir. A set of these power units were donated for this research. Each power unit is driven by an AMC servo amplifier/motor controller. The DC motors and servo drives are designed to operate with 24VDC supply power. Each power unit is connected directly to the actuator, either a hydraulic motor or a hydraulic cylinder.

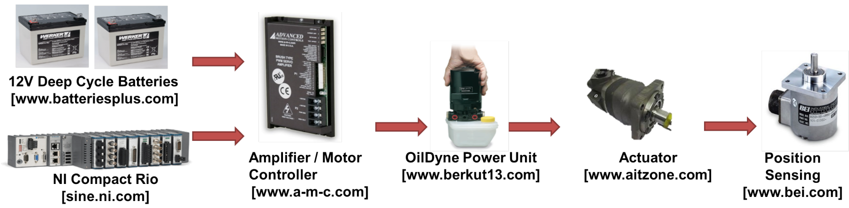


Figure 30: Actuation system for each degree of freedom

4.6.2 Electronics and Sensing Hardware

In this pump control architecture, the control input is the analog reference signal to the servo drive, which is supplied from an onboard NI Compact RIO controller. Available measurements include the electric motor current, actuator pressure, actuator position, operator input force, various other force measurements and ultrasonic proximity measurements. Position sensing is provided by encoders on the hydraulic motors and a linear position sensor in the hydraulic cylinder. The servo drive provides a specified current input to the electric motor, and it modulates the voltage as needed to maintain that current, up to the supply voltage of 24VDC. All actuation power is provided by a pair of onboard 12VDC deep cycle lead acid batteries in series.

Sensing and command signals are routed through a circuit board, which aids in distributing signals between the RIO devices and the appropriate parts of the machine. The electronics were all designed to be able to run from 24VDC, 12VDC, or 5VDC, all of which are available onboard the machine. The current draw from lifting a load is such that it causes a temporary reduction in the supply voltage; therefore, the same batteries cannot be used for both the actuation power and the controllers/signals. At this prototype stage, the low power electronics, including the RIO devices, all sensors, load cell amplifiers, and relays, are all powered from DC power supplies, which are connected to 120VAC power.

The electric motors for the OilDyne EHAs are available in lower power permanent magnet types and higher power series wound types. The permanent magnet types can be powered in either the positive or the negative direction using the same inputs. The higher power series wound type requires that a separate input is powered for each direction, and each accepts only positive voltage. Only one command signal output is available from the servo drive, so an external switch is necessary in order to power the motor in both directions. Solid state relays were used to switch between the forward and reverse directions.

Control gains on all four servo drives were tuned to match the motor performance based on the drive manufacturer specifications. Upper limits on motor current were also set, and input gains were adjusted such that the analog command signals from the NI RIO controllers map to an appropriate range of reference current signals for the application.

4.6.3 Hydraulic Actuation Circuit

Figure 31 shows a hydraulic circuit representing a standard OilDyne EHA, connected directly to an actuator, in this case a hydraulic cylinder; this basic circuit is used for each DOF of the PTAD. The hydraulic actuator is driven directly from the pump. The actuator speed and force/torque are controlled by varying the current in the electric motor driving the fixed displacement bidirectional gear pump.

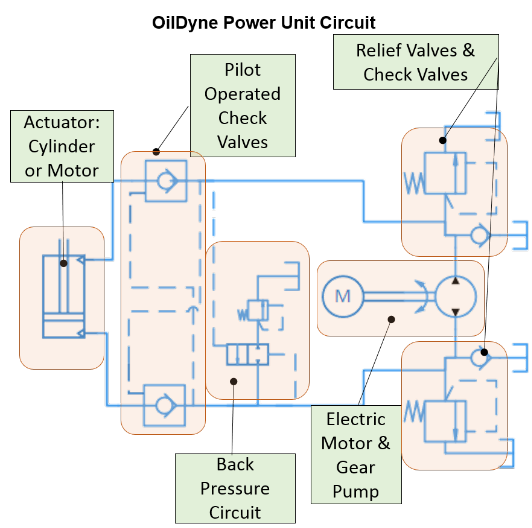


Figure 31: OilDyne hydraulic power unit circuit, with DC electric motor and pump for each actuator

The hydraulic circuit includes a locking valve circuit, which consists of a spool and two poppet valves. The circuit maintains the system pressure when the pump is not running. The electric motor and hydraulic pump share the same shaft. This feature is critical for holding a load against gravitational forces without having to apply constant power and continuously stall the electric motor in order to hold a load in place. There are no throttling valves in the circuit. It does include a set of high pressure relief valves that can be set to an appropriate pressure limit for the application. The circuit also includes a back pressure circuit that can account for some of the difference in flow between the rod side and cap side of a hydraulic cylinder by releasing some extra rod side flow to the tank; the back pressure circuit is nominally inactive in this system.

The locking valve circuit, which uses poppet style check valves to hold the load against gravity, causes some difficulties in control. The locking circuit is pilot operated, based on the differential pressure between one side of the actuator and the pump outlet. It takes some pressure to overcome the poppet valves, and once they do open, it tends to result in a sudden change in pressure and initially fast motion. This makes it difficult to control the machine at low speeds.

4.6.4 Electro-Hydraulic Actuation System Component Selection

Parameters for the actuation components were based on calculations of required pressures and flow rates, based on desired speeds, desired accelerations, necessary lifting capabilities, known masses, and estimated friction, using models of the mechanics. Actuators were selected based on the resulting actuator speed and force/torque output requirements, including hydraulic motors for the horizontal boom and wheels, as well as a hydraulic cylinder for the lifting scissor. Hydraulic power units were selected with the required output pressure and flow parameters. The resulting parameters for the horizontal boom extension and its hydraulic power unit are shown in Fig. 32. The use of hydraulic power units from the project sponsors' product lines were encouraged, which limited the available options; as a result, typical operation is low in the power range of the hydraulic power unit for the horizontal boom. The image on the right shows the flow/pressure curve for the hydraulic power unit.

Horizontal Boom Component Specifications

Component	Specification
Hydraulic actuator	Eaton low-speed high-torque geroler motor Displacement: 31.6 cm³/rev
Hydraulic pump	Parker OilDyne bidirectional gear pump Displacement: 0.526cm³/rev
DC Electric Motor	Parker OilDyne permanent magnet reversible brushed DC motor, Max: 24VDC/30A
Servo drive	AMC servo drive model 50A8
Position sensor	BEI H25 series optical incremental encoder
Pressure sensors	Wika C-10 pressure transducer
Actuator speed & flow at output boom max speed of 9 in/s	Motor angular velocity: 5.4 rad/s Flow rate: 1.86 L/min
Motor torque at 500 psi (3447 kPa) & 200 psi (1379 kPa)	Motor torque at 3447 kPa: 19.8 Nm Motor torque at 1379 kPa: 7.9 Nm
Force on Boom at 500 psi (3447 kPa) & 200 psi (1379 kPa)	Belt drive force at 3447 kPa: 535 N Belt drive force at 1379 kPa: 214 N

Horizontal Boom Hydraulic Power Unit Flow vs. Pressure

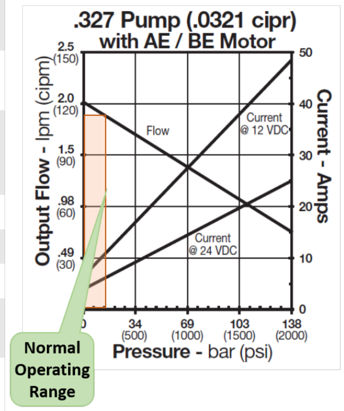


Figure 32: Components for horizontal boom extension, OilDyne hydraulic power unit (42)

Similarly, Fig. 33 shows parameters for the vertical lifting scissor. For a given output speed and payload weight, the pressure and flow requirements vary depending on scissor position. The maximum actuator force and subsequent pressure requirement occurs when the scissor is at its lowest position. The scissor mechanism is designed such that the ratio between cylinder velocity and scissor height velocity remains close to 1:10 throughout its range of motion. With this actuator and power unit combination, the scissor lift is able to lift a 700 lb. payload, but it is not able to obtain the maximum desired speed at the maximum payload.

Figure 34 shows specifications for one differential drive wheel. The wheels are 10 inches in diameter, and they are actuated and controlled independently.

Lifting Scissor Component Specifications

Component	Specification
Hydraulic actuator	Parker hydraulic cylinder Bore 5.1 cm, Rod 3.5 cm, Travel: 15.2 cm
Hydraulic pump	Parker OilDyne bidirectional gear pump Displacement: 0.526cm³/rev
DC Electric Motor	Parker OilDyne series wound reversible brushed DC motor, Max: 24VDC/45A
Servo drive	AMC vehicle servo drive model AVB250A060
Position sensor	Internal linear displacement transducer
Pressure sensors	Wika C-10 pressure transducer
Relays	Solid state relays
Actuator speed & flow at output boom max speed of 9 in/s	Cylinder velocity: ~0.9 in/s (varies with position) Flow rate: ~2.45 L/min (varies with position)
Maximum actuator force to hold 700 lb payload weight	Max 20965 kPa (3041 psi)

Lifting Scissor Hydraulic Power Unit Flow vs. Pressure

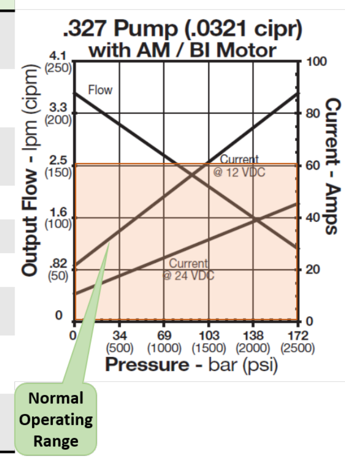


Figure 33: Components for vertical scissor lift, OilDyne hydraulic power unit (42)

Wheel Component Specifications

Component	Specification
Hydraulic actuator	Eaton Char-Lynn low-speed high-torque motor, displacement: 80 cm³/rev
Hydraulic pump	Parker OilDyne bidirectional gear pump Displacement: 0.526cm³/rev
DC Electric Motor	Parker OilDyne permanent magnet reversible brushed DC motor, Max: 24VDC/30A
Servo drive	AMC servo drive model 50A8
Position sensor	Incremental encoder
Pressure sensors	Wika C-10 pressure transducer
Actuator speed & flow at output boom max speed of 9 in/s	Motor angular velocity: 1.6 rad/s Flow rate: 1.23 L/min
Motor torque at 500 psi (3447 kPa) & 200 psi (1379 kPa)	Motor torque at 3447 kPa: 44.0 Nm Motor torque at 1379 kPa: 17.6 Nm
Force on cart at 500 psi (3447 kPa) & 200 psi (1379 kPa)	Wheel driving force at 3447 kPa: 352 N Wheel driving force at 1379 kPa: 141 N

Wheel Hydraulic Power Unit Flow vs. Pressure

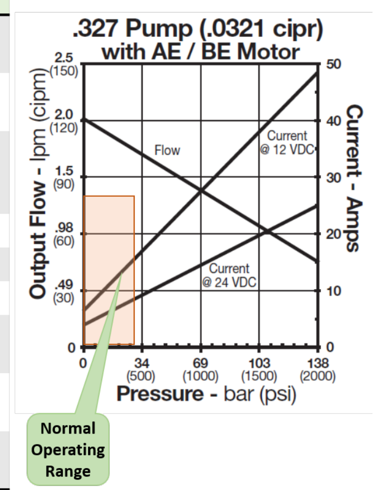


Figure 34: Components for one differential drive wheel, OilDyne hydraulic power unit (42)

4.6.5 Challenges in Hydraulic Actuation System

One thrust of this research is to utilize low cost, efficient electro-hydraulic actuators, and to maximize their effectiveness by compensating for nonlinear and non-ideal dynamics. This electrohydraulic actuation system has significant non-ideal features, and it presents a number of challenges in controlling forces and motion.

4.6.5.1 Overrunning Load Condition, Problem and Solution

One of the most significant problems with the hydraulic actuation system occurred when the EHA was first tested on the vertical lifting scissor. The circuit with the pilot operated check valves resulted in large pressure oscillations when the machine was moving down. This problem is known as an overrunning load condition. The original hydraulic circuit with the gravitational load is shown in Fig. 35. This overrunning load condition is known in industry, and a common solution involves a counterbalance valve, but that solution has low efficiency and is not effective in every case.

To explain the problem with an overrunning load, it is necessary to examine the states of the pilot operated check valves and the differential pressures that open and close them. In normal conditions, the check valves are opened by pump pressure, and then they close and hold the load when the pump is turned off. With a large gravitational load moving down, when the flow is moving in the same direction as the gravitational load is pushing, the differential pilot pressure that holds the check valve open is lost. Then the valve closes. Then enough pressure builds up to open the check valve, and it starts to move again. Then the required pilot pressure is lost again, and this results in a cycle. The resulting pressure oscillations are shown in Fig. 35.

A number of circuit variations were tested, based on input from industry hydraulics experts. The most effective result came from changing the circuit from double acting to single acting. In the modified circuit shown in Fig. 36, the cylinder is pushed down by the gravitational load, and the pump is used to meter the flow. The rod side port of the power unit is capped, and the relief valve on that side is set to a lower value. The rod side of the cylinder is vented to atmosphere. The pump pressure is also used to hold the check valves

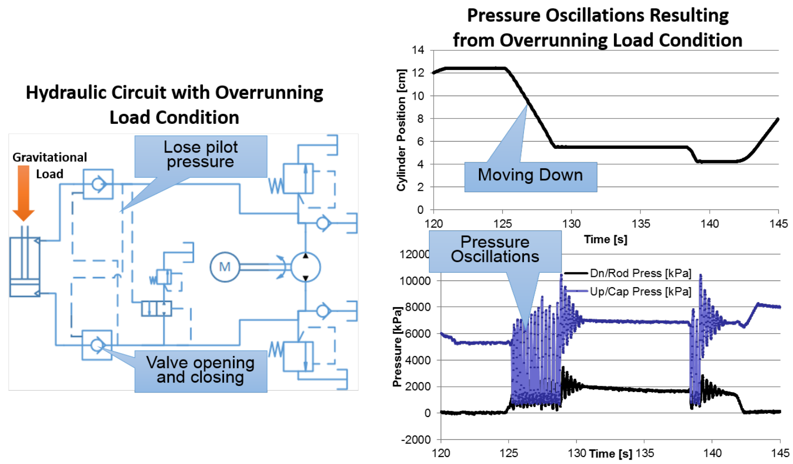


Figure 35: Pressure oscillation resulting from overrunning load condition

open. So when the cylinder is moving down, the flow is metered through the pump and over the relief valve to the tank. Figure 36 also shows the smoother pressure response resulting from the modified circuit; the motion profile corresponding to these pressure signals is sinusoidal. Note that the 'rod side' pressure measurement is at the capped port, which is not connected to the actuation. The single acting cylinder circuit is used for the vertical scissor lift throughout the research.

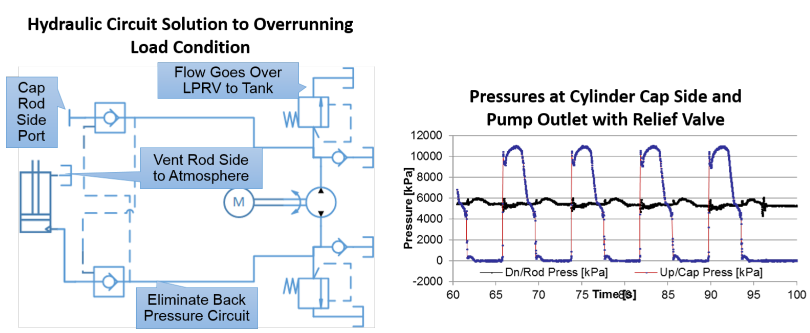


Figure 36: Hydraulic circuit solution to overrunning load condition

4.6.5.2 Other nonlinear and non-ideal features of EHAs

There are a number of nonlinear and non-ideal effects in the system that were not included in these models, such as voltage saturation, stiction and sliding friction, and deadband. Static and sliding friction forces for the boom mechanical system (separated from the hydraulic motor) have been measured, and the deadband range has been determined experimentally. These are discussed in more detail in Chapter 5 on control design.

4.6.6 Control Implementation using National Instruments Hardware and LabVIEW

All control of the PTAD is implemented using National Instruments hardware and LabVIEW Real-Time. The main advantages of NI/LabVIEW are the ability to quickly prototype software and options for plug-and-play digital and analog inputs/outputs. The scissor lift and horizontal boom are controlled from an NI Compact RIO 9081, with modules for analog and digital inputs and outputs, as well as an FPGA. The wheels are controlled from an NI single board RIO 9642, which has onboard analog and digital inputs and outputs. The controller code is written on a host PC and downloaded onto both RIO devices; real-time communication between all three devices is via Ethernet. The RIO devices include real-time controllers running LabVIEW Real-Time and field programmable gate arrays (FPGAs). The FPGAs are used only for hardware interfacing and minimal data processing, such as low pass filtering of measurement signals and computation of encoder quadrature, with a cycle time of 40kHz. All other control code is implemented in LabVIEW Real-Time with cycle times of 200-400 Hz, depending on the complexity of the particular program. Additionally, all analog measurement signals were low pass filtered in the real-time program. This LabVIEW implementation allows for fast prototyping, but it is not the form of control implementation that would be used in a marketable PTAD. The controllers are more costly than many alternatives, but they have modular, reconfigurable I/O with standard protocols for data acquisition and processing. However, LabVIEW Real-Time and its Control Design and Simulation toolkit have proved to be unreliable, producing many corrupt files and internal errors, which caused significant problems and delays in this research.

4.7 Modeling Overview

A first principles based model was developed for the horizontal boom and its actuation system. There are many unknown parameters for individual components, and there are not enough measurements available to be able to obtain estimates. The models from first principles were converted into lumped parameter models, with unknown parameters. Those unknown parameters were determined from system identification by spectral analysis, based on frequency response data. A dynamic model of the mechanical dynamics of the vertical scissor lift, horizontal boom extension system and payload was also developed and validated, and a simple impedance control was tested in simulation.

4.7.1 Hydraulic Actuation System Theoretical Model

This section describes a linear model for this actuation system for the boom. First, a linear first principles based model is developed (37). Then, rather than attempting to determine a value for every physical parameter in each component of the system, system identification by spectral analysis was used to determine approximate linear models between each measurable input and output. Models of the same form and order as the first principles based models were fit to the spectral analysis data. For the boom, the deadband range and static and sliding friction forces have been identified.

A schematic of the system for this model is given in Fig. 29. Equation 1 describes the equation of motion for the boom mass, in terms of the hydraulic motor rotation, or the torque balance on the hydraulic motor shaft, which is connected to a sprocket and belt that drive the linear motion of the boom extension.

$$(J_L + J_M)\,\ddot{\theta} + (b_L + b_M)\,\dot{\theta} = \eta_{at} D_a P_a \tag{1}$$

where J_L represents the inertia of the load, J_M is the inertia of the hydraulic motor, θ is the angular position of the motor, b_L is the damping coefficient of the load, b_M is the damping coefficient of the motor, D_a is the fluid displacement per revolution of the hydraulic motor (actuator), D_p is the displacement of the pump, P_a is the differential pressure across the hydraulic motor (actuator). Efficiencies are represented by η_{av}: actuator volumetric efficiency, η_{pv}: pump volumetric efficiency, and η_{at}: actuator torque efficiency. The leakage coefficient is represented by K. The differential pressure across the hydraulic motor is given by Eqn. 2.

$$P_a = \frac{\eta_{pv} D_p}{K}\omega_p - \frac{D_a}{\eta_{av} K}\dot{\theta} \tag{2}$$

where ω_p is the pump speed.

Available measurements in the boom actuation system are input motor current, hydraulic motor inlet and outlet pressures, and hydraulic motor angular position. It is desirable to obtain relations between input electric motor current and output hydraulic motor angular position, and between input current and output hydraulic motor differential pressure. Combining equations 1 and 2 and eliminating pressure, we obtain Eqn. 3 in terms of pump shaft speed (on the same shaft as the electric motor) and hydraulic motor angular position.

$$[J_L + J_M]\,\ddot{\theta} + \left[b_L + b_M + \frac{\eta_{at} D_a^2}{\eta_{av} K}\right]\dot{\theta} = \left[\eta_{at}\eta_{pv}\frac{D_a D_p}{K}\right]\omega_p \tag{3}$$

Similarly, combining Eqn. 1 and Eqn. 2 and eliminating hydraulic motor position, a relation for output differential pressure is obtained (Eqn. 4).

$$\begin{aligned}&\left[(J_L + J_M)\,\frac{\eta_{av} K}{D_a}\right]\dot{P}_a + \left[(b_L + b_M)\,\frac{\eta_{av} K}{D_a} + \eta_{at} D_a\right] P_a \\ &= \left[(J_L + J_M)\,\frac{\eta_{av}\eta_{pv} D_p}{D_a}\right]\dot{\omega_p} + \left[(b_L + b_M)\,\frac{\eta_{av}\eta_{pv} D_p}{D_a}\right]\omega_p\end{aligned} \tag{4}$$

The motor is powered by a servo drive, in current control mode; the drive adjusts the motor voltage as needed to regulate the current to the reference. The drive dynamics are very fast relative to the rest of the hardware system, so they are neglected, and an input motor current is used. One non-ideal, nonlinear feature to be addressed is the voltage saturation. The ideal relation between the motor current and shaft speed is given by Eqn. 5.

$$K_t i = J_E \dot{\omega_p} + B_E \omega_p \tag{5}$$

Combining Eqn. 3 and Eqn. 5 and taking Laplace transforms yields a transfer function from input electric motor current to output hydraulic motor angular position, in Eqn. 6.

$$\frac{\Theta(s)}{I_E(s)} = \frac{K_t \eta_{at}\eta_{pv}\frac{D_a D_p}{K}}{s\,(J_E s + B_E)\left[(J_L + J_M)\,s + \left(b_L + b_M + \frac{\eta_{at} D_a^2}{\eta_{av} K}\right)\right]} \tag{6}$$

Similarly, a transfer function from input electric motor current to output hydraulic motor pressure is given by Eqn. 7.

$$\frac{P_a(s)}{I_E(s)} = \frac{K_t\left(\frac{\eta_{pv}D_p}{K}\right)\left[(J_L+J_M)s+(b_L+b_M)\right]}{(J_Es+B_E)\left[(J_L+J_M)s+\left(b_L+b_M+\frac{\eta_{at}D_a^2}{\eta_{av}K}\right)\right]} \tag{7}$$

4.7.2 Boom Extension System Dynamics

System identification by spectral analysis was used to determine models corresponding to these two transfer functions representing the horizontal boom extension. Few of the parameters in the theoretical models are known. Models of the same form and order as the theoretical models were fit to experimental Bode plots for each input-output relation. These system identification based models were determined for the hydraulic motor system with and without the physical boom mass attached to the pulley; for the system without the load, the terms J_L and b_L are zero. The purpose of the model is for control design. It is important to capture dominant system dynamics, but it is not necessary to obtain very high fidelity models, nor to capture all nonlinear effects.

The unknown lumped parameters in the models were tuned to fit the data in the frequency domain. The hardware data for the Bode plots was obtained by running the horizontal boom extension in open loop with a swept sine input. With the swept sine, there is inherently lower signal power at the low frequencies, so it is expected that there is considerable variance in the low frequency data. Also, considerable stiction and the pilot operated check valves make the response highly nonlinear at low frequencies. The model parameters were tuned to the most reasonable fit to the data; least squares and other optimal fitting techniques were less effective because of the high variance at low frequencies, particularly in the pressure measurements.

Equation 8 shows the lumped parameter models that were fit to the horizontal boom transfer function from input reference current to output boom motor angular position. The corresponding Bode plot with both the model and measurement data is shown in Fig. 37.

$$
\begin{aligned}
\frac{\Theta(s)}{I_E(s)} &= \frac{d}{as^3 + bs^2 + cs} \\
d &= K_t \eta_{at} \eta_{pv} \frac{D_a D_p}{K} \\
a &= J_e (J_L + J_M) \\
b &= J_e \left(b_L + b_M + \frac{\eta_{at} D_a^2}{\eta_{av} K} \right) + B_e (J_L + J_M) \\
c &= B_e \left(b_L + b_M + \frac{\eta_{at} D_a^2}{\eta_{av} K} \right)
\end{aligned} \tag{8}
$$

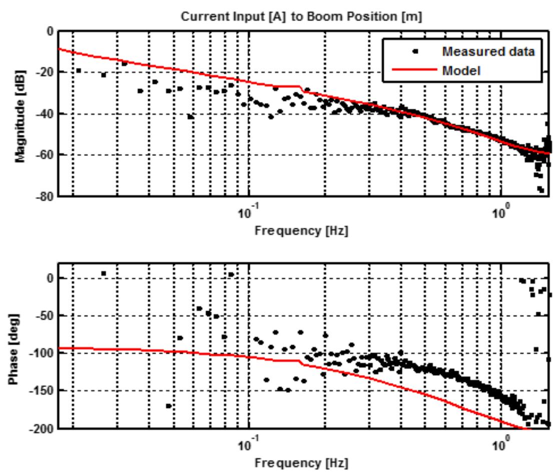


Figure 37: Input electric motor current to output boom motor angular position, measurement and model

Similarly, Equation 9 shows the lumped parameter models that were fit to the horizontal boom transfer function from input reference current to output boom motor differential pressure. The corresponding Bode plot with both the model and measurement data is shown in Fig. 38.

$$
\begin{aligned}
\frac{P_a(s)}{I_E(s)} &= \frac{gs+h}{as^3+bs^2+cs} \\
h &= K_t \frac{\eta_{pv} D_p}{K}(b_L + b_M) \\
g &= K_t \frac{\eta_{pv} D_p}{K}(J_L + J_M) \\
a &= J_e (J_L + J_M) \\
b &= J_e \left(b_L + b_M + \frac{\eta_{at} D_a^2}{\eta_{av} K} \right) + B_e (J_L + J_M) \\
c &= B_e \left(b_L + b_M + \frac{\eta_{at} D_a^2}{\eta_{av} K} \right)
\end{aligned} \tag{9}
$$

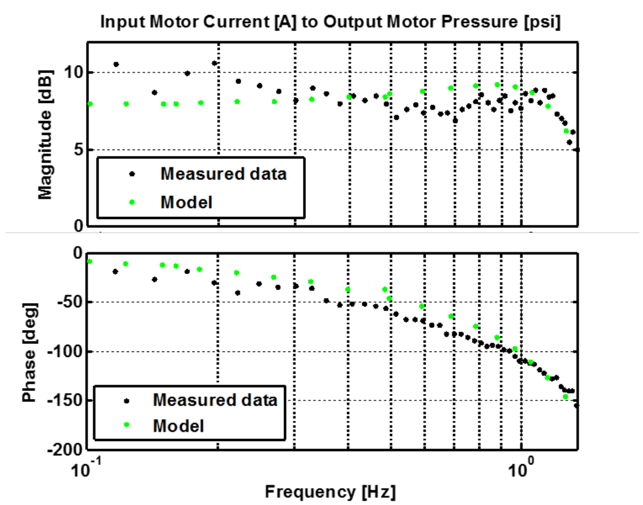


Figure 38: Input electric motor current to output boom hydraulic motor pressure, measurement and model

These system identification based models were used for design of the interaction controllers designed the next chapter. The results show that the controlled system performance of the models and the hardware system are similar, in spite of significant nonlinearities that were neglected in the models.

