Bot + Bot:
Multi-Robot Collaboration in Architecture

Ghada Mami

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Brian Johnson, Chair
Kimo Griggs

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Abstract

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Ghada Mami

Chair of The Supervisory Committee:
Brian Johnson, Associate Professor
Architecture

The use of robots in architecture and construction has gained importance in the last few years. They offer the possibility to change the way we build, expand the design ideas and possibilities, and add more automation on construction sites with the goal of enhancing the productivity. This work looks at robotic fabrication, and more particularly the use of multi-robot systems in architecture. A first look at the definition of robots and robotic systems as being an “assemblage” helps understand the characteristics needed for robotic systems in architecture. A classification of the types of coordination and communication according to the existing literature is then introduced. From existing fabrication projects, aspects and challenges of multi-robot fabrication are discussed. These include coordination, planning, communication and precision. Afterwards, a series of prototypes using an industrial robot arm and an educational mobile robot serve to illustrate some of

the challenges. The combination of these two robots, with their different types and specificities, also demonstrates the flexibility of robotic systems and their possibilities.

The work is concluded by a discussion on the integration of robotic fabrication in the design process.

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Chapter 1. Introduction

Architecture has always been under the influence of designers and thinkers who tried to change it through visionary ideas. Some of those were ahead of their time in imagining ways to change the built environment. One interesting and intriguing way was to introduce robots to architecture. The group Archigram envisioned in 1967 robots being part of a house transforming the furniture and serving the occupants. That was a “house for the year 1990” (Archigram 2010). French artist Villemard also foresaw in one of his postcards in 1910 how the construction site might look like in the Paris of the year 2000, where robots would be programmed by the designer onsite, to perform all the tasks that contemporary builders were manually performing (Tom 2011).

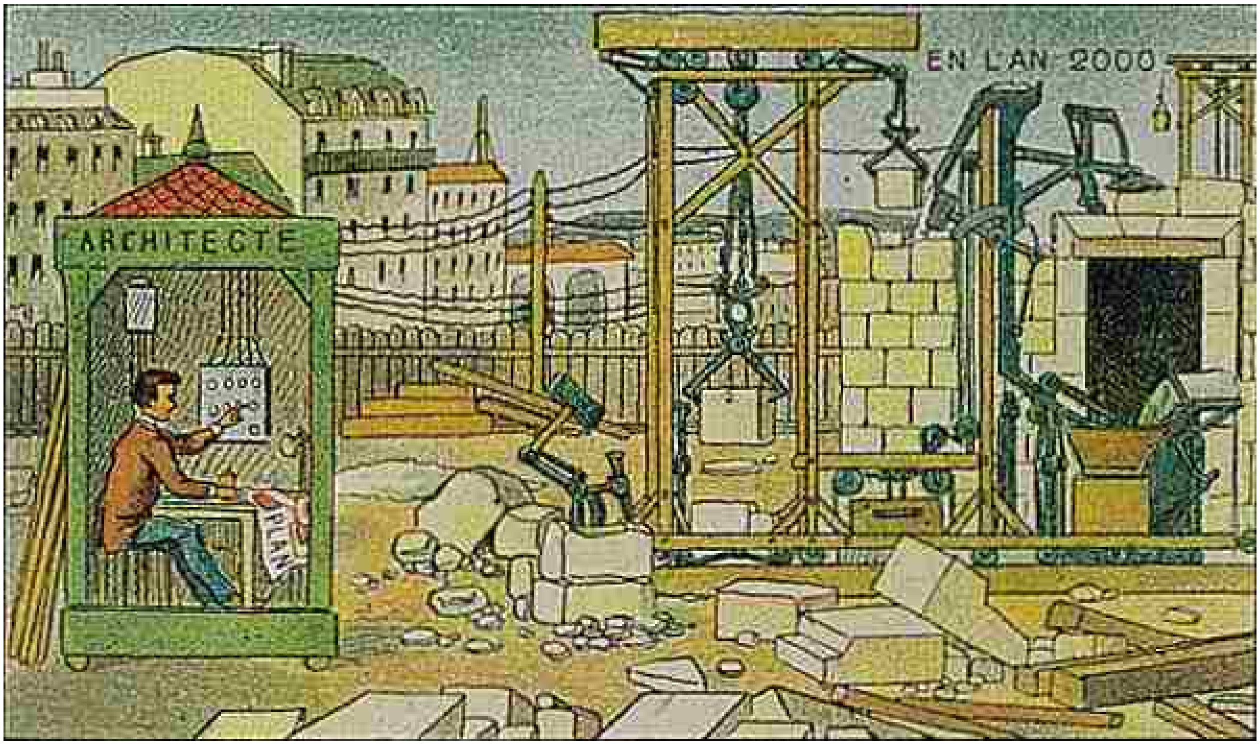

Figure 1 Paris of the year 2000 - Source: Villemard

Architecture has also been under the influence of other fields. In the recent years, we have seen designers acquiring and adapting tools from other industries ranging from software like CATIA taken from the aerospace field to hardware like robotic arms from manufacturing industries. Knowing that AEC field in the United States has seen a stagnation and decline in labor productivity compared to other fields (Teicholz 2013), borrowing and adapting tools from more productive industries might be an appropriate response. Many universities have acquired industrial robotic arms as a major tool for their architecture research laboratories. Among these we can cite the Institute for Computational Design and Construction (ICD) at the University of Stuttgart in Germany (ICD n.d.), the Robot Fabrication Laboratory (RFL) part of the Institute of Technology in Architecture at ETH Zurich in Switzerland (dfab n.d.), or the Robot House at Sci-Arc in the United States (Robot House n.d.). They have been equipped with multiple industrial robotic arms from ABB (ABB n.d.), Stäubli or KUKA (KUKA n.d.).

But construction sites are not formed by assembly lines, as in factories. Although automation might resolve some productivity issues, it is not the exact answer. Indeed, we need to take into consideration site irregularities, regional requirements, material choices, design ideas and more. We also need to have a look at how construction sites work today, with all the stakeholders and disciplines collaborating together. A construction site hosts many workers, machines and supervisors. They work in the same irregular and unpredictable environment, with different materials, tools and structures and following different schedules. They collaborate in a complex setup to be able to complete the architectural project. Introducing robotics in the construction site might improve their capabilities as well as their productivity.

Like in traditional construction sites, one actor cannot do it all. We would need multiple collaborating actors to accomplish the complex work that construction needs. Knowing that one large robot cannot go everywhere, and one robot cannot accomplish every type of task, and one large robot is not easily transported nor is it always affordable, combining many of them with the already available tools could be the right solution. We would then combine multiple robots of different types and capabilities, different sensors and different actuators, different materials and tools, with the already existing actors in construction sites; people. That could achieve a collective construction in the process of combining human, robots and materials (Tibbits 2017, 9).

Making those actors work together is the issue now. One of them has already demonstrated the ability to successfully work in groups, the human, and might provide clues on how to work with the other actors and make them work together. In fact, people have been successful in coordinating teamwork for the completion of a common goal. They demonstrated an ability to collaborate by distributing the tasks amongst the members of the team, sharing the space they all work in, planning the time for the execution of each task, while communicating with each other in order to ensure the right execution of the tasks.

This robotic collaboration should not only automate some construction processes, but should also add autonomy to these processes. Autonomy should here be considered for single robots executing their tasks, navigating the environment, and coordinating with other robots. That would achieve a collective autonomous construction.

1.1 Robotics and architecture

The use of robots in architecture and construction has gained considerable importance in the last few years. They have been integrated in fabrication and construction, whether through the design and fabrication of research pavilions, different scale prototypes, large-scale construction, or integrated in the building system. These can be industrial robotic arms, Unmanned Autonomous Vehicles (UAVs), smaller actuators or even new types of custom-made robots.

For some projects, one single robot is involved. Even though robots are meant to be flexible and multi-purpose, the scope of application of a single robot can be reduced. Combining different robots, however, can offer more possibilities and more applications. Using a multi-robot system for construction presents many advantages compared to single-robot systems.

One advantage is related to scale. In factories, the robots used might have a larger size than the objects they fabricate or assemble. For construction, some building elements are of a small enough size that robots of a larger scale can fabricate them. However, these elements need to be assembled, in factory or on-site, and having a large robot or machine build a structure smaller than it might not be practical. This can be resolved by the addition of mobility to the robots, which would add more degrees of freedom. It can also be resolved by the use of spatially distributed robots that would cover a larger work area.

Another advantage is related to the range of tasks performed by the robots. The difference in types of the robots, inherent to their different hardware and different behaviors, implies a difference in capabilities. Combining multiple robots with different capabilities, that perform complimentary actions, can offer unlimited possibilities in the applications.

Working with multiple robots can also make robotic fabrication more accessible, reducing the size can in fact result in reducing the cost but more importantly it can simplify the logistics that come with on-site construction and transportation.

However, multi-robot systems present several challenges. The most important one is related to coordination, especially in unknown or changing environments. Predefining their roles and actions in advance, as in a perfectly thought-through choreography, would simplify the coordination process. The choreography analogy implies that this process requires accurate pre-planning, which demands precision and predictability. Activities on a construction site however, are not always predictable. Materials used for example, are not necessarily perfectly homogeneous. The site itself can present irregularities and can be subject to unpredictable events. The choreography needs therefore to adjust to those conditions during the “performance”.

Modifying the choreography and allowing for a constant modification and adaptation in the robots’ behaviors, results from the communication with the environment and between robots. Indeed, the robots would react to their peers and to the environment during the execution of the tasks, which gives them the ability to constantly adjust. They would be able to sense the changes in the existing site, the evolving structure they are working on, and the eventual changes in the actions of their peers. This approach would make the coordination more complex, but would create a better synchrony between the robots themselves and the robots and their environment.

1.2 Method

This work is an exploration of the use of multi-robot systems in architecture. It first looks at the general definitions of robot and control. It then focuses on multi-robot systems and their coordination.

A classification of types of coordination is introduced according to the existing literature on the coordination of multi-robot systems in engineering.

Then, an overview of the use of multi-robot systems in architecture is presented. This section classifies fabrication projects according to the previous classification. It also explores concepts related to robot coordination in fabrication projects using multiple robots. These concepts include control, planning, precision and more. It also involves a discussion on the advantages of the coordination methods used and their disadvantages.

In order to illustrate those concepts, prototypes involving two types of robots have been made. These robots are a KUKA robot arm (KUKA n.d.), an industrial robot, and a Cozmo robot (Cozmo n.d.), an educational robot.

This is followed by an assessment of the limitations of these experiments.

Finally, this work concludes with a discussion on the future of robotics in architecture and construction, how it could modify the built environment, and how it would impact the discipline and evolve the role of the designer.

Chapter 2. Robotics

2.1 Defining robots

The word robot was first introduced in a play dating back from 1920, called Rossum's Universal Robots (R.U.R.). It is written by the Czech writer Karel Čapek (1890-1938). The word was previously coined by his brother (Stone 2004). The origin of the word comes from the Czech terms "robotnik" and "robota" which could be related to servitude and efficiency (Stone 2004). The reference to servitude relates to the role of the robots, which is to serve human needs. The need for efficiency in performing the tasks is related to the higher speed and precision required from robots compared to human-performed tasks. It can also be related to the time or safety gain by human when relaying certain tasks to robots.

Robots are also linked to automation, since repetitive tasks are among the tasks they perform. They have been used in the manufacturing industry, like automobile industry, to accomplish a multitude of tasks that require precision, automation and efficiency.

The robot was defined by the Robot Institute of America in 1979 as "a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks" (Robot Institute of America 1979). According to the International Organization for Standardization ISO 8373, industrial robots are "automatically controlled, reprogrammable, multi-purpose manipulator[s] with 3 or more axes" (International Organization for Standardization).

These definitions focus on the flexibility of the robots in performing the tasks. First by the possibility of *reprogramming* them, redefining therefore their actions and the way they interact with their environment. Second by *modifying* them, in order to physically adapt to the task. An example of this is the possibility of changing the end effector of robotic arms. The end-effector being the tool attached to the robot that will be in direct contact with the material and act on it.

2.2 Planning

The study of robotics requires two main parts, hardware and software. The hardware is related to the mechanical and electronic parts that form the robot. The software refers to the programming of the task the robot has to accomplish. The task to be accomplished by the robot as well as the environment in which the robot is deployed will also have an impact on both components. Hardware and software are strongly interrelated; the former imposes limitations on the latter, depending on its components. In fact, programming the robot depends on the type of data acquired by the robot's *sensors*, and the type of motion that can be performed by the robot's *actuators*.

In this section, we will focus on the software part, more precisely on understanding the programming phase, during which the actions performed by the robot have to be planned.

2.3 Plans and actions

Robotic programming is a problem-solving task, as it is for human activities' planning. An understanding of this is based on Suchman's thoughts about Human-Machine communication, related to the relationship between plans and actions, and their shared understanding (Suchman 2007).

Many aspects need to be taken into consideration to plan the robot's actions. The robot starts from a given state in a given environment and should reach a better state. This takes into consideration the conditions placed by the environment, whether static or dynamic.

The planning describes the path that needs to be taken in order to reach the goal state. In the planning model, a plan is described as "a sequence of actions designed to accomplish some preconceived end" (Suchman 2007, 52). The plan is a prerequisite for action, it needs to be established before the action is performed. It dictates the series of actions and their execution in time and space.

Interestingly, working backwards, the plan can also be inferred from the action, after it is performed. It is a reconstruction of the action, where the action is interpreted and "recognized" in a given situation. Interpreting actions is a way to speculate on the problem that is being solved by the action. This serves as a communication method using the "recognition" of plans. The actions are regarded as utterances in a conversation. Two speakers are discussing a matter, perhaps with questions and answers, or facts and arguments, and trying to interpret the other's position or plan throughout the speech.

The sequence of actions to perform a task is derived from the plan. In a given situation, with given conditions and a given background, the high-level plan is adapting to the situation to become a script, with more precise steps and rules. It acknowledges the physical and tangible situation in which the actions take place, as well as the abstract characteristics of the situation, related to the shared social and cultural background. It also takes into account the unpredictability that occurs during the execution of the actions. Starting from a plan that defines the path from a given state to a preferred one, the subject is likely to acquire more knowledge about the situation when executing the plan. The actions are more detailed and change to adapt to the situation, as does the plan (Suchman 2007).

Each situation and background comes with a set of rules and procedures that influence the type of actions. These also help with the interpretation of other agents' actions and the speculation on their plans. Indeed, understanding and sharing those rules is an important part of the communication process.

2.4 Robotic control

Different programming methods for robotic control exist. They have been explained and classified by Biggs and MacDonald (Biggs and MacDonald 2003).

The manual programming implies that the programmer will manually introduce the commands to control the robot flow. It consists of text-based systems and graphical systems. In the text-based systems, the programmer can either use a procedural language where the steps are individually described, or a behavior-based language where the programmer states the behavior taken by the robot in reaction to specific situations. In the graphical systems, the programming interface is a visual interface based on icons. Manual programming is often used for off-line robot control.

The automatic programming uses indirect control. It involves three different methods. The learning method where the robot learns the movement after watching it, this method can involve neural networks. The Programming by Demonstration Method (PbD) relies on the demonstration of the movement one pose at a time. The most traditional one uses a teaching pendent to record the different poses. The robot arm can also be directly positioned either manually or with a controller. Other methods may use visual, verbal, gestural or tactile modes to demonstrate the motion. Finally, the instructive method is based on a sequence of instructions that are already recognized by the robot. It uses voice or gesture recognition. Automatic programming is often used for on-line robot control. (Biggs and MacDonald 2003)

2.5 Robots and collaboration as an assemblage

In this study, the collaboration will be viewed as an *assemblage*. The idea of "assemblage" has been introduced by Gilles Deleuze and Félix Guattari. Deleuze defines an assemblage as a "multiplicity which is made up of many heterogeneous terms and which establishes liaisons, relations between them, across ages, sexes and reigns – different natures. Thus the assemblage's only unity is that of a co-functioning: it is a symbiosis, a 'sympathy'." (Deleuze and Parnet 2007, 69) as cited by (DeLanda 2016, 1).

