FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

CIDESI®

Mechanical design and construction of a low-cost robotic assembly cell oriented to Industry 4.0

A Thesis

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BY

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Querétaro, February 2018

(Signature)

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A mi familia, gracias por todo su apoyo y amor incondicional.

Ustedes son mi motor e inspiración.

Los amo.

Abstract

The success in the implementation of Industry 4.0 depends mainly on the development of smart factories. Such factories should fulfill the requirement of linking closely the physical and the digital world with the effective management of the information flowing in the production process. This document presents the design and construction processes of a robotic assembly cell oriented to Industry 4.0. The system is going to be used for assembling toy cars using commercial LEGO® DUPLO® construction blocks and is meant to be added to an existing network of machines at the FH Aachen with the intention of forming a smart factory for didactical purposes.

The assembly cell discussed in these pages uses a custom-made cylindrical robot for the assembly tasks. The construction of such robot was accomplished using commercial robotic modules to achieve a low-cost and space-effective unit. The assembly robot is fed with construction bricks by a passive gravity-driven material handling system that works both as on-machine storage space and material feeder to the assembly robot. One of the essential requirements of the machine is to offer easy mobility, as it is planned to be taken to exhibitions and trade fairs. An aluminum frame with predefined dimensions and incorporated wheels was chosen to enclose all the components of the system. This aluminum structure will also carry the electronics for powering and controlling the system.

Motion tests were performed on the assembled robot in the way of simple individual movements of each degree of freedom. The movements resulted to be steady and the joining parts stiff enough to achieve the tolerance required. The aluminum sliders were also tested and provide a good material flow for most the different scenarios. A special sequence to grip the LEGO® bricks was proposed and tested to achieve the proper flow in all scenarios. The electronic components of the system were pre-assembled to metallic panels for its future fixture in the machine. A final virtual assembly of the complete system was obtained with the dimensional requirements explained in section 3 of this document.

The assembled elements showed a positive behavior in general, and there are sufficient results to state that the goals of designing an assembly cell with high mobility, flexibility, and reconfigurability were accomplished.

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List of abbreviations

CAD	Computer Aided Design
CIM	Computer-integrated Manufacturing
CPPS	Cyber-Physical Production Systems
CPS	Cyber-Physical System
DIN	Deutsche Institut für Normung
DOF	Degrees of Freedom
ERP	Enterprise Resource Planning
FAC	Flexible Assembly Cell
FH Aachen	Fachhochschule Aachen
LED	Light Emitting Diode
NEMA	National Electrical Manufacturers Association
PFA	Product Family Architecture
QR	Quick Response
RFAC	Robotic Flexible Assembly Cell
RFID	Radio Frequency Identification Devices
SCARA	Selective Compliant Assembly Robot Arm
SME	Small and Medium Enterprises

1. Introduction

The increasing rate at which technology is evolving is affecting the way in which we consume and therefore, the way in which the products should be manufactured. For instance, with the growth of internet users, online shopping is becoming more relevant as a way of acquiring services and products. This growth in the e-commerce activity allows for industries to adopt new technologies and production paradigms that are associated with the use of the Internet.

“The vision of future production contains modular and efficient manufacturing systems and characterizes scenarios in which products control their own manufacturing process. This is supposed to realize the manufacturing of individual products in a batch size of one, while maintaining the economic conditions of mass production”[1].

This vision is embraced by the Industry 4.0 paradigm. Such concept also considers the fact of cloud computing as part of the whole manufacturing process for making decisions concerning the time and form and even the location in which the products are built. Under these considerations, it is also possible to have a group of production stations governed by an ERP (*Enterprise Resource Planning*) to make a more flexible manufacturing system. Some advantages of this approach are explained in the following sections of this document.

The FH Aachen has produced a series of machines under these principles as a practical way for students to learn about Industry 4.0 and to develop or to enhance existing assembly stations. The purpose of the thesis is to develop a new production station to be added to that manufacturing network.

The production station developed here must comply specific characteristics to be set into the existing network of machines at the FH Aachen. It should also have some specifications for easy transportation and autonomous operation, as it is intended for both academic purposes and exhibition at trade fairs.

The total design of this assembly station, including robotic control and communication protocols, was accomplished in collaboration with other students and this document only attempts to cover the mechanical aspects of the unit.

This document is divided into five main sections. The first part of the document is an introduction to the project, and the methodology followed. The second chapter briefly explains some background of Industry 4.0 and the development of similar projects documented in the recent decades. On chapter 3, the design of the developed system is described. Finally, chapters 4 and 5 are the discussion of the results obtained until the moment of writing this document and the scope of future work.

1.1 Justification

According to Statista[1], in 2017 around 1.66 billion people worldwide bought goods and services online. This number is expected to grow to over 2.14 billion in 2021. Similarly, the global e-retail sales in 2016 amounted to 1.86 billion US dollars, and projections suggest a growth to 4.48 billion US dollars in 2021 [2],[3]. Figures 1.1 and 1.2 show the graphs of these behaviors.

Looking at the rate e-commerce is growing, it is self-explanatory that both industry and education institutions have turned their efforts to develop smart factories for more efficient and sustainable production systems[4]. These smart factories need complex architectures to achieve the flexibility required for such approaches.

The quick change in production demands and shorter product life cycles force enterprises to adapt rapidly and cost-effectively to new production processes. Automation and robotics are enablers of such adaptation but even so, *Small and Medium Enterprises (SMEs)* tend to be left out of business for the high investment that they represent. The design of highly flexible and reconfigurable systems can help to avoid this phenomenon.

[1] Statista is an online statistic, market research and business intelligence portal.

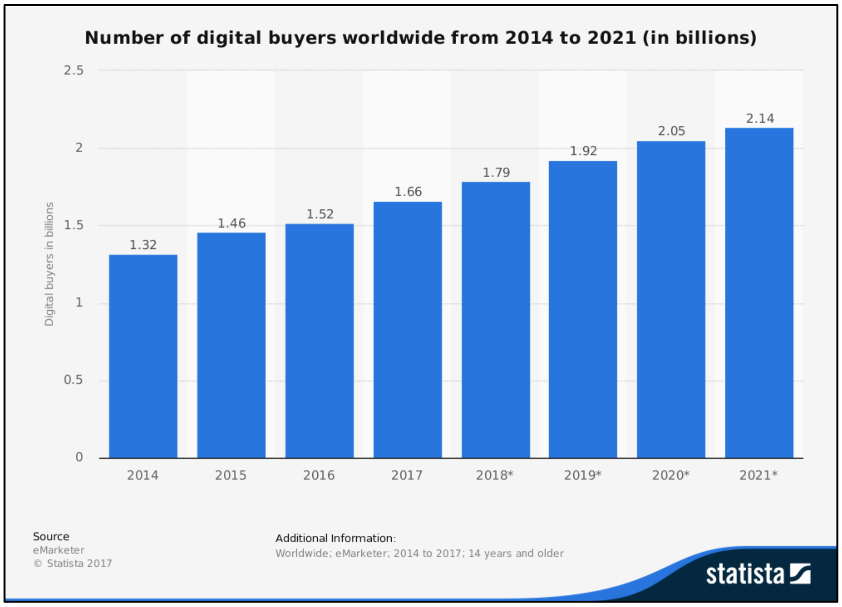

Figure 1.1. Expected growth in the number of digital buyers[2].

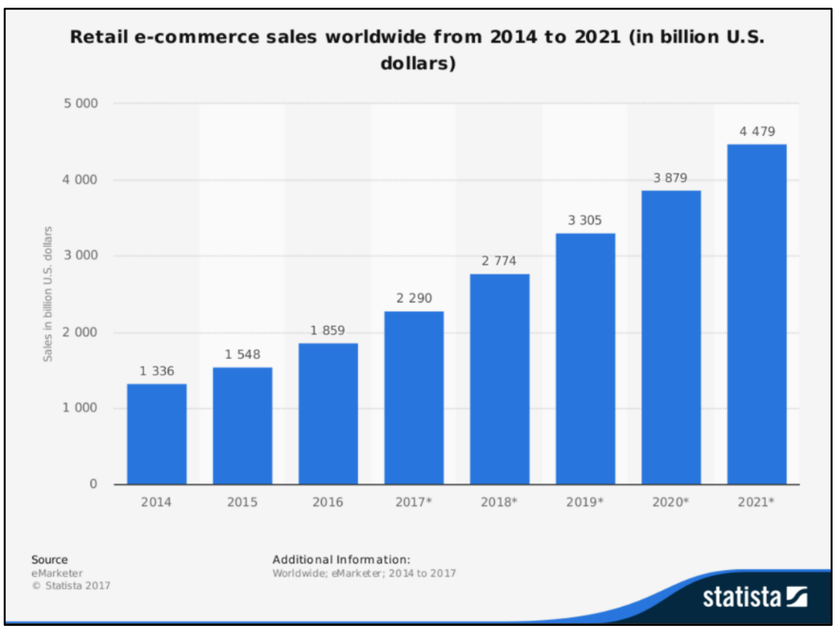

Figure 1.2. Retail e-commerce sales worldwide from 2014 to 2021[3].

1.2 Objective

To develop the mechanical design and construction of a manufacturing cell oriented to industry 4.0 with autonomous capabilities and easy mobility, aimed to assemble toy cars using LEGO® DUPLO® construction blocks, for academic and exposition purposes.

1.2.1 Specific objectives:

- To find a fast and the efficient physical configuration for both the robot and the supply of the construction blocks.
- To fit the whole machine into a volume so it can go through a door and into an elevator for easy transportation.
- To generate the complete CAD data of the machine for simulation, construction, and presentation.

1.3 Hypothesis

It is possible to develop a flexible, reconfigurable robotic assembly cell for didactical and exhibition purposes oriented to the Industry 4.0 concept by using prefabricated modular solutions for the different elements conforming the system.

1.4 Methodology

State of the art review: Review of the different approaches using flexible manufacturing cells from the Industry 4.0 perspective.

Conceptual design: Definition of the primary requirements and general outline of mechanical and electrical aimed attributes, including specification of all dimensions, tolerances and different component classes to be assembled.

Detailed design: Detailed design of mechanics and electronics using CAD and prototyping techniques.

Assembly: Construction of the machine.

Tests: The actual use of the robot to assemble end products. If the construction is not complete for any reason, the tests can be supported by simulation to consider the function of the complete system.

2. Fundamentals

One of the purposes of automation is to make production more efficient by using machines instead of human work for repetitive tasks. Machines can ultimately take on those tasks faster, with higher precision, and at a reduced cost compared to human labor. That is why automation became one of the most important goals for the modern industry during the last decades.

As mentioned in [5], the essential ingredient in automation is information and to handle it in an efficient manner demanded the establishment of a transparent flow of information inside automation systems. Since early stages, the amount and variety of information types were sophisticated enough to require computational processing and gave origin to the concept of computer-integrated manufacturing (CIM) [6].

With the evolution of products and processes, the information flowing in automation systems has grown in both complexity and quantity. The development of internet technologies has been the key factor to overcome that growth. The main advantage of Internet technologies is that they offer high-level concepts and solutions that are independent of hardware platforms and communication networks.

In this chapter some concepts will be discussed, which are derived from the influence of the Internet in automation technologies. Such concepts are the foundation background of this work and therefore, were considered during its development.

2.1 Mass customization

From the beginning of last century, the manufacturing industry has been switching through different production paradigms [7]. These changes in paradigms can be tracked with the disruptive increase in productivity that happens when adopting new industrial concepts. At first, the paradigm was “craft production,” which implied the manufacture of a product requested by the consumer but at a high cost. There were merely no manufacturing systems developed at this point of industry, so the scalability of production at that stage was not reliable, and many products were confined to a specific geographical region.

Later, the development of moving assembly lines marked the adoption of the mass production paradigm. At this point, production could be made in more significant quantities and replicated at different locations too. Under this production paradigm, the efficiency in the processes and profit rates got higher, and the final prices of the products were lowered. However, the variety of the products was weak, if existent at all, because the process design was made to lower costs by mass producing the same model of merchandise.

The next step in manufacturing evolution is mass customization. Mass customization seeks to deliver products that meet the needs or requirements of individuals while keeping efficiency and profits as close as possible to those of the mass production paradigm [7],[8]. As industry moves towards the mass customization, the variety of the products of different markets has increased significantly. An excellent example of that is automotive industry: nowadays consumers have the option to choose between different possibilities when buying a car; from the color of the paint to the performance of the motors that move such cars.

A remarkable example of the paradigm switch is the automotive industry. It is an excellent example because the Ford Motor Company is known as the precursor of mass production. Its founder, Henry Ford, once said: ‘‘Any customer can have a car painted any color that he wants so long as it is black’’[9]. This quote exemplifies the lack of variety characteristic of mass production that would be finally solved with the switch to mass customization paradigm. An overview of the characteristics of mass customization is found in Table 1.

The variety of a product can be originated from different stages during the production process: design, fabrication, sales, or from the usage of the product itself (see figure 2.1). For instance, when the variety is generated at the design stage by incorporating costumer design additions, the results are personalized, unique products. Many biomedical applications incorporate this high variation in the production to comply with the distinctions that humans and animals have by nature [10].

	Mass Customization
Goal	Delivering affordable goods and services with enough variety and customization that nearly everyone finds exactly what they want
Economics	Economies of scope and customer integration
Focus	Variety and customization through flexibility and responsiveness
Product	Product family and standardized modules assembled based on customer needs
Key Features	• Unpredictable demand pattern • Heterogeneous niches • Low-cost, high-quality, customized goods and services. • Short product development cycles • Short product life cycles
Organization	Flexible and adaptive
Customer Involvement	To meet the customer requirements with efficiency and effectiveness, active customers' involvement throughout the product lifecycle is essential. Thus, user innovation, co-design, customer configuration and others have become important tools in MC.

Table 2.1: Properties of mass customization [8].

At the sales stage, mass production articles can be modified to the need of the customer, e.g., tailoring pants to the adequate length or modifying the color of a particular paint with additives.

	Approach	Example
Design	Feature varieties are designed into the products	
Fabrication	Fabricated part or feature varieties by machining, rapid prototyping, etc.	
Assembly	Mix and match of functional modules through assembly	
Sales	Sizing and cosmetic tailoring from mass produced products, e.g., cut golf clubs to length.	
Use	Adjustment during the use phase, such as seat height on a bicycle	

Figure 2.1. Approaches to product variety [10].

“Assembly is one of the most cost-effective approaches to high product variety”[10]. The reason for that is that this approach is based on Product Family Architectures (PFAs). The architecture of a product is essentially the way in which the elements that form a product unit are arranged and how they interact with each other. A product family is a group of products with similar technology and construction characteristics. Finally, a PFA is the architecture of a product family. When a manufacturing process is designed with a well-defined PFA, the similarities in the products lead to an efficient process yet maintaining the variety inherent to the product family [11]. That is why variety through the assembly is the same approach most commonly used in the automotive industry and can also be considered in the application of this work.

The assembly system developed in this work pursue the assembly of toy cars made with LEGO® DUPLO® bricks. These construction blocks offer a very well-defined PFA and therefore, they lead to a highly customizable product. This is a desired characteristic of this project, as it is intended for didactical purposes and the efforts of students and professors can be focused on the production system itself instead of the product development.

2.2 Flexible and reconfigurable manufacturing systems

Flexible manufacturing is a concept that makes mass customization possible and reconfigurable manufacturing is closely related to it as well. In this section, both concepts will be discussed, and its integration to the present work will be explained.

Flexibility can be defined as the ability of a system to adapt to different states or to offer variable outcomes in response to different requirements with little or no compromise in time, effort, cost or performance [12]. The key to flexibility in a production system is the adaptation to the uncertainties added to the manufacturing process. Ten types of different kinds of flexibilities are listed in [13]. The list found in that article is as follows:

1) *Machine flexibility:* Various operations performed without set-up change.
2) *Material handling flexibility:* Number of used paths / total number of possible paths between all machines.
3) *Operation Flexibility:* Number of different processing plans available for part fabrication.
4) *Process Flexibility:* Set of part types that can be produced without substantial set-up changes, i.e., part-mix flexibility.
5) *Product Flexibility:* Ease (time and cost) of introducing products into an existing product mix. It contributes to agility.
6) *Routing Flexibility:* Number of available routes of all part types/Number of part types.
7) *Volume Flexibility:* The ability to vary production volume profitably within production capacity.
8) *Expansion Flexibility:* Ease (effort and cost) of augmenting capacity and/or capability, when needed, through physical changes to the system.
9) *Control Program Flexibility:* The ability of a system to run virtually uninterrupted (e.g., during the second and third shifts) due to the availability of intelligent machines and system control software.
10) *Production Flexibility:* Number of all part types that can be produced without adding major capital equipment.