4.7.3 Mechanical Dynamics

A model of the mechanical dynamics of the scissor lift and boom extension was developed for the purpose of simulating the impedance control in the full system, including the payload, assuming perfect control of actuator force. The dynamics of the electro-hydraulic system were neglected in this phase of the simulation. Equations of motion for the scissor mechanism, boom extension and suspended payload were developed using Lagrange's equations. A schematic of the system is shown in Fig. 92. Mass properties were based on measurements of the links and densities of the materials.

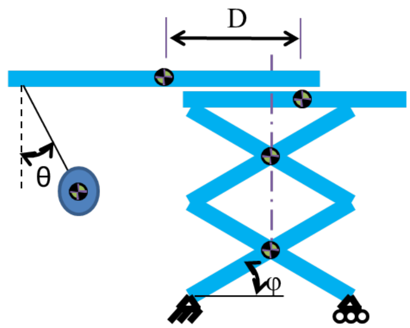


Figure 39: Mechanism for mechanical dynamics model

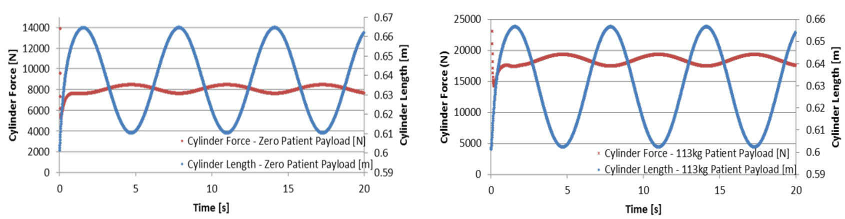


Figure 40: Simulated sinusoidal motion without patient (left) and with patient (right), full dynamic system model

The two inputs are the force applied to the horizontal boom by the belt drive and the force applied to the scissor lift by the hydraulic cylinder. The outputs are the horizontal and vertical motion in the base reference frame, of the boom endpoint and the payload. The actuation mechanisms (e.g. the hydraulic cylinder itself and its connecting rod) were treated as static relations rather than additional bodies in the mechanical dynamics model. The patient was treated as a point mass; this resulted in more payload swinging/oscillation than what would be expected with a human payload, but it provides a worst case scenario in terms of patient swinging. Figure 40 shows simulated cylinder position and force for a sinusoidal motion, with and without the 250 lb (113 kg) mannequin payload. More details on the mechanical dynamics model can be found in Appendix C.

CHAPTER V

OPERATOR INTERFACE AND CONTROL APPROACH FOR COLLABORATIVE MANIPULATION

5.1 Operator Interface and Control Overview

One of the most critical aspects of the PTAD design is the operator interface and control system. It must be efficient and safe to use, and it must be easily operable by a single caregiver. The machine is not intended to replace the caregiver, but to augment his/her capabilities. With the complex, high DOF payload of a human body, as well as the complex maneuvers required to properly posture and orient all parts of the body, it is not feasible for the machine to perform the entire transfer without the aid of the caregiver. In this type of operation, it is important that the caregiver is able to fine position and orient the patient, and the machine is used to do the heavy lifting and gross positioning. The caregiver and the assist device must work together, simultaneously applying forces to move the patient. So it is important that the caregiver is able to move the machine with one hand, while using the other hand to fine tune the patient motion. The caregiver must also be able to let go of the controls at any time to maneuver the patient with both hands. The control should be coordinated such that the caregiver does not have to think about inverse kinematics. The machine should also help the caregiver manage the motion of the machine in a crowded, cluttered environment. The operator interface proposed here uses a force sensing handle mounted near the patient as the caregiver input, using coordinated control to provide a reference velocity vector. An image illustrating the concept for the operator input mapping to machine motion is shown in Fig. 41. Most common forms of motion control for machines are designed for either autonomous control or for control by a human operator, but this system requires the caregiver and assist device to work together.

The base control frameworks that were applied to the PTAD are well-known in literature and highly studied and analyzed, with the exception of the addition of proximity based

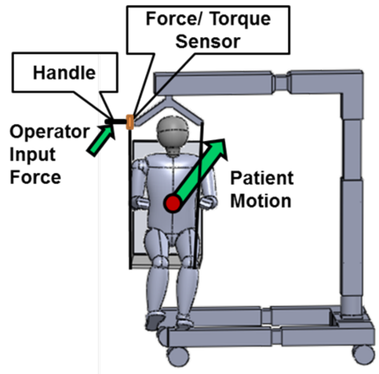


Figure 41: Caregiver input force to machine motion mapping

feedback to the impedance control framework. The primary challenge lies in applying such an interaction control to a machine with such inherently slow dynamics and highly nonlinear response as these low cost pump controlled hydraulic circuits. Similar forms of impedance control have been applied to hydraulic machines in the past, for instance, in Salcudean's work (46) on a teleoperated backhoe or in walking, as in the hydraulic humanoid SARCOS (4). However, they have not often been used in electro-hydraulic pump controlled systems, which have significantly different dynamics than typical valve-controlled systems. They also have not been proven effective in this type of application with large forces required, where the primary goal of the interaction control is to minimize any unwanted collision forces, while maintaining the ability to press lightly against obstacles in the environment. One of the goals of this research is to show that it is possible to manage environment interaction forces and unwanted collision forces with this type of low cost electro-hydraulic pump controlled actuation system.

5.2 Motivation for Interaction Control

In addition to being easy to use, the machine also needs to manage any potential unwanted external interactions. This is essential not only for prevention of injury or damage to objects in the environment, but it has potential to greatly improve the efficiency of operation by reducing the caregivers' mental workload so that they do not waste time checking around the machine to ensure that the motion path is free of obstacles in a cluttered environment.

One common operation that illustrates this need is transferring a patient into a car.

According to our needs assessment, this is one of the most difficult transfers (Fig. 42). There are a number of obstacles, including the door frame and the door. The caregiver's mental workload is high, and the focus is on the patient. It is probable that the caregiver will inadvertently run the machine into obstacles. In order to be able to maneuver and lift the patient, the machine must have the force capability to easily cause damage or injury in undesirable external interactions. However, the workspace is so restricted that the caregiver often needs to move the machine as close as possible to obstacles, or even press against them. Yet forces must be maintained at levels to minimize any potential damage or injury.

This chapter describes the control strategies used for each degree of freedom, as well as several other variations on the control approach that were tested but not used in the final implementation. The horizontal extension and vertical lifting degrees of freedom are dynamically decoupled, and the operator input is set to have inputs in the same vectors as the two degrees of freedom. So the control of the lift and extension is treated independently. The majority of the testing and analysis were done on the boom extension, in order to manage the scope of the project. Initially, the main concerns regarding the interaction control for this PTAD were related to the slow speed of response and high intrinsic stiffness of the hydraulic system. Interaction control is not a new concept and it has been well studied and broadly applied in literature since the 1980's. In a machine with high intrinsic stiffness, even with feedback of the external interaction force, the force in a high speed collision can reach a very high value before the controller is able to respond; if the machine also has a slow speed of response, this can exacerbate the problem. A goal of this research is to show that interaction control can be successful in this hydraulically actuated PTAD, even with its far-from-ideal hydraulic system dynamics.

In terms of this interaction control, there are multiple levels of questions. At a lower level, it is important to determine how to effectively manage interaction forces with the controller using this type of low cost hydraulic actuation system, with its high stiffness, low response speed, and highly nonlinear effects. At a higher level, it would be interesting to determine optimal parameters to best manage interaction forces while maximizing motion control performance as a function of the operator input. Because it is difficult to control interaction forces with this system, it is necessary to focus more on the lower level question first.

In a final implementation of the PTAD design, it would be desirable to be able to sense and respond to contact, or even impending contact, anywhere on the machine, and it must handle the kinematics and dynamics relations appropriately. It should slow its motion if it is quickly approaching an obstacle, and it should only allow small, well controlled forces to be applied to objects in the environment. In the (likely) case where the operator inadvertently runs the machine into an obstacle, the collision forces should be managed to remain at safe levels for humans, sometimes reported to be under approximately 15 lbf. It should also reliably inform the operator of any obstacles before interaction forces reach unsafe levels. Operators must be able to trust that capability in order to improve efficiency of transfer operations. It should do all of the needed interaction management while maintaining the desired motion control performance in free space.

Figure 42: Difficult car transfer

5.3 Forms of Interaction Control

Several different methods were considered for implementation of interaction control for this system. One of the biggest challenges is the control of forces, and subsequently pressure, in this low cost, non-ideal hydraulic actuation system. Three different types of interaction control were considered for the PTAD. All three forms of control were implemented, at least in a preliminary form. A summary comparison chart for the three methods is shown in Fig. 43. More detailed explanations of each approach are given in the subsequent sections.

Interaction Control Form	Pros	Cons
Passivity based human power amplifier	• Inherently accounts for human applied force	• Passivity too conservative
Impedance control	• Large body of literature; many variations • Can obtain better low impedance performance	• Does not inherently account for human operator force • Requires inner force control loop
Admittance based human force amplifier	• Better friction compensation • Better performance with very high stiffness actuators • Inner position control loop is easier to implement with high stiffness actuators	• Can be difficult to obtain very low output impedance with inner position control loop • Speed of response issue with slow actuators and inner position loop

Figure 43: Forms of interaction control that were tested

The first control strategy, called the Passivity Based Human Power Amplifier, was applied only to a pre-prototype version of a hydraulic patient lift device. The human power amplifier aims to cause the system to behave like a passive mechanical tool when interacting with the human and the work environment, with a specified power scaling factor. The formulation generates a fictitious mechanical system in order to obtain velocity coordination and force amplification. This approach directly utilizes the human operator input, amplifying the operator force. However, in order to maintain stability and passivity constraints, it was found that the force amplification scaling factor could not be made large enough to lift a heavy patient without requiring an excessive operator input force; larger force amplification scaling factors resulted in instability.

The second control strategy applied to this machine is known as impedance control, which aims to make the machine respond like a virtual spring and damper in the task space, to provide low output impedance, or force divided by velocity, and compliant interaction with the environment. The basic concept is to add a virtual spring and damper between the end-effector position and a virtual reference position in the task space, thereby controlling the output impedance to a desired value. Particularly with lightweight and low stiffness actuators, this approach can be very effective in achieving control with low output impedance. However, the approach requires a low level force control of the actuator, and in cases where such force control is difficult, such as intrinsically very high stiffness actuators, it is not always feasible to obtain very low output impedance (7); in such cases, admittance control may be a better approach. It is inherently a position control, i.e. the outer control loop servos to a reference position; in this system, it is desirable for the operator input force to map approximately linearly to the output velocity, not position, so it is necessary to account for this difference. In the low level pressure or force control, it is necessary to account for any gravitational load, and if the payload is time varying, it will be necessary to measure or estimate it in real time (though in this work, compensation for machine weight was demonstrated in experiments, but real time measurement of payload weight is a topic for future work). This approach produced the best results in terms of attaining desirable tracking of the operator input while managing external interaction forces, so it was the primary control structure, particularly for the horizontal boom extension.

The third control strategy tested was an admittance control. This approach is similar to the impedance control, in that it is essentially position control in free space, and it aims to control the response to an external interaction based on specified dynamics. But it aims to control the output admittance, or velocity divided by force, rather than impedance. There are a number of variations on admittance control, but in this implementation, any external interaction force is measured, and that measurement is used to compute a modification to the reference position based on specified desired dynamics. This approach can be more effective in machines with substantial nonlinear friction, high inertia, or high stiffness ((7)). This approach has advantages over impedance control for the scissor lift, since it does not require knowledge of the payload weight.

5.4 Horizontal Boom Extension: Impedance Control

The controller design for the horizontal boom extension is based on the structure of a classic impedance control with force feedback, originally developed by Hogan (24). It is designed to control the machine output impedance to specified values (Fig. 44). The impedance controller was used as a high level controller to define a desired actuator force; then a low level pressure control is used to obtain that desired actuator force. First, the standard impedance controller is designed to obtain sufficient tracking performance in free space, while minimizing any external interaction forces. Then, a virtual force term based on the measured distance from an obstacle was added, to be discussed in a later section.

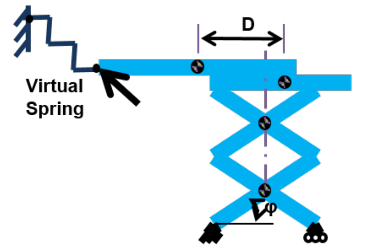


Figure 44: Impedance control aims for response of a virtual spring and damper in task space

The simplest impedance control law for a single degree of freedom is given by Eqn. 10, which is equivalent to a PD control in task space.

$$F_{act} = K_p \left[x_r - x\right] + K_d \left[\dot{x_r} - \dot{x}\right] \tag{10}$$

where F_{act} is the actuator force, K_p and K_d are proportional and derivative gains corresponding to the desired spring and damping parameters, x_r is a reference position, and x is measured position. The control law defines the reference actuator force. Obtaining this desired actuator force is treated separately.

5.4.1 Impedance Control with External Force Feedback

For the purpose of illustrating the concept of this controller design and how it can produce the desired dynamics in interaction and free space, and effectively cancel the inherent machine dynamics, a simplified model of the boom extension is used, consisting of a mass, damping, nonlinear friction, actuator force and external interaction force. A more detailed model is described in Chapter 2, and that model is used in later sections. The equation of motion for the boom extension can be represented by (11)

$$m\ddot{x} + b\dot{x} + f_f(x, \dot{x}) = f_{act} + f_{ext} \tag{11}$$

where m is the mass of the boom, b is a damping coefficient, $f_f(x, \dot{x})$ includes additional and nonlinear friction terms such as stiction, f_{act} is the force applied to the boom mass by the hydraulic actuator, and f_{ext} is the external interaction force. The friction f_f is variable in this system, depending on lubrication in the hydraulic system.

Hogan proposed adding an additional term to the impedance control to utilize a measurement of the external force, then using that measurement to aid in controlling the output impedance. This feedback is important in systems that are intrinsically stiff, such as hydraulics. The control law for the impedance control of the same simplified model using feedback of the external interaction force is given by (12),

$$f_{act} = K_p(x_r - x) + K_d(\dot{x}_r - \dot{x}) + K_f[f_{ext} + K_p(x_r - x) + K_d(\dot{x}_r - \dot{x})] \quad (12)$$

where K_p is the proportional gain, which also represents the desired virtual spring stiffness, K_d is the derivative gain, which represents the desired virtual damping, and K_f is a force feedback gain. The controller is designed such that the machine responds to an external interaction force with the impedance defined by the desired spring and damping parameters; it acts as though the machine has a virtual spring and damper added in the task space. A primary advantage of using feedback of the external force in this way is shown in the resulting controlled equation of motion in (13),

$$\frac{m}{1+K_f}\ddot{x} + \frac{b}{1+K_f}\dot{x} + \frac{1}{1+K_f}f_f(x,\dot{x}) + K_p(x_r - x) + K_d(\dot{x}_r - \dot{x}) = f_{ext} \quad (13)$$

where x_r is the position reference, and x is the measured position. *With sufficiently high force feedback gain K_f, the machine dynamics are effectively canceled*, leaving only the desired relation between external force and motion, defined by the desired impedance parameters.

5.4.2 Horizontal Boom Extension: Impedance Control Implementation with Force Feedback

This impedance controller with feedback of the measured external force is the basis for the controller used for the horizontal boom extension. A block diagram for this controller, based on a generic position reference, is shown in Fig. 45. It includes the high level impedance control, the low level actuator force control, and the feedback of measured external force.

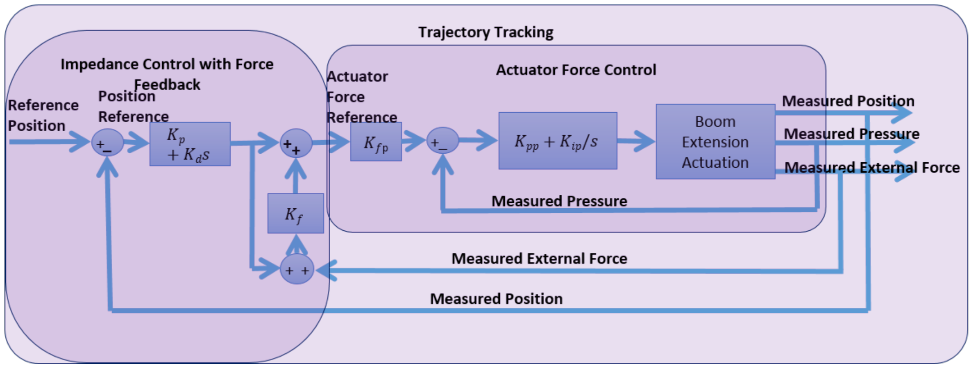


Figure 45: Impedance control with force feedback block diagram

In an ideal case, the actuator force would be controlled directly and precisely by the low level control. In this system, actuator force measurements are not available, but pressure measurements can easily be obtained. The dynamics between the hydraulic motor pressure and the actuator (belt drive) force can be assumed to be linear and constant, based on the static relation given in Eqn. 14,

$$F_{belt} = \frac{P_{motor} D_{motor}}{2\pi r_{sprocket}} \tag{14}$$

where F_{belt} is the actuator force on the boom extension mass, P_{motor} is the hydraulic motor pressure, D_{motor} is the hydraulic motor displacement, and $r_{sprocket}$ is the radius of the belt drive sprocket. The pressure dynamics are much faster than the dynamics of other parts of the system. This approximation of the relation between force and pressure is sufficient for this control design, though it does not account for substantial stiction in the hydraulic motor and linear actuator, nor the nonsmooth zero crossing resulting from the check valves in the hydraulic circuit. In this impedance control implementation, the desired actuator force is approximately obtained by controlling actuator pressure. The hydraulic motor pressure is controlled by a tuned PI controller. In this system, the tuned pressure control is dominated by the integral term. In the hardware system, the pressure control includes added compensation for deadband in the hydraulic system. In the simulation, the parameters for the outer impedance controller are the same, but the pressure control gains are slightly different since the simulation does not have the valve deadband nor deadband compensation. Throughout the experiments in this chapter, the higher level impedance controller gains are varied, but the pressure control gains remain constant.

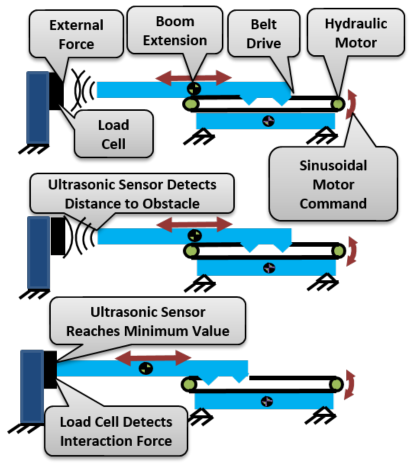


Figure 46: Schematic of impedance control experiment with software input

The impedance control scheme with force feedback shown in Fig. 45 was implemented in the hardware system on the horizontal boom extension. The impedance control gains were first set to obtain desired tracking performance in free space, with no feedback of external interaction force. Then the impedance control parameters were varied. Figure 46 illustrates the experiment in which the feasibility of a traditional impedance control with external force feedback was validated on this hardware system. The horizontal boom moves back and forth according to a software generated sinusoidal position reference. A rigid obstacle was placed in the path of the boom, and the interaction force between the obstacle and the boom was measured and used as feedback. The obstacle included a small stiff spring with spring constant $K_s = 10,000\frac{N}{m}$, to better evaluate the force control performance without focusing on the impact force resulting from collision with a rigid obstacle; in a marketable product design, it would make sense to cover the machine in a soft skin, or at least to add some compliance to the load cells to manage such initial impact forces in collisions with rigid obstacles; the compliance added to the force transducer is further examined in the stability analysis.

In Fig.47, results are shown for varying impedance controller gains. Note that the pressure control parameters are held constant throughout all experiments on the boom extension. In the impedance control, in free space, the desired spring and damping parameters K_p and K_d are multiplied by the force feedback scaling factor $K_f + 1$. All of the cases shown have the same gains in free space, but they are set to respond to the external force according to different spring and damping parameters based on this force feedback scaling factor; the gains were selected such that the resultant K_p and K_d in free space are equivalent in all cases. Note that the controller does not have any integral action, and *perfect tracking of the position reference is not the goal*, since the operator closes the position control loop; position control is used instead of rate control in order to obtain the effect of a virtual spring in task space.

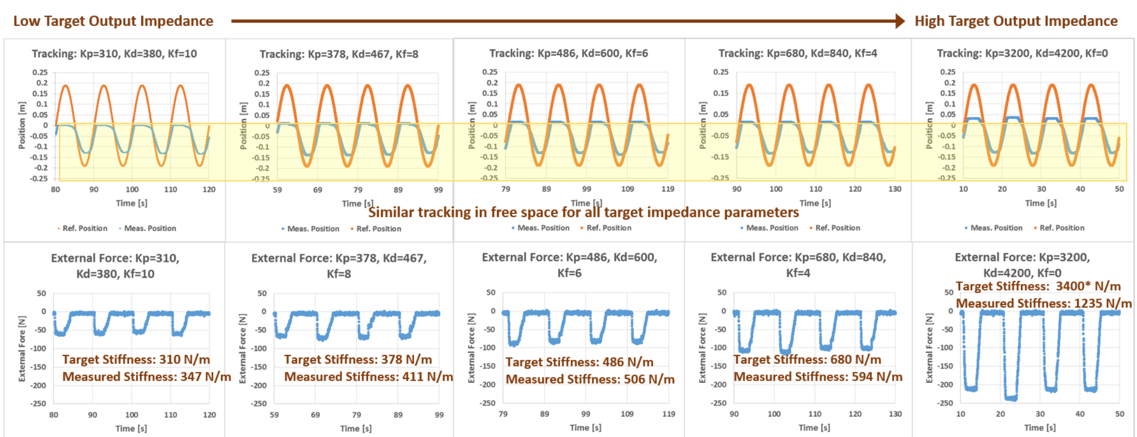


Figure 47: Hardware experiment; impedance control with external force feedback, desired impedance parameter variation and varying force gain; all cases equivalent K_p & K_d in free space

The aim of the controller is to respond to the external interaction force according to the spring and damper parameters K_p and K_d. The performance in achieving the desired spring parameter can be approximated by comparing the position error in contact with the external force, to obtain the actual spring constant of the boom response output impedance. The dynamic impedance parameters could be tested using a time varying external force, such as a shaker, but that was not deemed necessary for the purpose of this implementation. The results show that the machine is able to obtain the desired output impedance within about

10% of the target value, as long as the force feedback is used. When the force feedback is not used, and $K_f = 0$, then it does not achieve the desired stiffness value; this illustrates the importance of using feedback in such a system with high intrinsic stiffness actuators and slow dynamics.

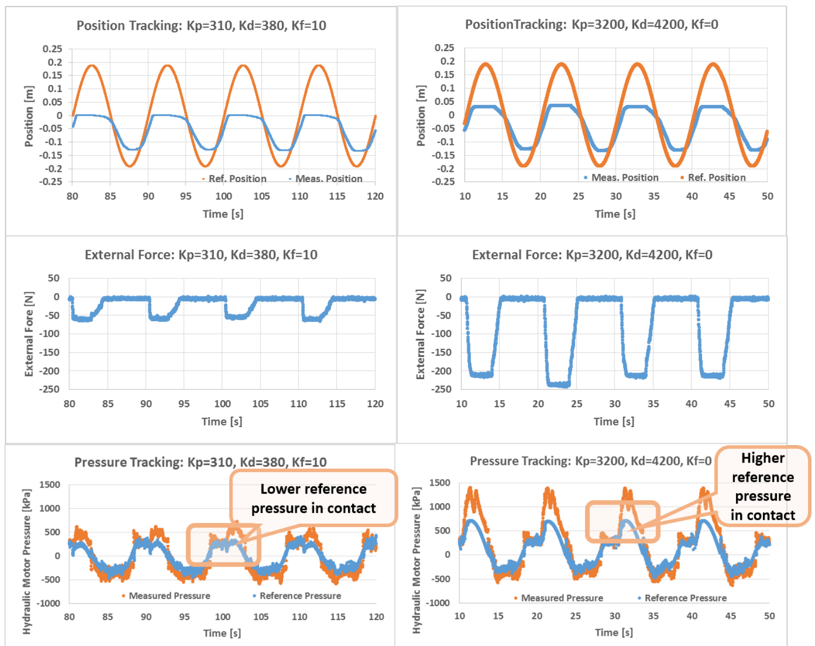


Figure 48: Hardware experiment; impedance control with force feedback, parameter variation; pressure tracking

5.4.3 Horizontal Boom Extension: Impedance Control with Additional Proximity Based Virtual Force Term

Impedance control with force feedback is a recognized choice for controlling interactions with the environment. However, in the case where the machine runs into an obstacle accidentally, if it is a high speed collision, the impedance controller may not be able to respond the the external interaction force before it becomes quite large. The slower actuator dynamics fo hydraulics systems can limit the machine's ability to respond to impact in a timely manner. In such cases, it would be beneficial to also use proximity feedback. Proximity feedback can also be useful in cases where no load cell measurement is available. Some might suggest using proximity feedback instead of force, as in a typical obstacle avoidance scheme. But it is important to recall the difficult car transfer; standard proximity based obstacle avoidance algorithms completely prevent any environment interaction, even with soft cloth, and are too conservative and prevent needed motions in applications when it is necessary to utilize every available inch of the workspace.