An assemblage is therefore composed of multiple parts forming a whole. These parts are heterogeneous and interacting with each other. They are combined in a harmonious way to augment each other.

An example of an assemblage is the "man-animal-weapon" assemblage (Deleuze and Guattari 1987, 404) as cited by (DeLanda 2016, 68). In this example, the man, the horse as the animal and the bow as the weapon are three entities that interact with each other to form a whole. The three entities are heterogeneous entities. They are also autonomous, as they can exist outside that whole. The human can exist independently and included in other types of wholes, in this particular one he fulfills the role of a warrior. The same applies to the horse that here serves for transportation, but also for augmenting the capabilities of the human with its speed and its physical characteristics. The bow is here used as a weapon. The autonomy of these parts is related to the type of “relations of exteriority” they maintain. (DeLanda 2016, 73)

These three parts are interacting with each other, and from these interactions new characteristics emerge. This assemblage creates a new way of fighting, that combines the speed of the horse, the strength and intelligence of the man, and the properties of the tool. That forms a sort of a war machine that wouldn’t be possible without the interaction of these parts.

The robot can also be defined as an assemblage. A robot is an assemblage of sensors, actuators and a controller. These parts are augmenting each other and expanding the capabilities of the whole they form. The actuators are the physical parts with which the robot acts on its environment. It can be a motor controlling wheels to move the robot, or a lift or an arm to move objects. External sensors provide the necessary information to understand the state of the environment, and internal sensors provide information about the state of the different elements composing the robot. Both sensors and actuators are controlled by a controller. It processes the information received from the sensors and sends action commands to the actuators.

In the assemblage described by Deleuze, the horse and the bow are used to augment the capabilities of the human, which himself serves as a warrior to accomplish a specific goal. The human is also the one controlling the other parts; those serve as biological or technical tools. The same applies to the robot, and the way it is controlled.

The “man-animal-weapon” whole is also interacting with similar wholes when it is part of a larger one, forming an *assemblage of assemblages*. This is the example of cavalrymen forming an army. While fighting alone is an option, fighting in team gives them more power, more spread in the field and more flexibility. DeLanda makes the distinction between a nomad army and a sedentary one. The sedentary army presents a more rigid control over the cavalry. Once an order has been given prior to the battle it cannot be modified. The cavalry members should follow the protocol and the given orders without exercising any personal initiative. The nomad army on the other hand gives the possibility to its members to take initiative in case of unexpected events, enabling them to easily adapt to different situations without continuous orders. They use the knowledge acquired during their training to be able to adapt to different conditions (DeLanda 2016). This notion of control is similar to the distinction made previously between a strictly pre-planned choreography and a more flexible control that allows the robots to adjust to the conditions of the environment.

A robot is also capable of being part of a larger assemblage of multiple robots. Accordingly, a team of robots is an assemblage of assemblages of sensors, actuators and controllers. They all work together in order to accomplish the same goal. They also augment each other by sharing information about themselves and about the environment. For example, information obtained from one robot's sensor can be communicated and used by another robot. Another example is two robots executing together a task that cannot be executed by a single robot, like moving a large object. A team of robots has therefore more capabilities than a single robot.

A social network formed by people is considered as an assemblage, but an interesting fact is that what forms the assemblage is not just the people but also the environment in which they evolve, their culture, their language and more. In talking about social wholes, DeLanda mentions that "we need to include, in addition to persons, the material and symbolic artifacts that compose communities and organizations" (DeLanda 2016, 20). An assemblage is therefore always composed of heterogeneous parts since it does not only consider the homogeneous elements but also refers to the different elements constraining their interactions.

The whole is also interacting with the physical environment and its different characteristics, ranging from the topological properties of the land to the meteorological conditions of the location. One characteristic of the robot is how it interacts with its environment and acts on it. The assemblage is not merely the robot's components but also the robot and its environment, as it forms a whole with the physical environment and adapts to it. It also forms a whole with the physical objects it manipulates. The robot's physical configuration needs to match the physical properties of the objects and the site in order to function properly. The types of robots and the characteristics of their environment also define the way the robots communicate with each other and with the environment.

In his study of “assemblage” and in order to define social wholes, DeLanda, in his book “Assemblage theory” (DeLanda 2016), refers to two main concepts, emergence and relations of exteriority.

Emergent properties are “the properties of a whole caused by the interactions between its parts” (DeLanda 2016, 9). The whole will have new properties that do not exist in the independent parts, along with the properties of the parts themselves, this is what DeLanda qualifies as blocking micro-reductionism. The parts will also be more than parts of a whole, since they keep their individuality and their respective properties, and this is blocking macro-reductionism with the “irreducibility of the whole”.

Wholes being formed of heterogeneous parts, they get their properties from the interactions of the parts due to emergent behaviors, but they also have an influence on the parts themselves through rules and conventions, in a downward causality way.

The second concept is related to the relations of exteriority between the parts. In fact, the parts will keep their independence; they can be part of one whole or another without being constrained to one in particular.

A team of robots working together will have these same properties. In fact, new characteristics would emerge from their collaboration, without making the robots lose their individual characteristics or their ability to work separately.

Chapter 3. Multi-Robot systems

A multi-robot system consists of a group of robots working in the same setting in order to accomplish a given goal. As opposed to a single-robot system, multi-robot systems (MRS) have a number of advantages. One main advantage is their ability to cover a larger area due to a better spatial distribution. They also improve the overall system performance (Yan, Jouandeau and Cherif 2013) (Farinelli, Iocchi and Nardi 2004), which can be based on the time required for the task or the energy consumed during the task (Yan, Jouandeau and Cherif 2013). The MRS is also a more robust and reliable system, this is due to the higher amount of information acquired and shared by the robots for example (Yan, Jouandeau and Cherif 2013). The reliability of this system is also related to the fact that in some systems the failure of one robot will not prevent the task from being completed by the rest of the robots in the system. Another advantage is related to the cost, in fact a MRS, if using simpler robots rather than one single complex robot, can reduce the cost of the system (Yan, Jouandeau and Cherif 2013). Simpler robots will also be easier and cheaper to build, and more importantly they are easier to transport. Flexibility and scalability are other advantages to MRS. Multi-robot systems are more flexible and versatile since combining multiple robots also means combing multiple capabilities (Yan, Jouandeau and Cherif 2013). They are also scalable systems both for the number of robots and the task and area they work on. Indeed, adding more robots to a given system should expand the range of application of the system without important modifications.

In some cases, MRS are mandatory since the work cannot be performed by a single robot. This can be the case where the robot works on a large area with time constraints, meaning that the task needs to be completed in different areas at the same time or without a long wait. An example can be with 3D printing on a large scale where curing time is a constraint. MRS are also necessary when different tasks need to be performed at the same time, like robotic assembly needing two cooperating robots working at the same time (Gandia, et al. 2018).

In multi-robot systems, a distinction is made between cooperative and competitive behaviors (Yan, Jouandeau and Cherif 2013) (Farinelli, Iocchi and Nardi 2004). Cooperative behavior implies that the robots are working together in order to accomplish the same goal. All the tasks they complete will contribute to that goal. In a competitive behavior, the robots evolving in the same environment will be competing against each other; their goals will be individual and competing. In the literature review, as well as in this study, only cooperative behavior is considered.

In classifying collaboration processes, we have relied on the classifications made by (Yan, Jouandeau and Cherif 2013) and (Farinelli, Iocchi and Nardi 2004). The first presents a survey of coordination of multiple mobile robot systems. The second presents a classification and a taxonomy of coordination of MRS in general, with examples from a literature review of existing projects. They use two types of "dimensions" for their classification. The coordination dimensions include cooperation, knowledge, coordination and organization. The system dimensions include communication, team composition, system architecture, and team size.

3.1 Types of robots

In the classification of multi-robot systems, a main distinction is made regarding the nature of robots forming the team. These robots can either be homogeneous or heterogeneous robots. In the case of homogeneous robots, they are identical in type, shape and size, they also have the same programmed behavior. Swarm robots, that are inspired by natural insect colonies like ants, are a good example of homogeneous robots. Even though these robots may perform different tasks to complete the project, they are all implemented with the same behaviors. In their classification, Yan et al. (Yan, Jouandeau and Cherif 2013) do not require the robots to be physically identical to be homogenous, only their capabilities need to be identical. An example of projects using homogeneous robots is one using a swarm of Cozmo mobile robots to assemble an origami-like structure (Kalantari, Becker and Ike 2018). "Termes" robots are also designed with a goal of using them as swarm robots (Petersen, Nagpal and Werfe 2011). “Fiberbots” (Kayser, et al. 2018) are also swarm robots used to fabricate a tubular structure.

In the case of heterogeneous robots, the robots can be physically identical or different; they can have more than one type, shape and size. The importance is that they are programmed differently, in order to accomplish different types of tasks. For example, the research pavilion developed at the ICD (Felbrich, et al. 2017) is fabricated using two robot arms and a UAV, the robot arms differ from the UAV in shape, size, capabilities and behaviors.

3.2 Control

In multi-robot coordination, the control of the group of robots, or the system architecture (Farinelli, et al.), can be classified similarly to the control of a single robot. It can be reactive (behavior-based paradigm) or deliberative, meaning programmed through a sequence of steps, whether it involves a feedback loop based on sensing (Sense, Plan, Act paradigm) or not.

Swarm robots usually demonstrate a reactive behavior. In Fiberbots (Kayser, et al. 2018), the swarm robots adjust their trajectory in reaction to the other robots’ trajectories.

The example of the ICD research pavilion (Felbrich, et al. 2017) shows an example of deliberative programming, where the robots have a sequence of consecutive steps to execute for the fiber weaving process, consisting for each robot of reaching a position and exchanging the fiber material.

A system can also involve both programming methods (Yan, Jouandeau and Cherif 2013) (Farinelli, Iocchi and Nardi 2004).

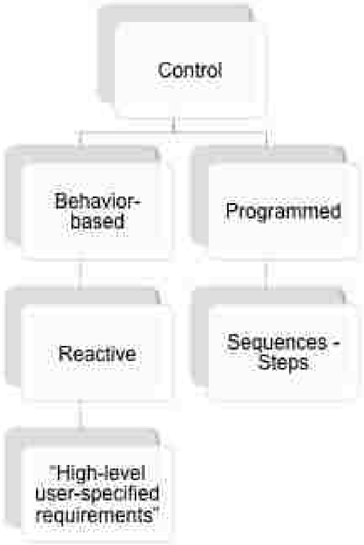

Figure 2 Type of control in Multi-Robot systems - according to (Yan, Jouandeau and Cherif 2013)

3.3 Planning

As mentioned before, cooperative robots work as a team in order to achieve the same goal. In order to do so, the robots have to perform a number of complementary tasks, in a shared environment. The tasks needed to achieve the goal have to be identified and distributed among the robots according to their capabilities or other criteria.

Time will also be considered for allocating those tasks, since the coordination has to be considered in terms of timing.

Space is another resource that has to be taken into consideration. Indeed, the robots will be sharing the same physical environment while performing their tasks. They need therefore to coordinate in time and space in order to avoid colliding with each other, or preventing other team members from correctly completing their tasks. They also need to avoid collision with other elements of the environment.

Resolving these issues in coordination is described as planning. According to Yan et al. (Yan, Jouandeau and Cherif 2013), it has two components, the task planning and the motion planning.

Task planning is divided into task decomposition (Multi-Robot Task Decomposition MRTD) and task allocation (Multi-Robot Task Allocation MRTA). Task decomposition consists of identifying the tasks that will lead to the completion of the project. Task allocation serves to distribute the tasks to all the robots working in the system.

Motion planning involves finding the path of each robot while taking into consideration the environment and the other robots.

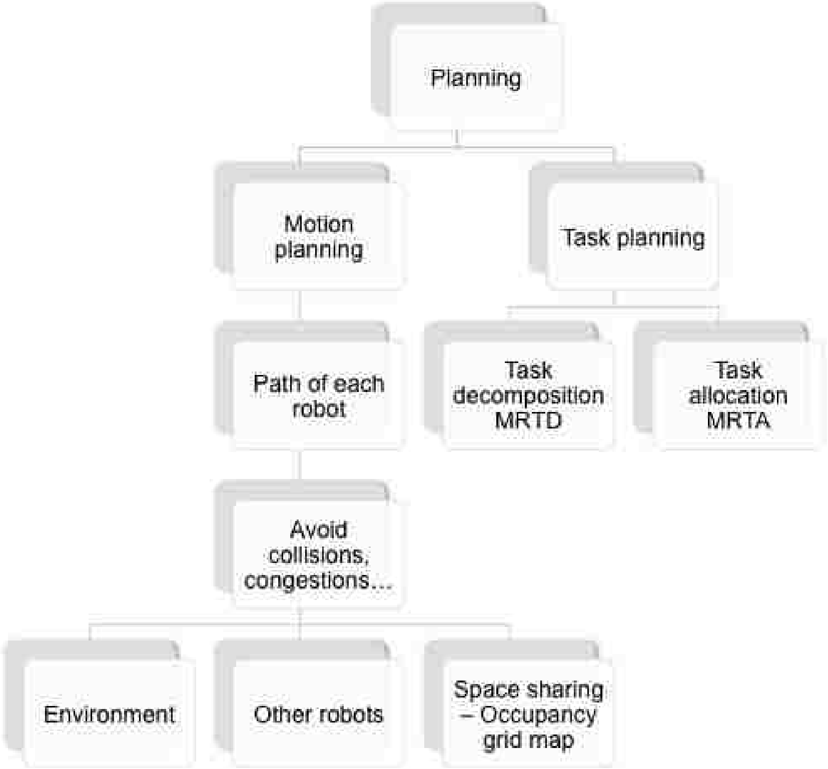

Figure 3 Planning components in Multi-Robot systems – according to **(Yan, Jouandeau and Cherif 2013)**

3.4 Dynamic / Static coordination

Coordination can either be dynamic or static.

In static coordination, also called offline or deliberative coordination, the robots follow conventions and rules that are predefined before the beginning of the task. These conventions are related to the way a robot should act in the case of predefined situations.

The advantage of static coordination is that it performs better with complex tasks, but it is not efficient when real-time control is needed. (Yan, Jouandeau and Cherif 2013)

In dynamic coordination, also called online or reactive coordination, the coordination happens when the task is being executed. The decisions made are based on information acquired from the communication. Dynamic coordination can be explicit or implicit. When it is explicit robots use explicit communication, and when it is implicit robots use implicit communication.

In “Designing for digital assembly” (Kalantari, Becker and Ike 2018), the robots are dynamically coordinated. Indeed, the allocation of the tasks to each robot is done dynamically, and is based on features like the proximity of the robot to the object.

An important attention has to be made to the type of environment the robots will operate in, which can be static or dynamic. In a static environment, there are no changes made during the task, while in a dynamic environment, the MRS will be interacting with other agents in the environment, either human or other robots, it will also adapt to the physical changes due to these interactions.

3.5 Communication

In order to achieve a dynamic coordination, the robots need to communicate. This allows them to gather information about the locations of other robots, the tasks that have been completed, the next task to accomplish, etc. Communication between the robots can be either direct or indirect.