In summary, a flexible manufacturing system can be used to produce a variety of products without substantially changing its hardware or software. The larger the number of products it can produce, the more flexible it is.

Having flexibility will undoubtedly improve the utility, usability, and life of a manufacturing system but another critical factor for that is reconfigurability. The reconfigurability of a system is defined by how easy it is to modify it for adapting it to a partial or complete change in the production process.

The reason why reconfigurability is decisive in the longevity of a manufacturing system can be observed in figure 2.2. In the diagram, it is visible how the change in requirements leads to modifications in the design of a system. The more effortless these upgrades can be done over time, the longer life a system will have.

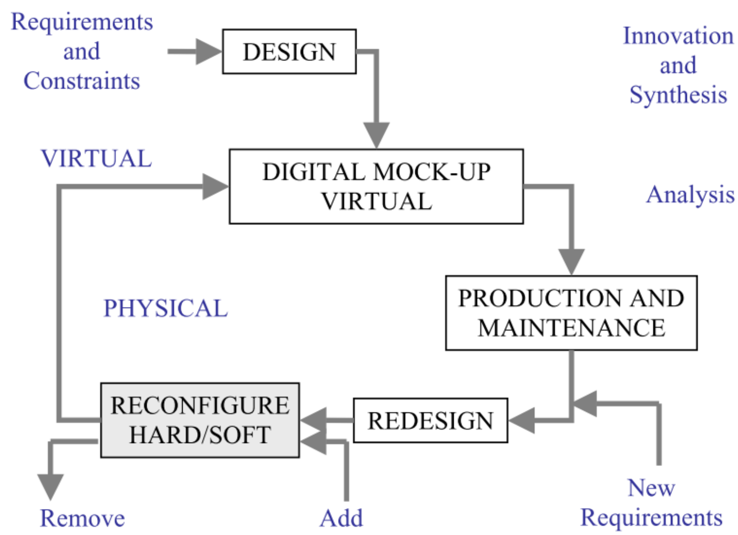

Figure 2.2. Manufacturing systems life cycle [13].

Both flexibility and reconfigurability are concepts that help the mass configuration production paradigm in the short and long term by addressing the adaptability of the production systems in two clearly differentiated ways. A summary of these differences is found in table 2.2. The characteristics of a dedicated manufacturing system are also summarized.

System	**Definition and objectives**
Dedicated manufacturing system	A machining system designed for the production of a specific part type at high volume.

	Cost-effectiveness is the driver achieved through pre-planning and optimization.
Flexible manufacturing systems	A Flexible Manufacturing System is an integrated system of machine modules and material handling equipment under computer control for the automatic random processing of palletized parts. The objective is to cost-effectively manufacture several types of parts, within pre-defined part families that can change over time, with minimum changeover cost, on the same system at the required volume and quality.
Reconfigurable manufacturing systems	A Reconfigurable Manufacturing System is designed for rapid change in structure to quickly adjust production capacity and functionality, within a part family, in response to changes in market requirements. The objective is to provide exactly the functionality and capacity that is needed when it is needed.

Table 2.2 Summary of flexible and reconfigurable manufacturing systems [13].

When a system can meet both the flexibility and reconfigurability concepts, then its utility and long life are assured. The system developed for this work is based on an architecture that is both flexible and reconfigurable for the targeted application. That is vital for the conception of its low-cost approximation.

2.3 Robotic flexible assembly cells

The most straightforward possible component of automated, flexible manufacturing or automated, flexible assembly system is a robotic flexible assembly cell (RFAC). It consists of one or more robots and some peripheral equipment such as material input/output buffers or automated material handling systems. A flexible assembly system traditionally consists of two or more flexible assembly cells, or systems, or both[14]. An example of an RFAC with two robots is shown in figure 2.3. The cell in the figure is taken from the ReconCell Project webpage [15].

The ReconCell project is aimed at developing a high-tech reconfigurable robotic cell capable of nearly automatic reconfiguration and economically viable also for SME's. It is a project funded by the European Union and counts with the participation of developers from nine different countries.

It is difficult to point a specific time for the appearance of this kind of cells, but many implementations of them were documented since the 1970's. At this early stage of development, they were mainly used for automated tool loading and unloading, metal-cutting, grinding, turning. With the evolution of technology and the growth in production demands, assembly cells evolved to cover a more extensive range of tasks. They are now commonly used in a wide variety of industries and at all production stages. Assembly cells have become more complex and require more designing tools to comply with simple implementations and cost savings [16].

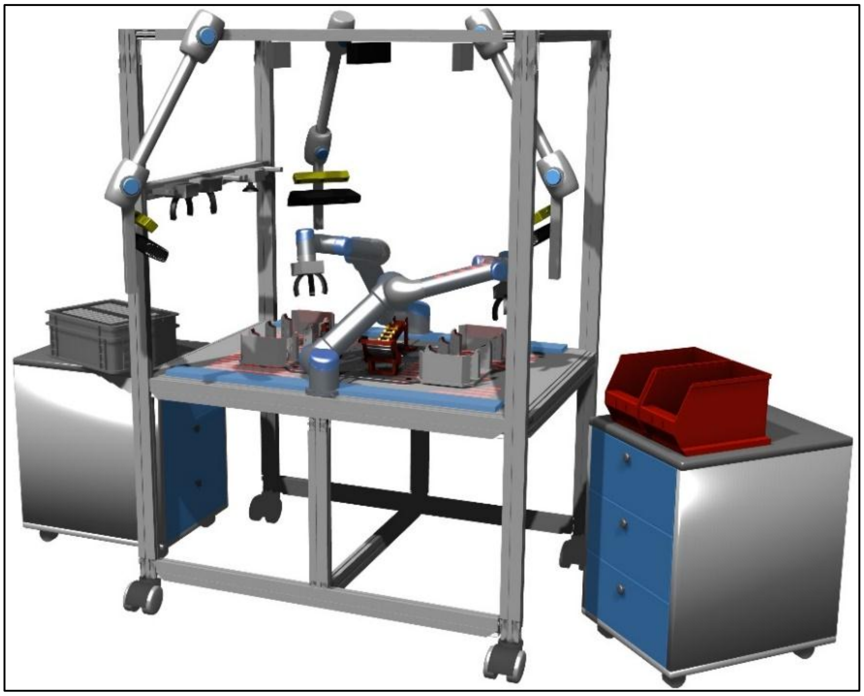

Figure 2.3. ReconCell System [17].

One of the reasons why FACs improve flexibility and reconfigurability in a system is the modularity they add to it. Because FACs are decentralized working units, they can be added or removed from the manufacturing or assembly system even for just temporarily. This is a significant feature for their application in fluctuating markets and companies in growth.

Another example of flexibility is end-effectors. In an RFAC, the implemented robot or robots can have multiple end-effectors either simultaneously mounted or as a set of swappable parts.

That characteristic can make a FAC alone suitable for a variety of tasks including, painting, welding, cutting, gripping, etc. [18]

Even though the cell assembly paradigm supposes a more cost-effective approach of adding flexibility to a system in comparison to linear assembly technologies, the cost of modern robotic systems is still a considerable investment for most SMEs. An RFAC must be provided with real "plug and produce" capabilities to be a reliable option. That also means that the system must be flexible and reconfigurable in at least some amount. That is the final consideration for most SMEs when opting for an RFAC [19].

2.4 Industry 4.0

The term "Industry 4.0" appeared for the first time in a publication by the German government on the High-Tech Strategy article to enhance the industrial capabilities of the country, in November 2011 [20]. Since then, it has gained popularity globally, and both industry and academia have channeled their efforts into the development of systems to embrace that philosophy. Industry 4.0 includes the concepts of mass customization, flexible manufacturing, robotic assembly cells, smart factories and many others that interact in many levels and sometimes recursively. This makes it complicated to formulate one definition for such concept.

While the first three industrial revolutions are considered to have come with mechanization, electricity and IT (in that order), Industry 4.0 is called to set the fourth industrial revolution through the full application of the Internet of Things and Internet of Services in the manufacturing scene [4].

The Industry 4.0 concept is based on the development of Cyber-Physical Production Systems (CPPS's) that form a "smart factory." Cyber-Physical Systems (CPS's) are basically integrations of computation with physical processes in which the computation changes the physical processes (and vice versa) using feedback loops [21]. A CPPS is just a CPS meant for production.

With the right development of the CPPS's, it will be possible to create flexible systems (smart factories) targeted to the production of highly personalized goods with real-time interaction between the consumer, the product and the process during the complete product lifecycle, among many more characteristics that are still part of a broad definition [20].

In the context of Industry 4.0, what makes “smart factories” smart is the efficient data flow between all the parts involved in the production process. The information flowing is rich in variety and quantity. It considers, for example, the information generated by the customer when placing an order and even using the product, the information being shared inside a CPPS, the one exchanged between two or more CPPS inside a network, among others.

The Internet of Things enables the flow of information also with the use of more technologies and techniques like radio frequency identification devices (RFID), laser scanners, global positioning systems, quick response (QR) codes, Bluetooth technologies, and more. All of this is utilized for quick identification, location, tracking, monitoring and management [20].

Zhou recognizes [20] the development of specialized CPPS’s networks as one of the leading points of the strategic plan developed by Germany to implement Industry 4.0. He also mentions the construction of such networks as one of the most significant challenges, due to the complexity involved in designing all the architecture of highly personalized systems that can collaborate with each other and the means necessary for verification and testing of those systems before their application.

Zhou also states, as a summary, that the core of Industry 4.0 strategy is based on intelligent manufacturing using CPS technology, to shift centralized production towards decentralized production, to shift popular products towards personalized products and to increase users participation, so that each user can experience the fun of creating products [20].

2.4.1 Industry 4.0 at the FH Aachen

In response to the trendiness of the Industry 4.0, the Faculty of Mechanics and Mechatronics at the University of Applied Sciences of Aachen (FH Aachen) has started the development of a conceptual smart factory with the integration of a network formed by various assembly stations that are in constant development done mainly by students. Some assembly stations have also been taken to expositions and trade fairs.

The task of this conceptual smart factory is to assemble toy cars using commercial LEGO® DUPLO® construction blocks. As mentioned in section one of this document, using this kind of product as example application offers high flexibility in the development of the systems, thanks to a robust PFA. When using it in trade fairs and expositions, it also offers the attendees familiarity with the problem, given the popularity of these toys worldwide. Figure 2.4 displays a group of blocks that will be used in the assembly tasks of this machine and one example of a toy car assembled.

Figure 2.4. LEGO® DUPLO® bricks and assembled toy car.

The assembly stations developed have considered diverse technologies for solving the task of assembly. The complete network is planned to be controlled by a unique ERP to complete the smart factory structure. Three of the assembly stations are described in the following paragraphs.

One of the implemented assembly stations makes use of augmented reality technology to assist an operator on the assembly of the toy cars. The assembly process is done by hand, with the assistance of the intelligent features of the machine. It uses a projector to indicate the target position of the bricks. The boxes containing the LEGO® pieces next in the assembly sequence are pointed to the user with the use of LED strips. Also, laser technology is used as the sensing technology to evaluate errors of assembly in real-time. This is the least automated machine but is the only one that can assemble any of the existing commercial bricks, thanks to the integration of human laboring. Figure 2.5 show a 3D model of this work station.

Figure 2.5. Augmented reality assembly station at the FH Aachen [22].

Another of the machines in the network uses a Cartesian configuration for assembly tasks. This assembly cell has a high level of mobility and has been taken to exhibitions in the past to show its capabilities of a full automated assembly station in the context of Industry 4.0. In the machine, the bricks are also stored on slides that take the pieces to the end of the slide closest to the robot assembly area. It uses a pneumatic actuator in the gripper and in the feeding systems. When an assembly sequence is finished, a motorized conveyor takes the finished product out of the system to a stationary tray. The documentation of this work can be found in [23]. This machine is shown in figure 2.6.

Figure 2.6. Car Manufacturing Cube 4.0 (CMC 4.0) at the FH Aachen [23].

Another development at the FH Aachen uses an ABB Delta Robot as the assembly solution. The delta robot offers a generous workspace for the system and that helps the flexibility of the system. As end-effector of the robot, a suction cup was adapted to hold the bricks during assembly. This machine is the least flexible of the network and must include many safety considerations because of the strong forces produced by the heavy Delta Robot. This development is documented in [24] and a general view of the system is illustrated in figure 2.7.

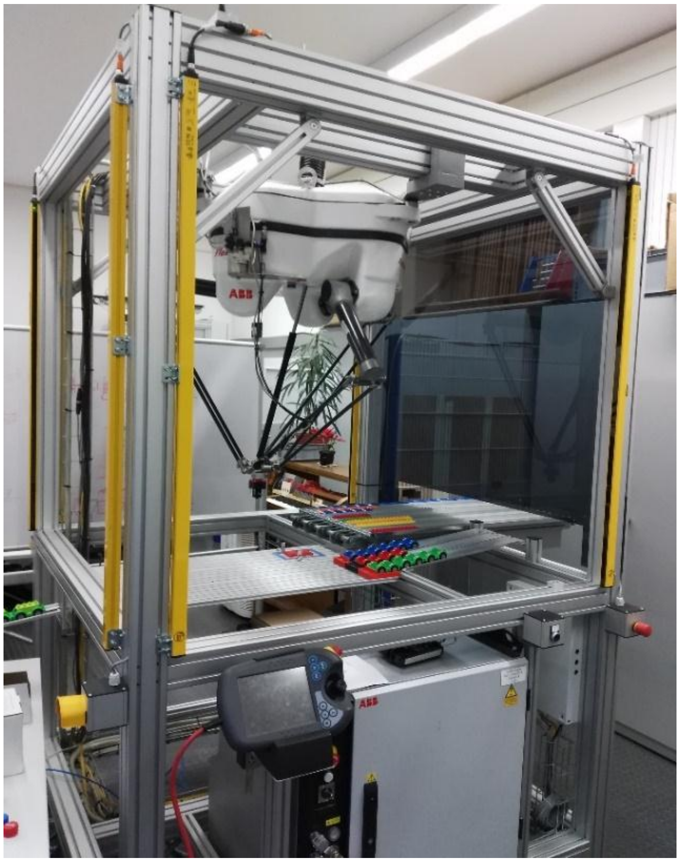

Figure 2.7. FlexPicker assembly station.

3. Requirements, analysis, and design

Since the machine developed in the present work is to be added to an existing network of machines, there are some specifications that it must achieve to be compatible. Besides, as mentioned in the motivation section of this document, this machine is not only intended for didactical purposes but is also planned to be transported to trade fairs and expositions to display the scope of Mechatronic studies at the FH Aachen, and some other requirements are added for this reason.

For the development of this work, the software packages of Autodesk Inventor®[2] and EPLAN[3] were used. Also, some web tools from the companies igus®[4], item[5], and WAGO[6]. The files generated are found in the appendixes.

Primarily, a brief description of the complete system is given. After that, the requirements of the machine are explained. Subsequently, analysis of each individual problem is presented. Then, the solution for each section of the development is presented.

[2] Autodesk Inventor® 3D CAD software offers professional-grade 3D mechanical design, documentation, and product simulation tools. More info at https://www.autodesk.com/products/inventor/overview

3 EPLAN Electric P8 offers solutions for project planning, documentation, and management of automation projects. More info at https://www.eplanusa.com/us/solutions/electrical-engineering/eplan-electric-p8/

4 Igus® manufactures Energy Chains®, flexible cables and harnessed cables, polymer bearings including bushings, ball joints, linear bearings and linear slides. More information at https://www.igus.com

5 item Germany– high quality aluminum profiles, linear technology, work bench systems, linear guides, lean production, automation, stairways & working platforms and equipment. More information at https://www.item24.de/en/home.html

6 WAGO provides products for electrical interconnection of systems and products for automation applications, as well as industrial, process and building automation interface modules. More info at https://www.wago.com/de/

3.1 Overview of the system

The machine developed in this work is illustrated in figure 3.1. The primary structure is a prismatic frame formed of extruded aluminum profiles. The frame is covered on the top and bottom, and most of the area on the sides with plastic panels. The structure is mounted on four wheels to add secure mobility to the system. The volume inside the frame is vertically divided into two sections by a plastic table that fits the silhouette of the structure. Both sections can be accessed through transparent plastic aluminum-framed-doors with incorporated door locks. The upper section is the assembly area, while the lower section contains the electronics of the machine. The material feeding system of the cell and a 3-DOF assembly robot are placed in the assembly section. Two screens necessary to enable the machine functions are added on the sides of the core structure through VESA-compatible commercial mounting arms. There are three emergency-stop buttons and a stack light distributed around the machine enclosure. On top of the system, a 5-DOF robot will be incorporated to automate the feeding of assembly material to the cell. The 3D CAD models of the parts and subassemblies of the machine can be found in Appendix A.