The next step is to incorporate the measured proximity from an obstacle into the impedance control. By adding in the proximity term as a repulsive force, it allows the operator to maintain the desired control of the interaction force in contact with the obstacle, rather than preventing contact completely as in obstacle avoidance algorithms. Also, if the boom is moving at high speed, the repulsive force should be significantly larger in order to prevent a hard collision; if the boom is moving slowly, the repulsive force should be small in order to maintain the desired impedance control in interaction. So, the virtual force is computed based on the momentum of the machine; it is defined as the force required to stop an equivalent mass moving at the current measured velocity within the current distance to the obstacle. This provides a quadratic relation between speed and virtual force. The virtual force term is computed based on the boom mass and distance to the obstacle, measured from the proximity sensor, as shown in Eqn. 15.

$$f_{prox} = \frac{m(\dot{x})^2}{d_{sat}} \ where \ d_{min} \leq d_{sat} \leq d_{max} \ and \ \dot{x} \geq 0 \tag{15}$$

where f_{prox} is the calculated virtual force based on proximity to the obstacle and momentum, d_{sat} is the distance to the obstacle (within saturation limits), x is the horizontal boom position, d_{min} is the minimum measurable distance to the obstacle of 2cm, and d_{max} is a maximum reasonable distance to affect the motion. The virtual force is set to zero any time the distance to the obstacle is outside the specified range, including if the distance is too small, to avoid division by near-zero. If the controller with the proximity term is doing its job, the boom should be moving very slowly by the time it reaches the minimum measurable distance to the obstacle; at that point the force measurement term takes over. The proximity term is also set to zero any time $\dot{x}$ is negative and the machine is moving away from the obstacle. In multiple degrees of freedom, for instance if the ultrasonic sensor was mounted on the wheeled base, the velocity vector used for the virtual force calculation would have to take into account the kinematics of the machine; the velocity vector would be the motion in task space along the axis of that particular sensor. A similar account for the kinematics was used in the obstacle avoidance implemented on the wheeled base.

If the computed virtual force resulting from the proximity sensing feedback is added, then the control law shown in Eqn. 16 is obtained, with the added proximity based virtual force,

$$f_{act} = K_p(x_r - x) + K_d(\dot{x}_r - \dot{x}) + K_f[f_{ext} + f_{prox} + K_p(x_r - x) + K_d(\dot{x}_r - \dot{x})] \quad (16)$$

where f_{act} is the actuator force, x_r is the position reference, x is the measured position, K_f is the force feedback gain, K_p defines the spring constant of the desired output impedance, K_d defines the desired damping of the desired output impedance, f_{ext} is the external interaction force, and f_{prox} is the proximity based virtual force term.

It is important to point out that the additional virtual force term is only active when the machine is moving in free space; it does not affect the impedance control in contact with an obstacle, so it does not affect the controller's ability to approach the desired spring and damping parameters in contact. It does slow the motion of the machine as it approaches an obstacle, so that the momentum of the machine approaching the obstacle is reduced; as a result, it may slightly degrade the tracking performance in free space, but this is a desirable result. Figure 49 illustrates the impedance control with the added proximity based virtual force term.

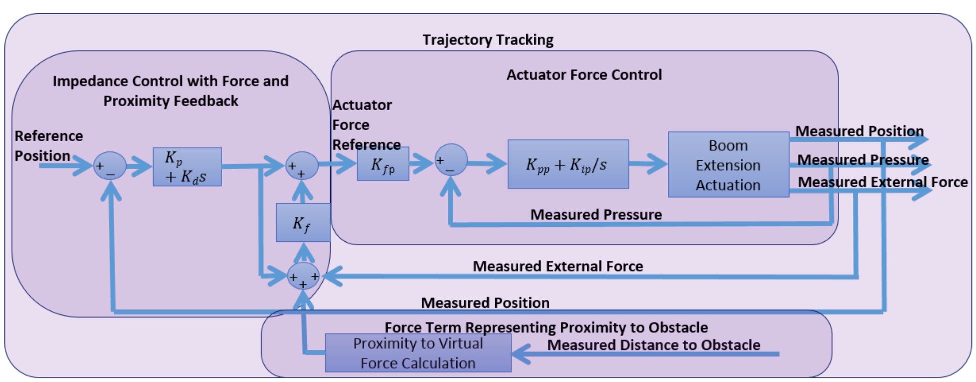


Figure 49: Impedance control with force and proximity block diagram

Figure 50 shows the results from a hardware experiment involving collision with the same obstacle, with a small stiff spring ($K_s = 10,000 \frac{N}{m}$) added to reduce initial collision effects. In practice, it would be reasonable to add such a small compliance to all load cells on the machine. The machine is tracking a sinusoidal software generated input, and the obstacle is mounted in its desired path. In this case, the system is set up to measure both interaction force and proximity to the obstacle. This is the same experiment setup as with the traditional force feedback control. The desired output impedance was set to $K_p = 310$ and $K_d = 380$, and the force feedback term (applicable to both virtual and measured forces) was set to $K_f = 10$. The plot shows four cases, first with no feedback of force nor proximity, second using feedback of measured force only, third using feedback of proximity only, and fourth using feedback of both proximity and force. It illustrates that in cases where either force or proximity measurements are available, the interaction forces can be significantly reduced, and in the case where both measurements are available, the *interaction force is reduced by about 87%*, from 470N to 60N. Note that in this case, the obstacle is near the position $x = 0$; a number of results from similar experiments are shown in the following sections, and in other experiments the obstacle position may be different. Also, the reference position signal is not the same in all cases, so the speed of the boom and the resulting momentum may also vary between experiments. In terms of collision force reduction, the results are dependent on a number of variables, including the speed at impact, impedance parameters, and obstacle stiffness and damping.

In practice, it would be feasible to mount both force and proximity sensors in key locations on the machine where collisions are most likely to occur, such as the end of the boom and the back of the cart, like the ultrasonic sensors often used in cars. In those cases, the results indicate that collision forces can be greatly reduced.

5.4.4 Horizontal Boom Extension Impedance Control: Simulations with Parameter Variations

This impedance control was simulated in Simulink using the transfer function models representing the full boom actuation and mechanics system. As described in Chapter 2, linear transfer function models were obtained from input reference current to output hydraulic

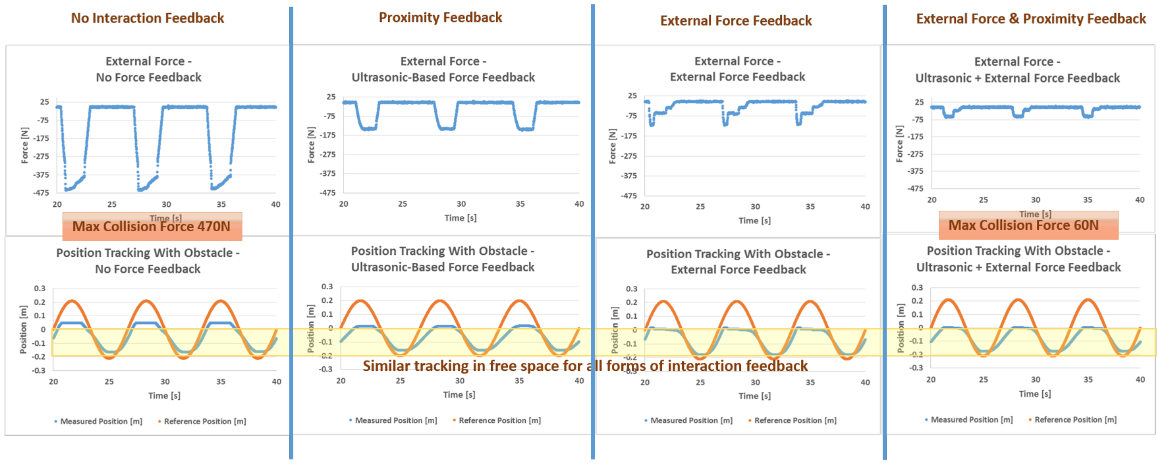


Figure 50: Hardware experiment; impedance control with force and proximity feedback results in collision

motor pressure, and from input reference current to output boom position, based on system identification. The relation between hydraulic motor pressure and actuator force was assumed to be linear, which provides a transfer function between the force applied to the boom and the motion of the boom. In this simple model, the response was approximated by linear transfer functions, neglecting the non-ideal features of the hydraulic system.

Figure 51 shows a simulated impedance control experiment, where the boom tracks a sinusoidal position reference and collides with a stiff spring with $K_s = 5000\frac{N}{m}$. It shows two cases of feedback, both external force & proximity and no interaction feedback. The bottom plot illustrates how the proximity based virtual force and the simulated external force feedback terms vary through the motion in free space, approaching an obstacle and in contact with the obstacle. In the top position tracking plot, it is also evident that the proximity based virtual force term slows the motion as it approaches the obstacle. The second from the top plot also shows the pressure tracking from two instances of the same parameter variation experiment, illustrating how the reference pressure, as well as the resulting measured pressure, are maintained at lower values with the low impedance control parameters when the machine is in contact with the obstacle and the position tracking error is high. When the impedance control is set to a stiffer value and the force feedback is not used, then the resulting pressures are considerably higher in contact, and subsequently the interaction forces are higher.

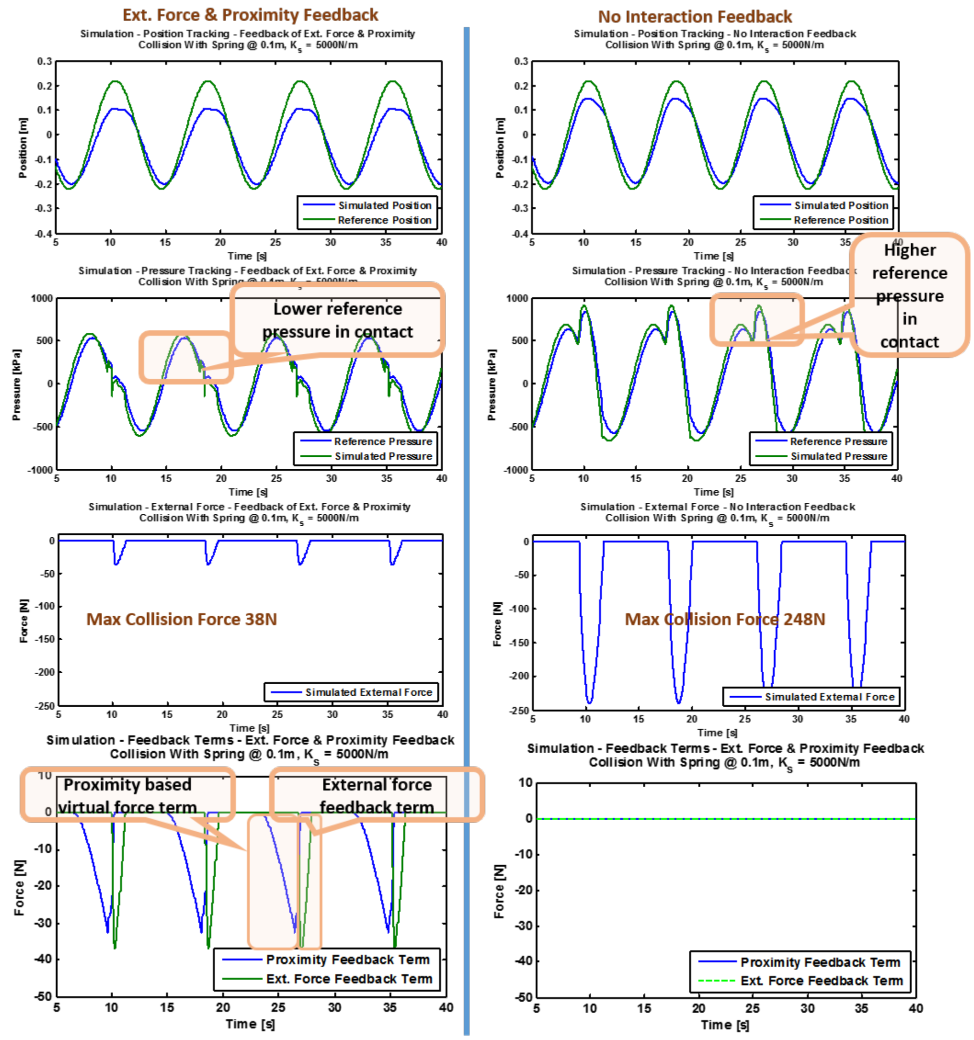


Figure 51: Simulation experiment; impedance control framework, external force & proximity feedback vs. no feedback. Collision with stiff spring with $K_s = 5000\frac{N}{m}$.

Figure 52 shows a simulation comparison of collisions with no interaction feedback, feedback of external force only, feedback of proximity only, and feedback of both force and proximity; this is similar to the hardware experiment shown in Fig. 50. While some parameters are different between the hardware and software experiments, namely the position reference signal and obstacle location, it is clear that the trends between the cases of feedback, as well as the tracking performance, are similar in hardware and simulation experiments involving variation of forms of interaction feedback. Note that in the hardware, the position tracking performance is degraded at very low speeds (at the maximum and minimum positions of the sinusoid) as a result of the deadband in the hydraulic system.

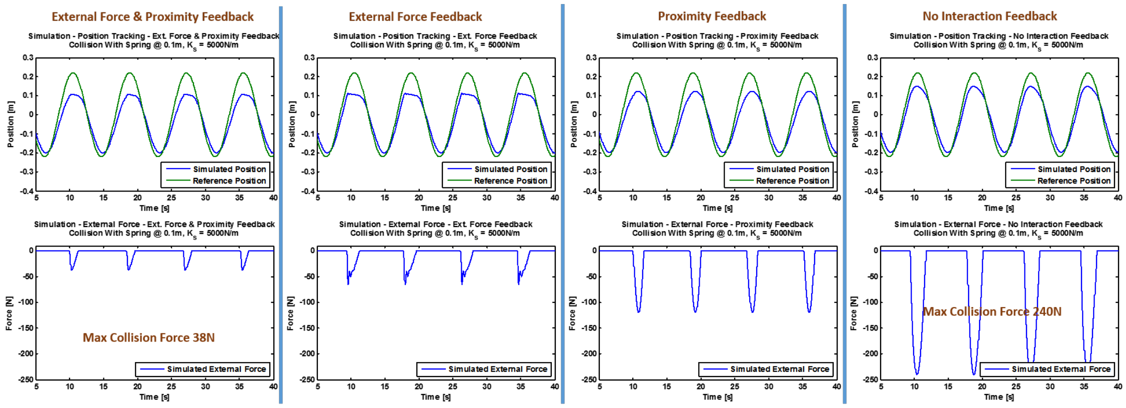


Figure 52: Simulation experiment; impedance control framework, comparison of feedback cases. Collision with stiff spring with $K_s = 6000\frac{N}{m}$.

Figure 53 shows the response from a similar simulation, but with all parameters held constant between cases, except the stiffness of the environment. As before, the boom moves in free space and collides with an obstacle. The impedance controller parameters were set to $K_p = 250$, $K_d = 300$ and $K_f = 10$. The three spring constants are each an order of magnitude apart, at $K = 100\frac{N}{m}\left(0.57\frac{lbf}{in}\right)$, $K = 1000\frac{N}{m}\left(5.7\frac{lbf}{in}\right)$, and $K = 10,000\frac{N}{m}\left(57\frac{lbf}{in}\right)$. The spring at $K = 10,000\frac{N}{m}\left(57\frac{lbf}{in}\right)$ is the same stiffness as the one used in the hardware experiments and in the human operator testing.

It is important to point out that in many of these comparisons between controllers, the comparison is between an impedance control with external interaction feedback and an impedance control without any external interaction feedback. Both are impedance controllers, with low level servo loops to control actuator pressure. But in the case of this intrinsically stiff hydraulic system, it is not feasible to obtain the desired compliant response nor the specified target output impedance without using feedback of external interaction forces. If the control designer was not interested in controlling forces at all, a standard control architecture selection would be a standard PID position servo control (or in this case, a PD, since it does not result in any steady state error). The main difference between a standard PD control and the impedance control without external interaction feedback is the low level pressure control loop. Comparing an impedance controller and a PD controller is dependent on gain selection. The choice to compare the impedance control with

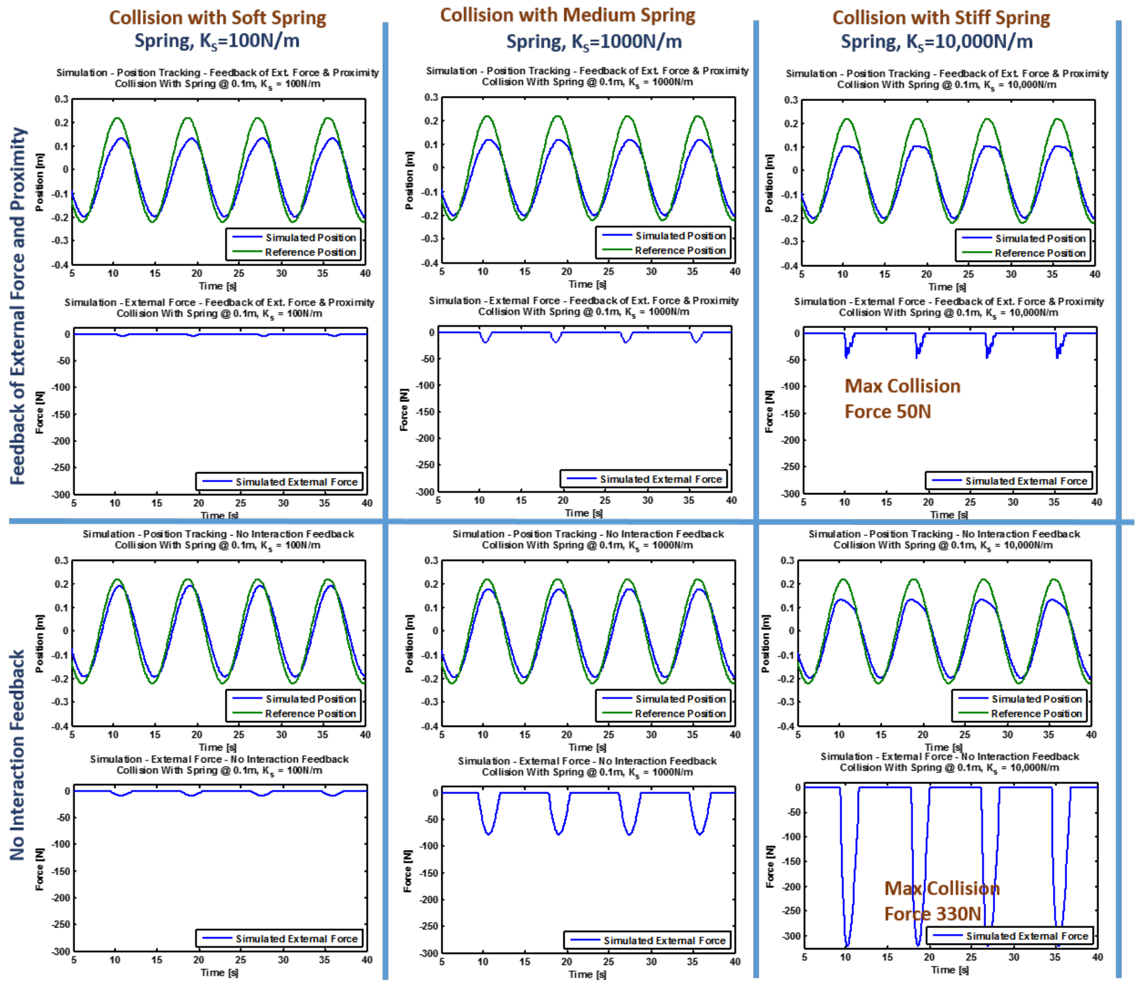


Figure 53: Simulated boom impedance control in various types of collisions. All cases $K_p = 250$, $K_d = 300$ and $K_f = 10$.

and without interaction feedback is intended to produce more structured comparisons that are less dependent on gain selection. In the impedance control, even without external interaction feedback, the low level pressure control still serves to regulate actuator force, and subsequently interaction forces, which can reduce any large pressure spikes from interaction.

Figure 54 shows a simulated comparison between a PD position control and the impedance control without interaction feedback. In the impedance control, even without external interaction feedback, the low level pressure control still serves to maintain pressure at a target value; in collisions, the low level pressure control does tend to slightly reduce pressure spikes and subsequently reduce interaction force as compared to pure position control. So, in all of these comparisons that are used to illustrate the reduction in external interaction force that results from using the impedance control with interaction feedback, it is expected that if the baseline controller was designed solely to produce the desired tracking performance (i.e. if a PD or PID control was used as a baseline instead of the impedance controller without external interaction feedback), the reduction in interaction forces would be even greater.

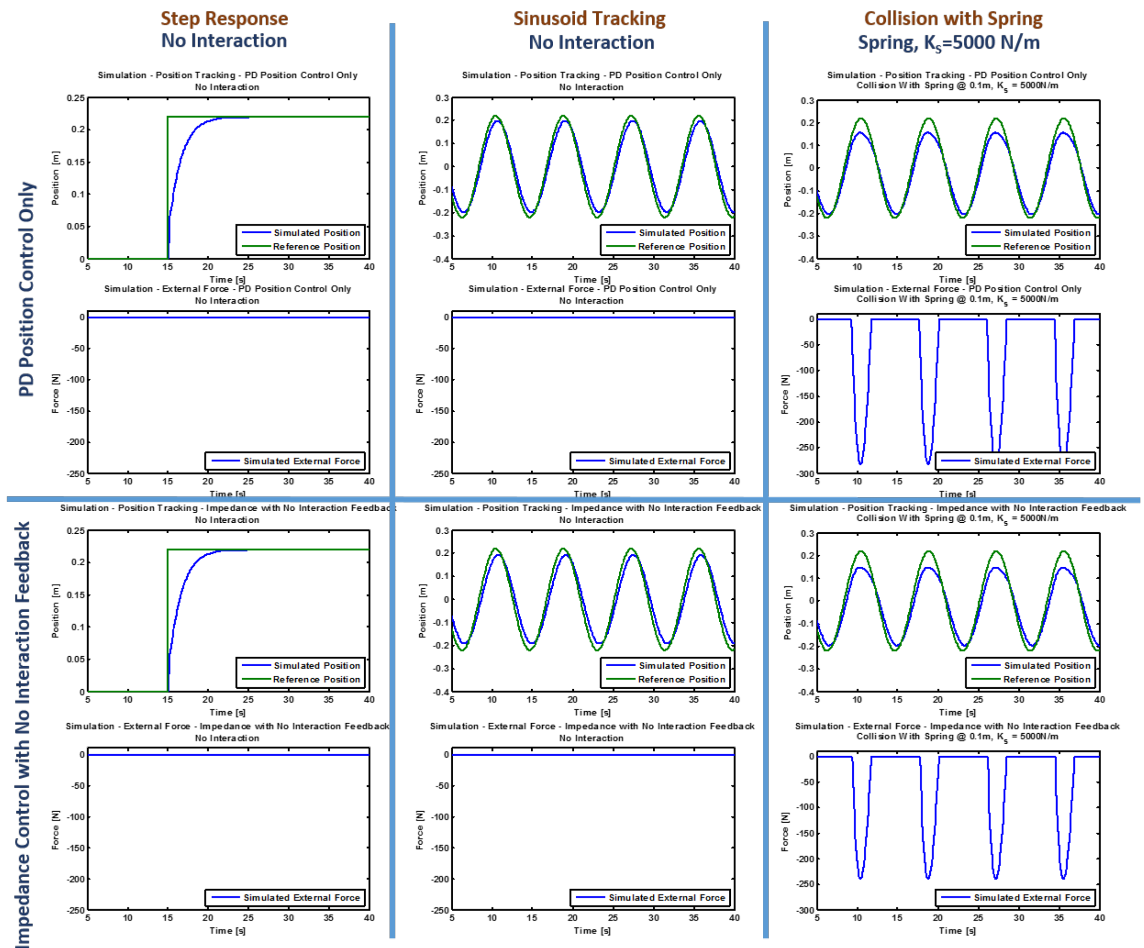


Figure 54: Simulation comparison: PD position control ($K_p = 60$, $K_d = 75$) vs. impedance control with no external force feedback

The simulations show that it is possible to obtain good tracking performance in free space, while responding with the desired spring and damper impedance parameters in interaction. They show that the impedance control is effective with this hydraulic system, with a range of impedance controller parameters, varying obstacle positions, and any combination of the available forms of interaction feedback. They also show that the controller responds as desired, in a compliant and stable manner (stability will be addressed formally in a later section), in interactions with a range of environment stiffnesses.

5.4.5 Horizontal Boom Extension: Impedance Control with Operator Input

Impedance control is known for its effectiveness at obtaining desired tracking performance in free space and management of environment interaction forces. However, in order to specify the output impedance spring constant, the impedance control must be a position control. But in this system, it is desirable for the operator input force to map approximately linearly to an output velocity. To obtain approximate velocity control from the operator input, the operator input force is integrated. However, this tends to result in sluggish response, since the operator has to wait for the integration to result in sufficient position error for the machine to start to move, particularly with the deadband in the hydraulic system. So an additional term was added, as the derivative of the operator input force, to improve the speed of response. Since the derivative term is obtained by differentiating the measured position signal, it is necessary to also apply a low pass filter; a first order low pass filter was applied. The operator input mapping to reference velocity is defined in Eqn. 17

$$X_{posref}\left(s\right) = \frac{1}{s}\left[K_h + K_{dh}\left(\frac{s}{s+a}\right)\right]F_h\left(s\right) \tag{17}$$

where X_{posref} is the reference position, F_h is the x-component of the input force vector from the human operator, K_h is a gain applied to map the input force integral to a reference position, K_{dh} is the gain applied to the derivative of the input force, and $-a$ is the pole location for the low pass filter. The block diagram for the impedance control using the operator input force to define the reference position is shown in Fig. 55.

Figure 57 shows a more detailed view of how the feedback terms are used in the impedance control, from the experiment illustrated in Fig. 83. Note that in this case, an operator input is used, rather than a software input. The top plot shows the feedback terms resulting from both measured force and measured proximity. It is clear that the proximity term is active as the boom approaches an obstacle, and the force term becomes active when it contacts the obstacle; with the proximity term active, the boom should be moving very slow when it makes contact with the obstacle. When the proximity term is

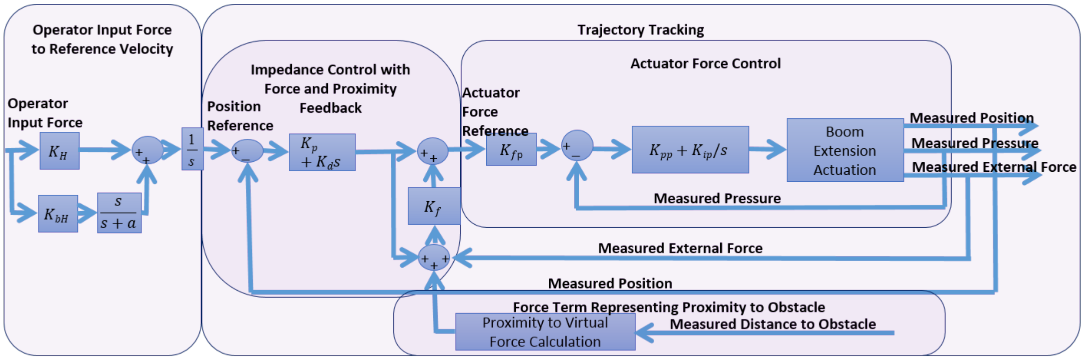


Figure 55: Impedance control with force feedback block diagram

active, it begins to slow the motion response of the boom, reducing the velocity response to the operator input. Then when it makes contact, the force term takes over to reduce the interaction force, according to the specified output impedance parameters. The effect of both terms can be tuned based on the specified output impedance parameters, or the impedance control gains.