Indirect communication relies on the information found in the environment. Stigmergic communication uses clues in the environment to share information. However, these clues can be either from other robots, or from other agents or factors in the environment, the robots are not able to distinguish the origin of these clues, but can use them to gather necessary information for their task (Farinelli, Iocchi and Nardi 2004). In nature, insects for example use pheromone as a way to communicate via the environment. In swarm robots, observing the environment gives clues about the state of completion of the project and an idea about the next step to accomplish.

Direct communication uses a communication system to send information either directly from a robot to another, or from the robots to a central communication system.

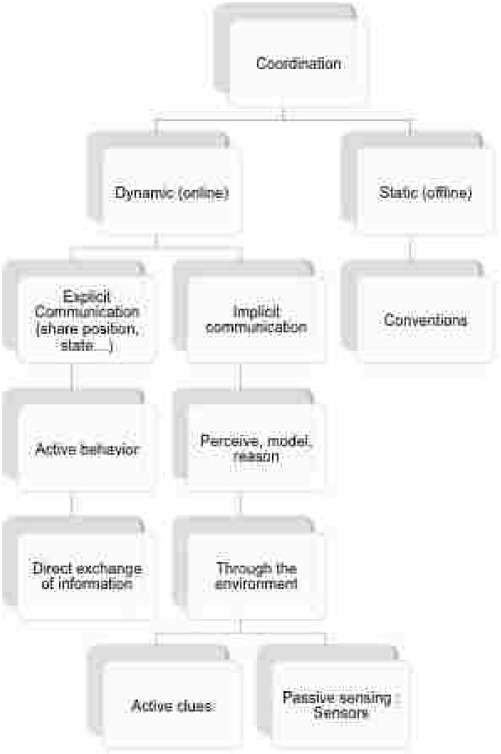

Figure 4 Coordination and communication in Multi-Robot systems – according to (Yan, Jouandeau and Cherif 2013)

3.6 Aware / Unaware systems

A classification of MRS based on the knowledge level of the system makes a distinction between aware and unaware systems (Farinelli, Iocchi and Nardi 2004). They characterize unaware systems as systems where the robots are not aware of the other robots in the system. Each robot will accomplish its task independently, without the need to know about the other robots, the group will still work on the same overall mission. The communication between the robots is indirect, they can use information from the environment to drive their decisions, without knowing the source of that information.

These systems are also not deliberative (the term deliberative is not used in the same sense as in the classification made by (Yan, Jouandeau and Cherif 2013)), where the robots will be independent in adapting to the changes in the environment. There is no coordination between the robots in unaware systems.

In aware systems on the other hand, the robots have knowledge of the other members of the group.

3.7 Level of coordination

MRS can be not coordinated, weakly coordinated or strongly coordinated. In a not coordinated system, the robots will not take into consideration the other team members during the task completion. In a weakly coordinated one, the robots use "simple methods to reduce interference among robots executing a cooperative task" (Farinelli, Iocchi and Nardi 2004) In such a system, there is an emergent property that results from the interactions between the robots and the dynamic environment they work in. In a weakly coordinated system, certain behaviors are used to allow the cooperation.

In a strongly coordinated system, a coordination protocol is used where the robots receive orders on the actions they should take.

A strongly coordinated system can use a strongly centralized system. Using a central controlling system, ROS (Robot Operating System) tracts each robot and sends command actions to the robots.

One robot of the team members can also play the role of the leader and be the one sending the orders.

In a weakly distributed system, the role of the leader is dynamic and can be performed by different robots during the task, this role is allocated depending on certain criteria.

In a distributed system, a coordination protocol is used and the robots take decisions autonomously.

Chapter 4. Robotic Collaboration in Architecture and Fabrication

Many architecture projects have relied on collaboration methods. In this section, a review of some projects is made. An understanding of these projects relies on the classification discussed in the previous section. The following table illustrates that classification.

Table 1 Classification of projects according to the collaboration classification

Project	Type		Control		Coordination		Communication		Level of coordination	
	Homogeneous	Heterogeneous	Reactive	Deliberative	Dynamic	Static	Direct	Indirect	Centralized	Distributed
Machine species (Yablonina and Menges 2018)	X (demonstrator 1)	X (demonstrators 2+3)		X	X		X		X	
Fiberbots (Kayser, et al. 2018)	X		X		X		X			X
ICD research pavilion (Felbrich, et al. 2017)		X		X	X		X		X	
Termes (Petersen, Nagpal and Werfe 2011)	X		X		X			X		X
Designing for digital assembly (Kalantari, Becker and Ike 2018)	X		X	X	X		X	X	X	X

4.1 Control

The control of the group of robots can be deliberative or reactive. For swarm robots, the control is usually reactive, where the robots can exchange tasks depending on their locations for example, they also adapt to the evolution of the structure.

As previously mentioned, swarm robots are a group of identical and simple robots working with the same capabilities in order to collaboratively accomplish a task. Usually, swarm robots are small in size, and it is their number and spatial distribution that allow them to accomplish fabrication tasks of objects at a larger scale.

“Termes” project (Petersen, Nagpal and Werfe 2011) is an application of construction using swarm robots. They have first developed the hardware for a single robot, with a goal to scale it and integrate more robots. The task is to assemble a structure formed by small building blocks. The scalability of the system allows the assembly of a stair-like structure by either a single robot or multiple robots. This particularity also adds to the robustness of the swarm system, in fact, if one robot fails in accomplishing its own task the whole operation does not fail.

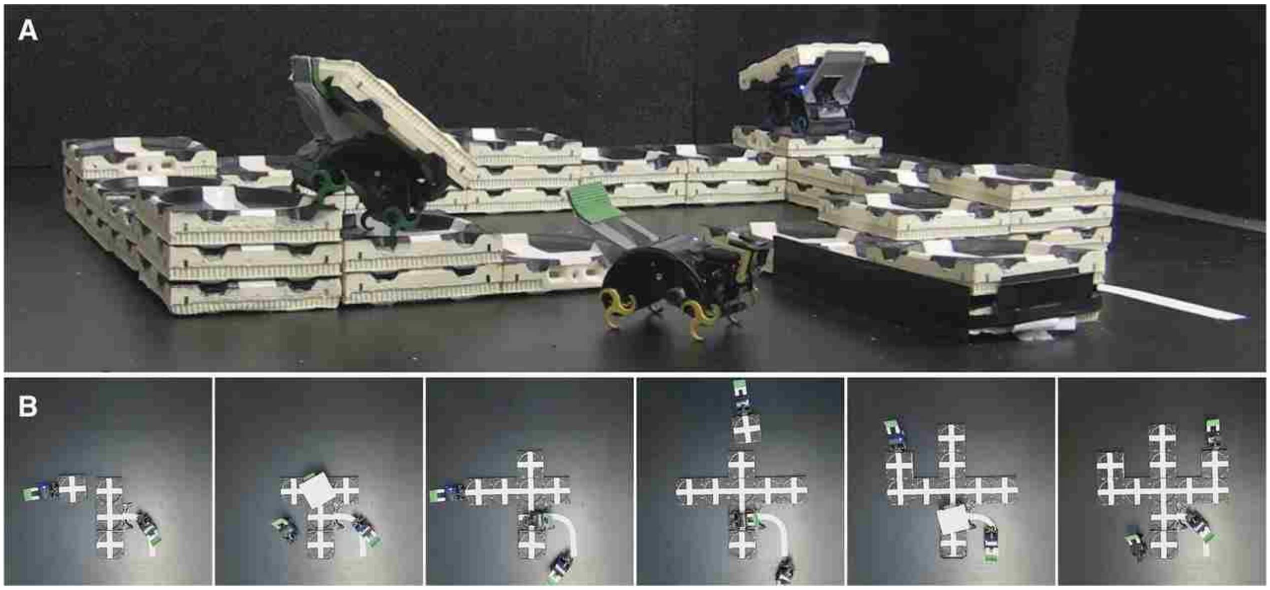

Figure 5 Termes robots **(Petersen, Nagpal and Werfe 2011)**

In their research project, researchers from the Institute for Computational Design and Construction in Germany (ICD) have used fiber composite material (Felbrich, et al. 2017). The digital fabrication technique eliminates the use of formwork, as it is usually necessary when using fiber composite. They have used a “multi-machine” fabrication method, combining drones and two KUKA robots. The control is deliberative, where the robots have to follow precise steps and target locations. The coordination between the two systems is maintained through infrared cameras installed on the robotic arms. The robots are controlled in an online process, where feedback is received between each step of the process. The Robot Sensor Interface (RSI, for KUKA) is used for the feedback. The geometry was optimized to achieve a thin but strong enough structure. A first frame is made using glass fibers, it is then reinforced with the carbon fibers.

In integrating different robots, the project dealt with the issue of feedback control.

Figure 6 Robotic fabrication of the pavilion **(Felbrich, et al. 2017)**

4.2 Communication

In Termes (Petersen, Nagpal and Werfe 2011), the autonomous robots use indirect communication using local information.

Another application of swarm robots uses five educational robots (Kalantari, Becker and Ike 2018). The Cozmo robot from ANKI (Cozmo n.d.) is used to fold and assemble a structure of origami shapes.

The system used combines two communication methods. The first is a direct communication through a centralized system where the positions of each robot are shared. The second is indirect using stigmergy, with clues from the environment. These clues are the positions of fiducial markers placed on the metal sheets. These are perceived by the robot's onboard camera. This helps each robot determine the stage of the folding process. Along with the centralized communication, it gives enough information to guide two robots and then the third to fold one flat sheet.

4.3 Tasks

Task planning is an important step in the planning process. Tasks need to be designed and assigned to the robots.

In a project developed at ICD, the researchers are not using industrial robots and augmenting them for a specific need, they are rather developing their own “machine species” to work with fiber materials (Yablonina and Menges 2018). The goal is to develop a toolbox of task-specific robots capable of working collaboratively to create a filament structure. The research showcases three consecutive demonstrations. The first uses two homogeneous robots to create a carbon fiber structure through winding. The mobile robots are wall-climbing robots, each is equipped by a marker localized by an external camera. This allows the system to know the current location and orientation of the robot. The robots receive each action order from the fabrication sequence step by step, these include the target points to go to and the actions to accomplish, like winding or filament exchange actions. Although this system demonstrated the feasibility of using custom-made robots, it lacked some precision due to the visual tracking system used.

4.4 Space

This section presents some topics related to space, one of them is about knowing the space the robots are working in, in order to locate themselves.

Space is considered as a shared resource between the robots, and therefore issues of motion coordination have to be considered.

Using fiducial markers like AR tags is a way of perceiving the environment and locating landmarks. In (Kalantari, Becker and Ike 2018), a fiducial marker is used to give a common coordinate frame for the robots and to help them locate the stack of building sheets. One of the issues noted in this project is the lack of accuracy in the localization of the robots using the AR tag, especially when the robot is too far away from the tag. As an improvement, they propose to use some of the robots for localization.

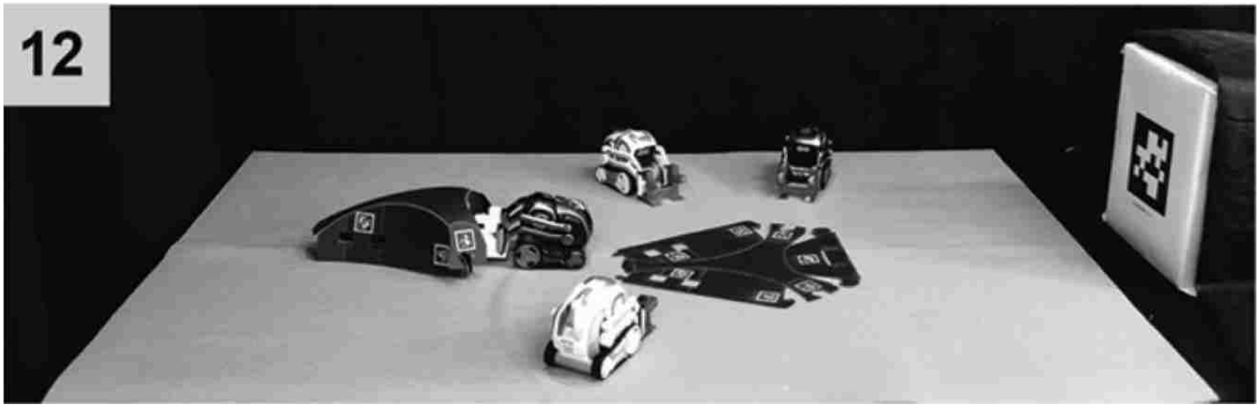

Figure 7 The use of fiducial tracking in the project (Kalantari, Becker and Ike 2018)

The fiducial tracking consists in visually tracking fiducial markers placed in the environment. These are used as reference points that are easily detectable. AR markers are a type of fiducial markers used in visual systems. AR Markers are used in Augmented Reality. These are black and white tags are square forms with a black border to determine their external boundary. A dictionary of markers contains the list of markers that are used, each one having a single ID inside the dictionary and is recognized via its unique graphical pattern. The size of the markers that are printed (or displayed on a screen) is determined within the program used to recognize and localize them.

The localization of the markers determines their pose or the pose of the object on which they are placed. The markers therefore provide a reference frame of the objects (Bergamasco, Albarelli and Torsello 2011). This process is called the pose estimation. The pose is determined by the position and the orientation. The position is the x, y, and z coordinates of the target. The orientation consists in the rotation around the three Cartesian axes (Correll 2016). The pose estimation definition gives information about the position as well as the rotation, the rotation gives the 3D pose of the object and the angle around the z axe.

Swarm robots have also been used for mapping. Although this work and the projects referred to are more focused on fabrication, mapping and localization are an important part of multi-robot navigation. The project was developed by Icosystem (Icosystem n.d.) (Rothermich, M. İhsan Ecemiş and Paolo Gaudiano 2005). It uses a distributed approach of a multi-robot system. They have used Swarmbots by iRobot (iRobot n.d.), small robots of about 15x15 cm equipped with infrared sensors to detect distances. They have tested their programs both in simulation and in physical settings. The algorithms they have developed focused on three parts. The first is the collaborative localization, where the robots localize themselves relatively to landmarks represented by fixed robots. The second is the dynamic task allocation, which dynamically determines which robots should play the role of landmarks and which ones are moving robots. Finally, the collaborative mapping algorithm uses the two first algorithms to draw the map of the environment in which the robots are placed. Each robot creates a map using the localization algorithm. The maps of all the robots are then combined to create a single map in the same global coordinate system.