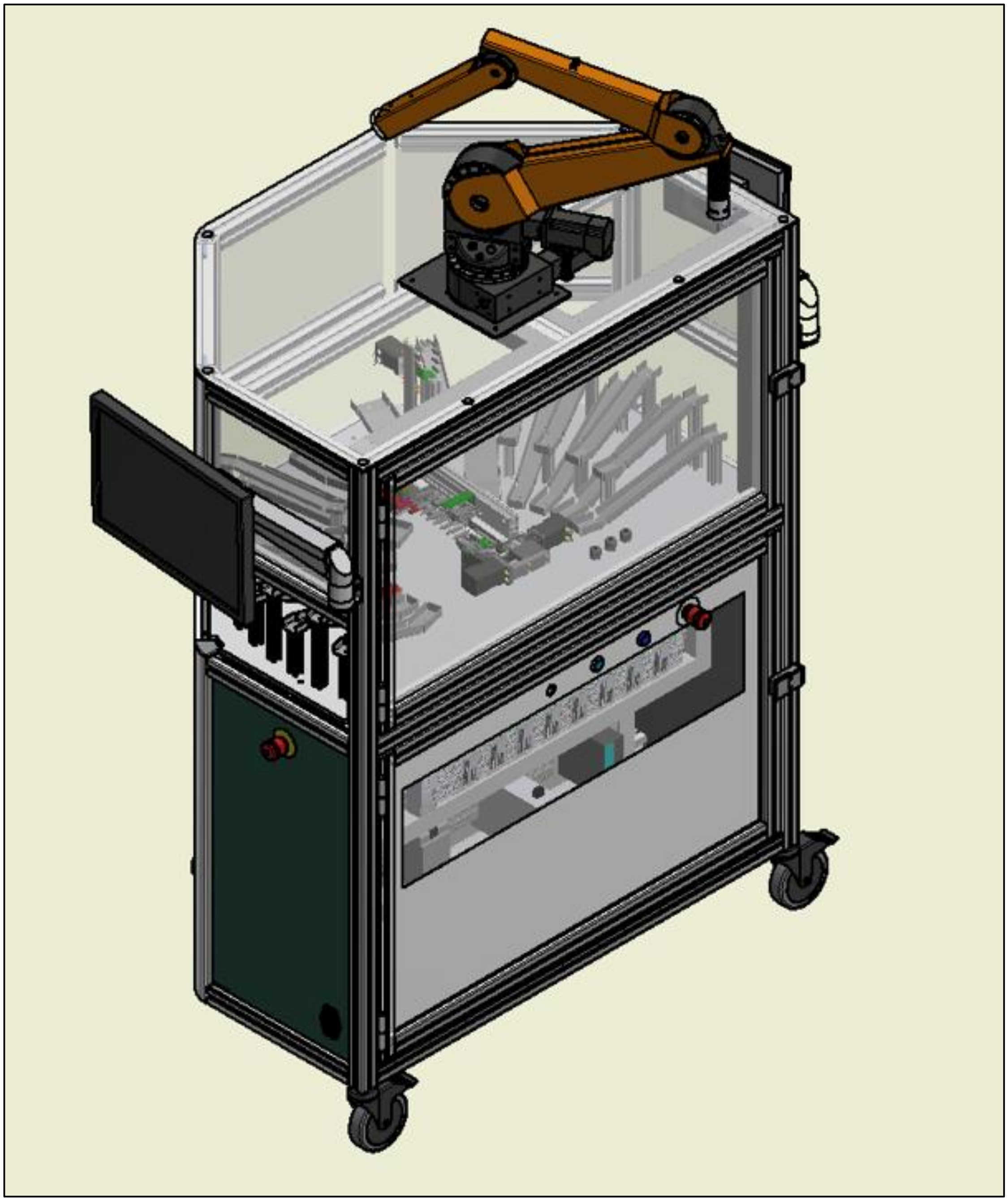

Figure 3.1. Overview of the complete system.

3.2 General requirements

The final system must be able to assemble toy cars using LEGO® DUPLO® construction blocks. There should not be any pneumatic or hydraulic actuator in the system to avoid the need of an air compressor. A second external robot for material feeding is planned to be added in the future, and the system should allow its easy addition both structurally and electrically. The robot planned for assembly tasks is chosen to be designed with the use of robotic modules from the igus® company because they offer reliable industrial solutions at low prices and they have worked in collaboration with the FH Aachen in prior projects.

As for the handling of the material and due to the low cost of nature the project, passive approaches such as gravity-driven solutions are desired. High modularity is desired To improve the reconfigurability of the system. The system should be able to produce at least eight assembled cars without the need of refeeding LEGO® blocks.

The final cell is thought to be taken to trade fairs and exposition events as well as to be transported inside the buildings of the FH Aachen when needed. Outer dimensions had to be controlled for this matter. Maximum width of 800mm for the system was set as a final parameter. The structure of the assembly cell should also consider sufficient space to allow the external material feeding of the cell as well as sufficient space for any peripheral that could be attached to it. Finally, the system weight should enable the use of incorporated wheels for easy transportation.

The system must be completely enclosed, meaning that every electrical component used to power the cell and its peripherals must be incorporated into the machine.

3.3 Analysis and design

The design of the robot, structure, and material feeding system was developed in a parallel way and are dependent on each other. However, these different aspects of the design are presented as isolated sections in this document.

All the datasheets, technical drawings and analysis reports of the components discussed in the next sections can be found in the appendixes.

3.3.1 Robot design

As mentioned in the previous chapters, the machine developed in this work is going to be used to assemble LEGO® DUPLO® bricks in the shape of toy cars. In this system, these toy cars will be assembled in a way that all the block centers end up aligned to the chassis piece by its center. Thanks to that, we can consider a central plane that crosses through the bricks always in the same way when assembled. This imaginary plane can be better observed in figure 3-2.

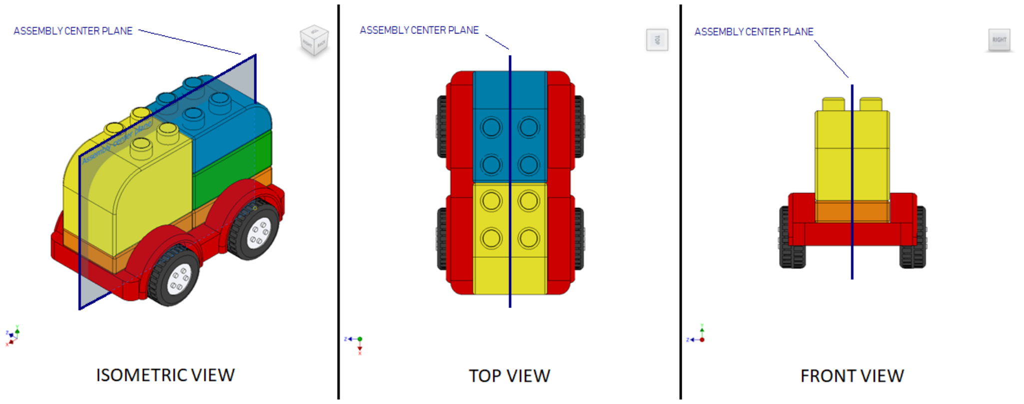

Figure 3.2. Plane of action for the assembly.

Since the plane in which the bricks are assembled will always be the same, it can be inferred that the robot must be able to travel along this plane. Due to the nature of the LEGO® DUPLO® bricks, the assembly will always be done from top to bottom. Therefore, it is also assumed that a movement from the end effector on this plane would be sufficient for the completion of the assembly of one car. Regarding the tolerance that the system should have, a variation of +/- 1 mm in the assembly was chosen.

Since space is a limitation, the room in the system must be optimized quite well to fit all its parts. A Cartesian robot was the first type of robot considered because of the simple requirements for assembly of the LEGO® cars. A Cartesian robot usually requires too much space for the installation and not all this space is used in the application itself. Although it usually fits as a solution for many practical uses, this characteristic could compromise the number of bricks that would make the stock of the system. In addition to that, cartesian systems tend to require multiple components to deliver stability, and that would mean an increase in the total cost of the robotics even considering the use of igus® modules in the design. Cartesian robots can cover large areas and hold big loads, but that is not necessary for this project.

A SCARA robot was also considered. SCARA robots are generally faster and have a smaller footprint than cartesian robots. SCARA robots are usually used for high precision applications and would be more than sufficient as a solution for the work presented. SCARA robots are a popular industrial solution, and there are many options in the market, but they are also an expensive solution, considering the budget for this project. Another option was to design a SCARA configuration using the igus® modules.

Finally, the decision was taken to design a cylindrical robot. It shares the small footprint of the SCARA robot and can be easily constructed with the modules offered in the igus® catalog.

Igus® offers a modular system for low-cost automation called robolink®. The robolink® line has a variety of low-cost robots from 4 to 6 degrees of freedom, and the company also offers the components used in those configurations as elements to build a custom solution. The robot of the system was made by combining different modules of the igus® catalog.

A robot is called cylindrical when its workspace covers a cylindrical volume. To accomplish this, it traditionally has three degrees of freedom as shown in figure3.3. Modules of the igus® catalog had to be chosen to allow the movement of each degree of freedom shown in the picture. In this section of the document, they are referred to as: “base joint,” which allows the rotation of the robot; “x-axis,” which allows the movement in and out of the end effector; and “z-axis,” which allows the movement up and down of the end-effector.

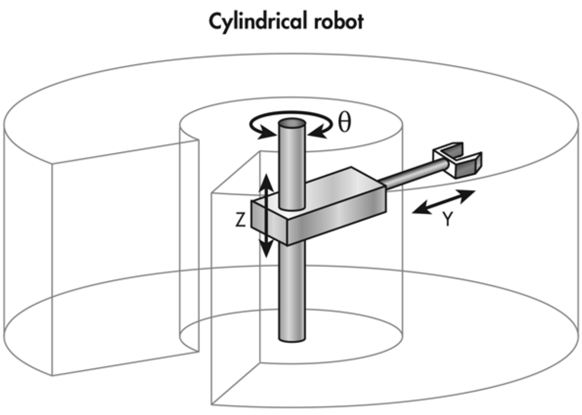

Figure 3.3. Example of a typical cylindrical robot workspace [25].

3.3.1.1 Complete robot assembly overview

The robot of the assembly cell has a cylindrical configuration and is composed of three different igus® modules fixed together using two pieces of aluminum profile extrusions and a set of machined aluminum plates. A robolink® RL-D-30 driven by a NEMA 17 stepper motor is used as the base of the robot, and it is directly fixed to from one face to the assembly surface using the eight threaded holes in the robot base.

On the second face, a 5-mm machined aluminum plate joins the RL-D-30 to a ZLW-0630 that works as an "X-axis" that takes the end effector inside and outside from the center of the working volume of the robot. The ZLW-0630 is an igus® linear axis with a movable carriage driven by a NEMA 17 stepper motor.

A piece of aluminum extrusion of 300 mm is fixed horizontally from one end to the movable carriage of the X-axis using two pieces of aluminum sheet of 3 mm. This allows the movement in the X-direction. On the other end of the 300 mm aluminum extrusion, the second piece of extrusion of 200 mm is vertically fixed using two plates of 3 mm aluminum sheet.

On the upper side of the vertical piece of extruded aluminum, the fifth plate of aluminum links the aluminum extrusion to the "Z-axis." The Z-axis movement is covered by an igus® GRW 0630 linear drive. This drive moves upwards and downwards and carries the gripper at its lower end.

The gripper is made by a push-pull solenoid and a modified LEGO® DUPLO® brick. The brick is perforated in the center to let the piston of the solenoid move freely. As extra support for the extruded aluminum pieces, an igus® DryLin® NK-11-27 was added to the static top part of the ZLW-0630, and the movable lower part of the 30 mm extruded aluminum piece.

Three more small aluminum pieces were machined to hold the power chains in the robot but do not have more functions than that. The robot has maximal strokes of 150 mm in X, 120 mm in Z and a maximal rotation of 240°, according to the igus® datasheets. The whole system weights around 3.75 Kg and is able to hold a load of 1 kg.

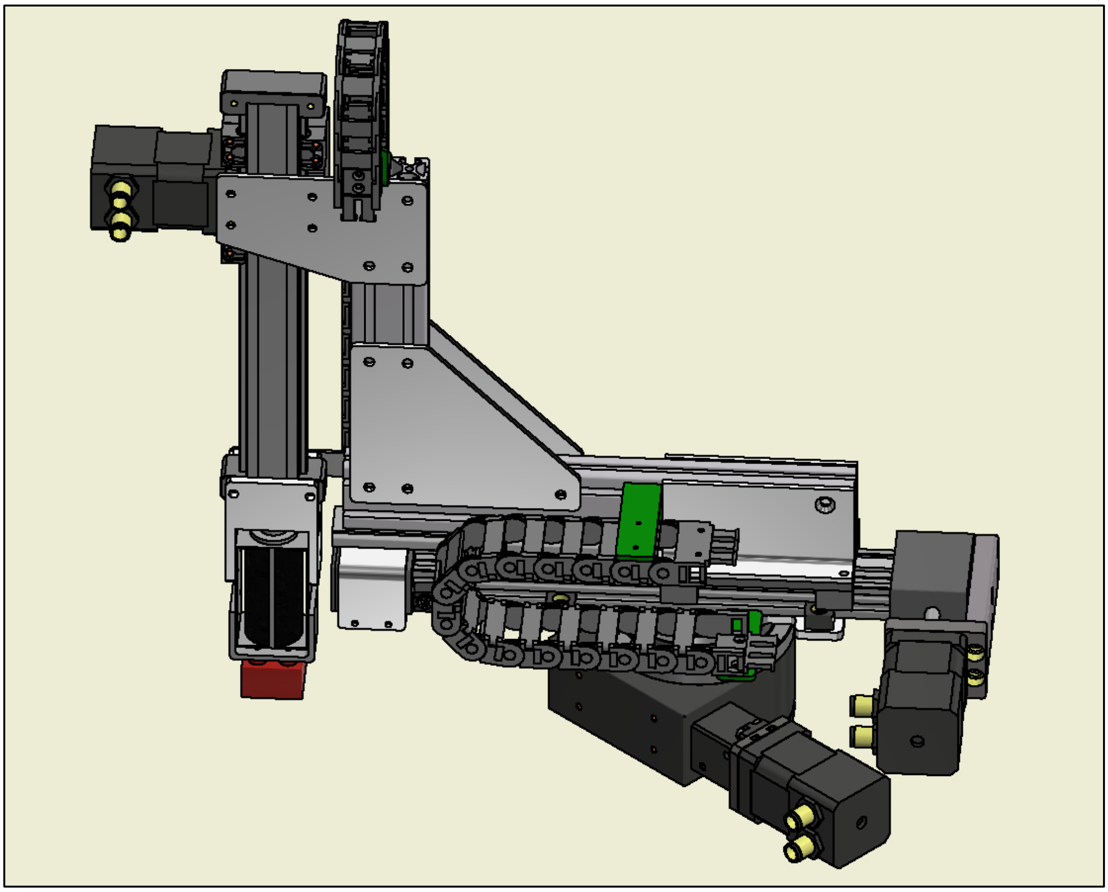

Figure 3.4. Complete assembled robot.

3.3.1.2 Base joint

Igus® has a product line of robotic direct drive joints under the name of robolink® -D. The main component of the module is a worm gear transmission. They are offered in three different sizes with optional stepper motor unit and initiator sensor. An example of the overall looks of the module with a motor attached is shown in figure 3-4. The technical information provided by the manufacturer webpage is found in the Appendix A.

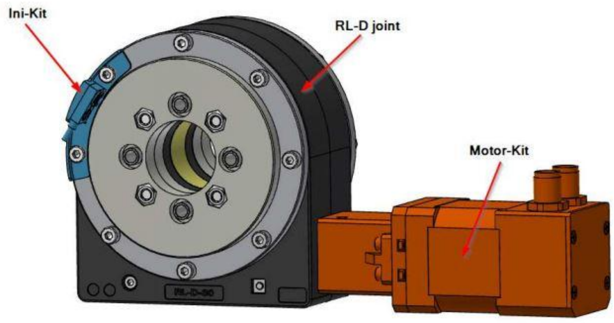

Figure 3.5. The overall look of the robolink® -D joints with stepper motor and initiator sensor [26].