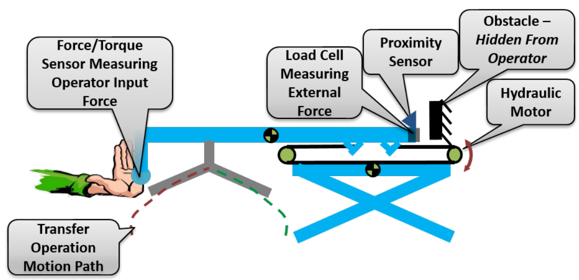


Figure 56: Illustration of interaction control experiment

The operator input force was treated as a negligible force on the machine in the analysis; it is assumed to be much smaller than other forces in the impedance (or admittance) control. In practice, it can be significant, on the order of up to 70N, but in most cases if the machine responds as desired, it should be expected to remain much lower, around 20N-30N. Analysis of the operator input force as another force on the body in the impedance control analysis would be another interesting point for future work.

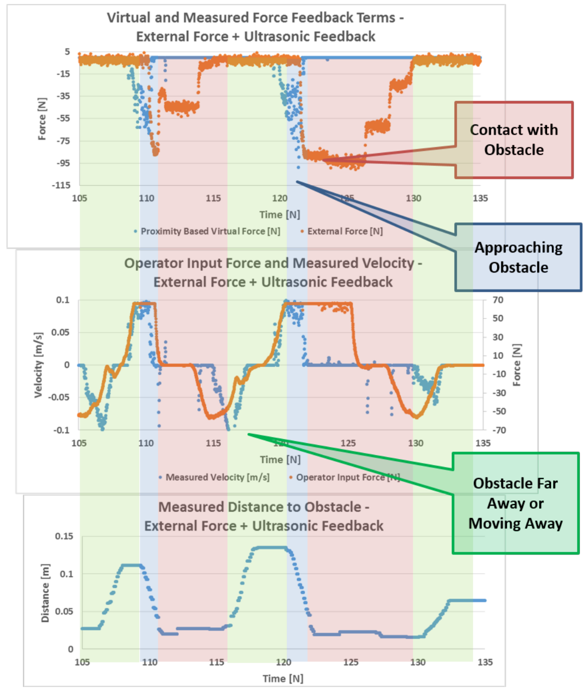


Figure 57: Impedance control with force and proximity feedback results in collision, with operator input

5.4.6 Horizontal Boom Extension: Management of Non-Ideal Features

Figure 58 shows the available measurements from an open loop sinusoidal input to the horizontal boom, showing velocity (differentiated position measurement) rather than position. The reference current has some compensation for deadband. The pressure measurement clearly illustrates the highly nonlinear effect of the check valves that are primarily intended to hold a load against gravity. The check valves are an integral part of the hydraulic system design, and since the electric motor is not designed to withstand stalling for a long period of time, they are necessary in order to stop the flow and hold the machine in place against any constant force, such as gravity, without requiring constant power from the hydraulic power unit.

These check valves are pilot operated, and they open when the pump pressure reaches a value higher than the pressure on the actuator side of the valve (enough to make it move), with some margin. So when starting from zero velocity, it takes some small amount of time to build up enough pressure to open the valves. Then, once the valve opens, then there is stiction in the hydraulic motor and in the mechanism. Once it overcomes both the valves

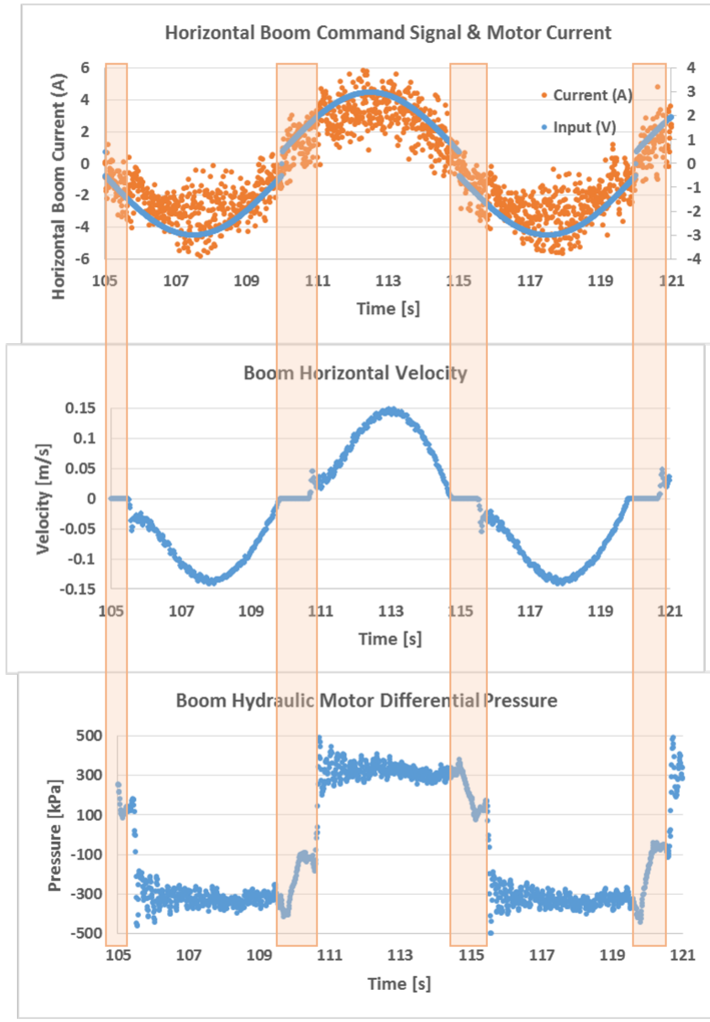


Figure 58: Horizontal boom open loop response

and the stiction, there is a sudden change in pressure, the machine moves quickly at first, and some small pressure oscillation occurs. As a result, it is very difficult to control these hydraulic power units at low speeds or low pressures (or low actuator forces). Furthermore, there is substantial stiction and friction in the hydraulic motors, and that stiction is highly dependent on lubrication; the motors tend to be "arthritic", making the system highly nonlinear and time varying.

In the horizontal boom extension, a few nonlinear terms were added to the low level pressure control to partially manage these nonlinearities. Some deadband compensation was added in the hardware low level pressure control; however, it is not desirable to make the deadband large enough to overcome static friction, since the force required is lower once it is moving. So the deadband compensation partially cancels the deadband in the machine motion, but not completely. Also, any very high speed switching of current in an electric motor can be damaging and cause excessive heating. To compensate for that, the reference current command is rate limited; this rate limit is high relative to the typical rate of change in the command signal produced by the controller, so in normal operation, its effect is negligible. Stalling an electric motor for a long period of time can also cause excessive heating. The control input is set to zero and the reference position is set to the current measured position any time the operator input is zero; if for some reason it cannot physically reach its reference position, the controller will not continue to try to reach the reference position after the operator lets go of the input handle. On the vertical lifting, all of these same compensation techniques are applied, plus additional features to manage the gravitational load and the larger forces; these will be described in a later section.

5.4.7 Horizontal Boom Extension: External Force Estimation

The system cost and complexity would be greatly reduced if it was feasible to estimate the external interaction forces based on known system parameters and measurements of position and actuator pressure, and for the lift, payload weight. There would be possibilities for external interaction force vectors that could not be measured from pressure, such as on the sides of the machine; proximity sensing alone could be used in those places. A disturbance observer was designed for the horizontal boom extension for the purpose of estimating the external force without the load cell measurement, but some issues were encountered.

It was determined that the earlier transfer function models did not capture some pressure dynamics that are necessary for estimating the external force. Specifically, there is some resistance in the hydraulic system, so when an external force is applied, it results in a change in the actuator pressure; these dynamics of the hydraulic system are not captured in the previously developed models. So these resulting pressure dynamics were estimated from a different form of system identification, using a linear regression. It is possible to model the equation of motion for the boom based on the force balance, as before, and to add the external force in the boom acceleration equation, as in Eqn. 18, where α is the assumed constant relation between motor pressure and actuator force, as defined in Eqn. 14. Then a new pressure equation was defined based on dependent variables of input current and the velocity and acceleration of the boom. One challenge with the linear regression model is that some of the terms in the model are noisy and non-smooth, such as pressure, velocity and force. Data for the regression model was taken from motions similar to those performed in the experiments, this time including measured external interaction forces, and the signals were filtered. The following linear regression model was used to relate the input current, boom velocity, boom acceleration and pressure. The coefficients $q1$, $q2$, $q3$ and $q4$ were determined from the linear regression, and p is the differential pressure of the hydraulic motor.

$$\begin{aligned} m\ddot{x} + b\dot{x} &= f_{ext} + \alpha p \\ p &= q_1\dot{x} + q_2\ddot{x} + q_3\dot{p} + q_4 u \end{aligned} \tag{18}$$

This system was converted to state space, as shown in Eqn. 19. A Luenberger observer was developed based on the linear regression model for motor pressure and the boom acceleration model and from the force balance on the boom. The model includes the unknown external force and estimates it as a state. In this test, feedback of position, velocity and pressure were used in the observer. Eqn. 19 shows the state vector x, state matrix A and input vector B used to develop the Luenberger disturbance observer.

$$x = \begin{vmatrix} x \\ \dot{x} \\ p \\ f_{ext} \end{vmatrix} \qquad A = \begin{vmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{b}{m} & \frac{1}{m\alpha} & \frac{1}{m} \\ 0 & -\frac{q_2}{q_3}\frac{b}{m} - \frac{q_1}{q_3} & \frac{1}{q_3} - \frac{q_2}{q_3}\frac{1}{m\alpha} & -\frac{q_2}{q_3}\frac{1}{m} \\ 0 & 0 & 0 & 0 \end{vmatrix} B = \begin{vmatrix} 0 \\ 0 \\ \frac{q_4}{q_3} \\ 0 \end{vmatrix} \tag{19}$$

.

This disturbance observer system was simulated in Simulink, along with the modified state space model of the plant, and it was validated to ensure that the response in free space is similar to previous models and to the hardware. The observer gains were chosen to be approximately two orders of magnitude larger than the system poles and placed using Ackermann's formula; they were tuned to produce desirable results in simulation.

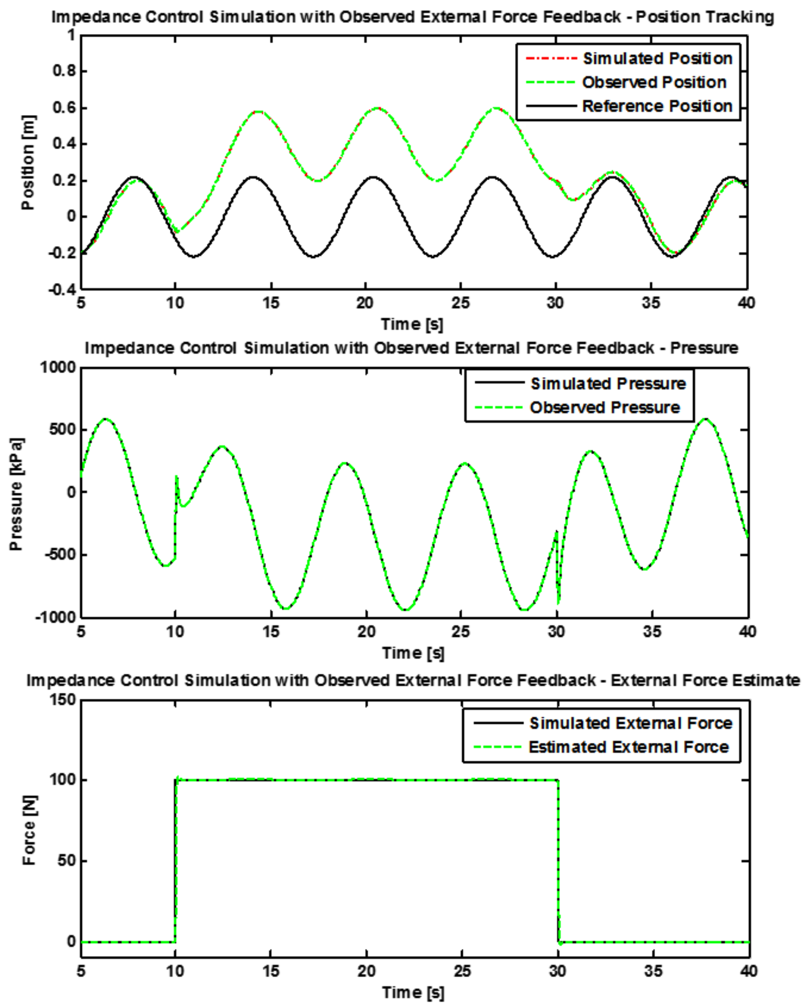


Figure 59: Disturbance observer estimate of external interaction force

The full impedance control system using observed external force as feedback was simulated, using the same impedance controller and low level pressure control as in the earlier simulations on the boom. The boom tracks a sinusoidal reference position, and a simulated pulse signal external force is applied. The results of that simulation are shown in Fig. 60. The result shows that, in this ideal case, the disturbance observer can accurately estimate the applied external force, based on feedback of position, velocity and pressure, thereby eliminating the need for load cells.

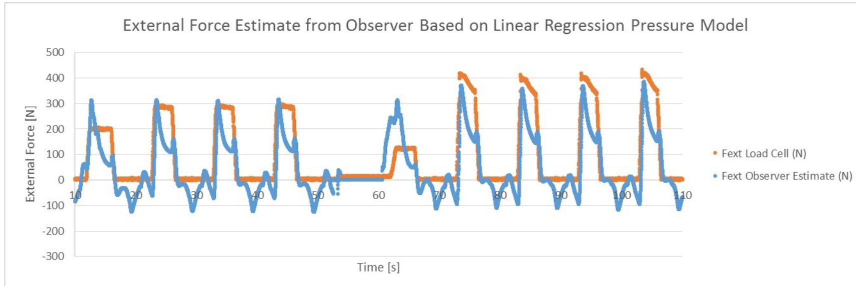


Figure 60: Validation of external force estimate from observer

In hardware, the observer produced the result shown in Fig. 60, from the same experiment as in the earlier impedance control experiments, with the boom following a sinusoidal motion in free space, then colliding with an obstacle and measuring external force. The observed external force does roughly approximate the measured external force, which could be sufficient for force feedback; high accuracy force measuring capabilities are not necessary in this application. But once the observer was used inside a closed loop control, with a highly non-smooth input signal, the nonlinear and non-ideal effects of the system became more dominant and the result was not a sufficiently close estimate of the external force to be used as feedback. The result in the hardware in closed loop was that the impedance controller with estimated external force feedback did not reduce the collision forces as compared with no external force feedback. It is possible that a better estimate could be obtained from a nonlinear observer, using an Extended Kalman Filter or particle filter, based on a better nonlinear model of the hydraulic system dynamics. The challenge lies in obtaining a sufficient model for all of the significant nonlinear effects in the hydraulic system, some of which are also time varying.

5.4.8 Horizontal Boom Extension: Stability Analysis

A stability analysis can be performed based on the linear time invariant (LTI) model of the horizontal boom extension. It can be divided into three states, (1) free space motion without contact, (2) motion moving toward an obstacle in close proximity (where the proximity based virtual force term is active), and (3) motion and force in contact with an obstacle. Analysis for state (1) can be performed on the LTI model for the horizontal boom extension and controller; state (2) includes nonlinear terms in the controller. However, the system has such significant nonlinearities and non-ideal features that such a stability analysis based on an LTI model has limited value. Stability analysis including all significant nonlinear and non-ideal features is an interesting topic for future work. It is important to note that there is a free space transition stage (state 1) of 2 cm where neither the force nor proximity feedback terms are active, occurring between the proximity-active state (2) and the contact state (3). At no point does the system transition directly between the proximity-active state (2) and the contact state (3).

For a stability analysis based on the LTI model, the contact state (3) can be addressed using a set of criteria for stability of a force-controlled manipulator in contact with any arbitrary passive environment, linear or nonlinear, developed by Colgate and Hogan (25). This stability analysis can be performed on the LTI model for the horizontal boom extension, and if the system meets the criteria, then it is stable in contact with any passive environment, which most environments are. Furthermore, as long as the environment is passive, then the transition between the free space motion state (1) and the contact state (3) should also be stable. Stability in free space can be determined based on the closed loop system poles, and it is simple to show that state (1) is stable. The virtual force term used as feedback in state (2) is highly nonlinear, but it only dissipates energy, and therefore is unlikely to cause any stability issues; similarly, because no energy is added, no stability issues are expected in the transition between the proximity feedback state (2) and free space motion state (1). Throughout all experiments and simulations, no signs of limit cycles nor instability have been observed as a result of the proximity based virtual force term.

While force feedback controlled systems do often have issues with stability and chatter in contact with very rigid obstacles, particularly in systems with inherently slow dynamics such as this one, those issues can sometimes be mitigated by adding compliance to the force sensor itself. No stability issues nor chatter were observed in the hardware experiments in collision with a stiff spring, and it would be reasonable in practice to add such a spring to all force sensors on the machine. Further discussion of stability with the LTI model in state (3), in contact with an obstacle, is included in Appendix A.

5.5 *Vertical Scissor Lift Control*

While the control development and analysis focused on the horizontal boom extension, several different types of control were also tested on the vertical lifting scissor in hardware. The control of external interaction forces was tested in hardware, but it was not used in the human operator testing.

Preliminary testing of several different types of control was also implemented on the vertical lifting scissor in hardware. The lift has some additional, significant control challenges. It is necessary to manage a large gravitational load, which is highly variable with varying patient weights. The kinematics of the machine are complicated and highly nonlinear. There are significant nonlinearities in the hydraulic system, and it is necessary to ensure that the electric motor does not overheat.

In the current PTAD hardware, both impedance control and admittance control frameworks were tested with a software input. Also, on a pre-prototype hydraulic lifting machine, a control strategy called a passivity based human power amplifier was tested, but it was determined to be insufficient for the needs of the application.

In the case of the vertical scissor lift DOF, there are tradeoffs between the admittance framework and the impedance framework. Impedance control is generally better at obtaining low output impedance, since it includes control of actuator force, which can be relatively fast. In this application with very high forces involved, it is necessary to have very low output impedance. However, the challenge with impedance control is that the low level control requires knowledge of all significant forces on the boom that are not externally applied, including the payload. As the patient is lifted or lowered and the payload weight transfers between a support structure (e.g. a chair or bed) and the machine, the payload varies significantly with time. Therefore, it would be necessary to measure or estimate payload weight in real time. The admittance control framework has the advantage that it does not require any measurement of payload weight, nor knowledge of all forces on the lift. However, disadvantages include that it is less able to achieve very low output impedance, and the response to external forces tends to be slower with a low level position control than with a low level pressure control.

5.5.1 Vertical Scissor Lift: Impedance Control Development with Gravity Compensation

The vertical lift is only a single DOF of the machine, but the kinematics between the actuator and the end effector are complex. As a result, the impedance control formulation for a multiple DOF system was, with low level force (pressure) control in cylinder space. The expansion of impedance control to a generic multiple degree of freedom manipulator is described in (24). The associated resulting reference actuator force is given in Eqn. 5.5.1. Note that the high level impedance control is in task space, but the reference actuator force is defined in joint space. So the reference positions and velocities are defined in task space, and the joint position and velocity measurements are mapped to task space by the Jacobian; the control is applied in task space, and then the resulting control effort is mapped back to joint space by the Jacobian transposed; the resulting desired actuator force is given in Eqn. 5.5.1

$$F_{act} = J^T \left(K \left[x_r - L\left(q \right) \right] + B \left[\dot{x_r} - J\left(q \right) \dot{q} \right] \right) - K_f \left(F_{ext} + K \left[x_r - L\left(q \right) \right] + B \left[\dot{x_r} - J\left(q \right) \dot{q} \right] \right) \tag{20}$$

where J corresponds to the Jacobian matrix for conversion between task space and joint space velocities, and similarly, L corresponds to the matrix for transformation between task and joint space positions q; in this case, the task space position is the scissor height and the joint space position is the cylinder position. In (29), this impedance control was applied to the mechanical dynamics simulation of two degrees of freedom of the patient transfer assist device, but at that stage the hydraulic system dynamics were neglected.

For this scissor lift, the L transformation, or the conversion from scissor cylinder position to scissor height is given by Eqn. 21

$$\begin{aligned} \phi &= acos\left(\frac{a^2 + b^2 - L_{cyl}^2}{2ab} \right) - \alpha - \beta \\ H &= 2L_l \sin\left(\phi \right) \end{aligned} \tag{21}$$

where L_{cyl} is the current cylinder length, H is the scissor height, L_l is the length of a scissor cross beam, and a, b, α and β are shown in Fig. 61.

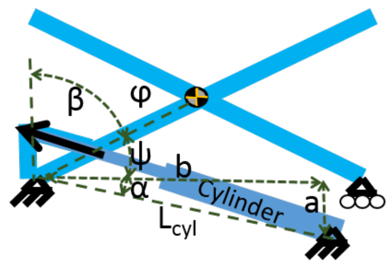


Figure 61: Scissor lift kinematics notation

In the impedance control, the low level loop controls actuator pressure. This is important; it is necessary for the controller to know the pressure necessary to hold the weight of the machine plus any payload in its current location in real time. In order to define a reference pressure, it is necessary to account for all forces on the scissor lift aside from any externally applied interaction forces. In this implementation, any forces other than the actuator force and payload weight are treated as unknown external forces.

The cylinder force required to hold the weight of the machine is computed in real time based on a static assumption, using known inertia and kinematics parameters of the machine and a measurement of the cylinder position, as shown in Eqn. 22

$$\begin{aligned}
\gamma &= \cos^{-1}\left(\frac{a^2 + b^2 - L_{cyl}^2}{2ab}\right) \\
\psi &= \sin^{-1}\left(b\frac{\sin(\gamma)}{L_{cyl}}\right) \\
\tau_{noload} &= 2L_l m_{bar} g \cos(\phi) + 4L_l m_l g \cos(\phi) + 2L_l m_{pl} g \cos(\phi) \\
F_{cyl} &= \frac{\tau_{noload}}{a \cdot \sin(\psi)}
\end{aligned} \tag{22}$$

where F_{cyl} is the cylinder force required to hold the weight of the lifting scissor, τ_{noload} is the torque on the scissor cross beam at the fixed base pin, g represents gravity, m_{pl} is the mass of the top plate, m_l is the mass of a scissor link, m_{bar} is the mass of the horizontal boom, and ψ, ϕ, and γ are angles shown in Fig. 61.

Similarly, the cylinder force required to counter an external force in the vertical direction is given by Eqn. 23

$$\begin{aligned} \tau_{load} &= 2L_l W_{load} \cos(\phi) \\ F_{cylload} &= \frac{\tau_{load}}{a \cdot \sin(\psi)} \end{aligned} \tag{23}$$

where $F_{cylload}$ is the additional cylinder force required to hold the weight of the payload, W_{load} is the weight of the payload, and τ_{load} is the additional required torque at the scissor base pin.

For gravity compensation, the machine and payload weight are converted to pressures based on a static assumption; for the purpose of the control, the static assumption is sufficient. Figure 62 shows the validation of the calculated pressure required for gravity compensation with no load, based on a position measurement in real time. Notice that this static assumption based model validates very well except when it first starts to move, as the check valves open, and when it is moving down. When it is moving down, the pressure is higher than the estimate because the flow is restricted at the pump outlet because it has to cross the relief valve in order to reach the tank. This restriction causes higher pressure on the inlet side of the pump as well. These dynamics were not modeled in detail, since the specifics of the power unit parameters were unavailable.

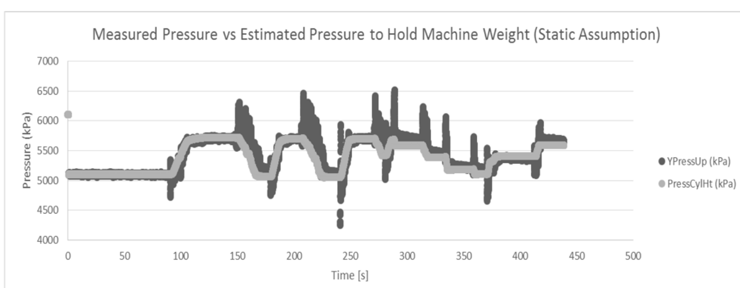


Figure 62: Validation of calculation of pressure required to hold weight of machine at different positions

If all forces in the vertical direction are known except for the external interaction forces, then it should be feasible to estimate the external interaction force based on known parameters. The only significant forces in the vertical direction on the scissor lift and boom are the actuator force, gravitational load, payload and any external interaction forces; other forces (e.g. friction and operator input force) are relatively small. The actuator force is known, and Fig. 62 indicates that the estimate of the required gravity compensation pressure is valid and sufficient for compensation in this generally slow moving system. The effect of any unknown load force in the vertical direction on cylinder pressure can be estimated by Eqn. 23, also based on a static assumption. This estimate is not using any observer; it is calculated directly based on the difference between the calculated pressure required to counter known forces and the actual pressure measurement.

Figure 63 shows this external force estimate for an external load applied to the horizontal boom in the vertical direction, near the hanger bar. This shows that the estimate of the external load is reasonably accurate, or at least should be sufficient for feedback to give the operator some indication that external interaction is occurring. The friction, leakage and other nonlinear, time varying effects are less significant in the cylinder than in the hydraulic motor, so a much simpler method of estimation can be used. This external force estimate is based on Eqn. 23.

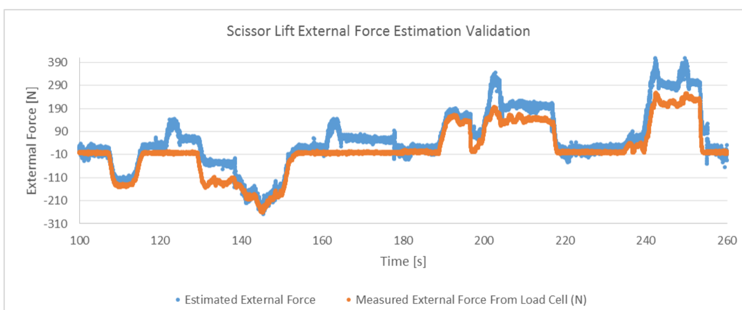


Figure 63: Estimated external force on vertical lift

5.5.2 Vertical Scissor Lift: Management of Non-Ideal Features

The non-ideal features are most prevalent in the lifting degree of freedom. Some of the most significant non-ideal and nonlinear effects are as follows.