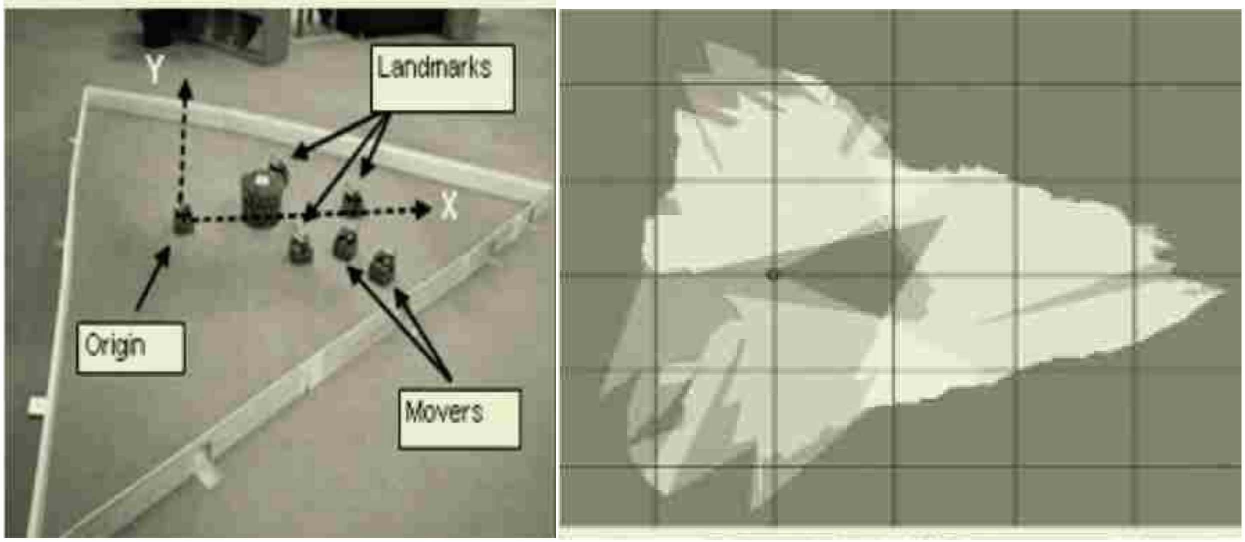

Figure 8 Distributed Localization and Mapping with a Robotics swarm **(Rothermich, M. İhsan Ecemiş and Paolo Gaudiano 2005)**

Motion coordination is also an important notion. Space being a shared resource, the robots have to coordinate their motions in order to avoid collisions and execute the tasks correctly and safely. In their project, “Towards automatic path planning for robotically assembled spatial structures” (Gandia, et al. 2018), the researchers have dealt with the motion coordination for two robotic arms assembling a timber structure.

In Fiberbots (Kayser, et al. 2018), tubular structures are made using swarm robots. Their paths are modified according to the other robots’ paths in order to achieve a structure that avoids collision between the tubes while having intertwining tubes.

Figure 9 Fiberbot fabricating the tube – Source: The Mediated Matter Group

Figure 10 Fiberbots tubular structure - Source: The Mediated Matter Group

4.5 Time

In (Yablonina and Menges 2018), one of the issues in the second system is the “Idle time”, where one robot has to wait for a long time until it receives the filament again, reducing its productivity. This issue has been addressed by adding a second thread walker making the two wall robots working simultaneously with two different filaments. The settings for this last demonstrator have also changed.

Task-oriented machines lose one important characteristic in robotics, which is the flexibility in accomplishing a multitude of tasks. However, using multiple heterogeneous robots compensates for the limited capabilities of each robot, as it is the case with a swarm of simple robots. This project also showcases some issues like the idle time that can be improved with robotic collaboration.

4.6 Imprecision

AR markers are easy to use and to detect. However, they present some limitations. These limitations include the additional effort of putting the tags in the environment and the difficulty of using them in exterior environments. They also noticed their reliability on the lighting conditions due to the use of the vision-based sensors (Feng, et al. 2015).

The second demonstrator in (Yablonina and Menges 2018) used two wall-climbing robots with a third “Thread walker” robot. The wall-climbing robots are on two parallel vertical surfaces, while the third robot moves on a thread linking the two surfaces. The filament is wound on a surface and handed off from a first robot to the thread walker that brings it to the second robot on the parallel wall to wind it there and give it back to the thread walker and so on. This system uses ArUco markers and a higher resolution camera.

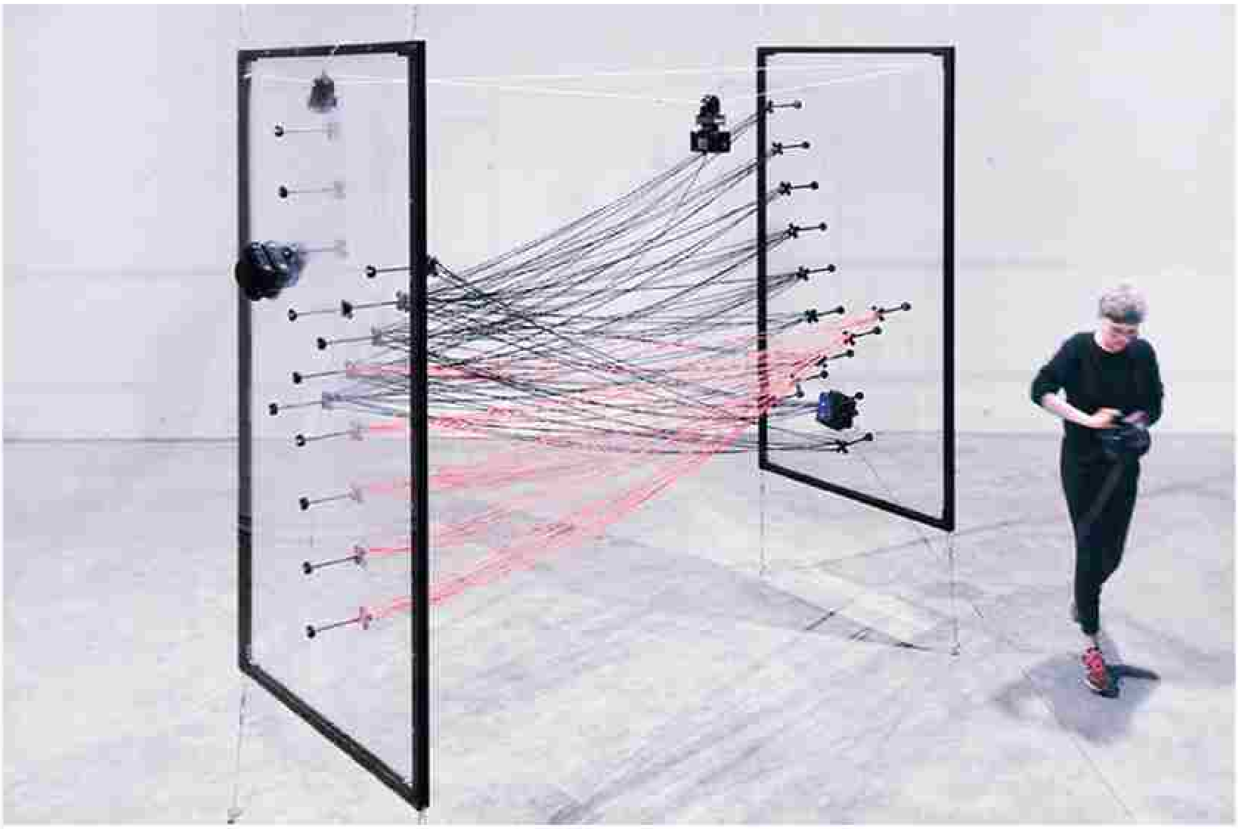

Figure 11 Machine species - Demonstrator 3 (Yablonina and Menges 2018)

4.7 Materials and Hardware

As a way to adjust to the imprecision found in many systems, projects use the materials as an adjustment method. We can refer to two types of adjustments related to materials, mechanical intelligence or smart materials.

In “Termes” project (Petersen, Nagpal and Werfe 2011), the robots and the building blocks were designed jointly, in order to give the robots more affordability in manipulating the blocks, therefore creating a “mechanically intelligent” system. The shape of the block, as well as the sensors and actuators of the robots, allow the robot to grasp the block with its arm and check its position through three sensors integrated it the arm (pushbuttons). The block contains magnets that are used for the assembly process.

The robots accomplish three different tasks; climbing, navigation and manipulation. Each of these tasks takes into consideration and influences the environment and the materials. The height of the blocks and the robot's hardware were tested in order to obtain the right proportion allowing the robot to climb the blocks. The blocks were labeled with black and white patterns and the robots with multiple IR sensors. This allows the robot to know the pose of each block and its relative position, which thanks to a state machine will also give information about the progress of the carried task.

In (Kalantari, Becker and Ike 2018), a mechanically intelligent system is used, each Cozmo robot has been augmented with a 3D-printed "forklift" attached to the robot's arm-lift, this helps the robot manipulate the metal sheets.

Cyber physical macro material as a UAV [re]configurable architectural system (Wood, et al. 2018) have used smart materials as building blocks. The smart building blocks are transported by UAVs to their location in the structure, they are then attached by activating the magnets integrated on the sides of the blocks. The magnet is deactivated when the block is removed.

Figure 12 Reconfigurable architectural system - Source: University of Stuttgart

Chapter 5. Prototyping

This section describes a series of experiments intended to understand and demonstrate the concepts encountered in the last two sections. It is therefore organized according to these concepts.

The prototypes presented utilize a KUKA robot arm and a Cozmo mobile robot.

The Cozmo robot is developed by Anki (Cozmo n.d.). It is an entertainment and educational robot designed for children. It has also been used for robotics programming courses at school and university levels.

The robot is small and fits in a bounding box of approximately 10x6x7 cm. It is a mobile robot with several sensors and actuators. As actuators, it has motors and 4 wheels, a vertically pivotable head, a robotic lifter and LED lights. It also has a display of 128x64 pixels and a speaker. As for its sensors, it is equipped with an accelerometer and a gyroscope, which are useful for its localization and movement analysis, and it has an IR sensor on the front. The head has a built-in 30fps VGA (Video Graphics Array) 0.3 megapixel, 640x480 pixels camera.

It comes with three power cubes with AR markers, LED lights, an accelerometer and tap detector. The AR markers can be used by the robot to find the location and orientation of the cubes.

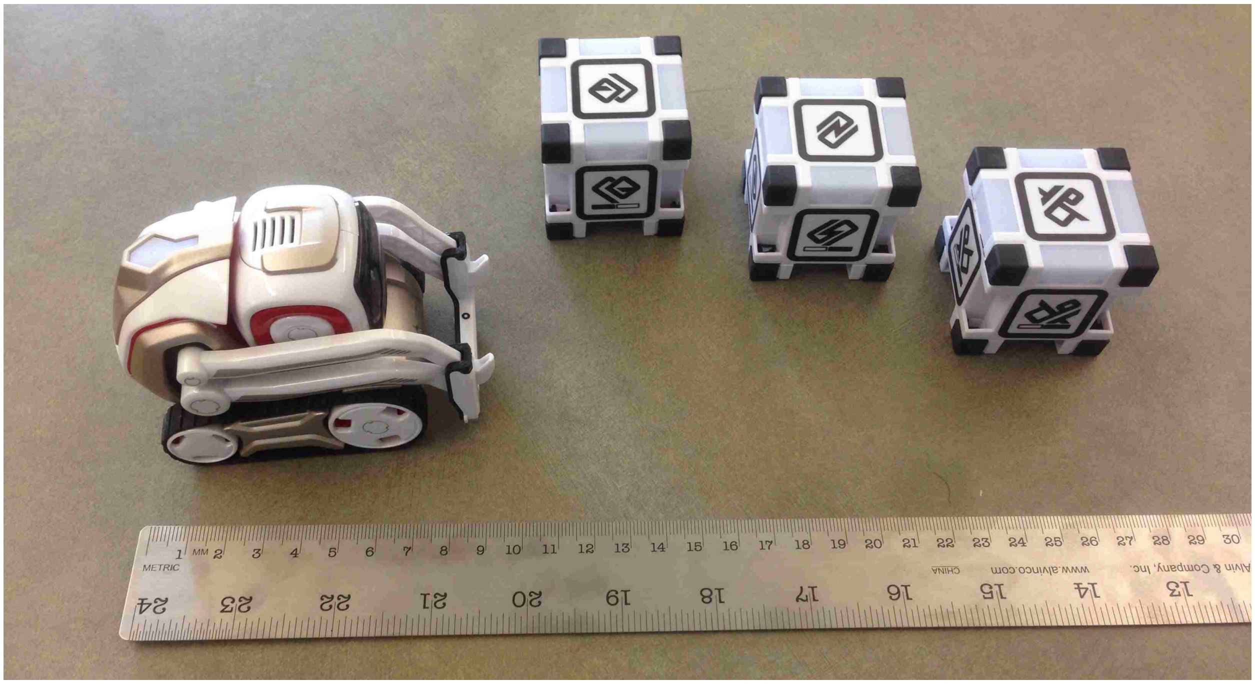

Figure 13 The Cozmo robot and the power cubes

The Cozmo robot can be controlled in three different ways. The basic way is by using a smartphone application and running built-in games. The second method is by using the visual programming interface “Code Lab”. It is similar to a Scratch interface (Maloney, et al. 2004) and it uses simple parts of code bricks that can be assembled to build a program. The third method is by using the Software Development Kit (SDK) developed by Anki in which programs are written in Python, an open-source high-level object-oriented programming language. (Kaiser 2017)

In order to run programs with the SDK, the robot has to be connected to a smartphone via WIFI. The Cozmo application will be executed with the option of running the SDK. The smartphone must be connected to the computer via USB cable. The python programs are then executed on the computer.

Figure 14 Cozmo communication

For our experiments, we have used starter codes from the Cozmo tutorials (Anki 2016), as well as starter codes from a University of Washington CSEP Robotics course (Cakmak 2018).

The second robot used is a KUKA KR6 R700 robot arm. Architects and researchers have experimented the use of the robotic arm as a fabrication tool. Industrial robot arms have been developed by many manufacturers, among these KUKA AG (KUKA n.d.), ABB robotics (ABB n.d.), Universal Robots (Robots n.d.) or Schunck (Schunk n.d.).

The robotic arm has the advantage of being a flexible tool. The different end-effectors and toolpathing give it the ability to perform additive and subtractive tasks, replacing in part and outmatching other CNC machines that are “task-specific” (Payne 2011). The toolpathing represents the movements the arm has to follow, including translations and rotations of the various joints. The end-effector is the tool placed at the end of the arm that allows it to perform specific tasks. It can be industrialized, or customized according to the user needs. The industrial arm has for instance been used as a milling tool (Brell-Cokcan and Braumann 2010), a knife-cutting and hotwire-cutting tool and a foam-deposition tool (Pigram and McGee 2011), an assisted bending tool (MacDowell and Tomova 2011) (Pigram and McGee 2011), an assembly tool (Helm, et al. 2012). All these tasks are made possible by changing and customizing the end-effectors of the robot.

The robot arm used in the project is a 6-axis arm, with 6 joints and 6 degrees of freedom. The degrees of freedom are related to the possible motions of each joint around its axis, either rotation or translation, the number of degrees is the number of variables needed to move the robot, one for each a (Association for Robots in Architecture 2015)xis (Schwartz and Park 2017). The arm has a reach range of 700mm and is placed in a safety robotic cell.

Two different ways have been used to program the Kuka robot. The first is through programming by demonstration (PbD) or teaching by demonstration. This is done using the teaching pendent (Smart Pad), where the user creates a new Kuka program. The keys or the mouse on the Smart Pad are used to move the robot's end-effector to the desired positions. Those positions are then saved in the program using the Smart Pad's interface (KUKA Roboter GmbH 2013). The interface also gives the option to choose the motion type, the speed and any wait times if needed. The gripper status, open or closed, is also selected.

The user then runs the program using either the manual/teaching mode or the automatic mode. The teaching mode is intended to save new programs, and to run them at a predefined maximum program speed.

The second method is by using the KUKAlprc developed by Robots in Architecture (Association for Robots in Architecture 2015). It's a plug-in for Grasshopper in Rhinoceros, that allows a "parametric robot control".

5.1 Communication

There are different ways in which the two robots can communicate. Here we demonstrate two possible ways.

5.1.1 Indirect communication

Stigmergic communication refers to the use of clues in the environment. It is used here through the visual sensing of brightness in the environment. A flashlight is attached to the robot arm as an end-effector. The robot arm is programmed using the teaching by demonstration method. The end-effector describes a curve above the horizontal plane. The room is set in the dark with the flashlight being the only light source. Using the Braitenberg vehicle experiment (Braitenberg 1984), the Cozmo robot's program uses the image from the camera to sense the brightness. The right and left wheels of the robot rotate relatively to the brightness level sensed in the left and right sides of the image, making the robot move towards the brighter side where the light source is. The Cozmo robot, by following the light source, follows the robot arm’s end-effector, without being aware of its existence, as the only thing that acts on the Cozmo robot path is the brightness of the environment.