There are three size variants of the robolink® D joints: RL-D-20, RL-D-30, and RL-D-50. The relative difference in size of these three models can be seen in figure 3.5. For this work, the medium size RL-D-30 was chosen for cost and volume reasons. It can be driven by a NEMA 17 or NEMA 23 stepper. Furthermore, the more prominent RL-D-50 works only with stepper motors NEMA 23 or larger, this meaning more power consumption.

The RL-D-30 joint has a transmission ratio of 1:50. The motor selected for the RL-D-30 is a NEMA 17 stepper motor. With this configuration, the joint will have a maximal output torque of 20 Nm at 9 RPM. It will weight 1.18 Kg.

Figure 3.6. From Left to right, robolink®: RL-D-20, RL-D-30, and RL-D-50 [26].

The robolink® joint to be implemented has a movable plate in only one of the sides and has 8 threaded holes on the other face as shown in figure 3.6. These threaded holes will be used to directly fix the motor on the assembly area of the machine.

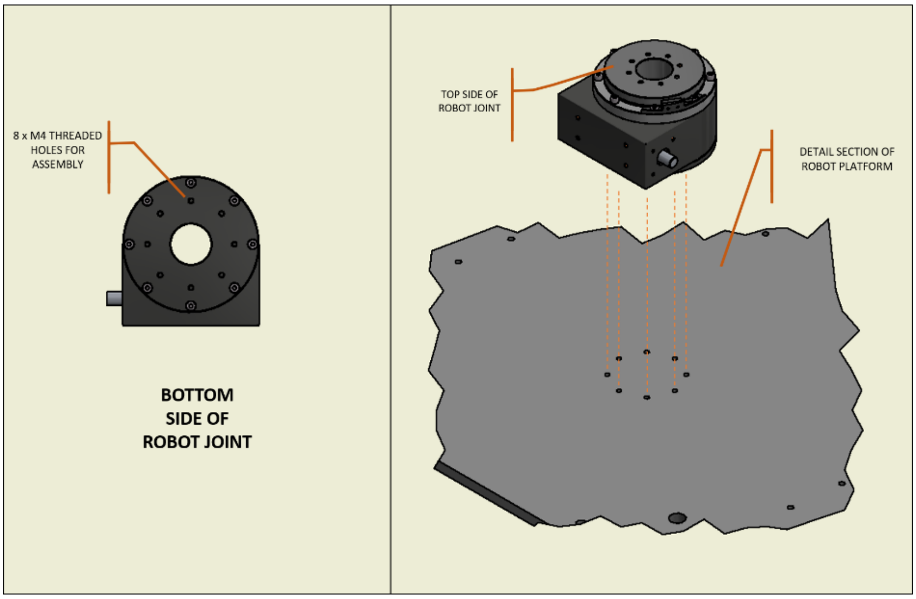

Figure 3.7. Threaded holes for fixing the motor on the system.

3.3.1.3 X-axis

As shown in figure 3.3, there is the need to add a DOF that lets the end effector to move in and out from the central axis to achieve the cylindrical work volume. For the X-axis, another product line of the igus® catalog was used.

The igus® DryLin® E is a product line of low priced electric linear axes driven by a variety of types of electrical motors. It is the natural solution from the igus® catalog for the second component of the robot since they are a compact, light, and robust solution for this kind of movement. More technical information delivered by the manufacturer is found in Appendix A.

The linear drive chosen for the X-axis of the robot is the igus® DryLin® E ZLW-0630 with 150mm of stroke. It was preferred over the other igus® options because it is the smallest version offered and is still powerful enough for the task. It is driven by a NEMA 17 stepper motor also provided by igus®. The manufacturer recommends this model for fast positioning of small loads. An overview of the linear drive is shown in fig 3.7.

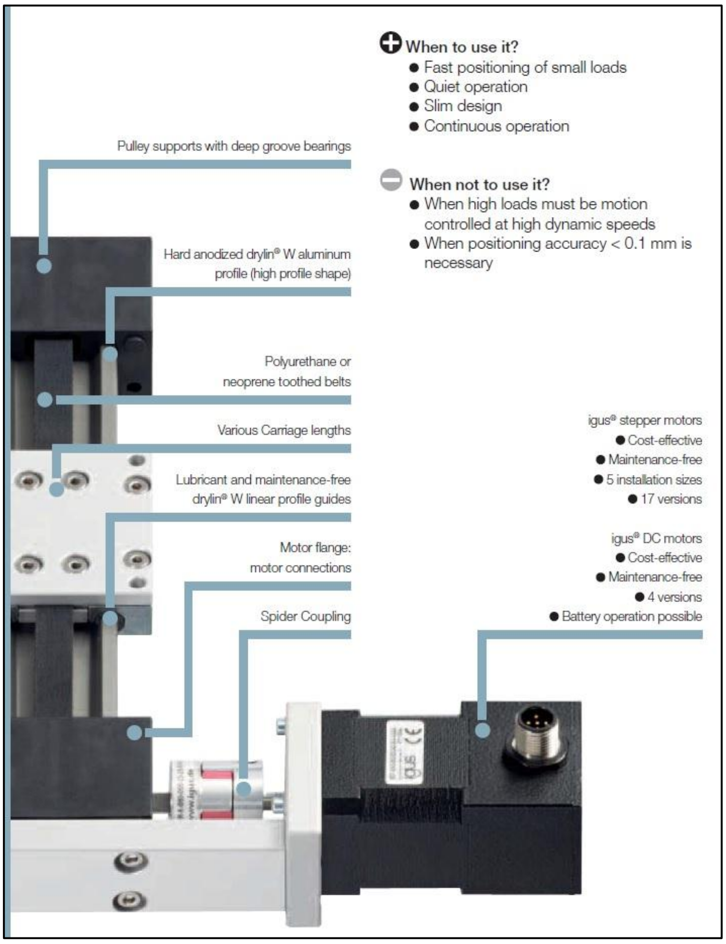

Figure 3.8. A general overview of the ZLW-0630 [26].

A joining plate was designed to mount this linear axis on the base of the robot. This plate is made from a 5mm thickness aluminum sheet and has holes to be fixed on to both the base and the X-axis drive of the robot using the mounting accessories offered by igus® (see Appendix A). Figure 3-8 shows the silhouette of the joining plate and how it assembles the X-axis to the base of the robot.

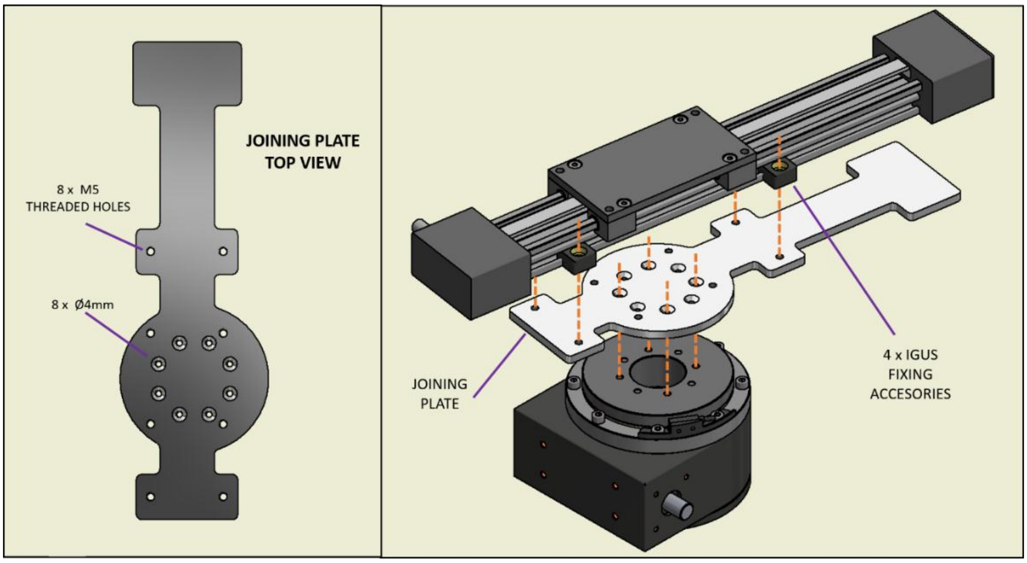

Figure 3.9.Silhouette of the joining plate and how it assembles the X axis to the base of the robot.

The joining plate covers most of the lower surface of the linear axis to offer more support and avoid bending of the aluminum extrusion of the ZLW 0630. The X-axis is not centered on the top of the robot's base joint, but there are some millimeters of asymmetry to compensate the position of the gripper.

3.3.1.4 Z axis

For the last DOF of the robot, another module from the igus® DryLin® E line was chosen. It is a module intended for pick and place applications and is also driven by a NEMA 17 stepper motor. According to the manufacturer, it can be used for dynamic loads up to 1kg, which is a lot more than the 20g that a LEGO® brick weights. It can be found in the igus® catalog as GRW-0630. Figure 3.9 shows the main parts of this module.

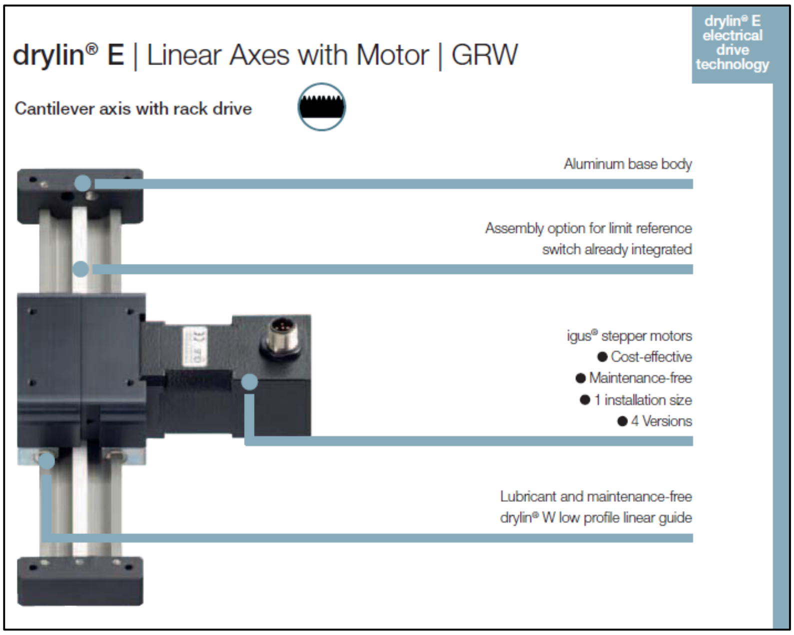

Figure 3.10. Igus® DryLin® E GRW-0630 linear axis [26].

3.3.1.5 End-effector

The end-effector of the system was designed by students working in another system of the FH Aachen Industry 4.0 network and is thought to be implemented in all the systems of such network[23]. It is an improvement over a former actuator that used a pneumatic piston. It consists of a modified LEGO® DUPLO® brick attached to a machined aluminum structure to a push-pull solenoid and whose center has been drilled. Through the hole in the center of the brick, the push-pull solenoid piston can move freely. The solenoid is attached to one end of the GRW by using another machined piece of aluminum. This gripper is shown in figure 3-10. The datasheet of the solenoid used can be found in the Appendix A.

For gripping the LEGO® blocks, the robot must take the end-effector above the target LEGO® block and then move it down until the targeted LEGO® block gets fixed to the gripper. The next step in the regular operation of the machine would be to take the gripped brick above the destination, where another brick should be already placed, move the gripper down until the gripped brick is fixed to the destination. For releasing the brick from the gripper, the robot must move the gripper upwards in the Z direction and activate the solenoid right after starting that movement. This last action will cause the LEGO® brick (previously gripped) to disassemble from the gripper and stay fixed to the third LEGO® block it was taken to. The steps of the process described in this paragraph are displayed in a sequence of images in figure 3.11.

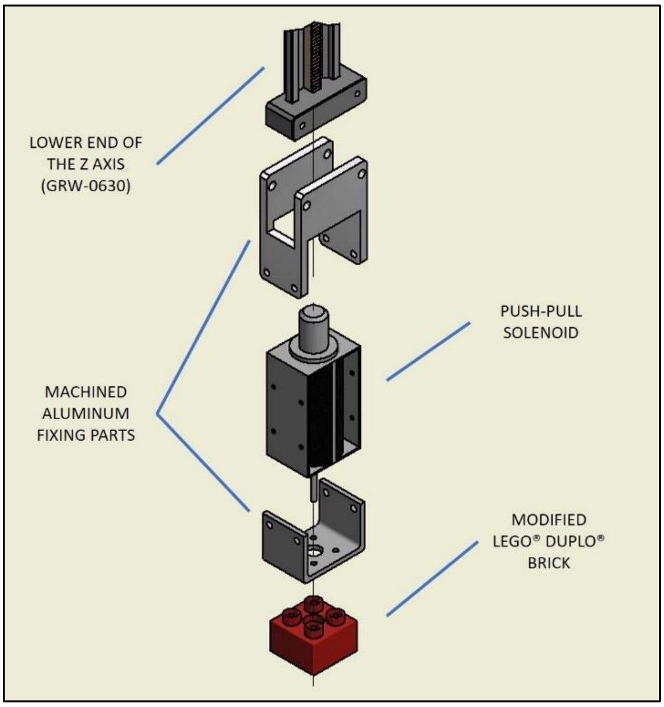

Figure 3.11. Isometric exploded view of the end-effector.

3.3.1.6 Z-axis to X-axis union

Finally, to assemble all the igus® ZLW-0630 (X-axis) together with the GRW-0630 (Z axis), two pieces of 20x40 aluminum extrusion profiles were used, one of them in a horizontal position and the second one perpendicular to the first one, in a vertical position. The two pieces of aluminum are joined by two pieces made of aluminum sheet. They are fixed to the movable carriage of the X-axis using another pair of aluminum pieces. The Z axis is held by a single piece of aluminum sheet at the top of the vertical extruded part. See figure 3.12. This is a simple solution that does not increase the cost of the robot in substantially and offers stability and durability.

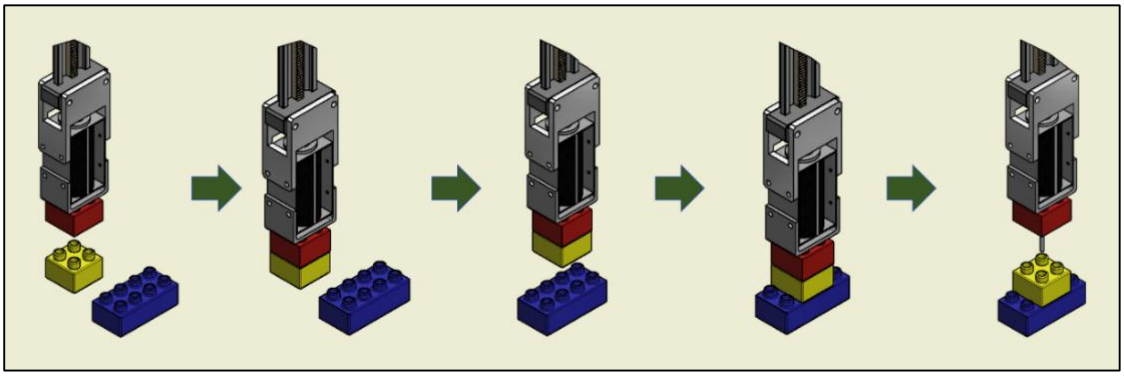

Figure 3.12. Example: assembly steps.

Since the aluminum extrusions were fixed to the X-axis by only one end of the horizontally oriented piece due to the lack of space in the carriage, the manufacturer suggested using extra support on one of the ends of the X-axis. The support suggested is a plastic, low profile linear guide system also found in the igus® catalog and is both compact and lubricant free. The specific model of the guide is the NK-11-27 and is part of the igus® DryLin® N family of linear guide systems.