- The most significant nonlinearity in the system results from the check valves that hold a load against gravity when the pump is not running. These check valves are pilot operated, based on the difference between the pump pressure and actuator pressure. It takes enough pump pressure to hold the load to open the valves. It takes a significant pressure to compensate for the gravitational load, often nearly half of the available signal range (corresponding to reference motor current). This makes for a large deadband nonlinearity in motion when moving up. There is also some deadband when moving down, but it is much smaller. Part of this deadband is directly canceled in the low level pressure control, by adding an offset to the command signal. But since the deadband is load dependent and varies with kinematic configuration, the offset is only enough to compensate for the minimum deadband, corresponding to zero load at the kinematic configuration with the lowest required actuator force.

- As discussed earlier, when the scissor is moving down, the flow is restricted by the current single acting cylinder circuit configuration with the relief valve. This effect is clear in Fig. 62, where the lift pressure goes high when the scissor lift is moving down.
- As with the boom, though to a lesser extent, there is some static friction in the hydraulic cylinder and in the scissor mechanism.
- The kinematics of the scissor lift between the actuator and end effector are complex and nonlinear; while the position relation remains approximately constant throughout the range of motion, the pressure required to hold the weight of the machine varies significantly; this nonlinearity is accounted for in the gravity compensation.
- With the larger force requirement of the scissor lift, ensuring that the electric motor does not stall too long is a more significant concern. This is handled in four ways.
  - The command signal (reference motor current) is set to zero any time the operator input force is zero.
  - At any time in operation when the machine is not moving and the command signal is above a threshold value, the command signal is changed to zero for a specified time, to let the motor cool.
  - If the position error remains very small, then the reference pressure is ramped down slowly to zero.

- The command signal is rate limited to ensure that the electric motor and driver do not attempt very fast switching of current.

5.5.3 Vertical Scissor Lift: Impedance Control Implementation

The impedance control framework was implemented on the scissor lift as shown in Fig. 64, using measured force feedback. Testing of proximity sensing was limited to the horizontal boom extension. The external interaction force measurement, the trajectory tracking and the impedance controller all operate in task space. The impedance controller produces a reference actuation force in the vertical direction, which is then converted to joint space for control of the cylinder pressure.

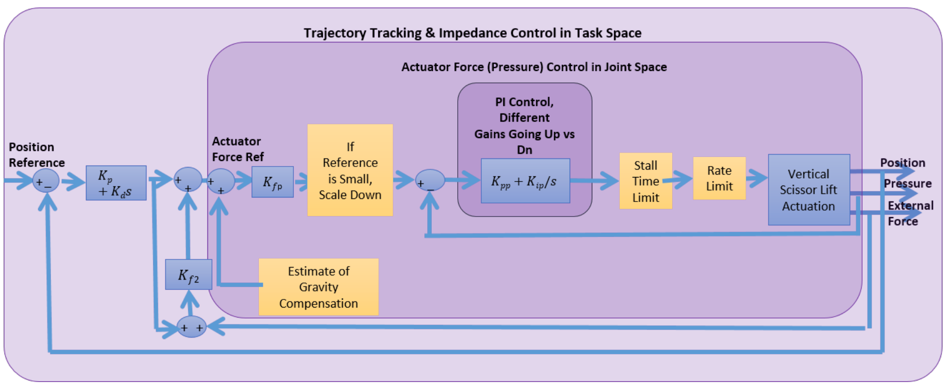


Figure 64: Scissor lift impedance control with force feedback block diagram

The impedance control on the vertical lift includes compensation for all of the nonlinear and non-ideal features as described in the previous section, including protection features for the electric motor, compensation for deadband, compensation for gravity, and the necessary nonlinear conversions between joint space and task space.

5.5.4 Vertical Scissor Lift: Impedance Control Results

Figure 65 illustrates a basic experiment that was performed on the vertical lifting to validate the effectiveness of the impedance control with respect to a measured external interaction force. In this degree of freedom, the necessary forces and pressures are larger, as required by the application. So it is important to ensure that the controller can manage forces within a reasonable range for a human. The impedance control was set to a target impedance of $K_p = 800\frac{N}{m}$ and $K_d = 600\frac{N}{m \cdot s}$, which is higher than the target impedance that was primarily used on the horizontal boom extension. Of the values tested, it was the minimum desired impedance that produced reasonable tracking performance in free space on the vertical lifting degree of freedom.

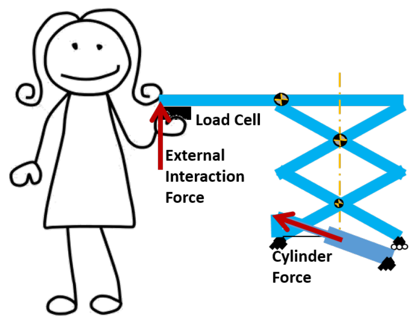


Figure 65: Schematic of impedance control test on vertical lift

As in Fig. 65, the external force was applied by a human hand, demonstrating its safety and ability to work within a reasonable range of forces for the human. The vertical lift was given a sinusoidal position reference, and the external force was applied upward. The plots in Fig. 66 show that the machine responds to the measured external interaction force, approximately according to the defined spring and damping parameters. This force was applied more slowly than it would be in a collision, so it is an important next step to consider the performance of the impedance control on the vertical lift, in a faster collision. These results do give some indication that the impedance control can manage interaction forces to maintain them at a reasonable level for a human in the workspace, even with this very heavy machine.

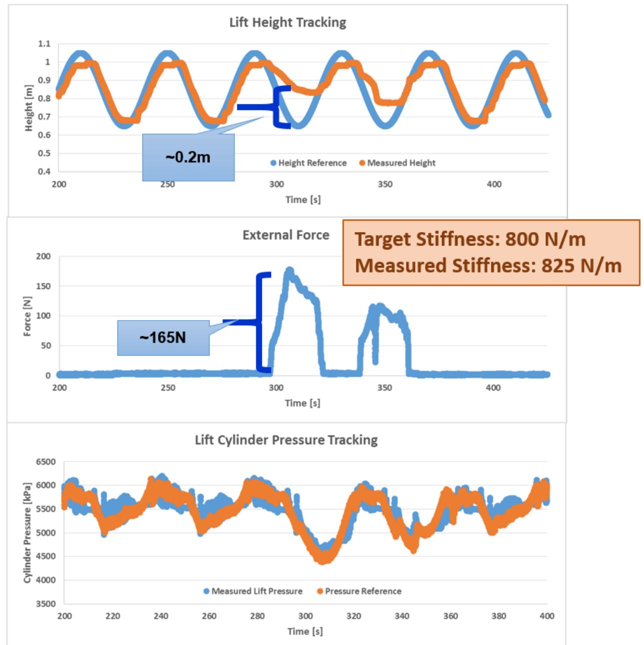


Figure 66: Result of impedance control test on vertical lift

5.5.5 Vertical Scissor Lift: Control Implementation for Operator Studies

For the purpose of this human operator testing using the full 4-DOF PTAD, a rate control from the operator input with a framework similar to the impedance control was implemented. The interaction control was left to the software input experiments only; further testing of interaction control with the human operator input on the vertical lifting scissor is left as future work. The controller used for the human operator studies (Fig. 67) uses a position control loop in task space for trajectory tracking, like the impedance control. The operator input force is integrated to obtain a reference position, such that the operator input force maps approximately linearly to a velocity. Within the height position control loop (in task space) is an inner cylinder rate control loop (in joint space), rather than a pressure control loop, which helps to smooth some of the nonlinear and non-ideal effects of the hydraulic system. This allows for testing of the operator force input concept, along with integration of the operator input force mapping to a reference position, without the complications of controlling cylinder pressure in such a high force application.

Figure 68 shows the height reference obtained from an operator input, along with the measured height. Recall that the reference height is set to be equal to the current height

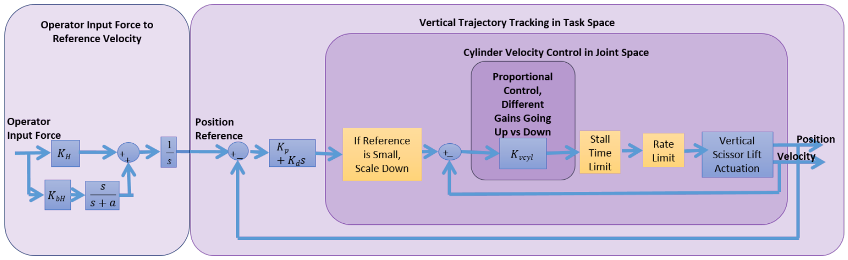


Figure 67: Vertical scissor lift control implemenation for human operator testing; outer height control loop with low level cylinder rate control

at any time when the operator input force is zero (or below a threshold), in order to ensure that the machine does not keep trying to attain a physically unreachable reference position; this also aids in ensuring that the electric motors do not stall too long. The plot shows the tracking performance with zero payload and with a 250lb mannequin. There is some difference in the tracking, but operators found the performance to be sufficient in both cases. If impedance control was used, then gravity compensation would be used to directly compensate for the change in payload weight, so there should be no difference between the two, at least at steady state.

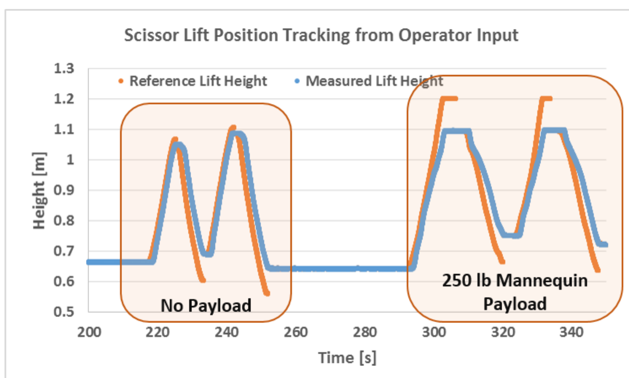


Figure 68: Scissor lift height tracking from operator input

In the human operator studies with all four DOFs of the PTAD, the impedance control was deemed not yet ready for testing with human operators. Some additional safety checks and features will be needed before testing an interaction control framework on the vertical lift, where the forces involved are much larger and the payload weight is highly time varying. Such next steps would include adding control features to ensure that actuator forces stay in a reasonable range, that the controller properly handles highly time varying patient weight measurements, that stability is certain in the presence of the significant nonlinearities in the hydraulic system, and that the machine motion is properly rate limited.

5.6 Wheel Control

The control analysis was focused on the upper degrees of freedom of the machine. A simple rate control was implemented on the wheels, where the reference patient velocity in the plane of the wheels is a constant multiple of the operator input force in that vector. The patient velocity at the end of the boom is mapped to a reference wheel velocity according to the kinematic relation in Fig. 69 and Eqn. 24,

$$\begin{aligned} v_R &= v_{px} - \left(\frac{d}{2}\right)\left(\frac{v_{py}}{L}\right) \\ v_L &= v_{px} + \left(\frac{d}{2}\right)\left(\frac{v_{py}}{L}\right) \end{aligned} \tag{24}$$

where v_R is the right wheel velocity, v_L is the left wheel velocity, v_{px} is the patient reference velocity in the task space x-direction, v_{py} is the patient reference velocity in the task space y-direction, and d and L are shown in Fig. 69. The corresponding block diagram is shown in Fig. 70. While L does vary with boom position, it is assumed constant at the minimum value; operators do not sense the small variation as the boom extension position varies.

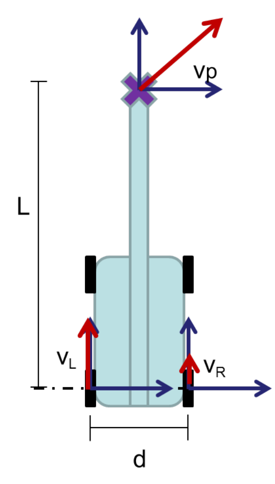


Figure 69: Wheels kinematics

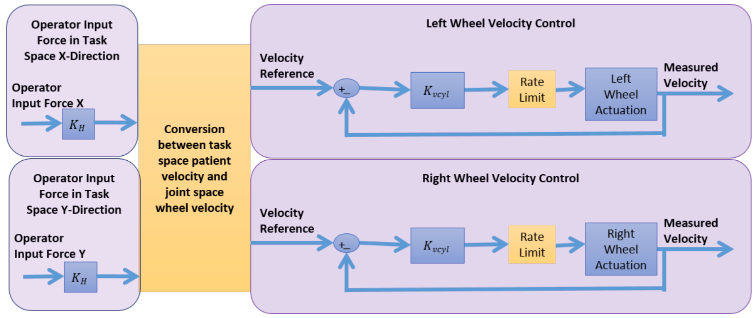


Figure 70: Block diagram for simple wheel rate control

5.6.1 Obstacle Avoidance with Proximity Sensing

Earlier in the project, the wheels and their control were tested on a separate cart, for the purpose of testing wheel controllers without any risk of damage to the rest of the machine. The same type of operator input was used, and a beam representing the horizontal boom extension was added. The cart had the same type of force sensing operator input as the main machine, and the operator input mapped to a reference velocity in the same way as in the full 4-DOF implementation.

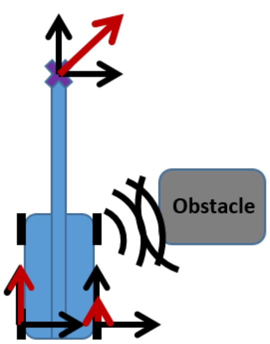


Figure 71: Obstacle avoidance on wheels

Obstacle avoidance using ultrasonic sensors was added to the wheels cart in a separate project, by an REU (Research Experiences for Undergraduates) student, Grace Deetjen. Twelve ultrasonic sensors were mounted around the proximity of the cart, as shown in Fig. 72. The utilization of the proximity measurements was based on a virtual force field. As the distance to an obstacle decreased, the operator input force required to move in a vector toward the obstacle increased. When the distance reached a set minimum distance of 2cm,

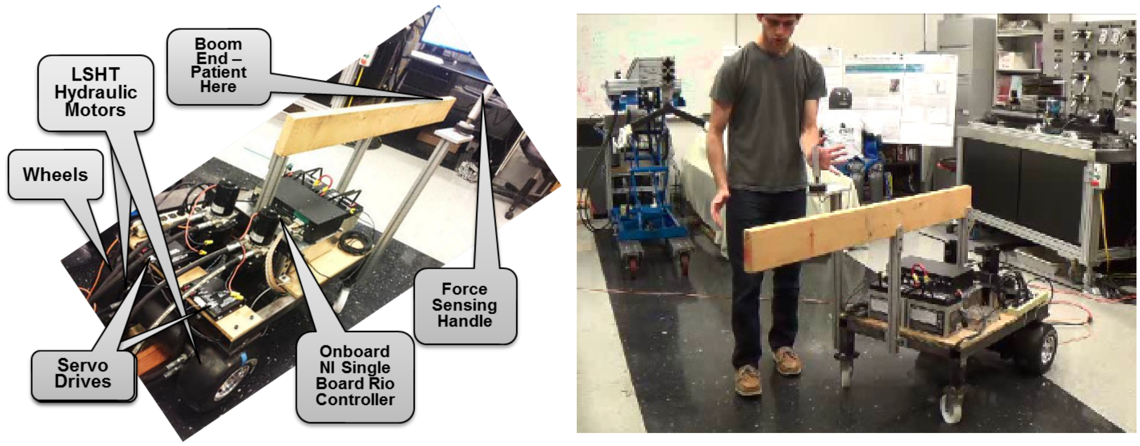


Figure 72: Wheels testing cart

the controller would not allow motion in a vector toward the obstacle at all (Fig. 71). The obstacle avoidance worked very well; too well in some cases. It did not allow for full utilization of the workspace, since it would not allow the machine to move within the set minimum distance from any obstacle, even if that obstacle was a bed sheet.

5.7 Alternative Control Approaches

Preliminary hardware experiments were performed on two other types of interaction control, an admittance control and a passivity based human power amplifier.

5.7.1 Admittance Control

Admittance controllers aim to control the output admittance, rather than impedance. The output of the admittance controller is a reference position, and a separate low level servo loop is used to track the reference position. There are a number of variations on admittance controllers. In this version, the external interaction force is passed into a desired admittance transfer function, consisting of a mass, spring and damper; the output of that transfer function is a modification to the reference position. The primary advantage of admittance control over impedance control, particularly on the vertical lift, is that it does not require knowledge of all forces applied to the mechanism. This form of admittance control was tested on both the horizontal boom extension and the vertical lifting scissor, with a range of target admittance parameters. But in both cases, lower output impedance with smoother position tracking could be obtained with impedance control.

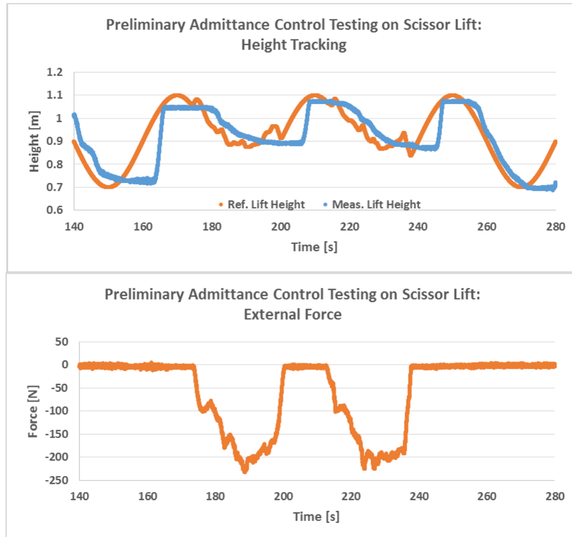


Figure 73: Preliminary admittance control test on vertical lift

Figure 73 shows the result of the same experiment on the lifting scissor as shown in Fig. 65 but this time using the admittance control. The admittance control is slower to respond to external interaction forces, the low level PID position control did not have sufficient compensation for nonlinear/non-ideal features, and it did not attain desired tracking performance. It is clear in the plot that when the scissor starts to move up, it takes time to build up enough pressure to overcome the gravitational load and start to move; then it moves very fast to catch up to the position reference signal. It is likely possible to obtain somewhat better tracking performance with better compensation for non-ideal features in the position controller. Still, the admittance controller results in a very non-smooth height reference signal when the external force is applied, and it is slower to respond to external forces.

5.7.2 Passivity Based Human Power Amplifier

Only preliminary tests on a pre-prototype machine were performed using the passivity based human power amplifier; it was soon found that it requires an excessive force from the operator in this application. The passivity based human power amplifier is a different approach to operator-machine collaborative manipulation, using force and velocity feedback. The formulation adds a virtual mass-spring system coupled with the physical system mass, and it uses the force balance on the virtual and physical masses to achieve both velocity and force coordination, according to the specified force amplification factor. Many types of controllers could be designed with the property of passivity. Power amplifier controllers are inherently prone to instability; because this system also physically interacts with humans, the property of passivity is desirable. Proving passivity for this particular case is a step for future work, but it has been shown for other similar hydraulic systems (33). The forces applied to the two system masses are shown in Fig. 74. The spring is based on the fluid compressibility and volume; the low compressibility of hydraulic fluid and resulting high stiffness are actually beneficial in this formulation.

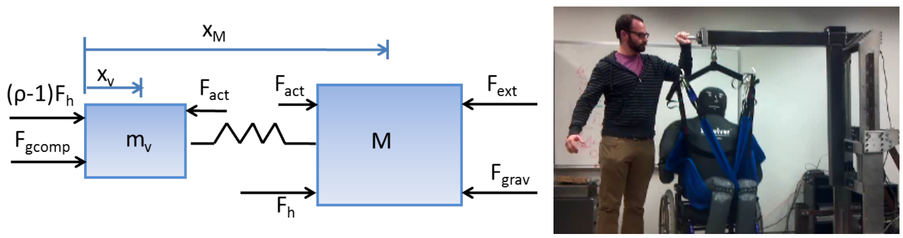


Figure 74: Left: forces on virtual and system masses; right: human power amplifier operator experiment

The force balance on the two masses is given in Eqn. 26.

$$m_v \ddot{x}_v = (\rho - 1)\, F_h - F_{act} + F_{gcomp} \tag{25}$$

$$M \ddot{x}_M = F_h + F_{act} - F_{ext} - F_{grav} \tag{26}$$

where m_v is the virtual mass, ρ is the force amplification factor, M is the system mass, x_v is the virtual mass position, x_M is the system mass position, F_h is the human applied force, F_{grav} is the gravitational force, F_{gcomp} is the gravity compensation force, F_{act} is the actuator force excluding the gravity compensation component, and F_{ext} is any external interaction force. The controller is intended to make the system mass track the virtual mass velocity, where the virtual mass velocity is determined based on the force balance, in Eqn. 27.

$$\dot{x}_v = \int \left[\frac{1}{m_v} \left((\rho - 1)\, F_h + F_{gcomp} - F_{act} \right) \right] dt \tag{27}$$

Applying a state transformation from x_v and x_M to a locked system velocity V_L and a shape system velocity V_E, and corresponding forces F_L and F_E, we have the following state transformed force balance (Eqn. 29) ((33)).

$$\phi_1 = \frac{m_v}{m_v + M} \qquad \phi_2 = \frac{M}{m_v + M} \tag{28}$$

$$\begin{pmatrix} F_L \\ F_E \end{pmatrix} = \begin{pmatrix} \rho F_h - F_{ext} - F_{grav} \\ F_{act} + \phi_1 \left(F_h - F_{ext} - F_{grav} \right) - \phi_2 \left(\left(\rho - 1 \right) F_h \right) - F_{grav} \end{pmatrix} \tag{29}$$

For velocity coordination of the two masses, we set $F_E = 0$; then solving for the actuator force F_{act} gives the desired actuator force F_{act}^{des} (Eqn. 30).

$$F_{act}^{des} = \phi_1 \left(F_h - F_{ext} - F_{grav} \right) - \phi_2 \left(\left(\rho - 1 \right) F_h \right) - F_{grav} \tag{30}$$

The following terms are defined (Eqn. 31):

$$F_{err} = F_{act}^{des} - F_{act}, \quad Z_f = \int F_{err} dt, \quad \dot{x}_v = K_{hyd} u \tag{31}$$

where F_{err} is the error term in force control, and K_{hyd} corresponds to the coefficient between an input voltage and the corresponding output flow, at steady state in open loop. Then the control input is comprised of two components, the first is a term corresponding to the input required to obtain the desired flow and velocity, and the second is a PI force controller.

$$u = \frac{x_v}{K_{hyd}} + K_p F_{err} + K_i Z_f \tag{32}$$

This passivity based human power amplifier was implemented on an earlier pre-prototype for the patient transfer assist device. The concept of this approach is promising. However, in the original testing, no compensation to counter the gravitational load of the patient was applied. The allowable force amplification factor ρ is limited by stability and passivity. As a result, the necessary operator force required to lift a patient was much larger than desired. In future work, separate compensation for measured patient gravitational load could be tested. Further details on results in the original testing are given in (26).

5.8 Control Strategy for Human Operator Testing

Human operator experiments were performed on the PTAD with all four DOFs controlled from a single operator input handle. A three-position switch was used to switch between three states: a) control of the vertical scissor lift & horizontal boom extension, b) all control off, and c) control of the wheels. The impedance controller was used on the horizontal boom extension, the position control with low level cylinder rate control was used on the scissor lift, and a simple rate control proved effective for the wheel control. In all four DOFs, the operator input maps approximately linearly to the patient velocity, and all were tuned to obtain a similar proportion between input force and reference velocity.

5.9 Recommended Control Strategies for Next Generation Design

The results on the horizontal boom extension using the impedance control framework to incorporate proximity sensing and external interaction forces are promising. Additional steps for the lifting scissor include incorporation of a measured payload weight and implementation with proximity sensing. By using hydraulic power units with less nonlinear/non-ideal effects, then more extensive modeling of those hydraulic power units, it would likely be feasible to use pressure measurements to estimate external interaction forces, thereby eliminating the need for load cells. This approach could be used on all four degrees of freedom, producing more similar dynamics among all of the degrees of freedom.

CHAPTER VI

HUMAN OPERATOR TESTING

6.1 Operator Testing Overview

The goal of the operator testing experiments was twofold. The first aim was to evaluate the performance of the prototype patient transfer assist device, focusing on demonstrating the concept of a force-assist machine. The second was to evaluate the ability of the controller to manage undesirable external interaction forces. The experiment protocol followed Georgia Tech IRB protocol number H16201.

The experiment consisted of transferring a 250 pound mannequin between a set of locations using the machine. Each participant performed the two parts of the experiment in one session, within about one hour. The first part of the experiment focused on full transfer operations, and the second focused on the interaction control. Participants were first given a set of printed and verbal instructions and a set of transfers to perform as practice. Then they performed a set of transfers between five locations. Time study data was recorded, as well as video if consent was given. Further details on the PTAD testing and procedures can be found in Appendix B.

6.2 Transfer Operations Testing

The primary goals of the transfer operations testing was to demonstrate and validate this concept of a powerful, multiple degree of freedom hydraulic force-assist machine and its potential for improving patient transfer operations for caregivers. At this early prototype stage, there are a number of aspects of the machine that are not yet optimized, particularly in the mechanical design, and it is challenging, sometimes infeasible, to fully separate these limitations from the focus of the research in the experiment results. However, it is still informative and important to run operator studies with this prototype, keeping in mind that there are some known design issues that are not yet addressed.

In the transfer operations testing, the primary test results included operator survey results, videos, and time study data. From these, it is possible to conclude which are the primary areas to focus for improvement in later versions of the design and to obtain information on any limitations. It also provides validation of the viability of the proposed operator interface and control approach.

After signing consent forms, participants were given a set of printed and verbal instructions on how to best operate the machine, including tips on managing some of the undesirable characteristics of the current prototype. They were given a few minutes to get a feel for the machine dynamics by moving each degree of freedom. Then they performed a set of three transfers as practice, moving from the wheelchair to the bed, then from the bed to the chair. These are the same as the first three transfer locations in the main transfer experiment.

As for the control of the machine, all four degrees of freedom were controlled from the force sensing handle, with the input force mapping approximately linearly to a desired velocity. The impedance control framework used for the interaction control does result in a slightly more sluggish response than a pure rate control, as a result of integrating the operator input and using a position control for the machine, so it was important to demonstrate that it is not too sluggish for the operators and is easily manageable. For the horizontal boom extension, the impedance controller described in Chapter 5 on control design was used throughout both sets of the experiment, with the high level position control paired with low level pressure control. For the main lifting degree of freedom, a similar control approach was used, still using integration of the operator input force to provide a reference position for a position control of the height. However, for the lifting, the impedance control approach requires low level control of high pressures, which are highly dependent on a highly variable load; this presents a challenge in the lift control. This approach with low level pressure control was demonstrated in the controller chapter, but additional safety and redundancy features would be preferable in order to test it in a human operator study. So, instead of using the impedance control with low level pressure control for the lifting, a similar framework with high level position control was used, but replacing the low level pressure control with low level rate control. This approach eliminates the pressure control for the lift and provides some smoothing of the highly nonlinear response of the hydraulic power unit in the low level rate control.