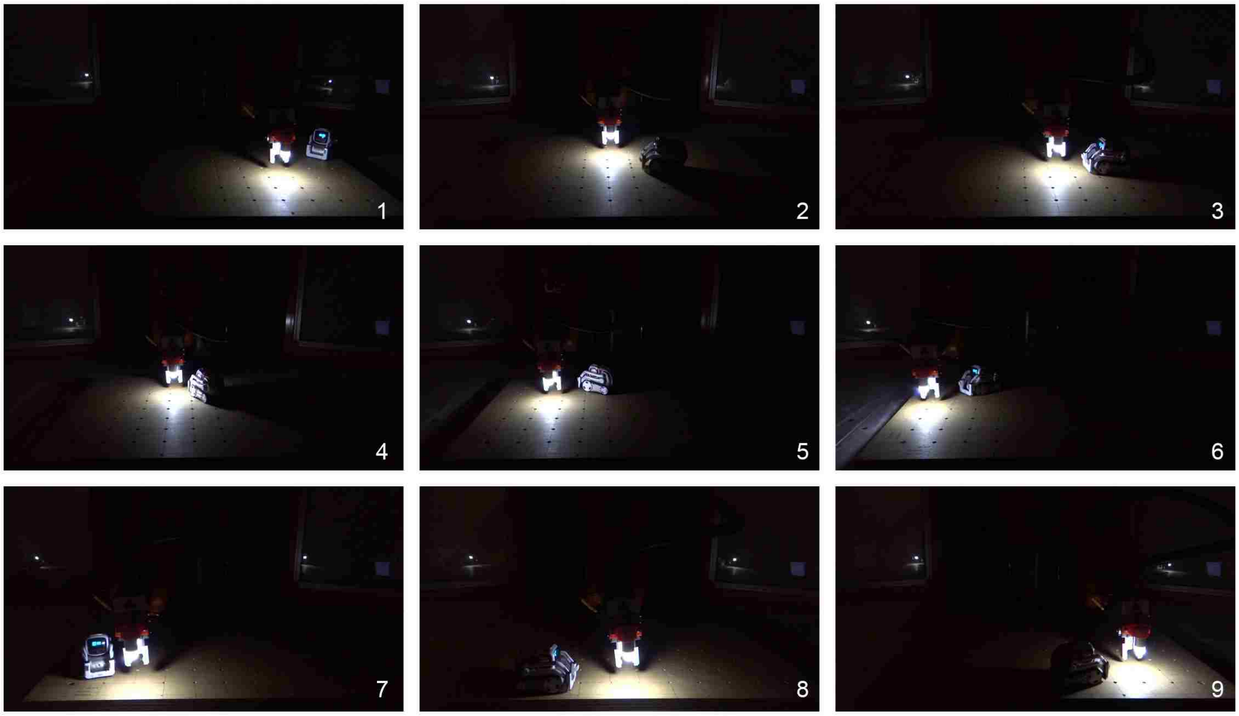

Figure 15 Stigmergic communication with Cozmo and Kuka robots

5.1.2 Direct communication

Figure 16 The mobile robot and the robot arm sharing positions in an asynchronous way

In order to illustrate a direct communication method, we have experienced the use of “GHowl” (Alomar, Fraguada and Piacentino 2011), a plug-in for Rhinoceros / Grasshopper that sends data using the computer IP address and a port number. In this example, the Cozmo robot moves on the platform and records its locations. The image of the Cozmo camera shows what is perceived by the robot. The Cozmo visualization platform shows the robot moving and new points representing its last location being created.

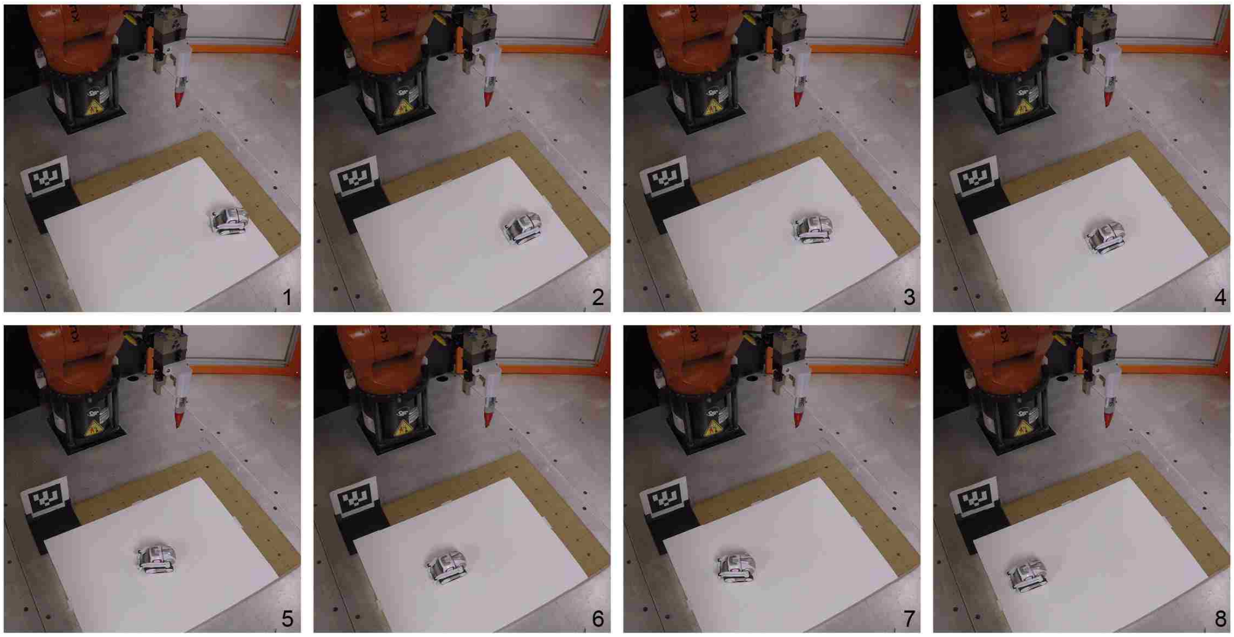

Figure 17 The mobile robot moving on the platform

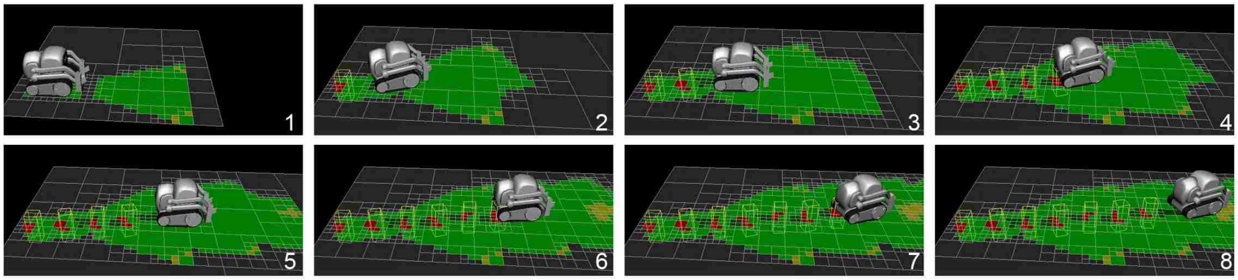

Figure 18 The visualization of the mobile robot

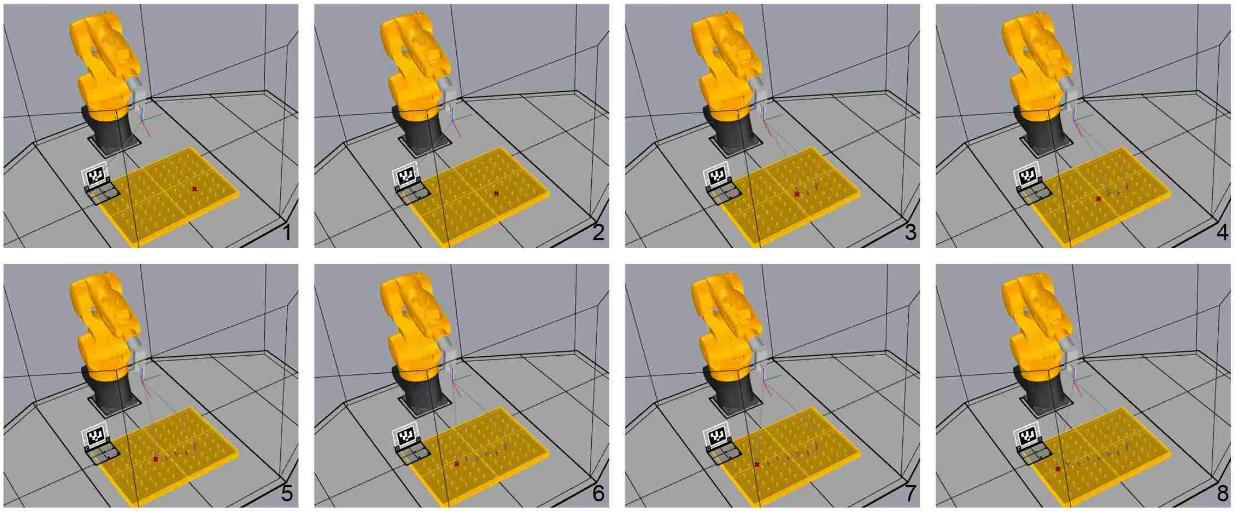

Figure 19 Locations of the mobile robot visualized using Rhinoceros / Grasshopper

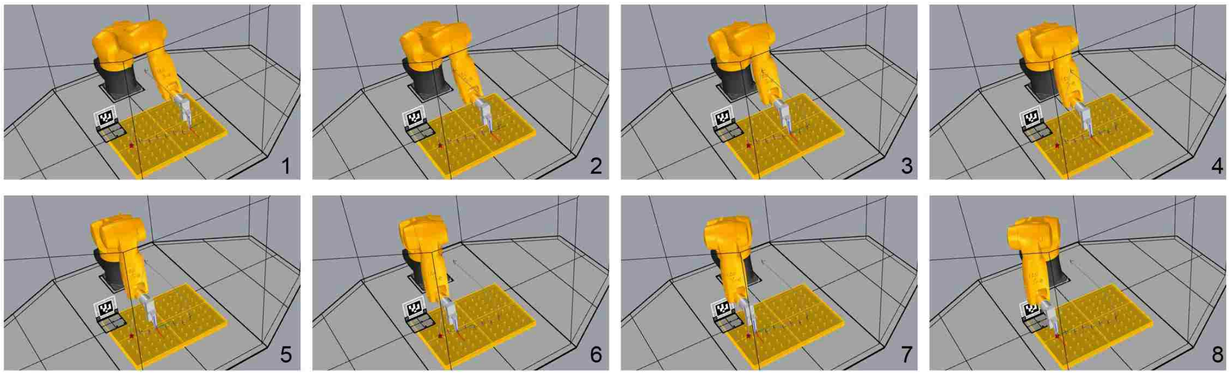

Figure 20 Kuka robot arm simulation using KUKAlprc for Grasshopper

The (x,y) coordinates are sent are received via the IP/TCP port and received in Grasshopper. An AR tag installed on the platform, and perceived by the robot's camera at the beginning of the task, serves as a common coordinate frame for the two robots. The robot's location coordinates are therefore transformed to match the origin in the CAD software. These are then used to create planes that serve as targets for the robot arm to reach. In order to generate the robot code, the plug-in KUKAlprc is used. The simulation on the CAD software allows to verify that the robotic arm moves along the pre-defined points. The code is then executed on the physical robot, where a pen is attached as an end-effector. The path taken by the Cozmo robot is then retraced using the transferred points and lines are drawn between each point.

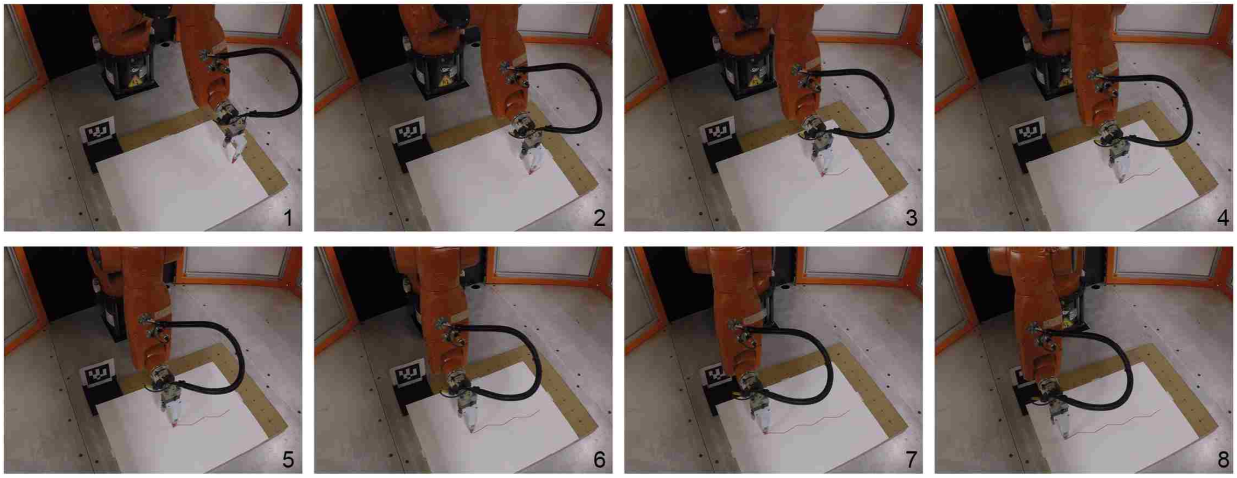

Figure 21 The robot arm following the mobile robot path

5.2 Planning

This section explores the elements needed in order to plan a robotics coordinated project. First, the task planning, where tasks are generated and allocated to each robot.

Then, space planning, which involves the motion planning of each robot in order to execute the task and to avoid collisions with other robots and elements from the environment.

Finally, time planning, which involves planning the time needed to execute each task and signals showing the beginning or completion of each task in order for the next planned task to start.