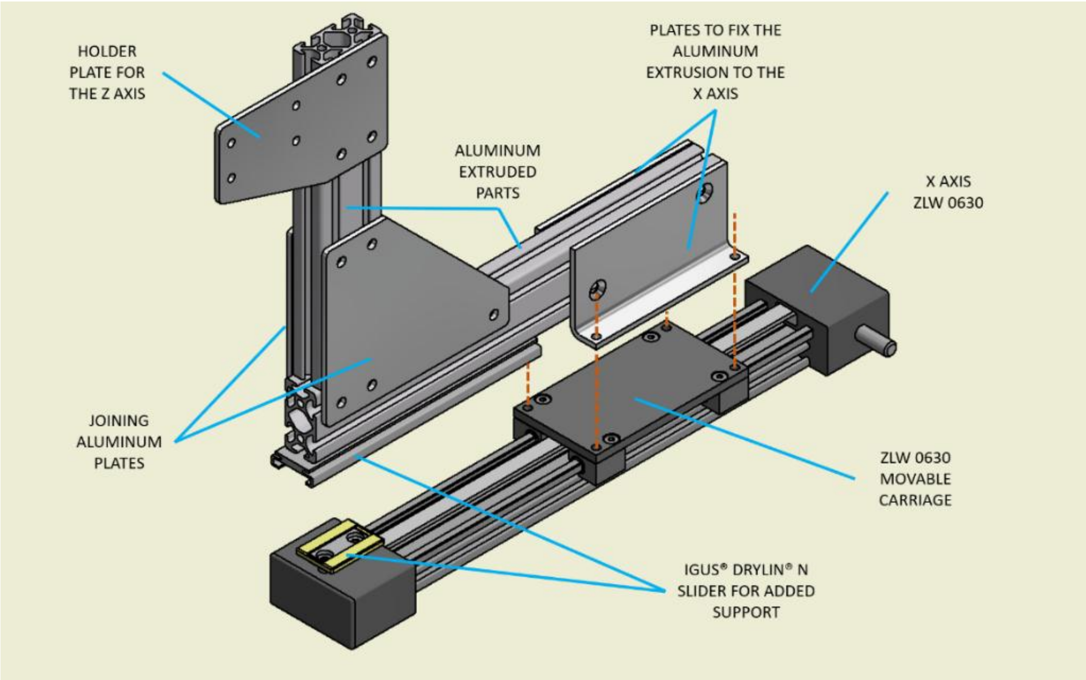

Figure 3.13. Aluminum extrusion connection to the linear axes.

This complete structure has a total weight of 0.734 kg, according to Autodesk Inventor and considering a material density for the aluminum of 2.7g/cm^3.

3.3.1.7 Stress analysis

For the parts joining the igus® modules to form the structure of the robot, a static structural analysis was performed with the inventor software to verify the dimensions used. Since the robot will work in a confined workspace where no human would be in touch with the movable parts, the analysis considered the force caused by the weight of all the parts with a safety factor of only 1.2.

For the plate linking the base joint and the X-axis, a maximum deviation of less than 0.75mm was obtained in the analysis. Even though this is a static analysis, the loads handled in the system are relatively light, and the system should operate without problems. Figure 3.13 shows a color map of this result.

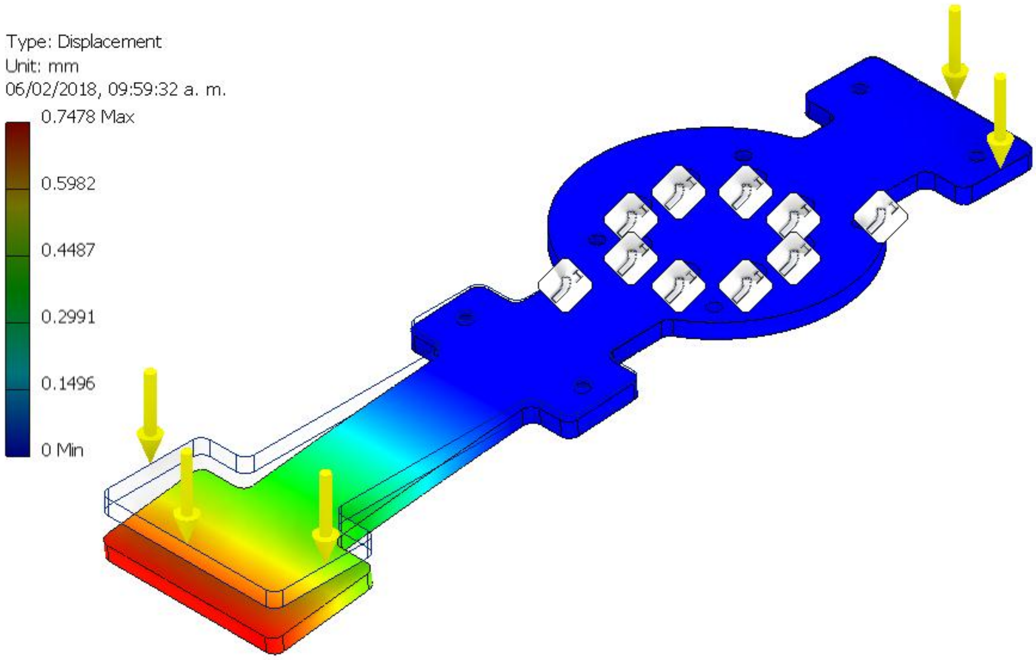

Figure 3.14. Stress analysis of the joining plate: color map.

As for the aluminum profiles connecting the X and the Z axes, the result was a maximum deviation of 0.011mm. This analysis considers only the weight of the gripper and the small load that the bricks would be even less when considering the force that the GRW-0630 could produce in the opposite direction when assembling. A color map of the results is shown in figure 3.14.

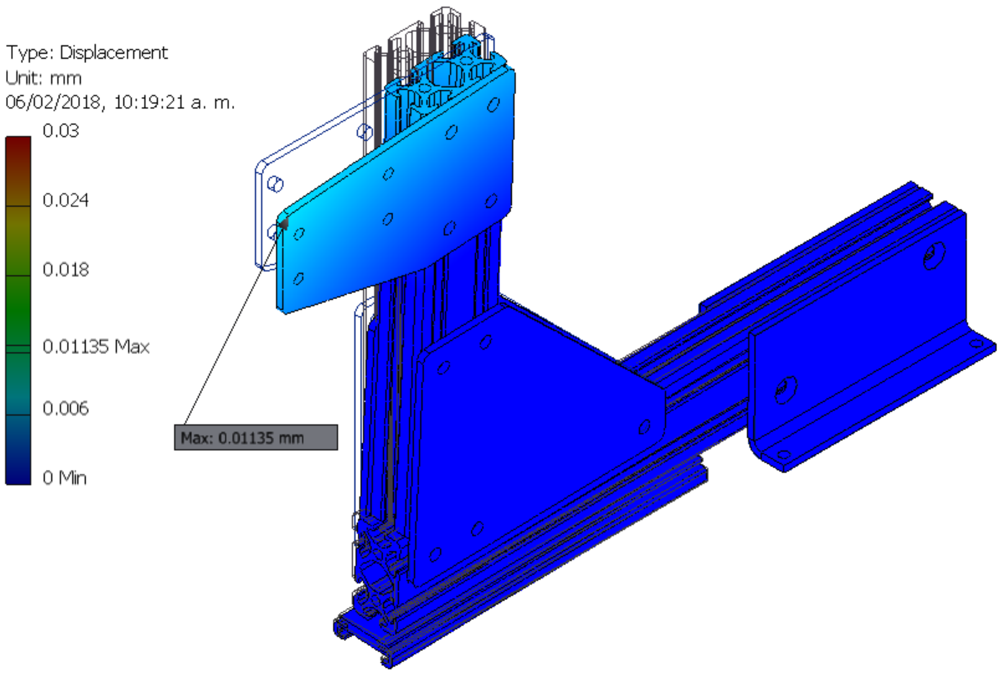

Figure 3.15. Stress analysis of the aluminum extruded profiles: color map.

3.3.2 Material handling

The material fed to the machine will be commercial LEGO® DUPLO® bricks from diverse shapes and colors. The most straightforward brick available for assembly in this machine is referred to as size 2x2 in this document because it has the dimensions of two lines of two assembly pins on top. Following this description, there will be bricks of the sizes 2x2, 2x3, and 2x4 in the machine. These bricks are somehow regular because they follow the same prismatic shape with slight variations in each size, like rounded corners and the height of the brick. Some examples of the pieces with these dimensions can be seen in figure 3.16. For each brick in the figure, there are several colors available.

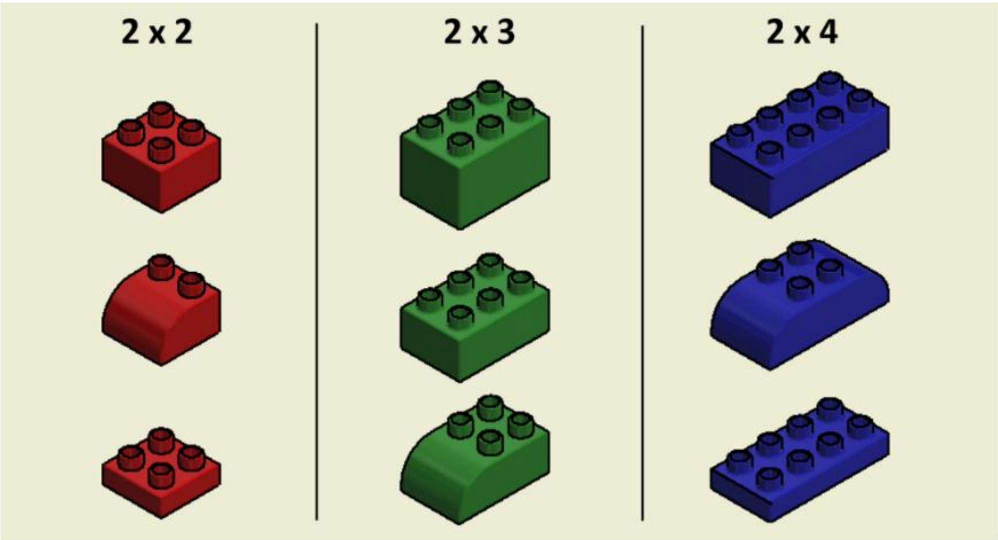

Figure 3.16. Regular LEGO® DUPLO® shapes to be used in the system.

There are also some bricks with irregular shapes. Only the brick called "Chassis" is included in all the machines, since it is the standard base for every toy car. The rest of the pieces are planned to be added in future work to this one and the other machines at the FH Aachen to enrich the offer of the whole assembly network. They suppose more complex assembly steps and material handling procedures. These special bricks are shown in figure 3.16. Apart from the Chassis brick, only the piece called "Motor" is considered in the functions of this machine, but the design allows modification for its addition in the future.

Figure 3.17. Irregular LEGO® DUPLO® bricks.

3.3.2.1 Slides for regular bricks

When designing the bricks feeders, the cylindrical nature of the robot's workspace had to be considered. The robot will move quickly around its own center, and that made it clear the bricks should be placed in a circumference. The idea was to position the feeder end of the system above a circular path inside the working field of the robot. Figure 3.18 shows a circumference that could work for this purpose. In the image, the whole workspace of the robot seen from the top is marked as a green area, and the path of the robot is the represented by a dotted line. The dimensions of the robot in the cell allows paths with a distance from around 221.5mm to nearly 331.5mm from the center of the robot

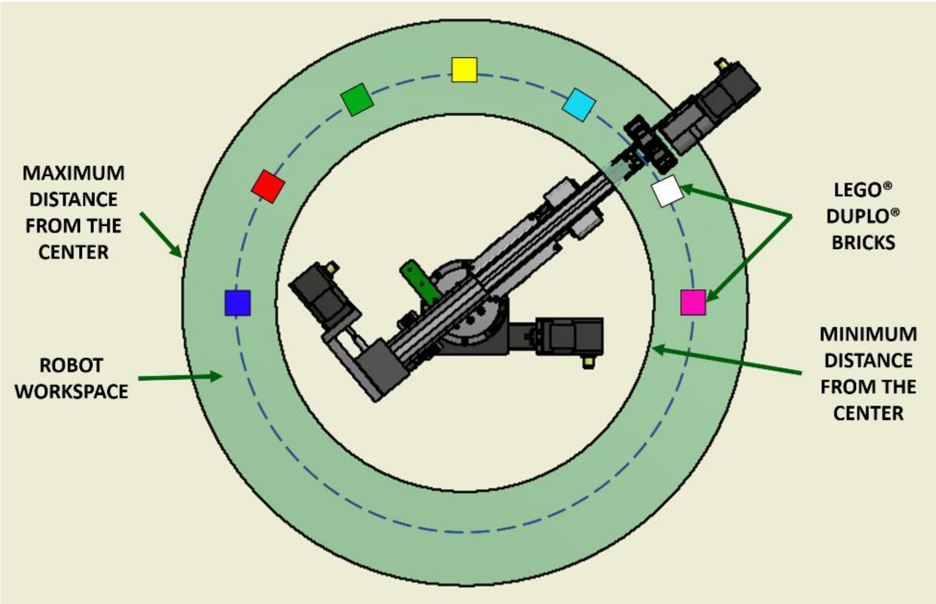

Figure 3.18. Conceptual fed material positioning.

Another requirement was to optimize the room available for stock in the machine. For this reason, some vertical storing units were proposed. This idea made the solution more complicated to implement and more expensive because other actuators were needed to feed the bricks from the storing position to the robot. Horizontal storing was also discarded because the space used for a circular arrangement was too much in relation to the storing capacity, at least with the solutions considered during the design.

With both vertical and horizontal options being discarded, the next natural answer was inclined slide feeders. Inclined feeders could work passively with just the action of gravity and would have the capacity to store more bricks than a horizontal solution with the same footprint.

Instead of roller tracks, a flat surface was proposed to simplify the construction and lower the price of the slides. The inclination of the slide must be such that the force of the gravity can overcome the friction between the slides and the LEGO® bricks but not so much that there is a risk of overlapping bricks. Some tests with the LEGO® bricks and a long flat metallic piece were made to find that angle, and it resulted between 20° and 25°.

The construction of these slides is simple and is shown in figure 3.19. Aluminum sheet metal parts were selected for the construction due to its lightness and ease of machining. As seen in the picture, the complete slide consists of the material entrance plane, the sliding and storing surface and the material exit where the bricks will be taken by the robot. There are walls to the side of the sliding area as well as to the front of the outlet area with a height of 18mm from the sliding surface to keep the bricks always on the same path. The different sized brick to be used for assembly have the same girth of 31.7mm, and that is why the slides for the regular bricks have the same width of 33mm.

There is also a piece of aluminum extrusion 20x20 to level both input and output surfaces of the slides. The difference in height from both surfaces is 100mm for all the slides, and the distance of the surfaces centers is 280mm. The angle for the different brick sizes varies because these measurements are constant and the material outlet surface is different for each brick size, but the angle is always around 21° and 22°. The technical drawings with the complete measurements are found in the Appendix B of this document.

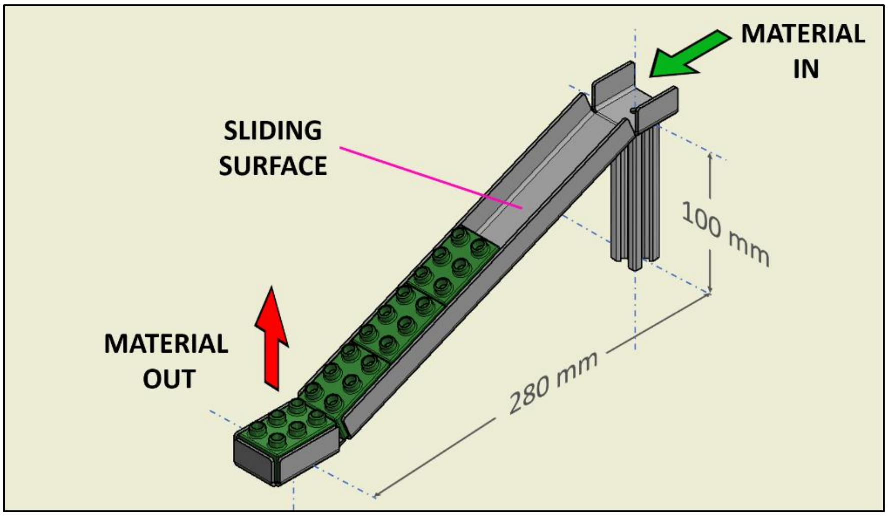

Figure 3.19. Concept overview of the material feeders.

The slides will be placed in a circular path around the center of the robot. All the slides should be aligned in the same way with the Y axis of the robot since the gripper does not have a rotational movement and it could not grip the bricks otherwise. Because of the circular arrangement of the slides, the distance of 280mm was required to maintain a total footprint of the slides assembly with 500mm of radius from the center of the robot.