For the wheel control, the operator input force maps linearly to a reference velocity, and rate feedback control was used for the wheels; this approach provides faster response to the operator input as compared with the impedance control approach, but it is very difficult to obtain smooth response because the operator input force measurement is inherently a noisy and non-smooth signal, as are the differentiated wheel position measurements. In the future, it is possible that the use of an extended Kalman filter observer or other form of estimation for nonlinear systems could improve the smoothness of the wheel response under rate control. The challenge is that the hydraulic system is difficult to model accurately and highly time varying, particularly based on varying lubrication. All degrees of freedom were tuned such that a the desired force produces a resulting reference velocity of the end of the boom in task space, regardless of the direction of motion.

Before beginning the experiment, participants were given instructions on how to operate the machine, including the use of the force sensing handle. They were also given tips and guides on best practices to manage specific known limitations of the prototype. For example, this prototype has a very long nonholonomic base, as a result of using readily available components and modular design, and it is difficult to learn to steer, like parallel parking. A more optimized design would definitely have a shorter base, and we can envision simple ways to do that, so that is not an aspect that we want to focus on evaluating in the experiment. So the operators were given an opportunity to practice the significant base maneuvers before starting the time study, and tape was placed on the floor to guide them on the most efficient path. Similarly, they were informed that the current caster wheels on the front of the machine can be difficult to align, so they practiced those maneuvers as well.

6.2.1 Transfer Operations Experiment

Transfers between a set of five common types of locations for patients were tested. Operators moved the 250 pound mannequin from a wheelchair to a bed, from the bed to a chair, from a chair to the floor, and from the floor back to the chair. The mannequin stayed in the sling throughout the experiment, since the sling design is not a focus of this research. Participants did include the steps of driving up to the wheelchair and attaching the sling at the start of the experiment, then detaching the sling at the end.

Figure 75 shows the set of transfers performed in the testing of the prototype PTAD, as well as the set of transfers performed in the benchmark testing of the current market patient lift. Details on the testing methods for the benchmark operator testing can be found in Chapter 3, Section 4. Note that the set of transfers are different, so a direct comparison of the total time required is not applicable. However, it is possible to compare specific subtasks, such as lifting or lowering, since the same chair, bed and wheelchair were used for the two experiments. The chosen sets of transfer operations are different based on the capabilities of each device. The current market lift could not quite reach the floor, so that operation was not tested. Also, in the experiment for the current market lift, the operation was limited to a confined space, similar to a small bedroom, to highlight the difficulties resulting from operating in a small space. The current prototype PTAD is too large to operate in such a confined space; the overall size is a known issue that must be addressed in a later stage design. So it would not be meaningful to test it in a very confined space at this prototype stage. Therefore, it was necessary to transfer between different locations with the two devices, but the same set of resting locations were used (e.g. bed, chair and wheelchair). Still, some information can be inferred from a comparison of the two machines using different sets of transfers. Figure 76 shows a set of images from the testing of the prototype PTAD testing.

The benchmark testing experiment using the current market lift was similar, but the locations of the bed, chair and wheelchair were different and the space was more confined.

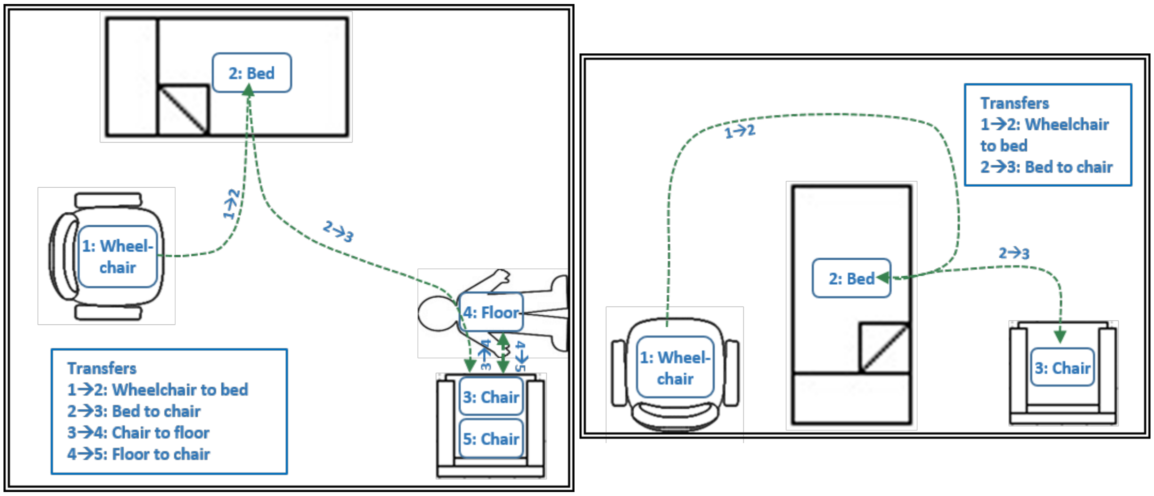


Figure 75: PTAD transfer set (left) and current market lift transfer set (right)

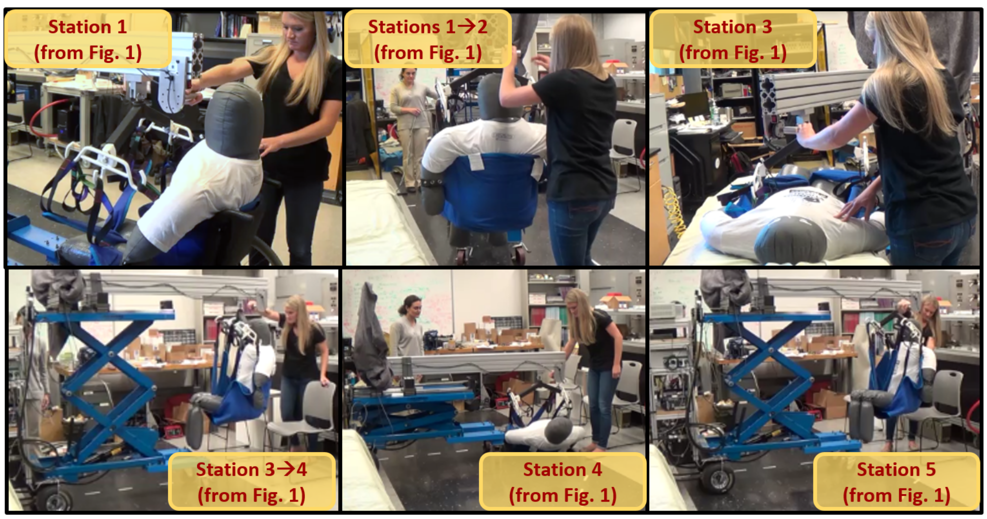


Figure 76: Photos from PTAD transfer set

6.2.2 Transfer Operations Evaluation

A task analysis was performed on the use of a current market lift, and that information was used to define a set of subtasks for a time study for the current market lift and the new PTAD. Each of those subtasks were timed for each of the 19 participants. The results of the time study for the PTAD are shown in Figure 77. A number of box and whisker plots are shown in the following sections. These are all standard box plots, with the whiskers representing the minimum to maximum values, the lower box representing the first quartile, the upper box representing the third quartile, and the line between the boxes representing the median; particularly with ratings data, it is common for some boxes and/or whiskers to be very small.

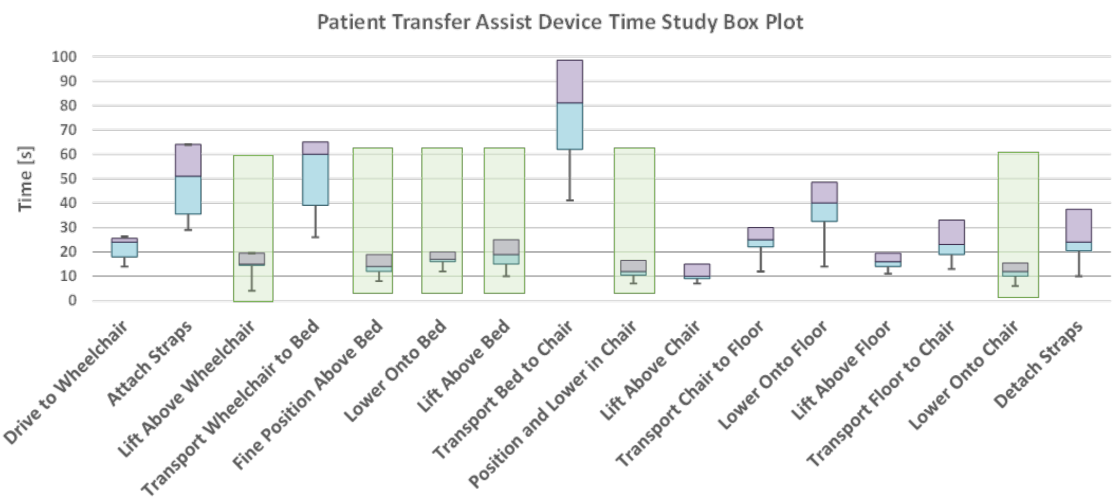


Figure 77: Time study results for PTAD transfer set

This time study gives some insight into which operations require the most time, and subsequently how design efforts should be focused to reduce the time required from caregivers. Figure 78 shows the time study results using the current market lift.

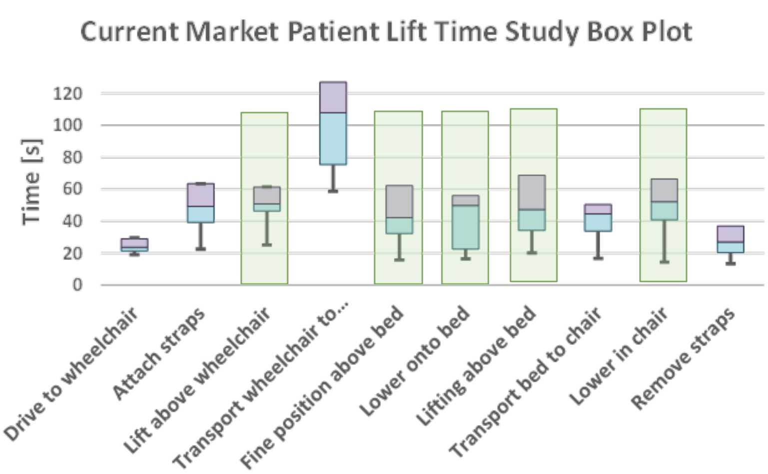


Figure 78: Time study results for current market lift transfer set

It is important to point out that the subtasks involving moving from one location to another are different between the two experiments, but certain subtasks can be compared.

Subtasks can be divided into three groups: transporting, lifting/lowering and other. Transporting subtasks, labeled “transport from A to B”, include only time in which the machine is transporting the mannequin in free space, for example moving from a position lifted above a chair to a position above a bed, ready to be oriented and lowered onto the bed. Examples of lifting/lowering subtasks include “lift above wheelchair” and “lower onto bed”, and other subtasks include “attach straps” and “remove straps”. The bed, chair and wheelchair were the same in the experiments with both devices, but the locations and space limitations were different. Therefore, the lifting/lowering and fine positioning subtasks can be compared directly, but the “transporting” subtasks cannot be directly compared.

It is promising to note that *most transfer subtasks involving moving the machine require considerably less time with the new PTAD*. For instance, to lower the patient onto the chair using the PTAD requires about 12 seconds (median), while it usually takes about 50 seconds (median) using a current market manual lift. Lowering a patient onto a bed takes about 18 seconds (median) with the PTAD versus about 53 seconds (median) with the current market lift. And surprisingly the data show that the “transport” subtasks are generally not slower for a motions of similar distance, even with this oversized prototype. With the current market lift, most lifting and lowering operations are typically performed in about 40-50 seconds, while with the PTAD, those same subtasks are typically performed in about 15-20 seconds. With some improvements to optimize the mechanical design to make the gross motions around the room more efficient, a PTAD can be expected to significantly reduce the personnel time required for patient transfers.

6.2.2.1 Operator surveys

Operators also filled out extensive surveys at the end of the experiments. The surveys were written with the help of our collaborators in human factors research, including Brittney Jimerson from North Carolina A&T. The surveys were divided into sections, in an attempt to evaluate different stages of the process and different aspects of the design independently. Figure 82 shows side by side comparisons of the participants’ overall ratings.

It is important to keep in mind that the transfer operations performed for the PTAD were not exactly the same as the transfers performed with the current market lift. The operations with the current market lift were limited to a more confined workspace, so the operators' experiences were somewhat different between the two machines. These differences most likely bias the operators' ratings to favor the PTAD, since it was tested in a less confined space. Still, there is considerable value in analyzing operators' performance ratings, even independent of any comparison, to determine what aspects of the designs most need improvement in future work and what features work well and should be continued.

Overall, participants rated the PTAD higher than the current market lift in almost every metric, though the differences were small in some cases. In the overall ratings, the average ratings for important metrics such as the ability to transfer alone, ease of obstacle avoidance, ability to transfer quickly, and overall maneuverability, all were improved over the current market lift, in spite of the bulky protoype design.

For the PTAD controller ratings, all of the metrics including overall controllability, accuracy, response speed and smoothness of the lifting arm, accuracy and response speed of the base, all had average ratings of good to excellent. The only exception was the smoothness of the base motion, which was rated as fair. Average ratings for all metrics were higher than those for current market lift except the speed of response of the lifting arm.

Operators found the smoothness of the base control to be particularly lacking; it is difficult to attain smooth motion control performance with these low cost power units, but

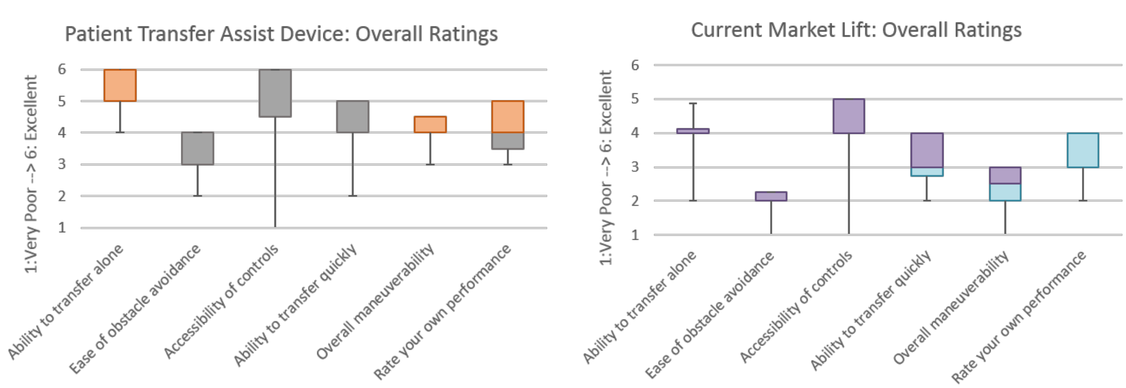


Figure 79: Left: PTAD overall ratings, 19 participants; right: current market lift overall ratings, 12 participants

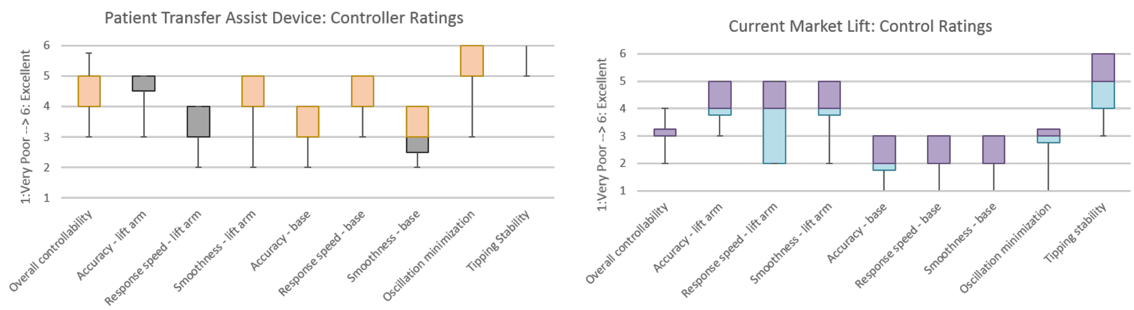


Figure 80: Left: PTAD controller ratings, 19 participants; right: current market lift control ratings, 12 participants

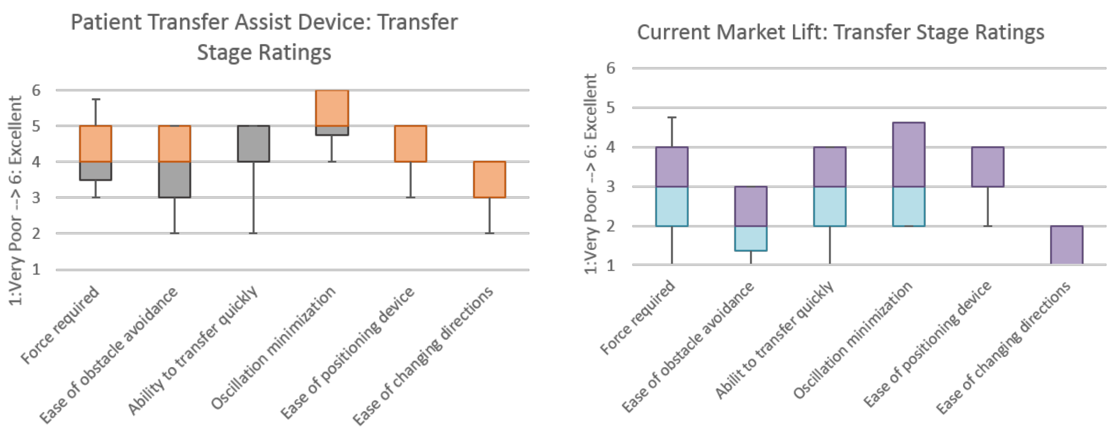


Figure 81: Left: PTAD transfer stage ratings, 19 participants; right: current market lift transfer stage ratings, 12 participants

it could likely be improved with better compensation for the non-ideal effects. Operators also found the speed of response of the lifting to be lower than desired, which is partially a result of integrating the operator input to obtain a position control reference, as well as the need for considerable damping in the control to obtain fairly smooth motion from these power units. This effect could likely be improved to some degree with better tuning. Several operators also noted that the machine dynamic response was not what they initially hoped for, but they felt that they could “get used to the machine dynamics” quickly. Ratings were divided into “lifting and lowering” stage and a “transfer stage”, where the transfer stage refers to the motions involved in transporting the mannequin from one place to another, when it is free from any contact with the starting and ending locations.

The ratings for the transfer stage are primarily focused on the wheel control and base

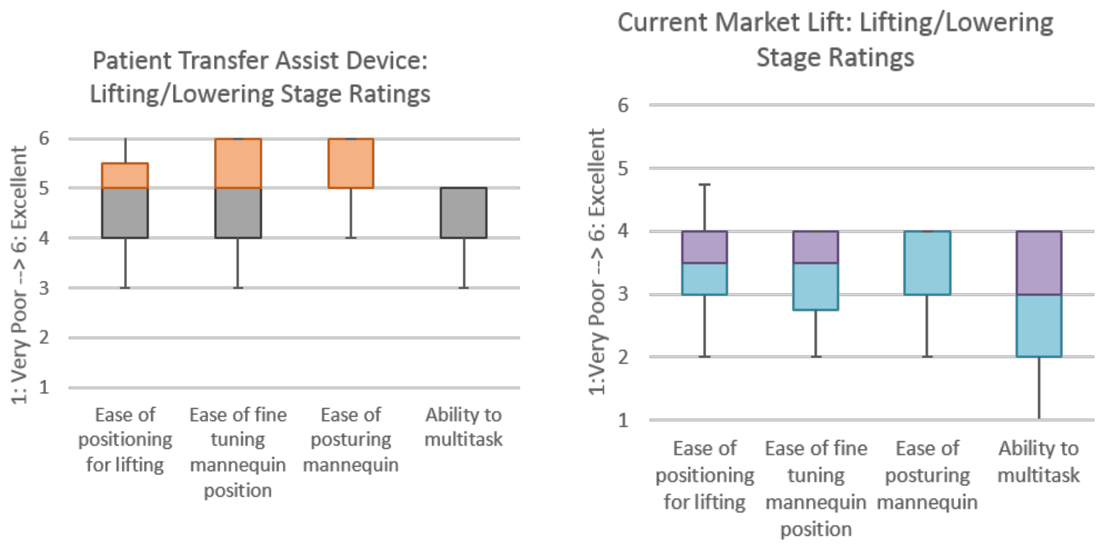


Figure 82: Left: PTAD lifting and lowering stage ratings, 19 participants; right: current market lift, lifting and lowering stage ratings, 12 participants

design, both of which are not yet optimized in this prototype. Still, the ratings showed improvement over the current market device in all metrics, and all metrics received average ratings between good and excellent, except for "ease of changing directions", which is primarily a result of the casters. A number of operators mentioned the known limitations, such as the difficult to turn casters and large overall size. But they also noted that the powered wheels are a significant improvement over the unpowered casters of the current market lift. Smooth control of fine motions is difficult with these hydraulic power units, as a result of the check valve circuit designed to hold the load against gravity without power. The check valves are pilot operated and remain closed until the pump reaches sufficient pressure to open them; that combined with stiction makes it difficult to obtain smooth control at low flow.

The most positive ratings and review comments were given for the lifting and lowering stages, with average ratings for all metrics falling between very good and excellent, and improvement in average ratings over the current market lift for all four metrics.

6.3 Interaction Control Testing

The second part of the experiment was intended to test the proposed form of interaction control in a transfer operation with the human operator. It is designed to demonstrate the ability of this control approach to manage any potential collision forces and inform the operator of obstacles, while maintaining desirable motion control performance in free space. This experiment was more structured and controlled, using only the vertical lift and horizontal extension to move the mannequin between two chairs.

Ideally, we want the machine to have the desired motion control performance in free space, slow down if it's approaching an obstacle quickly, keep collision forces small enough to be safe for humans, and allow for full utilization of the workspace. In an ideal case, the machine would have a force sensing skin such that interaction forces could be measured anywhere on the machine. Researchers are working on such a skin, but it is not yet feasible for a machine of this size. But it would be possible in the next generation design to place ultrasonic proximity sensors and load cells in key locations on the machine where collisions are likely to occur, such as around the perimeter of the base and at the end of the boom. At this stage, the interaction control is being tested on one degree of freedom, the horizontal boom extension.

6.3.1 Interaction Control Experiment Setup

This experiment was set up to answer two primary research questions. First, can the controller manage any undesirable accidental external interaction forces and keep them within a range that is safe for humans in the workspace, and can it inform operators of collisions quickly through haptic feedback, before forces reach unsafe levels? And second, can the controller achieve that goal without significant degradation in motion control and tracking performance?

The operators performed a set of two transfers multiple times, from the first chair to the second chair, then back to the first chair. They performed this set, or attempted to, eight times (Fig. 83). In some cases, a rigid obstacle was placed in the path of the horizontal boom, making it impossible to reach the second chair. The first two times were for practice, the first with no obstacle, and the second with an obstacle, to get a sense of what an obstacle feels like. Participants were asked to perform the transfers as they normally would transfer a patient, and if they felt an obstacle, they were asked to immediately back away and move the mannequin back to the first chair.

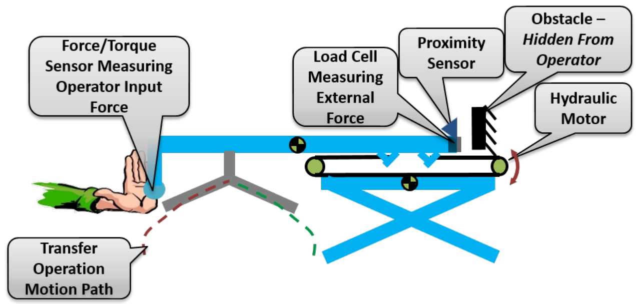


Figure 83: Interaction control test setup

For the purpose of this experiment, it is critical that the operators do not know whether or not there will be an obstacle in the desired motion path. A curtain was mounted between the operator and the back of the boom, so that they could not see if there was any obstacle in the path. For this test setup, it was easiest to mount the sensors on the obstacle rather than on the boom; this mounting demonstrates the control approach in the same way as if the sensors were mounted on the moving boom, as they would be in a final design, since both the measured forces and distances between the boom and the obstacle in this controlled experiment are equal and opposite. A small spring was mounted on the obstacle to soften the initial impact force measurement slightly. Images from the interaction control operator experiment are shown in Figure 84.

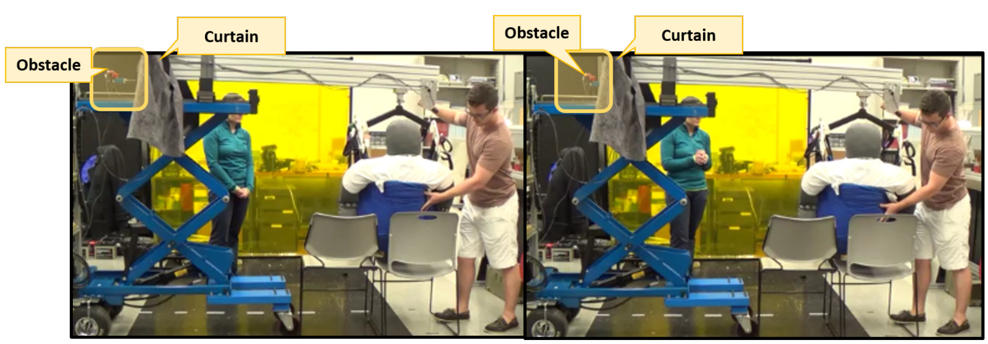


Figure 84: Interaction control experiment

After the two practice transfers, one with an obstacle and one without, the operators performed six more transfers. The six transfers had a randomized set of two possibilities for the controller and three possibilities for the obstacle. For the impedance control, the sensing of the external force and proximity could be either both turned on or both turned off. Then there were two possible locations for the obstacle, or no obstacle. For all operators, the first case was with no obstacle and the force and proximity sensing turned off. For the remaining five cases, the possible combinations of the controller and obstacle location were randomized. There were three possibilities for the obstacle location, with the first location at approximately 0.35m, corresponding to a patient location just before the midpoint between the two chairs, and the second location at approximately 0.55m, corresponding to a patient location near the center of the second chair. The third possibility for obstacle location is no obstacle.

6.3.2 Interaction Control Results

Figure 85 shows resulting external interaction forces from participant 13 for the first obstacle location. The plot on the left shows the result with no feedback of external interaction force nor proximity to the obstacle. The plot on the right shows the result for the controller using both feedback of force and proximity. For this participant and the obstacle at this location, the plots show a maximum collision force of about 240 N using the controller with no feedback of force nor proximity, and the maximum collison force is reduced to about 85 N using the impedance controller with feedback of both force and proximity. It appears that the obstacle locations are slightly different in the two experiments; actually the horizontal boom uses an incremental encoder for feedback, so the zero location is reset each time a new controller is started, so the difference is in the starting location rather than the obstacle location.