5.2.1 Task planning

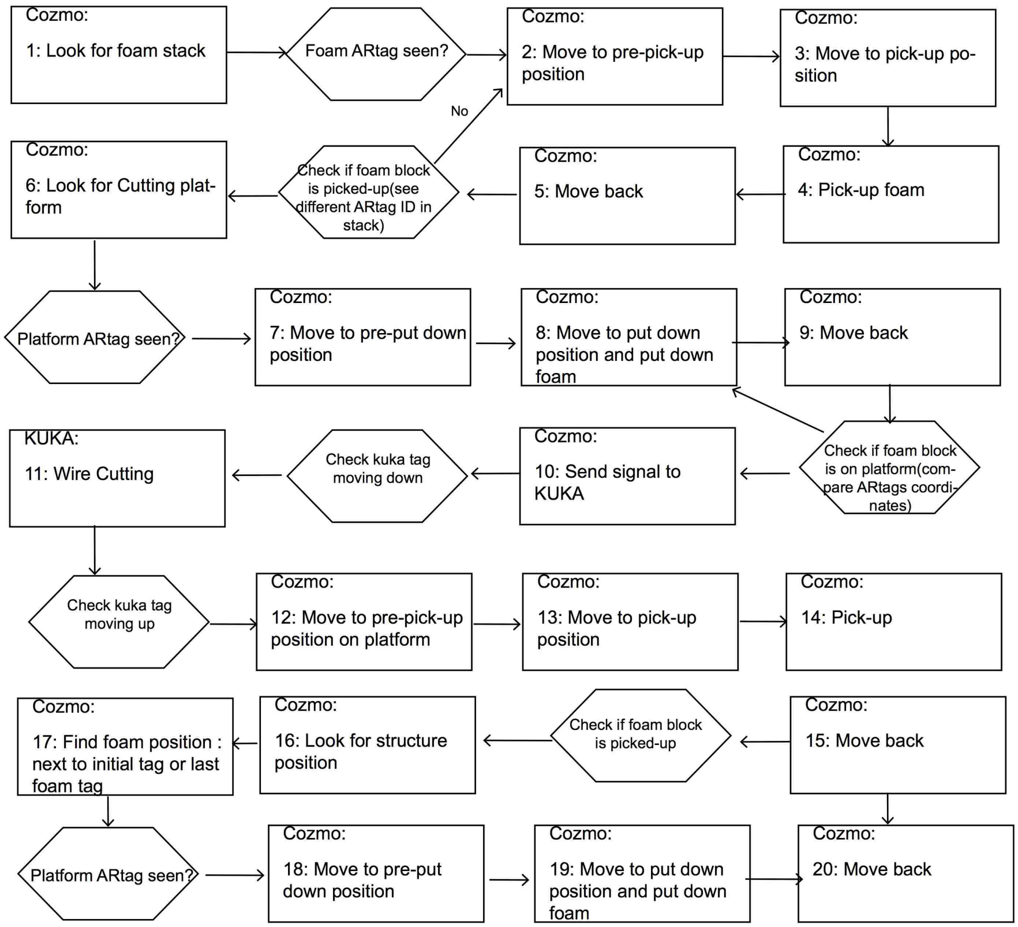

Figure 22 Diagram of the project steps

An experimental project has been conducted to demonstrate a coordination application between the robot arm and the mobile robot. The goal is to wire cut and assemble a structure made from foam blocks.

The diagram above shows the distribution of the tasks between the KUKA robot arm and the Cozmo mobile robot.

First, the mobile robot turns around in place in order to locate AR tags placed on the platform. It uses the AR tags predefined IDs in order to find them. Three tags are used for this step, one for the location of the foam blocks, one for the location of the wire-cutting station, and one for the location of the final structure. Each time a tag is located, and its ID matches one of the pre-defined tags' IDs, the current pose of the robot is stored.

Figure 23 The mobile robot looks for the locations of pre-defined AR tags

The robot will then start by going to the foam blocks stack. It first goes to a pose relative to the larger tag, it gives it the ability to see the smaller tag, and then goes to a pose relative to it. The second approximation is more precise, as the robot is closer to the tag. Finally, the robot moves straight and the 3D printed funnel corrects the its trajectory.

Once arrived to the foam block, the robot picks it up using its lift. A tag holder with holes similar to the Cozmo cubes is 3D printed and attached to the foam block, a tag with a specific ID is attached to it.

The robot then moves back in a straight line. In most cases, the pick-up function works correctly. However, in some cases, the robot does not pick up the block or does not pick it up correctly. An additional verification is needed to improve the function. After moving backwards, the robot can check the ID of the tag, if it corresponds to the first block's tag, then the block has not been picked up and the robot has to repeat this step. If it corresponds to the next block's tag, then the block has been picked up and the robot can start the next step. This verification step has not been implemented here.

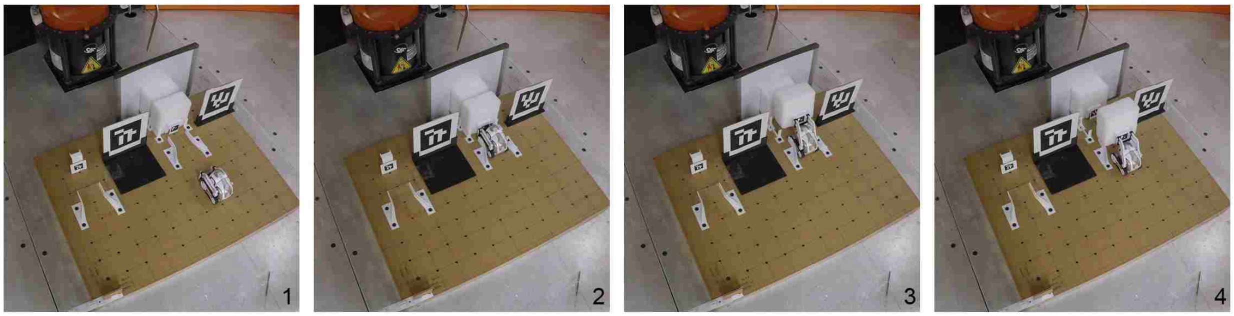

Figure 24 Picking up the foam block

The robot goes to the pose recorded when the wire-cutting station's tag has been seen. It then goes to a pose relative to the station's tag. It then moves straight where the funnel adjusts it orientation and blocks it.

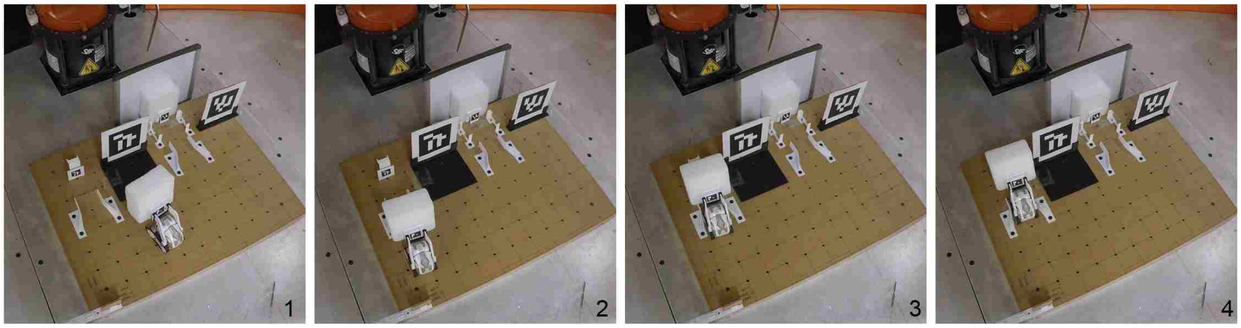

Figure 25 Going to the wire-cutting station

Following this last step, the robot sends a signal to the KUKA robot's operator to start running the wire-cutting program. The signal consists in the mobile robot saying 'Kuka start" and its back light turning green. The person operating the robot arm will then run the KUKA program. The program has been generated using KUKAlprc. A surface has been designed for the top of the block, control points have then been extracted and used to generate the target planes for the robot path.

The cutting process took about 9 minutes. The process was very slow in order to make sure that the block does not fall from the robot's lift. Once completed, the robot arm executes a straight motion to push the top section of the foam on the ground. The wire-cutting was done using a 3D-simo pen (3D Simo s.d.).

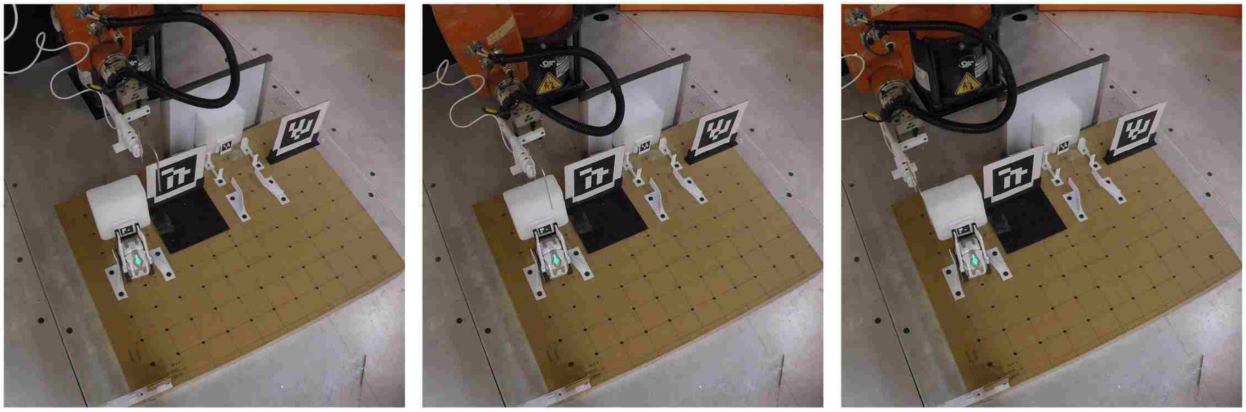

Figure 26 Wire-cutting process

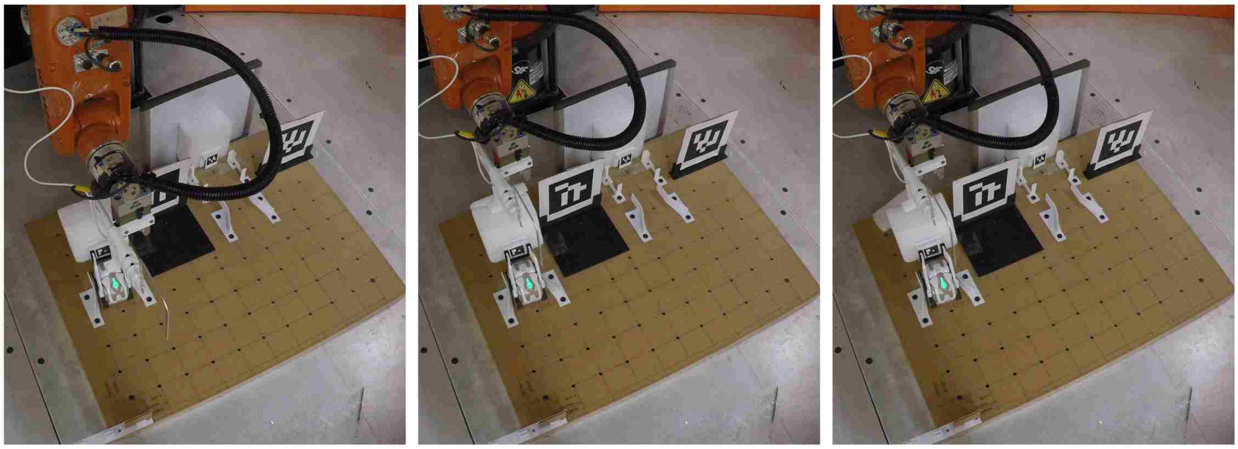

Figure 27 Pushing the top section of the block

Once the wire-cutting step completed, the human operator enters a keyboard input. This sends a signal to the mobile robot to start the next step. The robot's back light turns red.

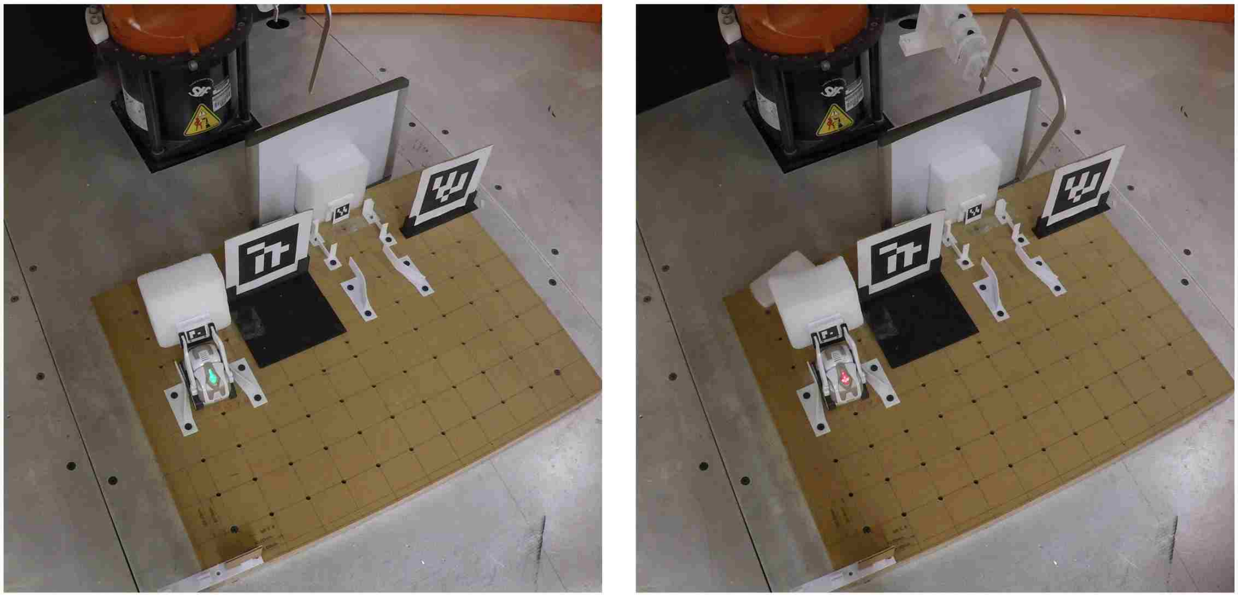

Figure 28 The Cozmo robot light turning green and red as a signal to the human operator

Finally, the robot goes to the pose recorded when the final structure tag was tracked. It goes to a pose relative to that tag, and puts down the foam block.

The next steps in this experiment include repeating the same process for multiple foam blocks. These would be assembled in a structure.

Figure 29 Putting down the block

5.2.2 Space and motion planning

Space is considered as a shared resource between the robots and the other actors. It also contains the fixed objects and the construction materials that won't necessarily always have the same position during the execution of the construction tasks. Space planning involves therefore two items, the motion planning according to the objects in the environment, which results in the obstacle avoidance, and the motion coordination between the different robots in order to coordinate in the execution of the tasks and to avoid collisions.

The figure below shows how the mobile robot gets around the power cube. Power cubes are part of the Cozmo robot's recognizable objects, the robot avoids them in its implemented programs. Indeed, Cozmo keeps a map of its environment to localize itself using its recognizable objects. However, in the first image the Cozmo robot hits the power cube and alters its position. Although it has recognized the power cube and recorded its position, the robot and the cube bounding boxes are interfering, since not enough distance has been kept between the two, which resulted in a collision.

Figure 30 Obstacle avoidance of recognized objects

Although the two robots operate in different plans, their motions need to be coordinated. In a cube exchange experiment, their target positions need to be matched. Indeed, the robot arm’s end-effector needs to go to a pre-grasp position and then to a grasp position right on top of the cube’s intended position. On the other hand, the mobile robot needs to go to a position relative to the cube’s intended position, a few centimeters behind it in order to position the cube correctly.

Giving a common coordinate reference to both robots also helps in the motion coordination process. The target positions can be shared relatively to the common reference.

The robots also need to avoid colliding with each other, by keeping a safety area around each one of them. In the light-follow experiment, the mobile robot collided with the robot arm, which resulted in the mobile robot altering its orientation, making it inoperable.