Even though the slides will be assembled with the lower surface as close as possible to the neighboring slide, the gap between them will be more significant at the other end of the slide, in the material entrance surface. In order to use more efficiently the room in the cell, another set of slides was planned to be assembled at a higher level and fitted to the more significant gap in the lower slides. The higher set of slides cannot have the same 280mm length of the lower because then they would get in the way of the robot when gripping the lower bricks. Also, instead of using one piece of aluminum for support, two of them are needed with 80mm and 150mm lengths. A close-up view of the arrangement of both levels of slides is shown in figure 3.20. In the figure, the blue and green bricks are in the same lower level, and the red and yellow bricks are in the same upper level. The bricks with the more extended size are preferred to be on the lower level.

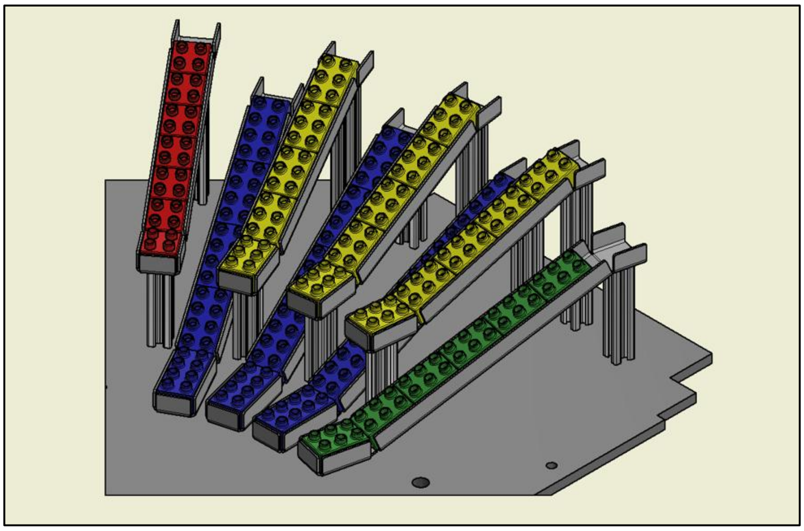

Figure 3.20. Close-up to both slide levels.

3.3.2.2 Slides for irregular bricks

The material feeding unit could not work for all the irregular bricks presented in the section 3.2.2. The two irregular parts used for assembly in the cell will use slightly different slides to address the alteration in shape. The “Motor” brick is similar in dimensions to the 2x2 regular brick. The main difference is the addition of a pair of bumps at two parallel sides of the block. A comparison of the two blocks can be seen in figure 3.21. The “Motor” block is similar enough to the regular 2x2 brick to use the same slide concept with just a lower height for the side walls to avoid the interference with the irregularities of the brick. The height of the walls was set to 9mm instead of the 18mm for the regular brick slides, and the result can be seen in figure 3.22. The “Motor” brick is among the shortest pieces and therefore, was placed on a slide at the upper level. As seen in the picture, up to seven units can be stored in this slide.

For the “Chassis” block, there were two changes made on the slides. The width of the slide had to be broadened to 63mm to fit the piece, and the inclination was also lowered because this specific LEGO® piece has a couple of wheels that allow effortless movement with a bit of inclination. It is the piece with more extension, so it was placed in the lower level slides. The distance from the working table to the entry of the slide is 40mm in this case. With those measurements, an inclination of 10.5° is obtained for the slide. Figure 3.23 shows the feeder for the “Chassis.”

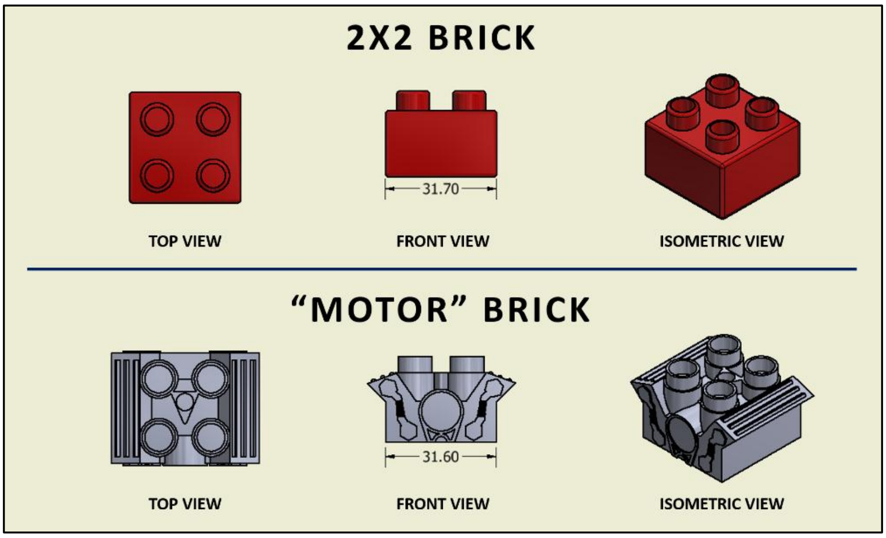

Figure 3.21. Comparison of the 2x2 and the motor brick.

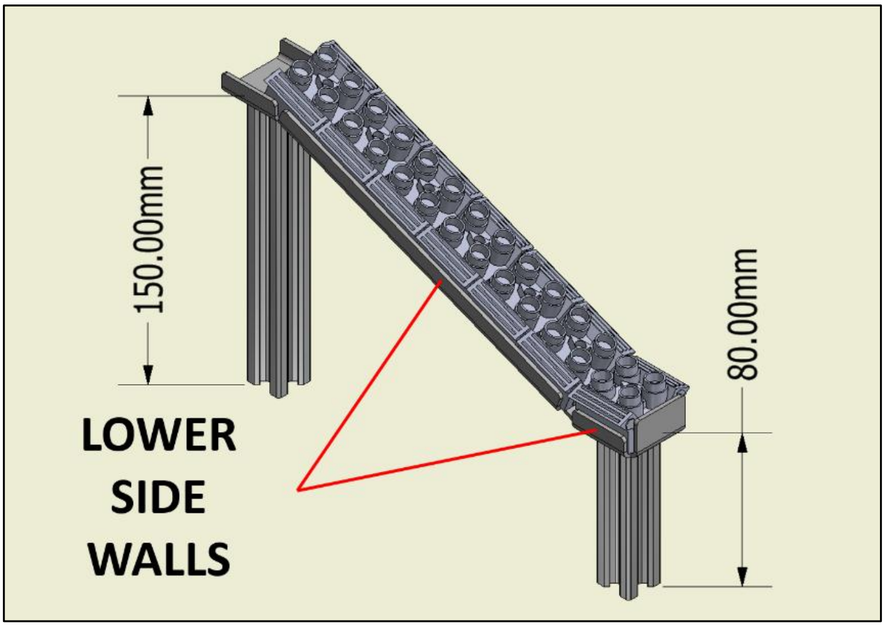

Figure 3.22. Slide feeder for the motor brick loaded with material.

Besides all these material feeders, an assembled item exit had to be added to the configuration. As it was already mentioned, the chassis piece is the base module for all the toy car models that could be assembled in this system, and the finished product exit should work according to that.

The exit slide has an elevated surface on its closest end to the robot on which the toy car would be assembled. This surface is elevated 65 mm from the working table. On the other end of the slide, there is a second surface laying on the working table where the assembled toy car would be placed after finishing the assembly process. For moving to that last surface, the car will be pushed by the robot and roll to the end of the slide. This slide is the shortest of all with only 286.5mm and has an inclination of 12.42°. It is not meant to store the produced cars but only work as a buffer before they are taken away from the machine.

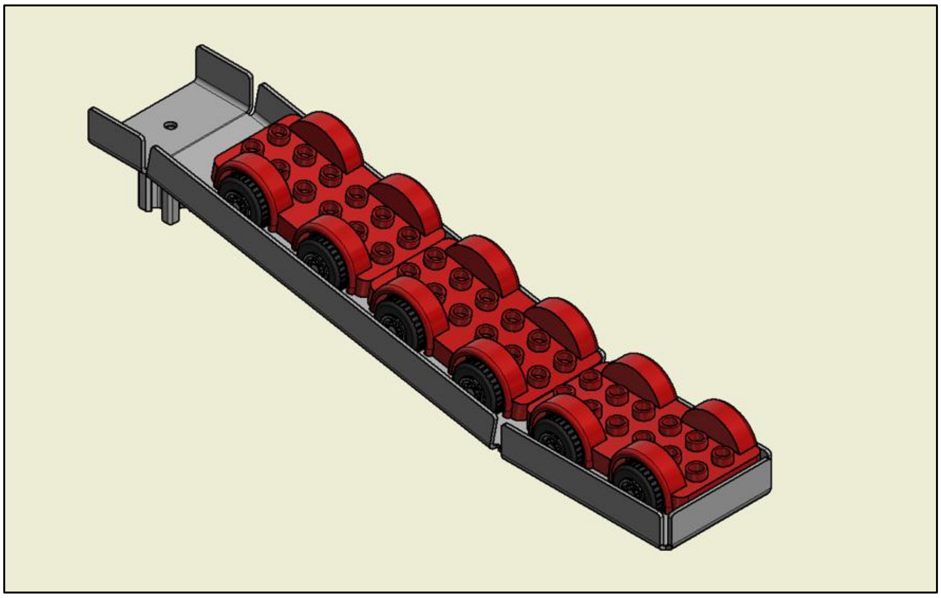

Figure 3.23. "Chassis" feeder loaded.

To hold the chassis piece while the car is assembled, a holding part is needed on the exit slide. This part has been already designed for other machines on the network, and it will be fixed to the slide with the use of two M3 screws. It is 3D printed at the facilities of the FH Aachen, and it has the simple task of avoiding a movement along the assembly surface, but sill let the car go when pushed with the robot to the front of the slide. Figure 3.24 shows this assembly holder mounted on the exit slide.

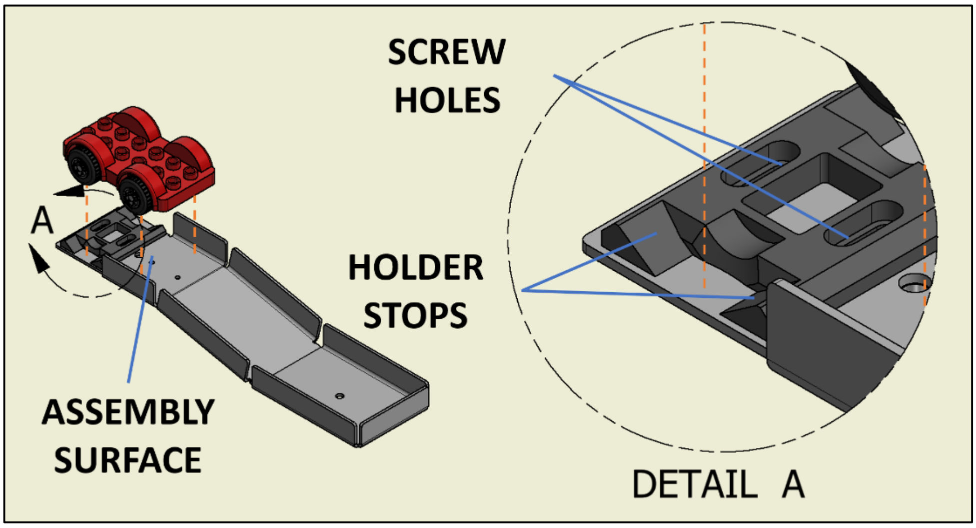

Figure 3.24. Assembly surface holder on the slide and detail view.

3.3.2.3 Assembly table

All the slides described in the previous section must be positioned on the same platform as the robot and take the rotation axis of the robot as reference. This platform will be a sheet of 5mm thick plastic provided by the company item, along with the aluminum frame of the machine. The robot will be directly fixed to this plastic sheet by using the eight threaded holes incorporated in the body of the robolink RL-D-30 module used as the base joint of the robot.

For having the smallest footprint possible, a semi-circle was chosen as the distribution shape for the material feeders. In this way, they can be longer and store more bricks. All the slides will be fixed to the table using two M3 screws, one at each end of the slide. From the two ends of the slides, the one closest to the robot will also be the closest to the table in height. The position of the screw in the closest end to the robot also marks the center of the brick on that slide and therefore will be the coordinate used by the robot during the production tasks. These coordinates are listed in Table 3.1. The other end of the slide will be used for feeding the system and is positioned in the same circumference for all the material feeders at 500mm from the central axis of the robot. Only the assembled product platform is located on different circumferences because it is the shortest and lowest slide of them all and because it has an opposite inclination to get the finished material away from the robot and not closer to it.

The machine frame will be built using aluminum extrusion, and a circular construction would be expensive, if possible at all. Therefore, the assembly table was designed with a shape that could also be achieved with the aluminum frame. It will be shaped like the half of an octagon to make it as similar as possible to a semi-circle. In this way, all the material feeders could be reached by an external robot or human operator to load the assembly material. The narrowest side of the table must be smaller than 80mm to comply with the dimensional requirements.The top view of the final assembly of the feeders on the designed table is shown in figure 3.25. In the figure, there are some cavities on the corners of the table that correspond to the columns of the aluminum frame of the structure.

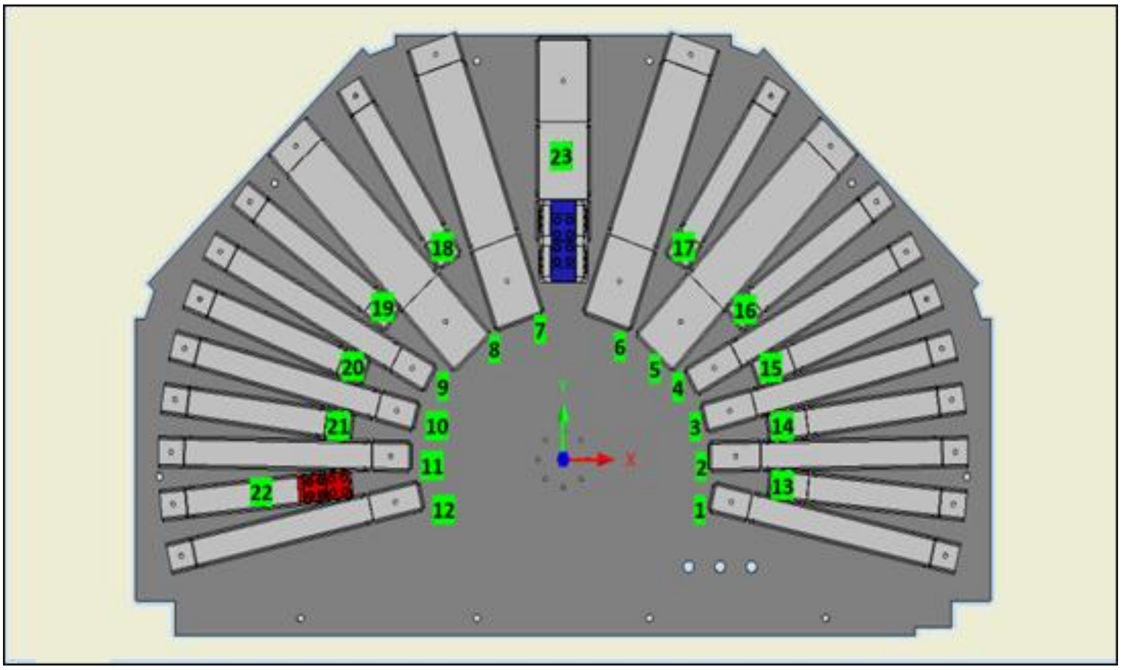

Figure 3.25. Top view of the feeder's assembly. Coordinates in table 3.1.