The plots in figure 86 are from the same two experiments, participant number 13, with the first obstacle location. The plots show the reference boom position and the measured boom position. The reference boom position is calculated by integrating the operator input force, then adding a small term as a function of the derivative of that input force to improve

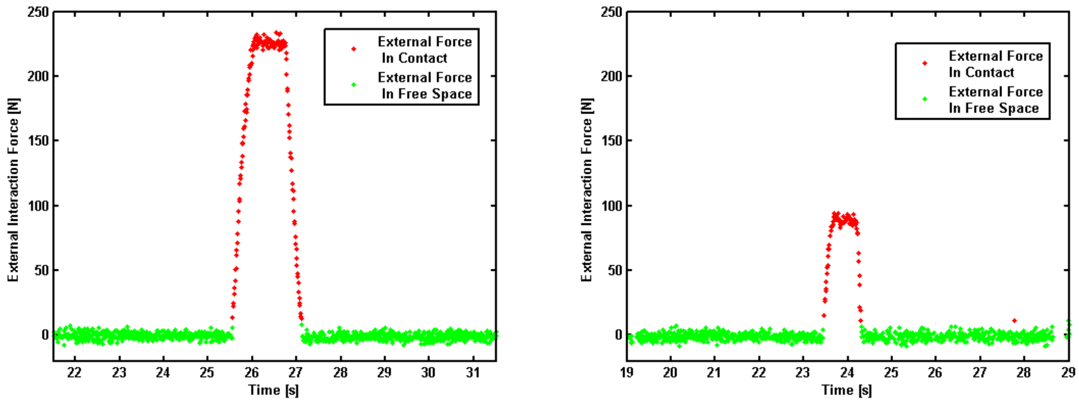


Figure 85: Participant 13, collision force, obstacle at 0.4m; left: without feedback of force & proximity, right: with feedback of force & proximity

the speed of response; this operator input approach is explained in detail in Chapter 3. Any time the operator releases the input force to zero, the position reference is reset to the current measured position. The plot shows when the boom is moving in free space and when it is in contact with the obstacle, determined based on the corresponding interaction force. In both experiments, the tracking performance is similar. Once the boom is in contact with the obstacle, if the operator continues to apply force to the input handle, the desired position continues to change, even though the machine is physically unable to reach the target. In practice, this effect could be beneficial or detrimental, depending on specifics of the task, but it would allow the operator to slowly increase the force applied to an obstacle if desired. In these experiments, the operators always realized that they had encountered an unmoveable obstacle and needed to back away before any noticeable increase in the interaction force was observed. The tracking performance metric is computed based only on times when the machine is in free space.

To answer the research questions regarding the interaction controller, two Analyses of Variance (ANOVAs) were used, one for each dependent or output variable, the maximum measured external interaction force and the root mean squared (RMS) position tracking error in free space. Both were two-factor ANOVAs, with the two factors or treatments as the controller feedback (on or off) and the location of the obstacle. First, descriptive statistics were computed for both of the outputs. The resulting box plot for the maximum

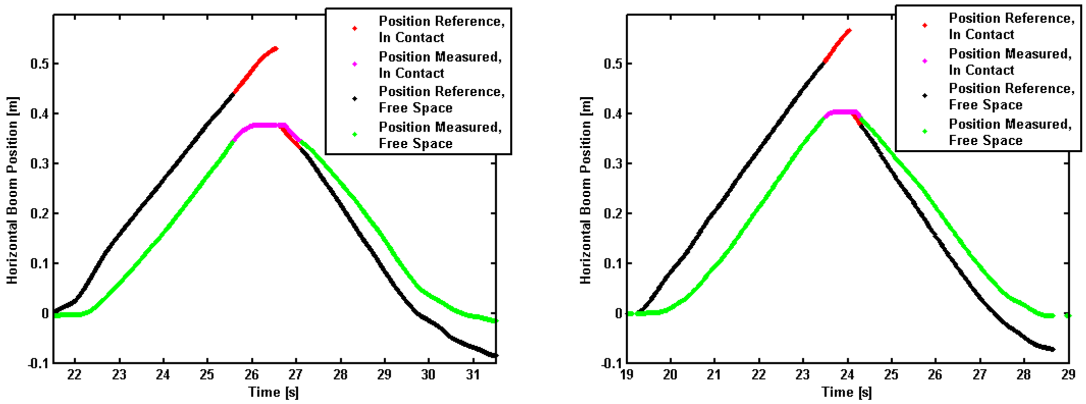


Figure 86: Participant 13, root mean squared tracking error, obstacle at 0.4m; left: with feedback of force & proximity, right: without feedback of force & proximity

collision force is shown in Figure 87, and the box plot for the resulting RMS tracking error is shown in Figure 88. For the collision force, the controller treatment has two levels, force and proximity feedback on or off; the obstacle location also has two levels, the first location and the second location. In the case of the external interaction force, the data with no obstacle is irrelevant, so it was excluded. The box plot for the external force shows four cases, representing all combinations of levels of the two treatments. The results show that the **means of the maximum collision forces are reduced by 53%** when feedback of external interaction force is used, including data from both obstacle locations, from 210 N (47 lbf) to 98 N (22 lbf). More importantly, the maximum collision forces in some cases without force or proximity feedback reached as high as 477 N (107 lbf), but in all cases with force and proximity feedback, they were maintained below 140 N (31 lbf). This indicates that as the operator moves faster, increasing the momentum of the boom, the effect of the force and proximity feedback increases and the collision force is reduced by a greater margin; this is the expected and desired result from the momentum based proximity feedback term. For operators who move slowly and generate smaller collision forces, the effect of the feedback control is smaller. The ISO Standard 13482 (1) sets a maximum acceptable collision force of 150 N, and the interaction forces are maintained below that limit in all cases. However, other researchers cite a lower target of 50 N; it may be possible to achieve that lower target using this type of interaction control design with further development of the controller and better tuning. Even larger percentage reductions in collision forces were obtained in the software input experiments; this difference is at least in large part a result of the fact that the percentage reduction in collision force is a function of the trajectory at the time of collision, which is determined by the human operator in this case.

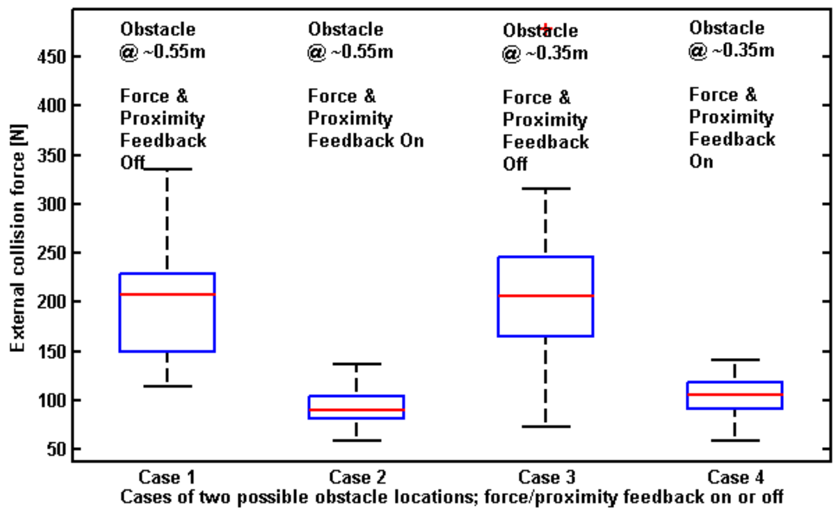


Figure 87: Maximum external interaction forces in interaction control experiment

It is also important to demonstrate that the addition of compensation for external interaction forces does not significantly degrade the motion control performance in free space. In this system, the best way to numerically analyze the motion control performance is by computing RMS position tracking error. However, it is important to keep in mind that the operator is in the loop, and the goal of this controller is not necessarily to obtain the best possible position tracking, but it is to obtain the operator's desired motion. The operator input force and resulting velocity can also be considered, but those are much noisier and faster varying signals, and it would be difficult to obtain meaningful results. A discussion of the relation between the operator input force and resulting velocity can be found in Chapter 3. So, while these tracking errors do give an indication of the relative performance of the different controllers, this should be only a small consideration in the evaluation of the overall performance of the motion control relative to the operator input. In the case of the RMS tracking error, all three possibilities for the obstacle location are meaningful, including the cases with no obstacle. Therefore, the box plot includes six cases, including all combinations of the three possibilities for the obstacle location and two possibilities for the controller feedback. Qualitatively, the means are similar, and statistical analyses were used to show that any small difference in the means is not statistically significant. However, the plots do show slightly higher tracking error in the cases where there is an obstacle and the feedback is turned off, as compared with the cases where there is an obstacle and the feedback is turned on. This is an expected result of the proximity feedback; as the boom reaches close proximity to the obstacle, the proximity feedback term slows the motion, slightly increasing the tracking error in the region close to the obstacle.

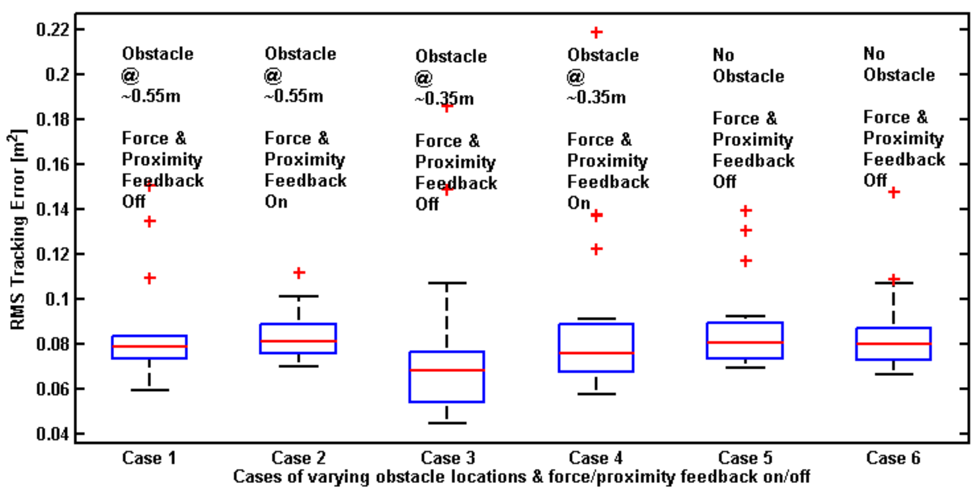


Figure 88: Root mean squared tracking error in interaction control experiment

A two way ANOVA was used to show that the difference in means of the external interaction forces between cases with the force and proximity feedback on or off are statistically significant, and that the difference has at least a medium effect size, as shown in Table 4. The result shows that the difference between the external forces with the controller feedback on vs. off is highly statistically significant, with a p value of $\ll 0.001$, indicating that the difference is very likely to be present any time the test is run again. The medium effect size of 0.52 indicates a strong relationship between the independent variables (controller feedback on vs. off, obstacle location) and the dependent variable (maximum external interaction force); the effect size also indicates that the size of the difference in means is large, accounting for the variance. Learning effects were neglected in the analysis, but operators performed the full transfer experiments first, so by the time they began the interaction control experiments, learning effects should be minimal; also, the order of the controllers and obstacle locations was randomized to minimize learning effects. The obstacle location treatment yielded a statistical significance of $p = 0.29$, indicating that the difference is not statistically significant; similarly, the resulting effect size of 0.007 indicates a very small effect size.

Table 4: ANOVA Table for Output External Interaction Force

Source	Sum of Squares	DoF	Mean Squares	F	p	Effect size
Feedback On or Off	237723	1	237723	80.76	$\ll 0.001$	0.525
Obstacle Location	3340	1	3340	1.13	0.29	0.007
Interaction	101	1	101	0.03	0.853	
Error	211948	72	2944			
Total	453112	75				

Similarly, another two-way ANOVA was performed with output RMS tracking error. As before, the independent variables were the controller feedback on vs. off and the obstacle location. In this case, all three obstacle location possibilities were used, including no obstacle, resulting in three levels of the obstacle location treatment. In this case, the statistical significance of the mean difference between treatments with the controller feedback on or off was $p = 0.78$, indicating that any difference in the means is not statistically significant; the effect size is also very small. For the three obstacle location possibilities, the resulting statistical significance value of $p = 0.89$ indicates that the difference between the three means is not statistically significant, and the effect size is also very small. A post hoc paired comparison of the three cases of the obstacle location also resulted in no statistically significant differences between pairs. These results indicate that there is most likely no significant difference in tracking performance to be found; this is the desirable result.

Table 5: ANOVA Table for Output Root Mean Squared Tracking Error

Source	Sum of Squares	DoF	Mean Squares	F	p	Effect size
Feedback On or Off	0.00006	1	0.00006	0.08	0.776	0.00007
Obstacle Location	0.00018	2	0.00009	0.12	0.888	0.0022
Interaction	0.0016	2	0.0008	1.07	0.346	
Error	0.0807	108	0.00075			
Total	0.0825	113				

6.4 Open-ended feedback

In addition to the quantitative data, the participants were asked to respond to several open ended questions about the performance of the machine and its control, and they were asked to include additional comments whenever possible to explain reasons for their ratings. One participant gave very encouraging feedback.

> "I was impressed by how easy this was and how awesome it would be to have for my sister....I did use a Hoyer lift for a long time, and this machine would be a God send. The cranking manually is hard to control and gets harder over time due to rust and wear and tear. My sister is relatively light, so I would hate to lift Brutus in a Hoyer lift. When my parents aged, I had to take over. So parents with a disabled child or relative would have a limit on using a Hoyer lift. When I went off to college and couldn't do it anymore, my sister had to be moved to a facility. So I would be quite excited to see where work on this machine goes. One day it might mean my sister could come home more often, as we only see her at Christmas time now."

Several other comments were repeated by a number of participants. The most common complaints were the following.

- Participants found the casters to be "difficult to turn" and "hard to move", and they "made small movements difficult".
- Participants thought the overall base design was too big, too bulky, and "difficult to parallel park".

- Participants wanted faster response from the machine. However, many noted that it takes some practice to adjust to the dynamics of the machine, and they thought they would "get used to it" after performing more transfers. This could be adjusted somewhat by changing the tuning of gains.

- Participants found the base motion to be less smooth than they would like.

The following were aspects of the design that the participants found advantageous.

- Participants found the controls to be "intuitive" and "easy to learn to use".

- Participants appreciated the ability to multitask, or to simultaneously control the machine and manually fine tune the position and posture of the patient.

- Participants who had used manual or powered current market lifts noted that the PTAD requires significantly less force from the operator and is overall considerably easier to use.

Some suggestions also came up repeatedly in the surveys.

- Having a handle on both sides of the boom would allow for easier access. The available space for the operator to stand is often limited.

- Some participants thought a vibration or audible feedback notification of an obstacle nearby would be more helpful. However, they based this suggestion on their experience with the controlled interaction experiment. In a real world operation with proximity sensing all around the machine, operating in a confined space, the noise and vibration would likely be almost constant in some operations and would become annoying.

- Omnidirectional wheels could make the base motion easier.

- One additional degree of freedom of a rotation with respect to the base would make fine tuning of the patient position much easier, because it would not be necessary to move the base at all to move side to side. The range of motion would have to be very small to manage tipping stability, but it would be helpful.

- It would be nice for the machine to fold into a compact unit for storage.
- Users thought it would be helpful if the base had an open or spreadable midsection to envelop a wheelchair.

Overall, the participants found the machine to be fairly easy to use, and they felt that some form of assist device is necessary in order to move a heavy patient. Most of the primary complaints can be addressed with simple changes to the machine design, optimization of component sizing, replacement of hydraulic power units with types with more linear response, and better optimization of the control gains.

CHAPTER VII

CONTRIBUTIONS, CONCLUSIONS AND FUTURE WORK

7.1 Results Summary

Primary experimental results from testing of the prototype PTAD can be divided into four main parts: simulation testing of tracking and interaction control, hardware testing of tracking and interaction control using software inputs, full transfer operations using 4-DOFs of the machine performed from human operator inputs, and 2-DOF interaction control experiments using operator inputs. Additional experiments included interaction control experiments on the vertical lifting scissor, operator input experiments, estimation of external interaction forces using measurements of actuator pressure and position, and preliminary testing of various other types of interaction controllers.

In the simulation experiments, a linear model of the horizontal boom extension was tested with the impedance control framework. Tracking performance in free space, control of external interaction forces in interaction, and response to an obstacle in close proximity were evaluated. Performance was compared with a range of impedance control gains, with all combinations of external force and proximity feedback on/off, with a variety of reference position signals, and with varying environment stiffnesses. Results show that desirable tracking performance can be maintained, while the controller can significantly reduce interaction forces by using feedback of external interaction force or proximity to the obstacle. The specific amount of reduction depends on a number of factors and gains, but overall in most cases of simulated typical operation, any measurable external interaction forces can be maintained below approximately 50 N (12 lbf) in all but one simulation experiment; in the same simulated tests, typical collision forces without compensation for interaction are in the range of 240-320 N (54-72 lbf).

Similarly, in hardware experiments with software inputs, the same form of controller was tested with low level pressure control to regulate actuator force to the reference, and high level impedance control to achieve motion tracking and manage external interaction forces. Hardware experiments were performed with varying forms of interaction feedback and with varying impedance control parameters. In one experiment, in the case with no interaction measurement feedback the collision force reached 470 N (105 lbf), while in the same experiment, the feedback of both proximity and external force led to a collision force of 60 N (13 lbf), a reduction of 87%. Other experiments also showed that the controllers produce similar acceptable tracking performance in free space, and the addition of feedback of measured proximity or external force have capability to significantly reduce interaction forces, depending on target impedance parameters.

Considerable recent research has focused on developing robots for industrial applications that are safe for humans in the workspace, and most use electrical actuation. This research demonstrates the feasibility of control for safe interaction using low cost, efficient electro-hydraulic pump-controlled actuation, in spite of the associated high intrinsic stiffness, slow dynamics and highly nonlinear and non-ideal effects.

In the first part of the operator experiments, participants performed a set of transfers of a 113 kg (250 lb) mannequin between a wheelchair, bed, floor and chair. A time study was performed, and participants filled out a survey rating the machine performance in terms of a number of metrics. On average, participants rated the prototype performance better than the current market patient lift in almost every metric, in spite of its bulky size and non-ideal hydraulic components. And for the stages of the time study that could be compared with earlier experiments with the current market lift, operators were able to perform transfers faster with the prototype PTAD. The operator experiments also highlighted some design details that need improvement and lead to significant difficulties for the operator, such as the caster wheels.

In the second part of the operator experiments, participants performed a set of transfer operations of the mannequin using the vertical lifting scissor and the horizontal boom extension. In some cases, unexpected hidden obstacles were placed in the desired path. Controller performance was compared with and without feedback of external force and proximity, in terms of trajectory tracking and collision forces. Results show statistically significant reductions in maximum collision forces with a mean of 53%, and more in cases where the machine is moving faster and the resulting forces are larger. In all cases with interaction feedback, collision forces remained below the maximum allowable force cited in ISO standard 13482 of 150 N; without interaction feedback that was not the case.

Additional experiments on the vertical lifting scissor showed that it is possible to control external interaction forces using impedance control with feedback of external interaction forces on the vertical lifting scissor, where the forces involved in the operation are much larger, using gravity compensation in the low level pressure control. In addition, experiments were performed to show that it is feasible to roughly estimate external interaction force based on measurements of pressure and position, using a Luenberger observer.

In addition to the experimental results, a set of guidelines and ideas for design of an improved patient transfer assist device were developed, based on extensive input from users and a range of stakeholders in the current market patient lift industry.

7.2 Research Contributions

1: Developed guidelines for design of an improved marketable patient transfer assist device

A needs assessment for an improved patient lift has been performed, based on input from a wide range of stakeholders in the patient lift industry. That information has been compiled into a set of guidelines for design of a new patient transfer assist device, and it has been used to guide the development of the first prototype.

2: Developed a prototype to validate concept patient transfer assist device design, actuation system and control approach, using low cost direct drive hydraulic actuation

A new prototype patient transfer assist device with four actuated degrees of freedom has been fully designed, fabricated and tested. It utilizes low cost electro-hydraulic pump controlled actuators for all four degrees of freedom, and it is controlled from human operator input force.

3: Formulated control algorithms for a collaborative manipulation assist device

Control algorithms have been developed to obtain smooth motion control and manage undesirable external interaction forces, using low cost direct drive hydraulic actuation.

The controllers also mitigate undesirable effects of the significant nonlinearities and non-ideal features of the system, complex kinematics, and intrinsic stiffness and slow dynamics.

4: Formulated and implemented a control strategy to manage any unintentional external interaction forces, using low cost direct drive hydraulic actuation

An impedance control framework has been developed to manage any unintentional external interaction forces, using feedback of measured (or potentially estimated) external interaction forces, measured proximity, and position. The control architecture includes a virtual force feedback term that is computed based on the proximity to an obstacle, as well as any external force; results show that it can significantly reduce external interaction forces using either or both forms of feedback. Preliminary tests were also performed on several other forms of interaction control. Compensation for some nonlinear and non-ideal effects in the hydraulic system was included in the low level pressure control.

5: Implemented impedance control with force feedback by using low level pressure control to approximate actuator force control.

Low level actuator force control was approximated using low level pressure control of the hydraulic actuators.

6: Added proximity measurements into a traditional impedance control framework as a virtual force term, for added redundancy and improved management of unwanted collision forces.

A virtual force term was calculated based on the momentum of the machine and distance to the obstacle was computed, and this term was used to aid in reducing any undesirable collision forces.

7: Developed an operator interface that provides intuitive, simple, coordinated control from a force sensing handle, with dynamic response suitable for a human operator

The implemented control architecture uses an operator input force on the machine as input for coordinated control. The operator pushes on a handle on the machine in the desired direction of patient motion; the controller generates a patient velocity approximately proportional to that force vector, so as the operator pushes harder, it moves faster.

8: Validated control of unintentional external interaction forces through controlled experiments with software inputs

A set of hardware experiments was performed to validate the performance of the controller in terms of tracking a desired motion trajectory and controlling external interaction forces.

9: Evaluated and analyzed a patient transfer collaborative manipulation assist device concept through human operator studies

A set of human operator studies was performed, to evaluate and analyze the patient transfer assist device machine design and control. The performance was compared with a benchmark study using a current market lift. Metrics included a time study and an operator survey.

10: Evaluated and analyzed a control strategy to control external interaction forces through human operator studies

The human operator study was also used to evaluate and analyze the impedance-based control framework used to control external interaction forces, with a human operator input. Performance in unexpected collisions was compared with and without compensation for interaction. Metrics included motion tracking performance and interaction forces, and statistical analyses of the results were performed using ANOVAs.

7.3 Future Work on Collaborative Manipulation with Interaction Control

While this work demonstrates and validates the use of an impedance control framework with redundant sensing (or estimation) of external force and proximity, there are some additional steps needed in order to make the impedance based control approach work well with the full 4-DOF PTAD. Further development is needed to be able to accurately estimate external force based on pressure and position measurements; this would be a valuable addition and would reduce the dependency on a number of sensors. For the vertical lifting, while compensation for the gravitational load of the machine was tested with the impedance control, compensation for the additional gravitational load of the payload was left for future work; this requires an additional load cell for measurement of payload weight. Also, the added proximity based virtual force term was tested only on the horizontal boom extension;

this is expected to significantly improve the ability to minimize unwanted collision forces on the vertical lifting scissor. For the wheels, an obstacle avoidance algorithm was tested, but the impedance control with feedback of external force and proximity was also left for future work.

7.4 Future Work on a Marketable Patient Transfer Assist Device

In terms of the patient transfer assist device, a number of steps would be needed in order to move from this prototype to a marketable device. The primary focus of the next step would be on developing a more compact mechanical design with a base that can easily maneuver around chair legs, wheelchairs, etc. Additional safety features would also be needed, such as a bellows cover to protect the user from pinch points in the scissor lift, additional rate or flow limits, and a soft foam cover. Control to prevent tipping is also important, including extendable feet to account for the shift in center of gravity with the moving boom, as well as control to prevent motions where tipping would occur and warnings for the operator when the machine is approaching a configuration in which there is a risk of tipping. Several suggestions for additional features for a later stage were also provided, such as an actuated patient posture rotation and an actuated side-to-side motion of the patient with respect to the base. The focus of the next stage of the PTAD design needs to be on compactness and maneuverability around obstacles.

7.5 Conclusions

These results demonstrate feasibility of using a mobile electro-hydraulic pump controlled machine with multiple degrees of freedom for collaborative manipulation to aid a caregiver in transporting a heavy mannequin representing a patient, requiring forces from the operator that are less than 15 lbf to move the machine. For the subtasks in the time study that were directly comparable with the current market lift, the results showed typical reductions in time required to perform the subtasks by more than half. It also demonstrates viability of intuitive coordinated control of multiple degrees of freedom from a single operator input handle.

Furthermore, results show that it is feasible to manage external interaction forces using a combination of sensing of proximity and external forces (or estimates of external forces), using cost effective electro-hydraulic pump controlled actuation, in spite of the inherent slow dynamics and far-from-ideal dynamic response. The operator experiments showed reductions in collision forces of 53%, and in all cases with interaction feedback, collision forces were maintained below the ISO standard safe threshold of 150 N.

These results can be generalized for application in other areas, such as moving heavy payloads in construction or industrial applications, through restricted and unstructured workspaces. With further development, implementation of interaction control on all degrees of freedom, and optimization of the mechanical design, it is expected that this new type of patient transfer assist device design can lead to more efficient transfer operations, allow for safe transfers with only one caregiver present, reduce caregiver mental workloads while resulting in less damage to the environment from collisions, improve maneuverability and accessibility around obstacles and in tight workspaces, improve utilization of assist devices for patient transfers, and reduce injuries to both caregivers and patients.

APPENDIX A

STABILITY IN CONTACT WITH AN OBSTACLE

Continued from Chapter 5, this section discusses stability in the case of the horizontal boom extension in contact with an obstacle, based on an LTI model of the system. Colgate developed a set of criteria for analyzing stability of a force feedback controlled system in contact with *any passive environment*, which most environments are, based on analysis of the impedance transfer function $Z(s) = \frac{sX(s)}{F_{ext}(s)}$ (11). However, these criteria are based on passivity, which means that they are conservative; not passing the criteria does not necessarily mean that there is any physically realizable environment in which the feedback controlled system is unstable. The criteria are as follows.

- $Z(s)$ has no poles in the right half plane.
- $Z(s)$ has a Nyquist plot which lies wholly within the closed left half plane.