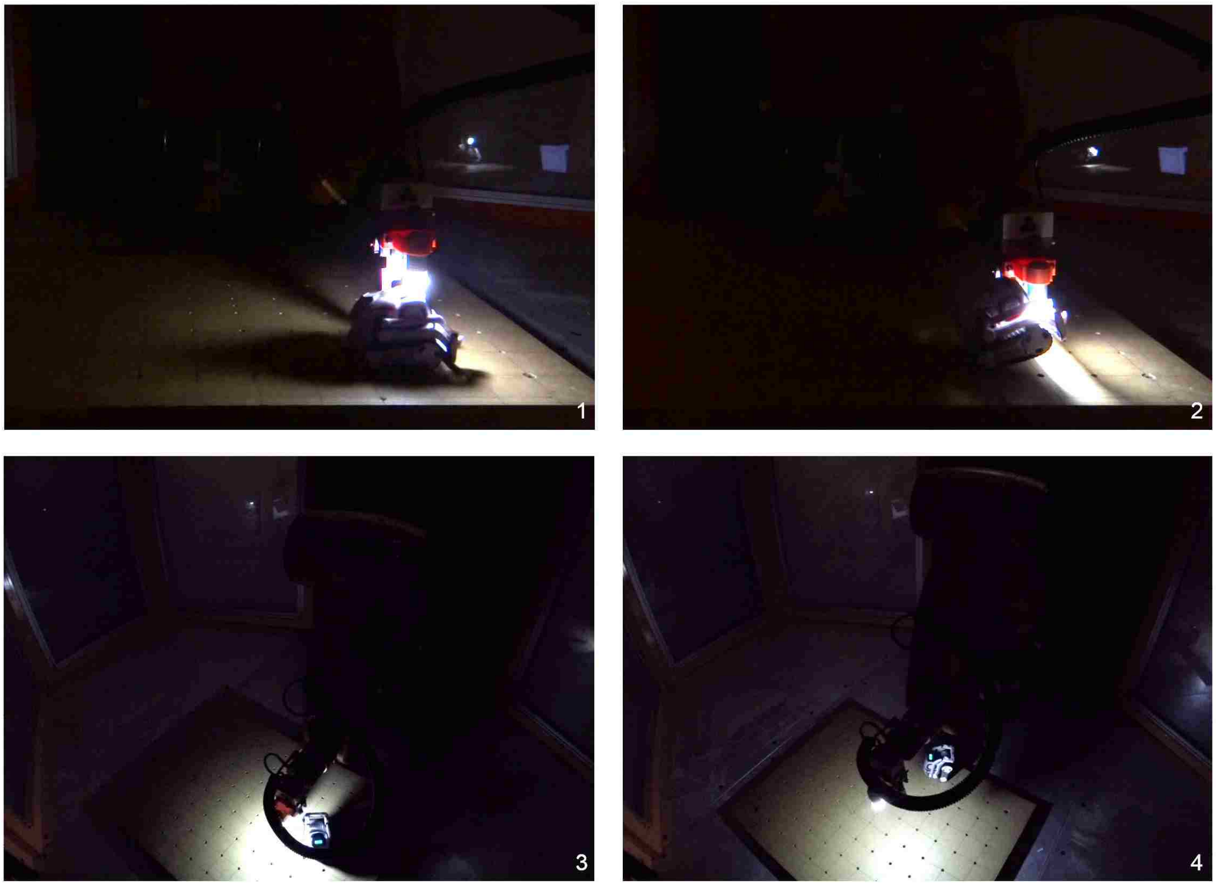

Figure 31 Collision between the Cozmo and Kuka robots

5.2.3 Time planning

The robots need to be coordinated in time. There are different ways in doing that. The time coordination can use a fixed timeline, where the robots start their actions at specific times that are fixed in advance. This model can work when there are no interruptions in the execution of the tasks, and when all the actions are performed in a precise manner without delays. No communication between the robots is needed. However, this type of settings is hard to obtain in construction sites, where there are many delays and unpredictable events. Communication between the robots, whether direct or indirect, needs to be established in order to complete the timing coordination.

Robots working together to accomplish a single goal perform a series of tasks, for a task to begin the previous task needs to be completed. This is easy when the tasks are performed by the same robot, it is more complicated when two successive tasks are performed by two different robots. The second robot needs to know when the first one has completed its task. This can be done with direct communication, when an order to proceed with the task is received by the second robot. It can also be done with indirect communication. The illustrations below show a cube exchange exercise. It uses the Cozmo built in function “put_on_cube”, where the Cozmo robot looks for a cube and puts it on top of another one. The robot arm, programmed by demonstration, picks up the cube. In order to make sure that the cube has been picked up, the mobile robot observes the cube until its position in the z-axis changes by a certain value superior to a threshold. The change in the z coordinate indicates that the cube has been picked up. The images from the mobile robot camera illustrate that (4 and 5). The robot can then proceed to the next action and go look for another cube.

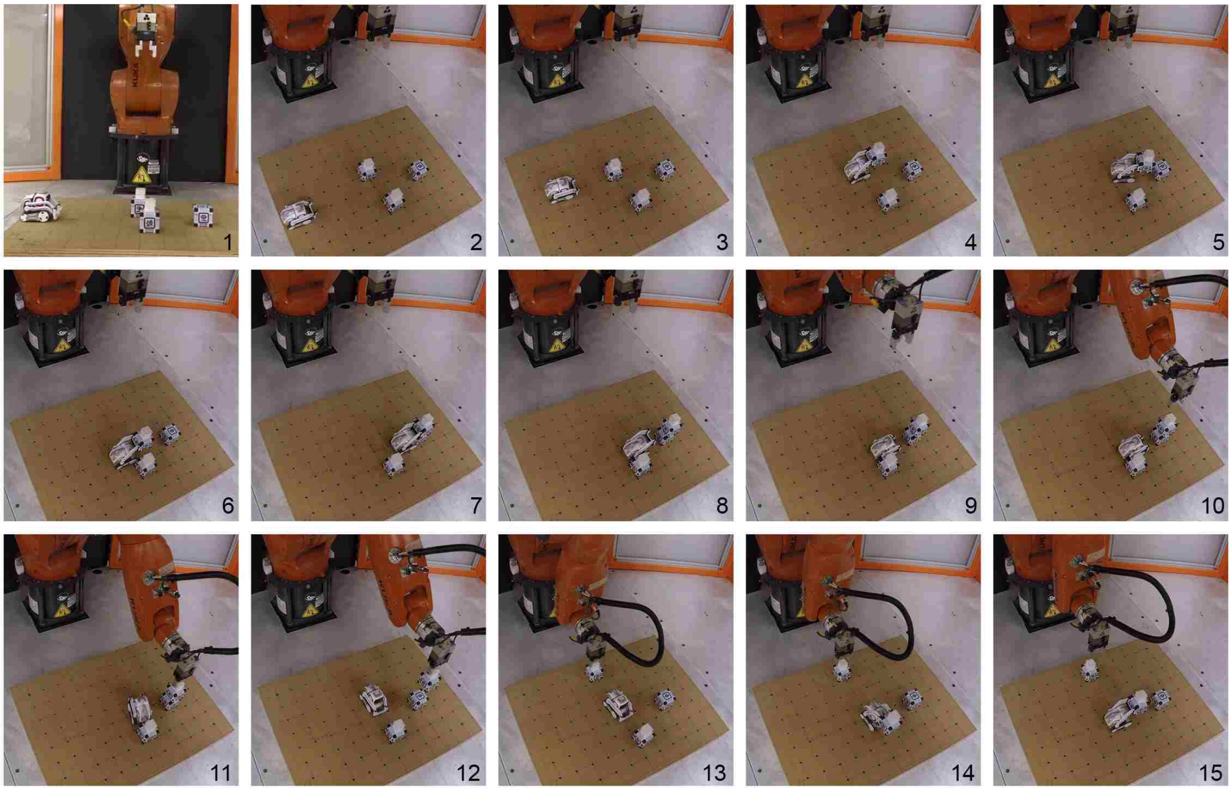

Figure 32 Cube-exchange task - World view

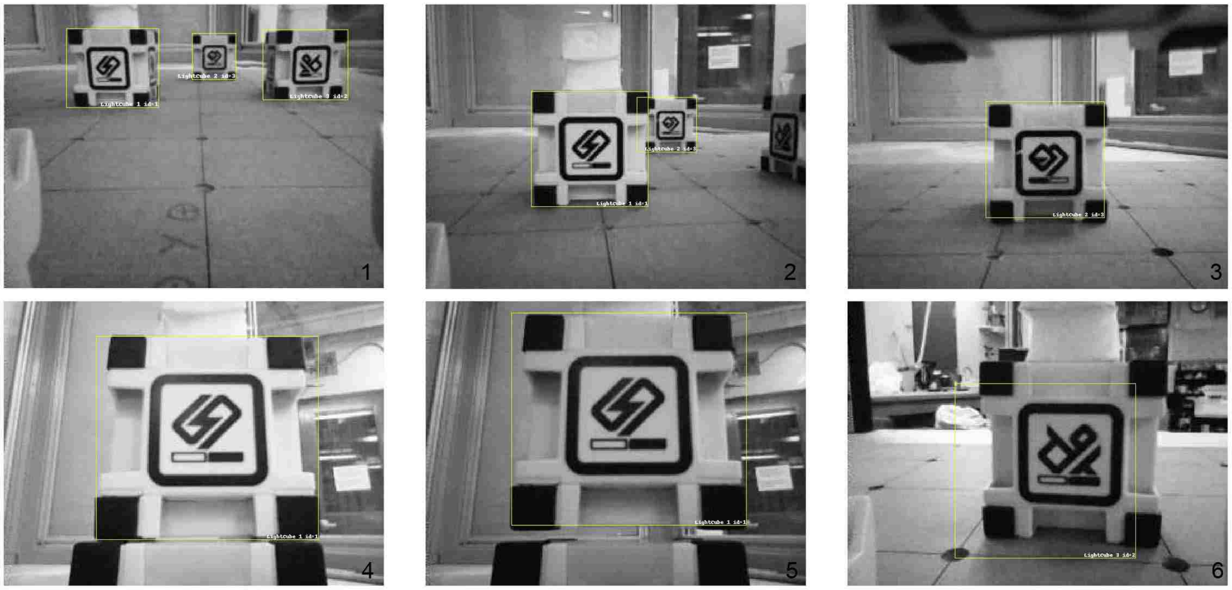

Figure 33 Cube-exchange task - Cozmo camera view

5.3 Precision

Precision is an important issue in robotics. Industrial robot arms tend to be extremely precise in the actions they perform, and repetitive actions always lead to the same result. However, a mobile robot is not that accurate, and errors appear during localization. Indeed, one of the ways a mobile robot keeps track of its position is through odometry. Indeed, by knowing its initial position, and the velocity of its wheels, it computes its new position. However, the friction of the wheels with the ground makes that estimation inaccurate, and the more it moves the more errors accumulate. The following experiments demonstrate the impacts of the inaccuracies in the position of the Cozmo mobile robot. The Cozmo robot locates its power cubes, picks up the first one and put it in a given position, where the KUKA robot arm comes and picks it up with the gripper used as an end effector and puts it somewhere else. The robot repeats the same sequence with the second and third cube. The robot arm reaches the same position each time to pick up each cube.

The first attempt shows that the mobile robot puts the cubes in approximately the right position for the robot arm. In the second attempt, the mobile robot performs more movements which results in more inaccuracies in it localization. This results in the cubes being placed in different locations in the physical space although the same (x,y) location has been used in the program.