Slide ID	X	Y	Z	r	Angle	Slide name
1	214.3	-49.4	21.1	220	-13.0	LowFeeder_3x2
2	219.9	3.8	21.1	220	1.0	LowFeeder_4x2
3	212.5	56.9	21.1	220	15.0	LowFeeder_4x2
4	192.4	106.6	21.1	220	29.0	LowFeeder_4x2
5	150.0	160.8	21.1	220	47.0	ChassisFeeder
6	71.6	208.0	21.1	220	71.0	ChassisFeeder
7	-71.6	208.0	21.1	220	-71.0	ChassisFeeder
8	-150.	160.8	21.1	220	-47.0	ChassisFeeder
9	-192.4	106.6	21.1	220	-29.0	LowFeeder_3x2
10	-212.5	56.9	21.1	220	-15.0	LowFeeder_3x2
11	-219.9	3.3	21.1	220	-0.9	LowFeeder_3x2
12	-214.3	-49.4	21.1	220	13.0	LowFeeder_4x2
13	288.4	-30.3	101.1	290	-6.0	UppFeeder_3x2
14	287.1	40.3	101.1	290	8.0	UppFeeder_3x2
15	268.8	108.6	101.1	290	22.0	UppFeeder_3x2
16	231.6	174.5	101.1	290	37.0	UppFeeder_2x2
17	153.6	245.9	101.1	290	58.0	UppFeeder_2x2
18	-153.6	245.9	101.1	290	-58.0	UppFeeder_2x2_Motor
19	-231.6	174.5	101.1	290	-37.0	UppFeeder_2x2
20	-268.8	108.6	101.1	290	-22.0	UppFeeder_2x2
21	-287.1	40.3	101.1	290	-8.0	UppFeeder_2x2
22	-288.4	-30.3	101.1	290	6.0	UppFeeder_2x2
23	0	255.0	32	255	90.0	Exit

Table 3.1. Positions of the feeder system in cartesian and polar coordinates.

3.3.3 Structure design

The mandatory requirements for the structure of the assembly cell are merely dimensional. The structure should be able to fit the complete assembly system and the electronics for powering it and still have ease of mobility. Besides, the geometry of the structure should allow an external robot to feed the assembly material to the assembly cell.

Aluminum extrusion was selected to develop the frame of the machine because it is easy to assemble, and it is a cost-effective solution both for prototyping and final construction. The complete frame was bought from the company item, along with the platform on which the robot and feeder system are mounted.

The frame is designed with a prismatic shape to adapt to the assembly table silhouette. It uses a 40x40 aluminum extruded profile for the most part and some special extrusions to help the corners with angles broader than 90°. To that prismatic shape, all the peripherals and components must be added without compromising the integrity of the structure.

3.3.3.1 Sections

Although the structure is built has a non-separable construction, two main parts physically isolated from each other can be considered to describe it. The section above the assembly table will be referred to as assembly section, while the section underneath will be referred to as electrical enclosure. Figure 3.26 shows the complete frame and these two physical sections.

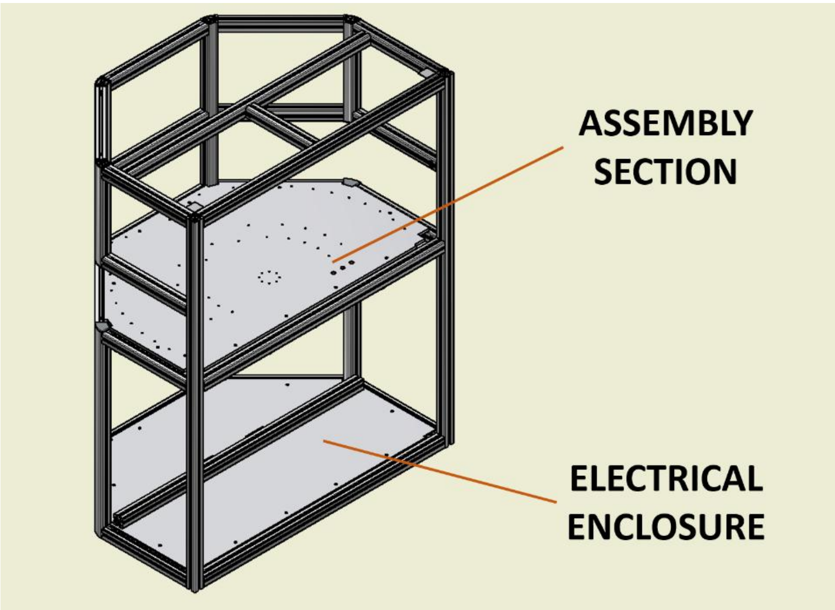

Figure 3.26. Divisions in the structure.

All the electronic components for power and control will be housed in the electrical enclosure section. It will have a one-sided door to access those electronics and will be covered entirely using non-transparent plastic panels in the spaces left by the aluminum frame including the sides facing the floor. All the electronics will be fixed to a sheet of metal of 1000mm x 700mm, following the construction standards for industrial control panels. That panel will be fixed to two vertical 40x40 aluminum extrusions. More details of the electronics are given in the next section.

The door of the electronics section will have a transparent plastic that will make the electronics visible from one side of the machine. This is an attractive characteristic, considering that this assembly cell is planned to be taken to trade fairs and expo shows. Figure 3.27 shows the inside view of the electronics section with the plastic panels at the walls.

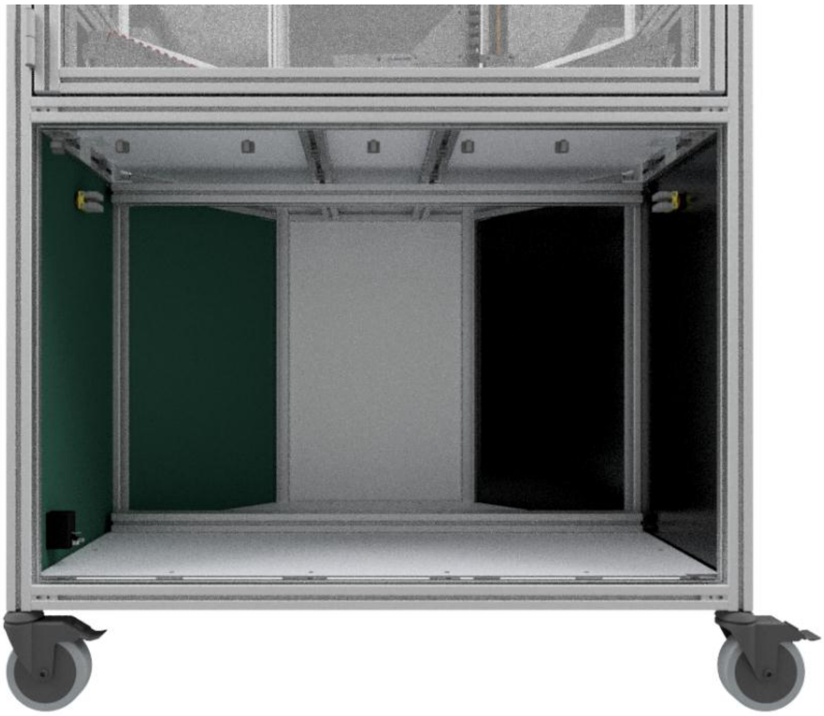

Figure 3.27. View of the empty electrical enclosure.

The assembly section is where the material feeders and robot will be placed. This section will be covered on the top by a transparent sheet of plastic on the top and the sides to make the assembly process completely visible. Besides the visibility on the sides, there must be accessible from the outside to feed the system with more bricks. For this reason, open areas were left in the side walls of the system with a height of 240mm. The aluminum extrusions working as columns for this section were also modified to clear the entrance of the feeding units of the cell. This section also incorporates a one-sided door that permits the access to the assembly area. Figure 3.28 shows the assembly section of the structure already covered with the plastic panels.

As peripherals, two screens will be mounted on the sides of the structure using mounting arms also offered by item. One of them is a WAGO screen to directly interact with the WAGO modules to operate the cell in demo mode and to access some maintenance features. The other screen will be used to show a local toy car configuration screen like the one found in the cloud developed at the FH Aachen, but to be used offline. This is thought as a demo tool of the capabilities of the system.

Figure 3.28. Assembly section with door and partially covered on the sides.

3.3.3.2 Second robot

Additionally, the structural analysis was performed to add a second robot on top of the frame that could work as the external feeding robot. The characteristics of a commercial 5-DOF igus robot, like the one in figure 3.29, were considered. Such illustration was generated with a web tool from the company igus® and the part-list generated is presented in table 3.2. The weight of this robot is around 17kg (16,94kg, 166.24N), but a total force of 300N was considered, since the model of the second robot to be used is not yet defined.

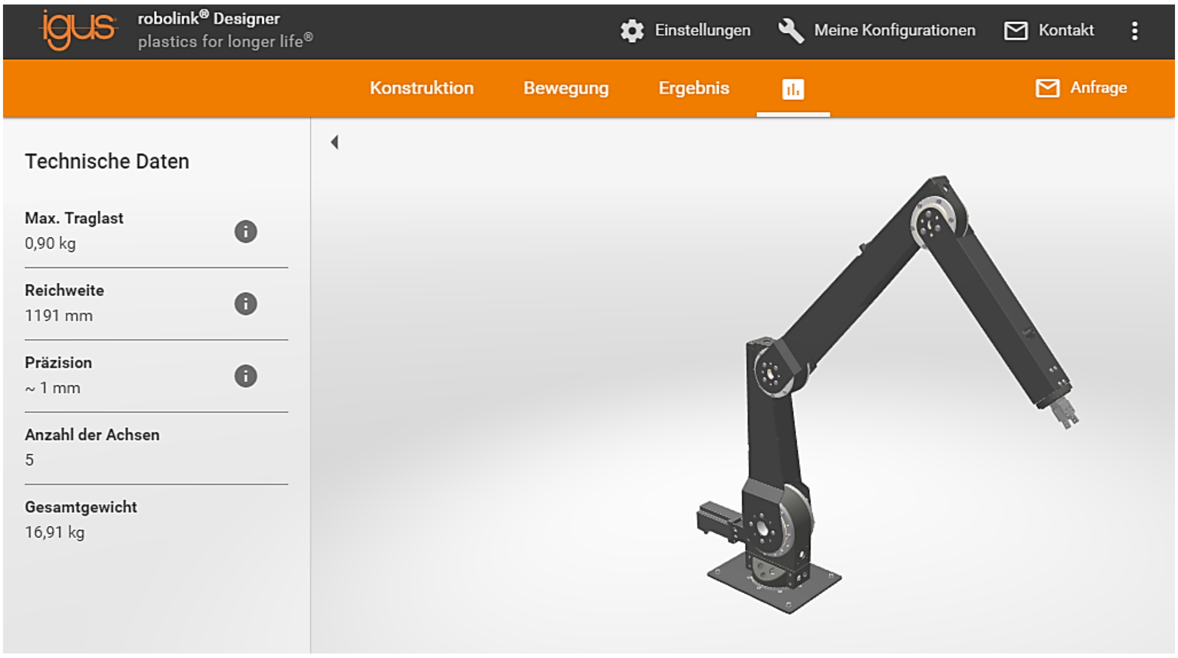

Figure 3.29. Concept of the second robot to be mounted. From the robolink® designer web tool [27].

According to the manufacturer, the robot in figure 3.29 has a precision around 1mm, a maximum scope of 1120mm when extended, and is capable of a useful load of 0.9kg. These values are acceptable for feeding the system, considering the general outer dimensions of the cell.

A static analysis using the inventor software tools was performed to determine the robustness of the frame before mounting this robot on the system. The maximum displacement obtained under the 300N was 0.6889mm and the maximal normal stress was 9.535MPa. The yield strength of the material is 195MPa. The displacement caused by the electronics would be 0.3623mm when the assembly is complete. A color map with the displacement resulted from this analysis is shown in figure 3.30. This analysis also considers around 60 Kg of weight form the electronics acting on the frame.

Gelenke

Artikel Nr.	Anzahl	Beschreibung
RL-D-50-102-48-01035	1x	Asymmetrisches high-end RL-D 50 Gelenk
RL-D-50-101-48-01033	1x	Symmetrisches high-end RL-D 50 Gelenk
RL-D-30-101-50-01000	1x	Symmetrisches RL-D 30 Gelenk
RL-D-20-101-38-01000	1x	Symmetrisches RL-D 20 Gelenk
RL-S-17-N11-00-28-020K0	1x	RL-S 17 Wellgetriebe

Motor Kits

Artikel Nr.	Anzahl	Beschreibung
RL-D-50-MK-C-N23XL-02	2x	NEMA 23XL
RL-D-30-MK-C-N23-02	1x	NEMA 23
RL-D-20-MK-C-N17-02	1x	NEMA 17
MOT-AN-S-060-001-028-L-C-AAAC	1x	NEMA 11

INI-Kits

Artikel Nr.	Anzahl	Beschreibung
RL-D-50-IK-001	2x	INI-Kit für RL-D-50 Gelenk
RL-D-30-IK-001	1x	INI-Kit für RL-D-30 Gelenk
RL-D-20-IK-001	1x	INI-Kit für RL-D-20 Gelenk
RL-S-17-IK-01	1x	INI-Kit für RL-S 17 Wellgetriebe

Sonstige

Artikel Nr.	Anzahl	Beschreibung
RL-DC-BL-50-MP-01-P	1x	Montageplatte für RL-D 50 Basisgelenk
RL-DC-50-50-T-01	1x	Verbindungselement 50-50
RL-DC-50-30-AA	1x	Verbindungselement 50-30
RL-DC-30-20-AA	1x	Verbindungselement 30-20
RL-DC-20-S-AA	1x	Verbindungselement 20-S

Table 3.2. Part list of the considered 5DOF-robot.

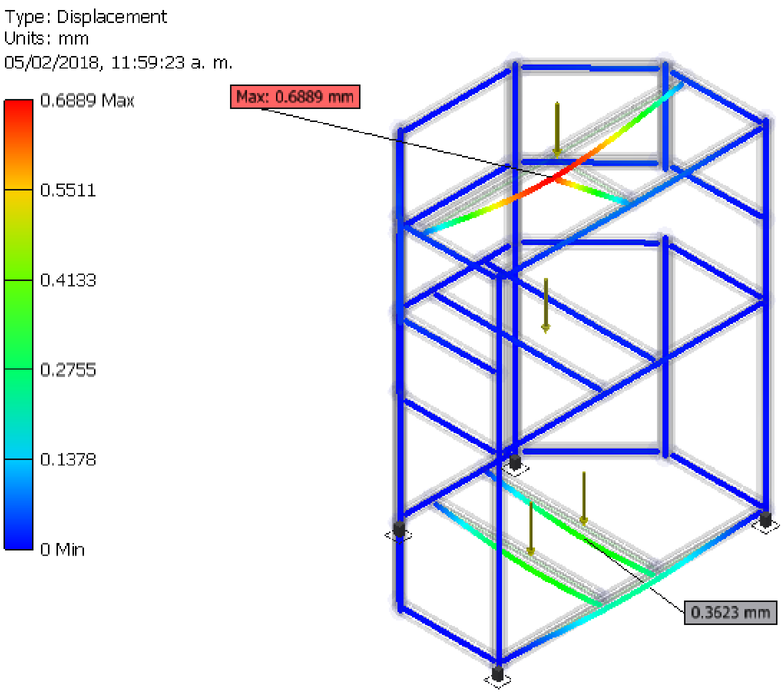

Figure 3.30. Color map of the deformations in the frame.

3.3.4 Electrical enclosure

The electrical components of a machine must be isolated from the surroundings for protection of the electronics but also for the safety of the users. The enclosures used for the electronics of a system are usually placed near the location where the machine is meant to operate. In the case of this assembly cell, the electronic cabinet should be incorporated into the structure of the machine itself, to fulfill the mobility requirement.

For this system, the electronics were sent to the lower section of the machine frame. The characteristics of this area are explained in the section 3.3.3 of this document. The components included in the electrical enclosure are mounted on standard DIN 35 rail sections which are just normalized bars of metal. These rails are fixed to a pair of stainless metallic plates with screws. The main plate is fixed to the aluminum profiles of the structure by four M8 screws, one at each corner of the plate.

The use of two separate plates for mounting the electronics was necessary due to the number of components involved. The main plate houses most of the electronics separated into three different sections of DIN 35 rails. A layout of the components is shown in figure 3.31, and its components are listed in Table 3.2. The second plate of the system covers the functions of giving extra space for the electronics and is where the control modules are mounted.

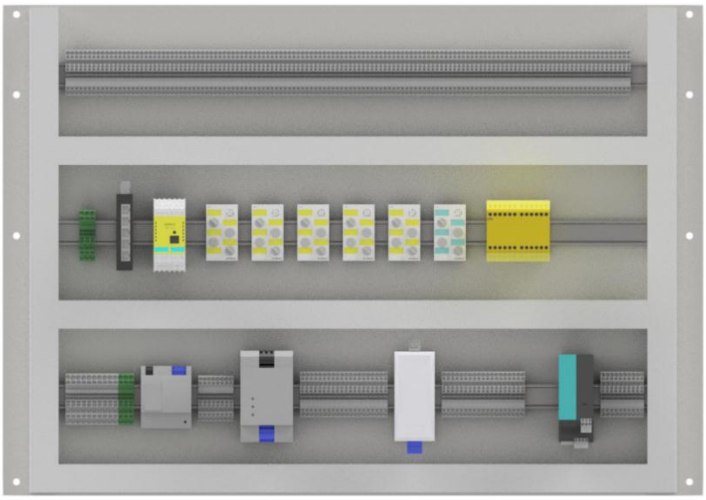

Figure 3.31. Main plate of the electrical enclosure.