Most common stability issues in force feedback controlled systems occur in contact with rigid environments. In some cases, it is possible to mitigate these issues by adding some compliance, in the form of a spring and damper, in series with the force sensor itself. The physical spring included in most hardware experiments had a spring constant of $K_s = 10,000\frac{N}{m}$; it would be reasonable to add a similar spring to all force sensors on the machine. These criteria for stability were tested using the simulation impedance $Z(s)$, from the closed loop impedance controlled system, including the model for the low level pressure control loop. A Bode plot for this full impedance controlled system model output stiffness and the target stiffness are shown in Fig. 89.

The criteria for stability in contact with any passive environment were tested with three forms of sensor compliance (or none). The first case included no added sensor compliance, the second included sensor compliance of $K_s = 10,000\frac{N}{m}$ and $B_s = 100\frac{N*s}{m}$, and the third included a theoretical sensor pure damping of $B_s = 100\frac{N*s}{m}$. The full system model does not

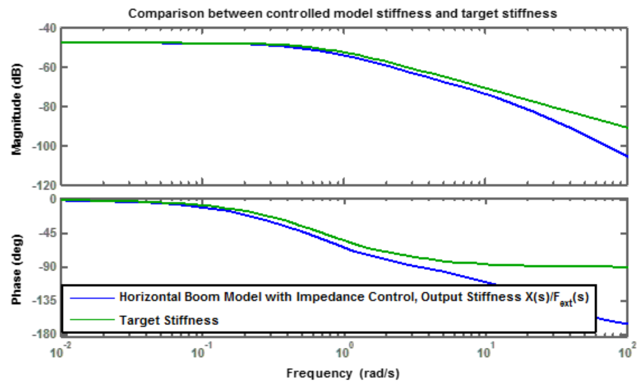


Figure 89: Bode plots for LTI model impedance controlled system stiffness and target stiffness

have any poles in the right half plane, and addition of sensor compliance does not produce any poles in the right half plane. Figure 90 shows the Nyquist plots for these three cases. Only the case with pure damping added to the sensor can be proven stable in contact with any passive environment; the case with the added sensor spring and damping is only slightly into the right half plane. None of the Nyquist plots have any encirclements of -1.

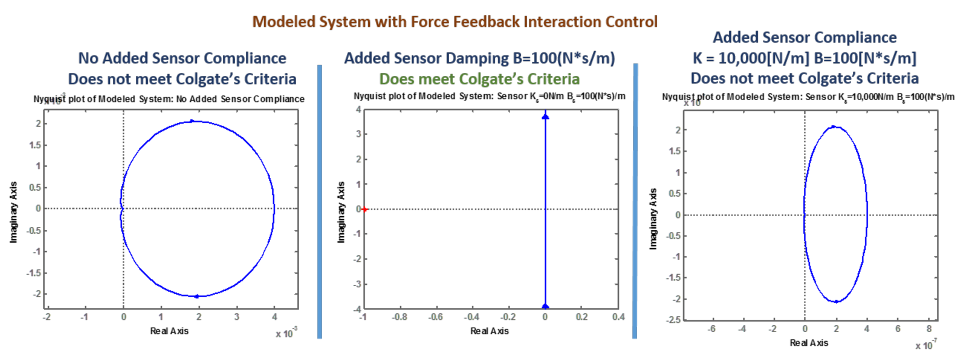


Figure 90: Nyquist plots for passivity based evaluation of stability in contact with any passive environment

Next, the full feedback controlled system was simulated in contact with a set of passive environments, including a very stiff pure spring. Load cell sensor compliance was also added in some cases. Six cases of environment/sensor combinations were tested for stability: a soft environment $K_s = 1,000\frac{N}{m}$ and $B_s = 100\frac{N*s}{m}$, a very stiff pure spring environment $K_s = 1,000,000\frac{N}{m}$ and $B_s = 0\frac{N*s}{m}$, and a very stiff environment with damping $K_s = 1,000,000\frac{N}{m}$ and $B_s = 100\frac{N*s}{m}$, with and without added sensor compliance. The results show that with this LTI model, all cases are stable in contact with these linear spring/damper environments. There may be lightly damped oscillations, but no instability. However, including nonlinearities in the system and/or the environment may induce limit cycles or instability.

APPENDIX B

OPERATOR TESTING METHODS

Continued from Chapter 6, this section discusses details on the human operator testing methods for the final experiments with the PTAD. As discussed earlier, there were two main parts to the PTAD testing. The first part included a set of four transfers of a 250 lb. mannequin in a simulated home/clinical environment, and the primary test results include operator survey results, time study data, and videos. The second part included a set of shorter transfers for testing the interaction control, and the primary test results include tracking performance data, interaction force control data, and survey results.

Participants were recruited using flyers posted on Georgia Tech campus and on Georgia Tech affiliated social media sites. The full set of experiments occurred in one session and lasted approximately 60-90 minutes. Participants were compensated $20 for their time on completion of the experiment. They signed consent forms according to the IRB protocol, as well as video consent forms. None of the participants were clinicians nor regular caregivers for patient lift users, but three participants did have some prior experience using patient lifts in the past for transferring family members. Four participants were included in both the benchmark operator testing and the final PTAD testing. A total of fourteen of the participants in the final PTAD testing had no prior experience with patient lifts, neither from external experience nor from the earlier benchmark testing.

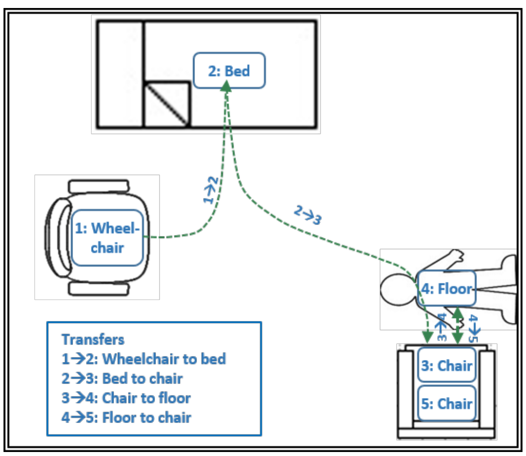
Each of the 19 participants completed the following steps in the testing session:

1. Read and signed consent forms and read instructions on the full transfer operations portion of the experiment set.
2. Listened to verbal instructions and performed basic motions with the machine to gain familiarity with its operation.
3. Performed three mannequin transfers as practice, the first three transfers in the time study experiment, to learn the optimal route for transporting between locations.

4. Performed the full time study set of transfer experiments, a set of four transfers.
5. Listened to verbal instructions on the interaction control portion of the experiment set.
6. Performed two practice mannequin transfers for the interaction control experiment, one with an obstacle and one without any obstacle.
7. Performed a set of six transfer operations for the interaction control experiment.
8. Completed the survey questions.

B.1 Transfer Operations Testing

For the full transfer operations testing, the set of transfers for the PTAD is shown in Fig. 91. This transfer set was designed to test the main functionalities of the PTAD. After



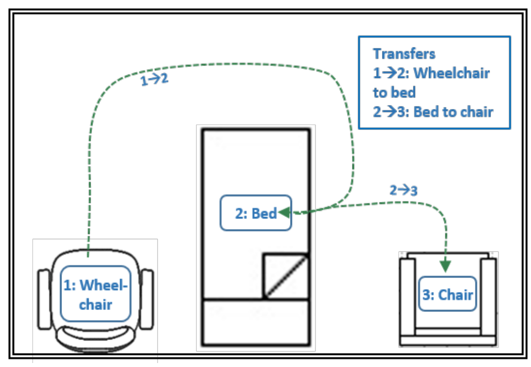


Figure 91: Transfer operations for PTAD (left) and current market lift (right)

signing consent forms, participants were given a set of printed and verbal instructions on how to best operate the machine, including tips on how to manage some of the known undesirable characteristics of the current prototype (e.g. how to manage the difficult to turn casters). They were given a few minutes to get a feel for the machine dynamics. Then they performed three transfers as practice (the transfers with the largest base motions), to determine the most appropriate paths between locations for the nonholonomic vehicle. Then they continued to the set of four transfers and the time study. A total of 19 official participants completed the study, in addition to 15 participants in a pilot study.

The machine operating instructions given to participants for the full transfer operations stage of the experiment are given below. These instructions were provided in addition to a verbal introduction to the project and its goals, as well as a set of verbal instructions on how to operate the machine. The instructions included demonstrations, and participants were encouraged to test the functions associated with each operator input function and each item in the list of instructions.

Patient Transfer Assist Device Instructions:

> The focus of this research is on the concept of a force-assist machine to help operators move heavy payloads. The machine was designed to be able to do the job, to have the necessary range of motion and force and speed capabilities, but it is a prototype and is not optimized. In particular, it is a very long nonholonomic vehicle, which makes for difficult path planning. And these particular casters can be difficult to turn. The following are some tips to help you operate the machine efficiently and overcome the limitations of the prototype mechanical system.
>
> Switch & Degrees of Freedom
>
> - This machine has four actuated degrees of freedom, a vertical lift, a horizontal boom extension, and two differential drive wheels.
> - Flip the switch UP to control the lift and extension.
> - Flip the switch DOWN to control the wheels.
> - Flip the switch to NEUTRAL when not in use, or if you need to walk under the boom.
>
> Force Sensing Handle
>
> - Push in the direction you want the patient to move.
> - The handle has a 15 lbf limit. If youre pushing harder than that, it doesnt read it.
> - Push toward the inside of the handle so that theres less of a moment.
>
> Casters

- Be cognizant of the direction of the casters at all times! They are not always visible. If the casters are turned in a direction different from the way you want to go, first get it moving and rotate the casters to the desired direction. Then start to move the machine in the desired direction.

Hydraulics

- This approach to controlling a hydraulic actuation system has advantages in terms of the force density and ability to manage interaction forces. One drawback is that the system may feel sluggish, and it may take a few minutes for you to become accustomed to the machine dynamics. Be aware that it may sometimes take a short time for it to start to move.

Transfer Set

- Transfer from the wheelchair, to the bed, to the chair, to the floor, then to the chair. Transporting Between Locations
- It is difficult to maneuver such a long nonholonomic vehicle. An optimal design would be much shorter. Try to follow the tape on the floor. It is there to guide you.

Sling

- The hanger bar rotates freely 360 degrees. Utilize that capability.
- You will be asked to attach the sling to the hanger bar. It is important that you attach to the right set of hooks. Use the hooks below the green tape.

Upon completion of the instructions and practice session, all participants completed a set of full transfer operations, and a time study was performed. The list of subtasks for the time study was developed with the aid of our CCEFP collaborator in human factors research, Brittney Jimerson.

The set of subtasks involved in the PTAD transfer set and time study is as follows:

1. Drive to wheelchair

2. Attach straps
3. Lift above wheelchair
4. Transport above wheelchair to above bed
5. Fine position above bed
6. Lower onto bed
7. Lift above bed
8. Transport above bed to above chair
9. Position and lower in chair
10. Lift above chair
11. Transport chair to above floor
12. Lower onto floor
13. Lift above floor
14. Transport above floor to above chair
15. Lower onto chair
16. Detach straps

B.1.1 Comparison with benchmark testing

Some comparisons were made between the new PTAD and the current market patient lift, although this comparison is not the primary focus of the research at this stage of development. Details on the testing methods for the benchmark operator testing can be found in Chapter 3, Section 4. The PTAD is a complex system and a new type of design, using a new type of actuation and control for this application. There are a number of further development steps required to achieve a marketable device, particularly related to optimization of the mechanical design. As a result of different capabilities of the two devices and limitations with this prototype version, it was necessary for a different sets of transfers to be performed for testing the PTAD and the current market lift.

For the benchmark testing with the current market lift, the following subtasks were performed by the operators.

1. Drive to wheelchair

2. Attach straps
3. Lift above wheelchair
4. Transport above wheelchair to above bed
5. Fine position above bed
6. Lower onto bed
7. Lift above bed
8. Transport above bed to above chair
9. Position and lower in chair
10. Remove straps

Operators performing the benchmark testing also answered the same set of survey questions as those for the current market device, with the exception of a few PTAD-specific questions at the end of the survey. The lift model used for current market device testing was the Invacare 9805, which was recommended as the most commonly used option from the locally available rental patient lifts; other commonly used patient lifts on the market are very similar designs.

B.2 Interaction Control Testing

In the second part of the experiment, all participants tested the interaction control. First, the operators were given a set of verbal instructions and information on the purpose of the experiment. They were instructed to move the mannequin from the first chair to the second chair, then back to the first chair. They were asked to back away and put the mannequin back in the starting position if they felt an obstacle. The obstacles were hidden from the operators by a curtain. Two obstacle locations were used. They were instructed to complete the transfers as efficiently and smoothly as possible, but to back away from any obstacles as soon as they became aware of them.

Each of the 19 participants performed a total of eight mannequin transfer sets between two chairs, with each set consisting of a transfer from the first chair to the second chair, followed by a transfer back to the first chair, unless they encountered an obstacle, in which case they moved back to the first chair. Two sets were for practice, and those were followed by six recorded sets. First, they performed the transfers with no obstacle, for practice. Next, they performed the transfers again, this time with an obstacle, and they were informed verbally by the test administrator when they reached the desired 50 N force limit in the interaction, to get a feel for how much force they were applying to the environment.

Then they performed six more transfer sets, a combination of tests with and without obstacles, with two different obstacle locations, with and without compensation for interaction. The order of the six recorded transfers and associated obstacle locations were randomized to minimize learning effects and to ensure that participants could not predict whether or not an obstacle would be present. Tracking performance and external interaction force data were recorded.

B.3 Operator Survey

The operator survey was developed in collaboration with a human factors research collaborator through the CCEFP Brittney Jimerson with North Carolina A&T. The survey was developed early in the project, in the benchmark operator testing, with the new design in mind. An initial draft set of questions and information to be obtained was reviewed and edited by the human factors collaborator for clarity and effectiveness. Pilot studies were performed prior to both sets of operator studies, and pilot study participants were asked to not only complete the surveys, but to provide feedback on the clarity of the questions. The questions were modified as needed after each pilot study, and if needed, verbal instructions were added to clarify certain questions. The same survey questions were used for both the current market lift and the new PTAD, with a few additions for the PTAD.

PAYLOAD TRANSFER ASSIST DEVICE TESTING QUESTIONNAIRE

MANNEQUIN TRANSFER TESTING

SUBJECT # ___

Demographics:

1. Are you **left** or **right** handed? (circle one)

2. What is your current position/title? ____

3. Do you work in an institution or home care setting? ________________________________

4. How much experience do you have using patient lifts? How frequently do you use a patient lift in a typical day? ____
   ____

5. If you have experience with patient lifts, what model(s) have you used? Are they manual or powered?
   ____
   ____

6. Have you had adequate training on the proper use of the lift (circle one)? **Y N**
   a. If yes, what type and how much? ____
      ____
   b. If no, what type and how much? ____
      ____

Controller:

How would you rate the following machine performance characteristics?

a) Overall controllability of the machine

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

b) Accuracy – of the lifting arm

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

c) Speed of response – of the lifting arm

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

d) Smoothness of machine motion – of the lifting arm

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

e) Accuracy – of the base

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

f) Speed of response – of the base

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

g) Smoothness of machine motion – of the base

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

h) Minimization of mannequin swing/oscillation

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

i) Stability of the machine (in terms of tipping)

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

What do you like and/or dislike?

____

____

Preparation and completion stages (including sling attachment and detachment):

How would you rate the following machine performance characteristics?

a) Ease of use of sling loading/attachment

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

b) Ease of positioning the device for lifting

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

What do you like and/or dislike?

____

____

____

Lifting and lowering stages:

How would you rate the following machine performance characteristics?

a) Ease of positioning the device for lifting

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

b) Ease of fine tuning position of the mannequin position

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

c) Ease of orienting the mannequin, or getting the mannequin into an appropriate posture

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

d) Ability to multitask, or simultaneously control the lift device and maneuver the mannequin

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

What do you like and/or dislike?

____

____

____

Transfer stage – gross motion:

How would you rate the following machine performance characteristics?

a) Force/torque required to maneuver the device

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

b) Ease of obstacle avoidance

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

c) Ability to transfer quickly

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

d) Management of mannequin oscillation

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

e) Ease of positioning the device

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

f) Ease of changing directions

1 2 3 4 5 6

Very Poor *Fair* *Excellent*

What do you like and/or dislike?

____

____

____

Overall:

How would you rate the following machine performance characteristics?

a) Ability to perform the transfer operations alone

1	2	3	4	5	6
Very Poor		*Fair*			*Excellent*

b) Ability to maneuver in tight spaces / ease of obstacle avoidance

1	2	3	4	5	6
Very Poor		*Fair*			*Excellent*

c) Location/accessibility of device controls

1	2	3	4	5	6
Very Poor		*Fair*			*Excellent*

d) Ability to transfer quickly

1	2	3	4	5	6
Very Poor		*Fair*			*Excellent*

e) Overall device maneuverability

1	2	3	4	5	6
Very Poor		*Fair*			*Excellent*

f) Rate your own overall performance

1	2	3	4	5	6
Very Poor		*Fair*			*Excellent*

What do you like and/or dislike?

____

____

____

Open-Ended Questions:

1. What was the most difficult transfer, and why?

2. Is there anything you would like to do that the current assist device design does not allow?

3. If you could change one or two things about your lift, what would they be?

4. What possible safety issues do you identify using the payload transfer assist device?

APPENDIX C

MECHANICAL DYNAMICS MODEL

This section describes the development of a model of the machine mechanical dynamics based on the Lagrange formulation. The model includes the vertical lifting scissor, horizontal boom extension and payload. The payload was included for the purpose of analyzing payload swinging or oscillation. Table 6 shows a list of relevant parameter values. This is a planar analysis; addition of the drive wheels would expand the motion into a third dimension. Table 6 shows the mechanical system parameters. Figure 92 shows a schematic of the system, including labels for each of the components corresponding to the equations. For the scissor lift mechanism, the hydraulic cylinder linkage is omitted and the equations of motion use the input as the torque generated by that linkage, rather than the cylinder force.

Table 6: Mechanical dynamics model parameters

Parameter	**Variable**	**Value**
Scissor link mass	m_l	30 lbf
Scissor top plate mass	m_{pl}	65 lbf
Horizontal boom mass	m_b	80 lbf
Payload mass	m_h	250 lbf
Scissor link width	w_l	2.5 in
Scissor top plate width	w_{pl}	0.125 in
Horizontal boom width	w_b	6.25 in
Scissor link thickness	t_l	1.0 in
Scissor top plate thickness	t_{pl}	20.5 in
Horizontal boom thickness	t_b	3.125 in
Scissor link length	L_l	34 in
Scissor top plate length	L_{pl}	40 in
Horizontal boom length	L_b	48 in
Payload suspension length	L_h	22 in

This section describes the formulation of a Lagrangian dynamics model for the system shown in Fig. 92. Equations of motion are developed, but the final simplification steps are omitted due to their complexity and length.

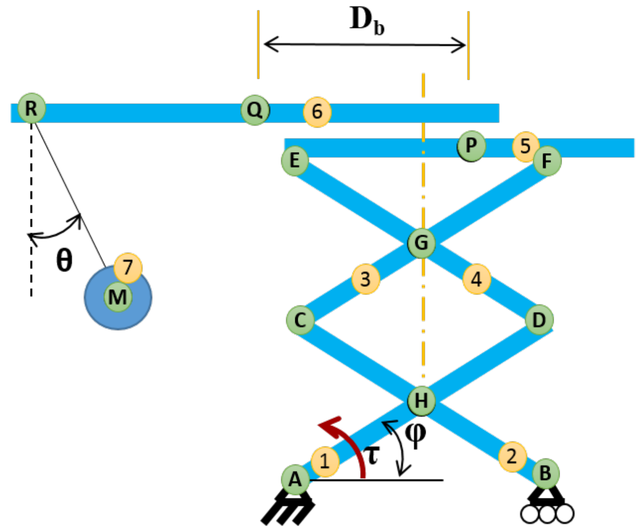


Figure 92: Mechanism with labels

Equations 33 through 38 show the velocity vectors of the centers of mass with respect to base frame, where r represents the position vector, ϕ is the scissor angle, θ is the payload swing angle, D_b is the horizontal boom extension position, and other parameters are as shown in Table 6.

$$v_{HA} = \begin{bmatrix} 0 \\ -\frac{L_l}{2}\sin(\phi(t))\,\dot{\phi}(t) \\ \frac{L_l}{2}\cos(\phi(t))\,\dot{\phi}(t) \end{bmatrix} \tag{33}$$

$$v_{GA} = \begin{bmatrix} 0 \\ -\frac{L_l}{2}\sin(\phi(t))\,\dot{\phi}(t) \\ \frac{3L_l}{2}\cos(\phi(t))\,\dot{\phi}(t) \end{bmatrix} \tag{34}$$

$$v_{PA} = \begin{bmatrix} 0 \\ 0 \\ 2L_l\cos(\phi(t))\,\dot{\phi}(t) \end{bmatrix} \tag{35}$$

$$v_{QA} = \begin{bmatrix} 0 \\ -\dot{D}_b(t) \\ 2L_l \cos(\phi(t))\,\dot{\phi}(t) \end{bmatrix} \tag{36}$$

$$v_{RA} = \begin{bmatrix} 0 \\ -\dot{D}_b(t) \\ 2L_l \cos(\phi(t))\,\dot{\phi}(t) \end{bmatrix} \tag{37}$$

$$v_{MA} = \begin{bmatrix} 0 \\ -\dot{D}_b(t) + L_h \cos(\theta(t))\,\dot{\theta}(t) \\ 2L_l \cos(\phi(t))\,\dot{\phi}(t) + L_h \sin(\theta(t))\,\dot{\theta}(t) \end{bmatrix} \tag{38}$$

Similarly, the angular velocities for the bodies are given in Eqns. 39 - 41.

$$\omega_1 = \omega_3 = \begin{bmatrix} \dot{\phi}(t) \\ 0 \\ 0 \end{bmatrix} \tag{39}$$

$$\omega_2 = \omega_4 = \begin{bmatrix} -\dot{\phi}(t) \\ 0 \\ 0 \end{bmatrix} \tag{40}$$

$$\omega_7 = \begin{bmatrix} \dot{\theta}(t) \\ 0 \\ 0 \end{bmatrix} \tag{41}$$

Moments of inertia for the bodies are given in Eqns. 42 - 45, where I_l is the inertia matrix for any linkage, I_b is the inertia matrix for the boom, I_{pl} is the inertia matrix for the top plate, and I_h is the inertia matrix for the payload.

$$I_l = \frac{m_l}{12}\begin{bmatrix} \left(L_l^2 + w_l^2\right) & 0 & 0 \\ 0 & \left(L_l^2 + t_l^2\right) & 0 \\ 0 & 0 & \left(t_l^2 + w_l^2\right) \end{bmatrix} \tag{42}$$

$$I_b = \frac{m_b}{12}\begin{bmatrix} \left(L_b^2 + w_b^2\right) & 0 & 0 \\ 0 & \left(L_b^2 + t_b^2\right) & 0 \\ 0 & 0 & \left(t_b^2 + w_b^2\right) \end{bmatrix} \tag{43}$$

$$I_{pl} = \frac{m_{pl}}{12}\begin{bmatrix} \left(L_{pl}^2 + w_{pl}^2\right) & 0 & 0 \\ 0 & \left(L_{pl}^2 + t_{pl}^2\right) & 0 \\ 0 & 0 & \left(t_{pl}^2 + w_{pl}^2\right) \end{bmatrix} \tag{44}$$

$$I_h = \frac{m_h}{2}\begin{bmatrix} L_h^2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{45}$$

The kinetic energy equations for the links are given in Eqns. 46-52, and the gravitational potential energy equations are given in Eqns. 53-57.

$$T_1 = \frac{m_l}{2} v_{HA}^T \cdot v_{HA} + \frac{1}{2}\omega_1^T \left(I_l \omega_1\right) \tag{46}$$

$$T_2 = \frac{m_l}{2} v_{HA}^T \cdot v_{HA} + \frac{1}{2}\omega_2^T \left(I_l \omega_2\right) \tag{47}$$

$$T_3 = \frac{m_l}{2} v_{GA}^T \cdot v_{GA} + \frac{1}{2}\omega_3^T \left(I_l \omega_3\right) \tag{48}$$

$$T_4 = \frac{m_l}{2} v_{GA}^T \cdot v_{GA} + \frac{1}{2}\omega_4^T \left(I_l \omega_4\right) \tag{49}$$

$$T_5 = \frac{m_l}{2} v_{PA}^T \cdot v_{PA} \tag{50}$$

$$T_6 = \frac{m_l}{2} v_{QA}^T \cdot v_{QA} \tag{51}$$

$$T_7 = \frac{m_l}{2} v_{MA}^T \cdot v_{MA} + \frac{1}{2} \omega_7^T \left(I_h \omega_7\right) \tag{52}$$

$$H_1 = H_2 = m_l g \frac{L_l}{2} \sin\left(\phi\left(t\right)\right) \tag{53}$$

$$H_3 = H_4 = m_l g \frac{3L_l}{2} \sin\left(\phi\left(t\right)\right) \tag{54}$$

$$H_5 = 2 m_{pl} g L_l \sin\left(\phi\left(t\right)\right) \tag{55}$$

$$H_6 = 2 m_b g L_l \sin\left(\phi\left(t\right)\right) \tag{56}$$

$$H_7 = m_m g \left[2 L_l \sin\left(\phi\left(t\right)\right) - L_m \cos\left(\theta\left(t\right)\right)\right] \tag{57}$$

The general Lagrange formulation for the equations of motion is given by Eqns. 58 - 59.

$$L = \left(T_1 + T_2 + T_3 + T_4 + T_5 + T_6 + T_7\right) - \left(H_1 + H_2 + H_3 + H_4 + H_5 + H_6 + H_7\right) \tag{58}$$

$$Q_i = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} \tag{59}$$

where Q_i is the i$^{\text{th}}$ generalized force, and q_i is the i$^{\text{th}}$ generalized coordinate, corresponding to each degree of freedom.

The equations of motion are given by Eqns. 60 - 62. Substitutions and simplifications are omitted, but all terms have been previously defined. The relation for the external torque τ and the angle ϕ of the first scissor link are given by Eqn. 60, the relation for the external horizontal force F_{boom} and the horizontal boom extension D_b is given by Eqn. 61, and the equation for the payload swing angle θ, with no external torque, is given by Eqn. 62.

$$\tau = -\left[\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\phi}}\right)\right] + \frac{\partial}{\partial \phi}\left(L\right) \tag{60}$$

$$F_{boom} = -\left[\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{D}_b}\right)\right] + \frac{\partial}{\partial D_b}\left(L\right) \tag{61}$$

$$0 = -\left[\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{\theta}}\right)\right] + \frac{\partial}{\partial \theta}\left(L\right) \tag{62}$$

These models were used for initial simulations of impedance control in Matlab. The scissor link torque input for the model resulting from the lifting cylinder force was calculated, and the cylinder linkage was assumed to be massless; this assumption is reasonable since other inertias in the system are much larger.

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