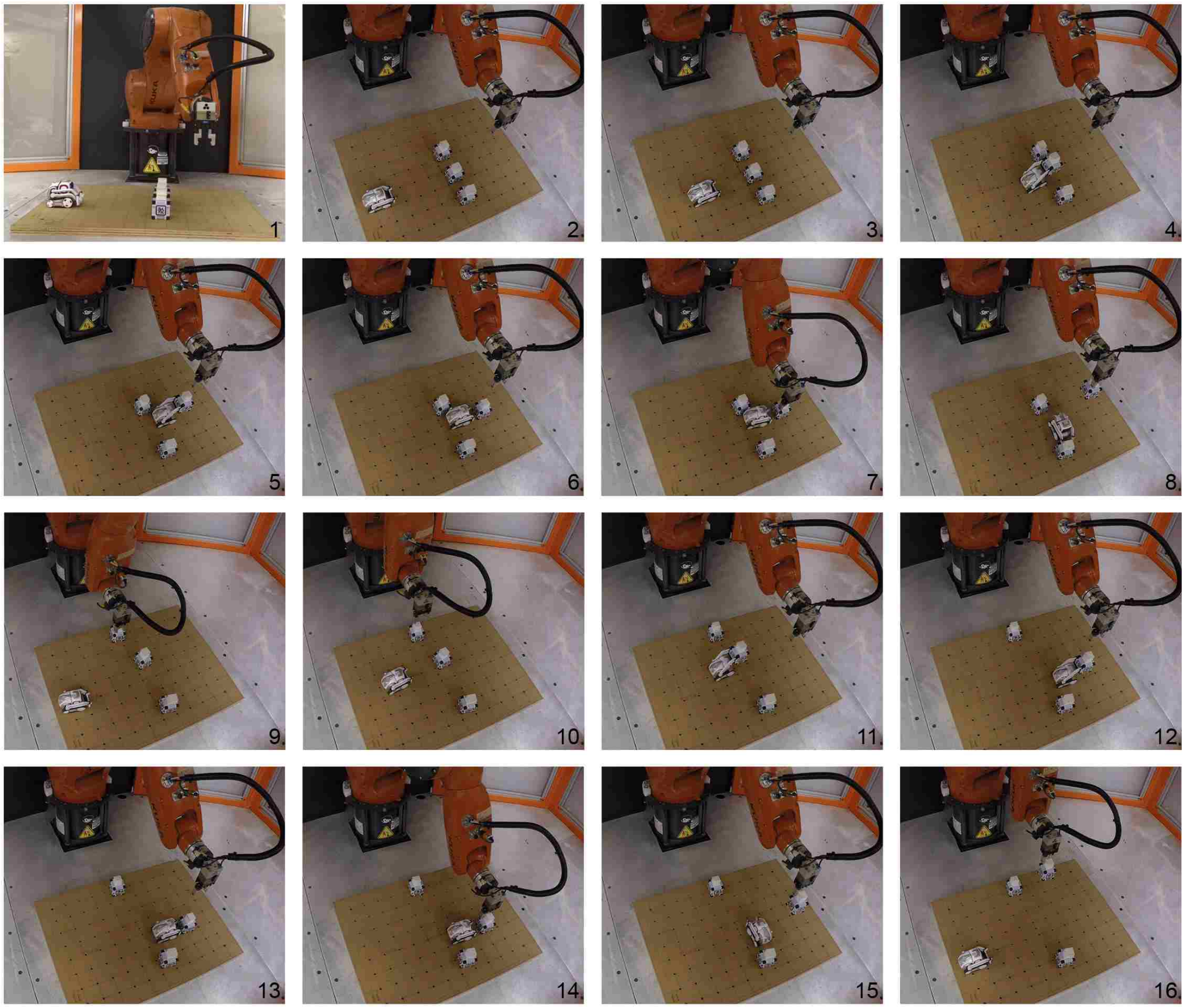

Figure 34 Cube-exchange using coordinates

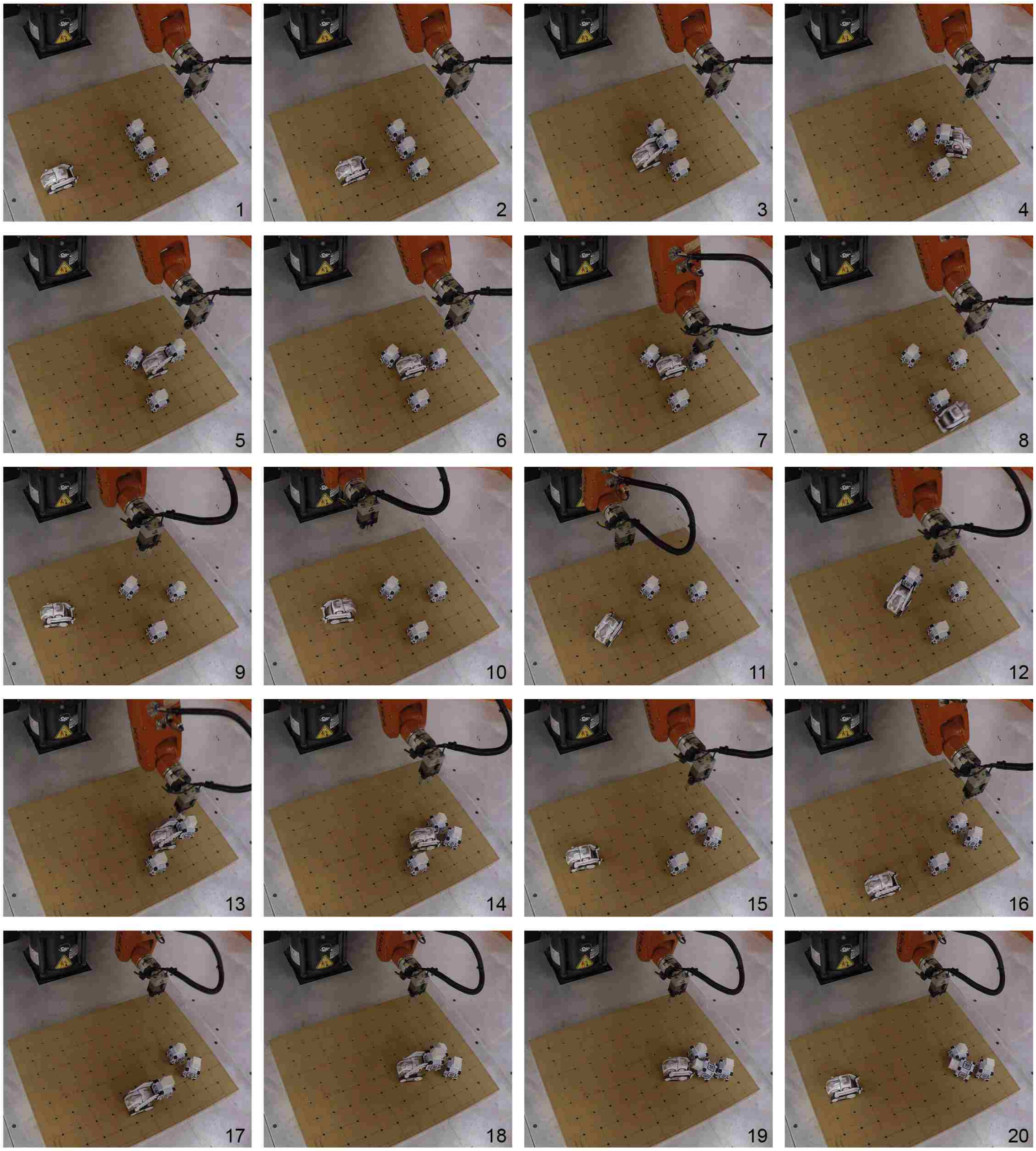

Figure 35 Failesd cube-exchange task using coordinates

In order to make the target position more reliable in the physical space, a reference added to the environment can be used. In the next experiment, a fiducial marker has been added to the environment to serve as a reference point. Instead of going to an (x,y) position on the platform, the mobile robot locates the AR tag, and goes to an (x,y) position relative to it. Here, the AR tag is only located at the beginning, the robot then goes to the target position using the robot's predefined function "go_to_pose". This method shows improvements compared to the previous experiments.

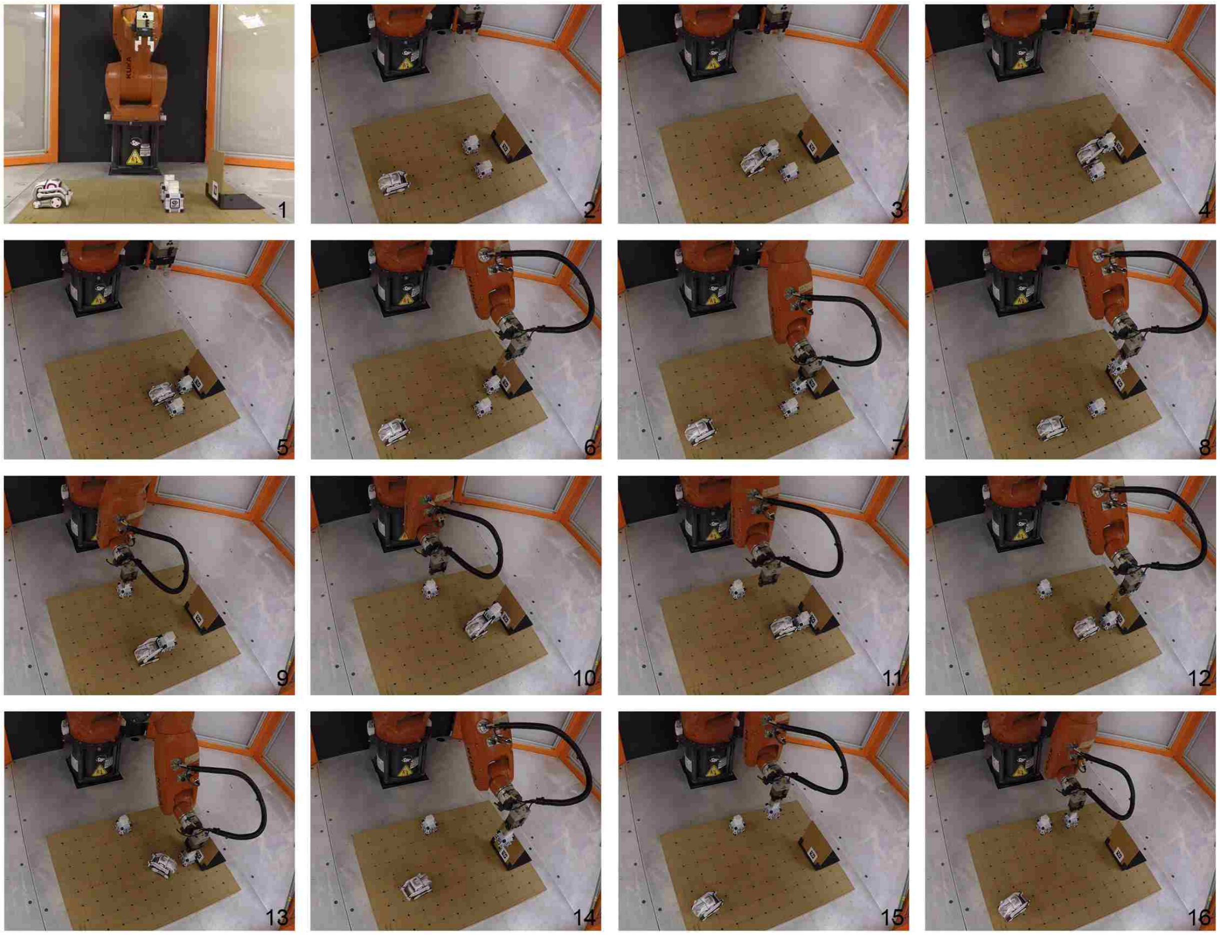

Figure 36 Cube-exchange using a reference tag

The robot arm's gripper permits enough mechanical backlashes to pick up the cubes even when they are not at the exact same position. This is not possible when the task requires more precision. An example of this is when the robot needs to pick up a cube or a similar object using its lift. The mobile robot relies on a smaller mechanical backlash, and needs therefore to be more accurately positioned. A guide placed on the platform adjusts the robot's path. In the next experiment, a 3D-printed funnel is used as a guide to lead the robot to the target position.

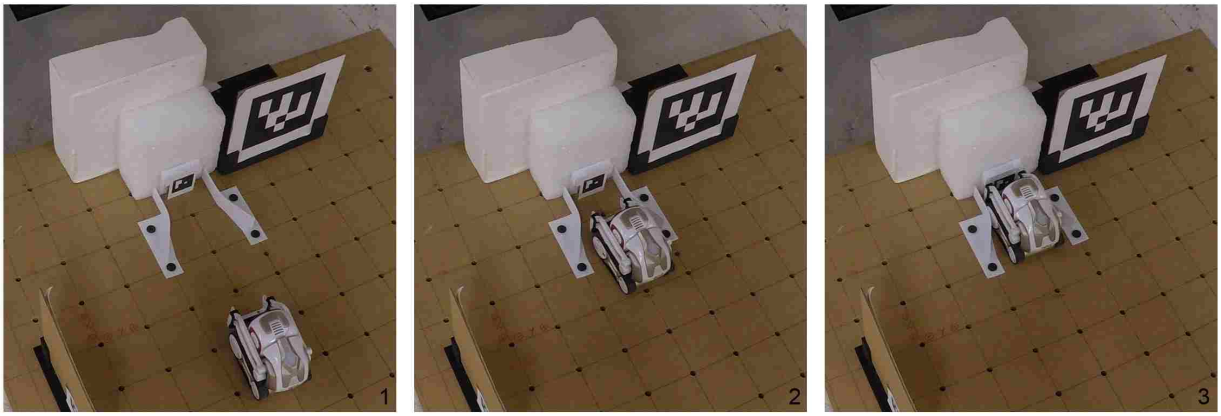

Figure 37 Correcting the robot's trajectory with a funnel

5.4 Materials

In order to make the manipulation of the building materials easier, the materials need to adapt to the robots capabilities, and the robot capabilities can be improved by modifying its end-effector. Material intelligence refers to the relationship between the materials and the end-effector. These need to be designed in conjunction in order to reduce the need for external tools or additional motion or verification during the program execution.

In the experiment with the foam blocks, a tag holder has been pasted on the foam block, it contains the tag related to the block, but also fixtures similar to the Cozmo power cubes making it easy for the Cozmo robot to pick up the block. A mass has also been place behind the foam block to avoid having the foam fall from the robot's lift.

Figure 38 3D-printed tag holder

Chapter 6. Conclusion and future work

In this thesis, robotic collaboration for architecture has been investigated. The concept of assemblage was a driving point in understanding the definition of robots, robotic collaboration and adaptation to the environment. The robot was defined as an assemblage of sensors, actuators and a controller, as they complement each other in order to perceive the environment and act on it. Multiple robots form all together an assemblage of assemblages as they all complete each other by sharing information about each other and the knowledge acquired about the environment. They also act collaboratively on the environment in order to modify it. Finally, the robots form an assemblage with their environment and the objects they need to work with. This illustrates a symbiosis needed when choosing the type of robot or material for the right environment and the right tasks. Indeed, seeing the system composed by the robots, the objects and the field as a whole is important in architecture and fabrication. The design of the robots and their behavior should take into account the complex settings they need to evolve in and the complex tasks they need to execute. The whole multi-robot fabrication system needs to be designed simultaneously while maintaining a symbiosis between all the elements involved, in order to form the assemblage of a robotic construction platform.

This work also relies on the understanding of communication between human and the relationship between actions and plans. This relates to many aspects in understanding coordination and communication. Using actions in order to understand the plans from which they derive as a communication method is important in coordination. Indeed, actions and their impact on the environment are used as a way to communicate and to keep track of the task's progress. It also serves to know to which agent the task is allocated in the case of dynamic task allocation.

The difference between an intended action and a performed one is also important. Indeed, in robotics, system failures are a possibility, a method to understand and correct these failures is needed. Making the distinction between an action that has been performed as planned and an action that has been performed in a different way or that has failed is needed to be able to correct this and go back to the initial plan or dynamically modify the plan for the right execution of the overall goal.

Situated actions are also important, and this is related to the concept of assemblage and seeing the whole system as an assemblage. In order for agents to communicate correctly and to jointly perform the tasks, they need to have a common understanding of the world. A common culture or language are metaphors for robots that need to work together.

This thesis has also explored a classification of Multi-Robot Systems in engineering, which allowed for an understanding of the requirements needed in order to create an MRS.

The literature review of fabrication projects using a group of robots showed a number of aspects and challenges related to MRS used for fabrication. Among these the importance of planning, communication, and more importantly the need for precision.

In order to illustrate those concepts, small experiments have been conducted using a Cozmo robot and a Kuka robot. These experiments can be expanded by improving some parts. For example, in order to localize itself the Cozmo robot has relied on odometry. A more precise and reliable way uses SLAM, Simultaneous Localization and Mapping.

The path planning for Cozmo was using implemented functions of Cozmo SDK, an improvement would be to write a specific path planning that also takes into consideration the obstacles and the presence of other robots.

The use of a synchronous online collaboration and constant feedback between Kuka and Cozmo was also needed.

Construction sites are complex environments, with many agents working and many physical elements. Obstacle avoidance and path planning are therefore important. This needs to be done in a dynamic way as these are constantly moving and evolving.

In many projects in the literature review as well as in the experiments conducted, a modification to the environment was necessary. This includes adding tags in the environment to elements that would correct a robot’s trajectory. Some modifications are necessary for the robots, however these take time and precision to be installed which reduces the system’s overall autonomy. In order to be able to use robots for construction, we need not only to add automation, but also autonomy. This includes the programming of autonomous robots, but also a minimal prior modification of the sites.

A focus also needs to be made on human-robot collaboration. As people are part of the construction sites, safety issues need to be considered. A more human-friendly way of working with the robots needs to be used, as interaction is an important part of collaboration.

Chapter 7. Discussion

It is important to question the technology that has been introduced by the robots, and to which aim we should be using them for construction. One of the reasons this subject has been chosen, is because it gives the possibility to make multiple robots of lesser precision collaborate and compensate for their imprecision in order to accomplish their task. This, along with their limited cost and ease of transportation, would make robotic fabrication more accessible to many regions.

First, this is needed in disaster areas, where it is not safe enough for human. It is also needed in non-accessible areas.

Combining low-cost robotic fabrication with local materials would also achieve a collective collective robotic local fabrication, a robotic lo-fab that takes into consideration the techniques and materials used locally with the more advanced robotic fabrication tools. This expands the range of application of the local techniques and adds the technological aspect to fabrication while respecting the local culture. This goes back to the notion of seeing the robotic fabrication system as part of an assemblage that is rooted in a certain culture.

Another aspect to consider is the workflow from design to fabrication. How will we change the way we design and how the buildings will look like with the implementation of robotic techniques. The example of 3D-printed houses showcases a change in a building technique with the introduction of a new construction tool. There is a need to modify the way we build and the way we use the materials in order to be able to adapt them to the new tools.

There is also a need to create a smooth workflow from the design phase to the robotic fabrication phase. There was an evolution from the CAD software to the BIM tools that looks at the building as a complete model and not a combination of 2D drawings. The same evolution is needed for the transition from CAD to CAM, where preparing fabrication files should not be a separate step but part of the building model itself. This will also impact the way buildings are designed. Indeed, while some robotically fabricated structures are very similar to traditional ones, new types of structures are being designed and fabricated by robots, like fiber woven structures. However these are designed as temporary pavilions. There is a need to continue the process and make these structures more inhabitable. A question that is raised is also related to the role of the architect, is he just a designer or a roboticist, will being a robot programmer become part of the designer role, which interfaces will be used for the robotically built design, a text-based programming, a visual programming, or our regular 3D modeling interface?

As Isaac Asimov has stated the “three laws of robotics” in 1942 (Asimov 1950), architects also have to state today the laws of architectural robotics. These can include the respect of local cultures and ideas, keeping architecture as a cultural product and not a universal industrial product, involving the human workers in the process of design, as in design for and by the people, a respect for the environment in the production of the robots but more specifically in the materials and building techniques used. And finally, making this technology accessible to all regions and people, and not use it to create a greater gap between developed and developing areas.

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