Along with other electrical components, the controlling units for the system were sponsored by the company WAGO and cover all the necessary modules to control 2 robots: the 3-DOF-robot described in section 3.3.1 and a 5-DOF-robot meant for external material feeding to the system not yet incorporated to the machine. The layout of these components mounted on the small plate of the enclosure is shown in figure 3.32. These components are listed in detail in Table 3.3 starting with slot 0 for the module at the left side of the image and increasing the number to the right.

Figure 3.32. The front plate of the electrical enclosure.

Slot	Model	Type
0	750-8206	PFC 200 Controller
1	750-655	AS-I Master
2	750-430	2x 8 Channel Digital Inputs
3	750-430	2x 8 Channel Digital Inputs
4	750-672	70VDC Stepper Motor Driver
5	750-637	Incremental Encoder Module
6	750-672	70VDC Stepper Motor Driver
7	750-637	Incremental Encoder Module
8	750-672	70VDC Stepper Motor Driver
9	750-637	Incremental Encoder Module
10	750-672	70VDC Stepper Motor Driver
11	750-637	Incremental Encoder Module
12	750-672	70VDC Stepper Motor Driver
13	750-637	Incremental Encoder Module
14	750-672	70VDC Stepper Motor Driver
15	750-637	Incremental Encoder Module
16	750-672	70VDC Stepper Motor Driver
17	750-637	Incremental Encoder Module
18	750-637	Incremental Encoder Module
19	750-672	70VDC Stepper Motor Driver
20	750-637	Incremental Encoder Module
21	750-600	Fieldbus End Cap

Table 3.3. List of components on the front plate of the electrical enclosure.

These two plates are fixed together by using four pieces of aluminum extrusion with a length of 200mm each. An isometric view of the assembled plates is shown in figure 3.33. The complete electrical plans and connection diagrams, taken from [28], are found in the Appendix C. Finally, a rendered image of the electronic enclosure with the door unattached is displayed on figure 3.34.

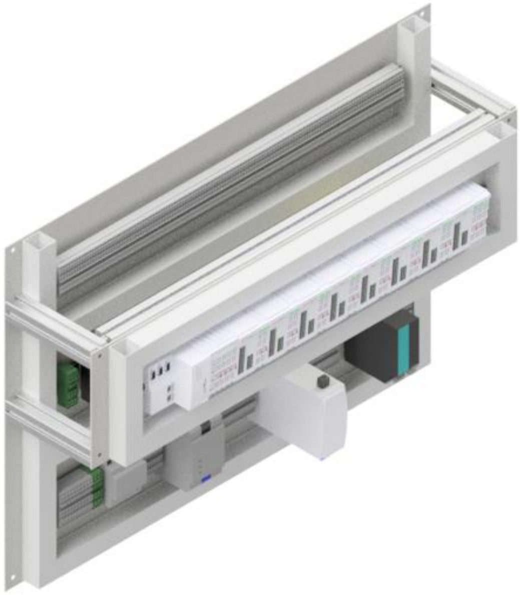

Figure 3.33. Isometric view of both electrical panels assembled.

Figure 3.34. Electronic enclosure with electronics assembled.

4. Results and discussion

At the end of this project, the robot of the assembly cell was assembled almost entirely. The plastic energy chains for channeling the wires are still missing due to delays in the buying process. The base joint of the robot has a worm gear reducer. This kind of reducer allows the direction of transmission only in one way; this means that the output shaft can only be moved from the side in which the motor is incorporated in the robotic joint and not by hand from the side where the X-axis is fixed. Therefore, the joint was moved using the WAGO PLC to test its dynamics. The libraries and software configurations used for testing this movement is part of another thesis and can be found detailly described in [28]. The base joint moves the rest of the mechanical parts with no issues, and it feels stiff in general. It has only a small output reverse play, as was already expected from the datasheet of the product. In practice, this reverse play affects the position of the end effector in less than 1mm when the end-effector is at its furthest operation point from the center of the robot, which is inside the tolerance planned for the system.

The added igus® NK-11-27 slider, described in section 3.1, turned out to be a practical solution. During the tests done without it, robot tended to lean down on the side of the end effector. After adding this support, the movements of the robot were a lot steadier. The NK-11-27 also provides smooth sliding for the X-axis. This solution is both practical and economical and should be considered for future works in the machine for these reasons.

The X- and the Z-axis use a toothed belt as means of torque transmission, and they were easy to move by hand to test the volume in which the robot can operate. Nevertheless, the WAGO PLC was used again to test the dynamic stability of the construction. The movements were smooth and steady as well. The Z-axis is strong enough to lift the gripper from the ground and hold it in any position without problems. All the aluminum parts joining the igus® modules fit, and efficiently provide steadiness to the robot. Figure 4.1 displays the assembled robot without wires.

The gripper itself was also put to the test. When it was designed, a compromise in the total active stroke of the solenoid was made because of the space necessary for mounting it on the Z-drive. Nevertheless, when assembled, the actual stroke of the solenoid was even less. This was a result of some dimensional parameters not mentioned in the datasheet and made it necessary to modify the gripper construction for its proper use. Two options were considered: the first one was to manufacture a different upper holder for the push-pull solenoid and the second option was to cut the slug of the solenoid. The second solution was faster and cheaper, and so the slug was cut, but for the implementation of this same gripper in other machines, the design should be modified. Overall, the gripper performed well when holding and releasing the different kinds of LEGO® bricks considered for the machine.

The construction shows good behavior and steadiness. The simple joints with which the robotic modules were joint add easy reconfigurability to the system because the modification of these parts can be done fast and cost-effectively.

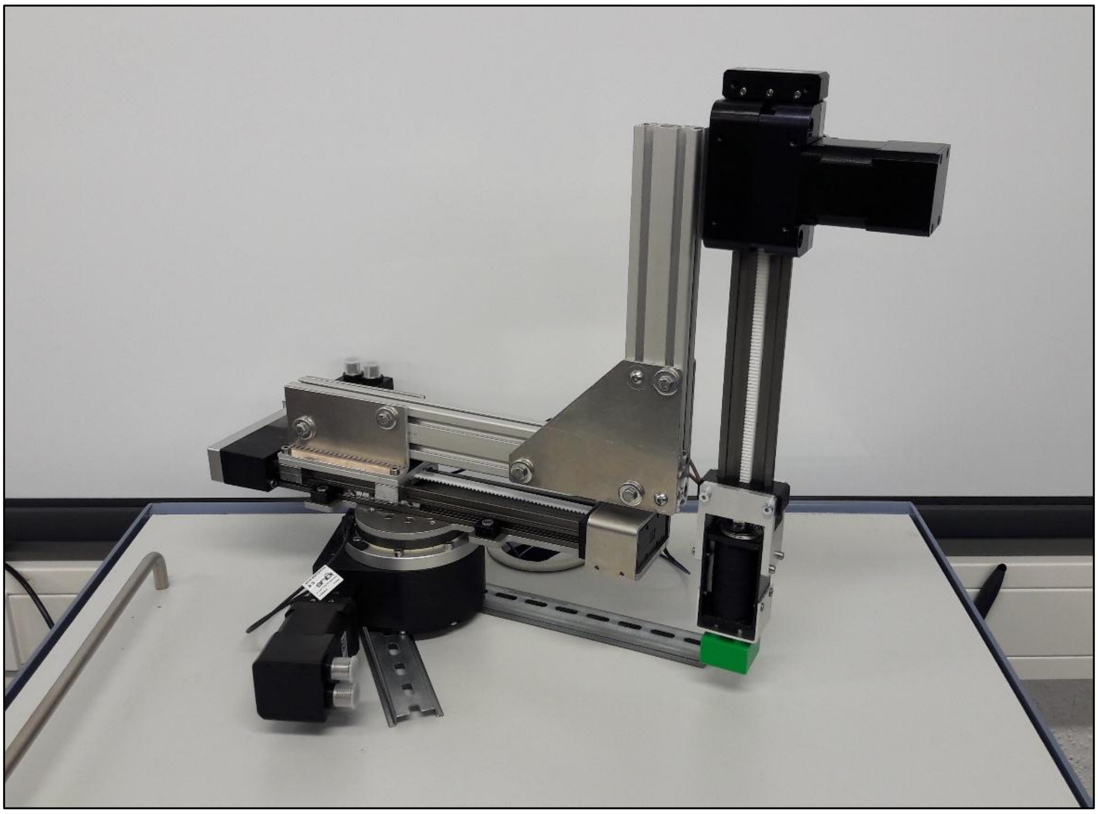

Figure 4.1. Robot assembled.

All the parts made from aluminum sheet metal arrived at the FH Aachen as flat metal cut patterns as seen in figure 4.2. Using the machines at the workshop of the FH Aachen, they were all bent following the design specifications and are now ready to be mounted on the assembly table of the cell.

The slides have variations in the measurements and shapes which are results of the basic equipment used for the bending process. These variations do not seem to affect the function of the slides and some of them, such as the variations in inclination, will be lessened when the slides are fixed to the assembly table. The aluminum offered ease of work during the production of the slides. This was a desired characteristic for the final units, given the didactical nature of the system and the future addition of sensors and or actuators in the slides. Figure 4.3 shows the bent slides with some bricks on them that were used for manual testing of the material flow.

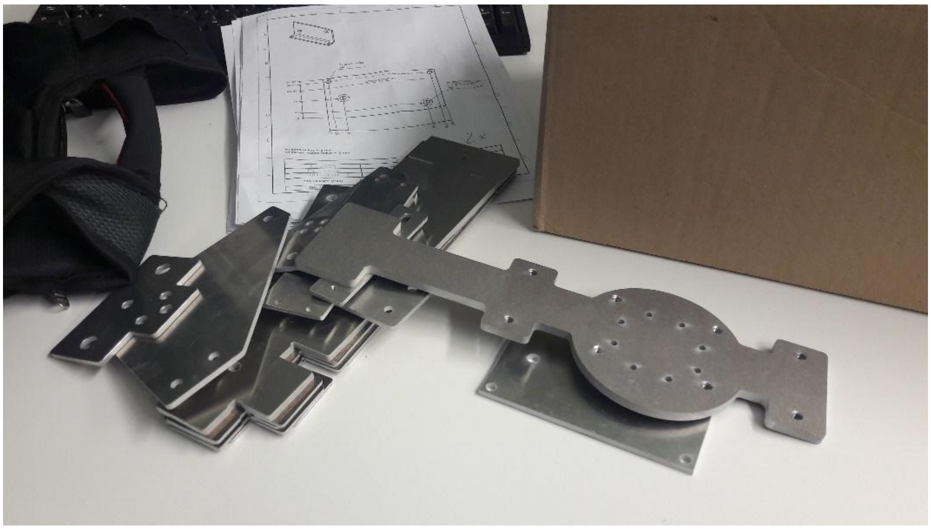

Figure 4.2. Aluminum flat patterns for building the slides.

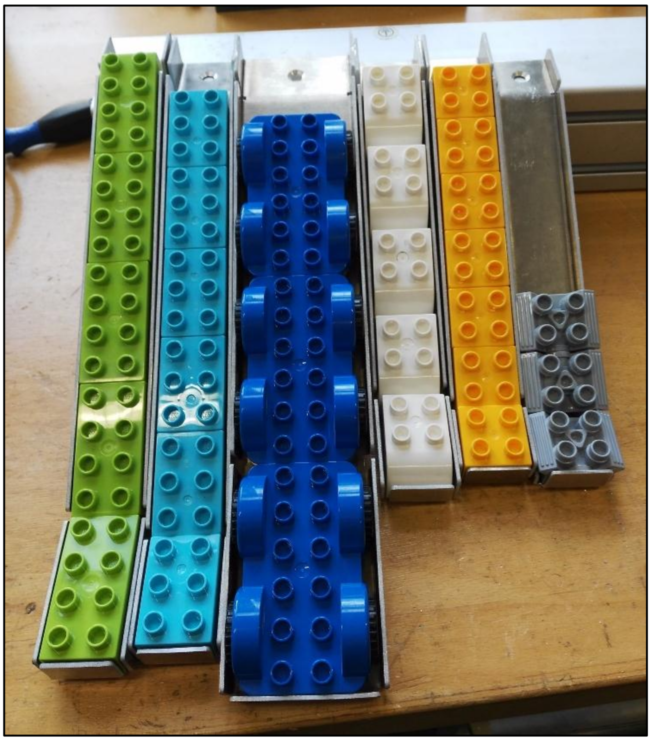

Figure 4.3. Built slides for regular and irregular LEGO® DUPLO® bricks.

The slides were manually tested and performed well for a stock on the slide of more than two LEGO® pieces. When there were less than two pieces, the remaining bricks could not always push the next brick in line for the picking position. Two actions are proposed to address this issue. The first one is to polish the surface of the slide to lower the friction coefficient between the brick and the slide. The second one is to add extra movements on the robot sequencing when the remaining bricks are three or less. These extra movements would push all the bricks remaining on the slide upwards with the use of the gripper, gaining more acceleration for the bricks when sliding back down. Testing manually these extra movements resulted positively, and the sequence is displayed on figure 4.4. In general, a positive behavior in the material flow was achieved with the aluminum slides.

The material handling system provides flexibility to the manufacturing process by offering a wide variety of bricks to be used in the assembly tasks, and it also helps in the reconfigurability of the system, since the slides are an economical solution and can be easily switched and modified.

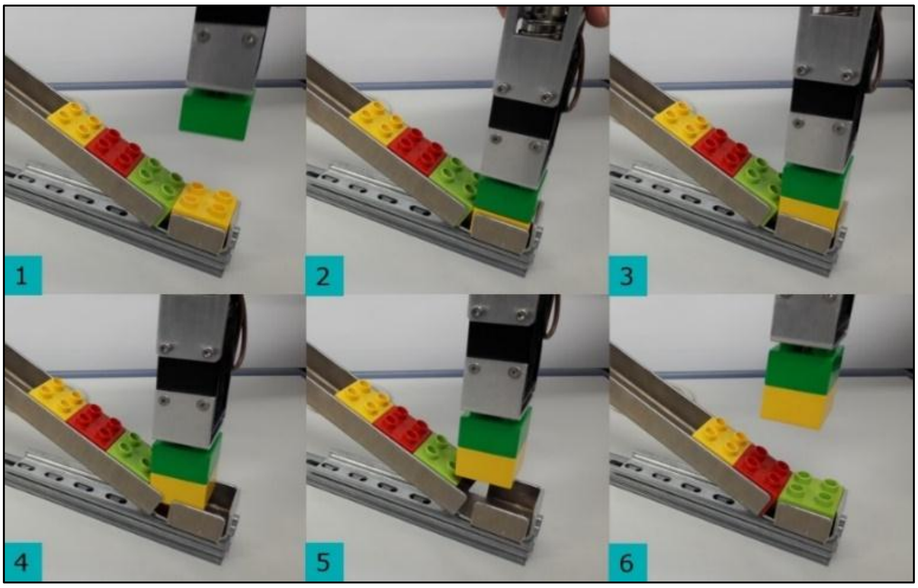

Figure 4.4. Picking sequence for correct material flow.

The complete aluminum frame structure has not been delivered by the manufacturer. From the stress analysis performed using inventor, no significant deformation is expected. The total volume of the machine will allow easy transportation through doors and elevators, as the measurements from the requirements were met by the final virtual assembly.

After the completion of the virtual assembly, the need for additional components emerged. For instance, to enable the exhibition capabilities of the system, a computer is planned to be added to the system in which a product order would be placed. This process could be done with the assistance of one of the two screens mounted on the machine and would require the addition of hardware into the cell. The space destined for this and any future addition to the system is located behind the metallic panels carrying the electrical components with a storage volume of approximately 150 liters.

Regarding the electrical components mount to the system, the two metallic panels were cut and drilled at the workshop of the FH Aachen. All the electronics were fixed to the plates with the use of DIN 35 rail sections and wired to make it possible to use it for development and testing. It is now working and ready to be mounted inside the electrical enclosure of the assembly cell. Wiring must be finished inside the machine frame.

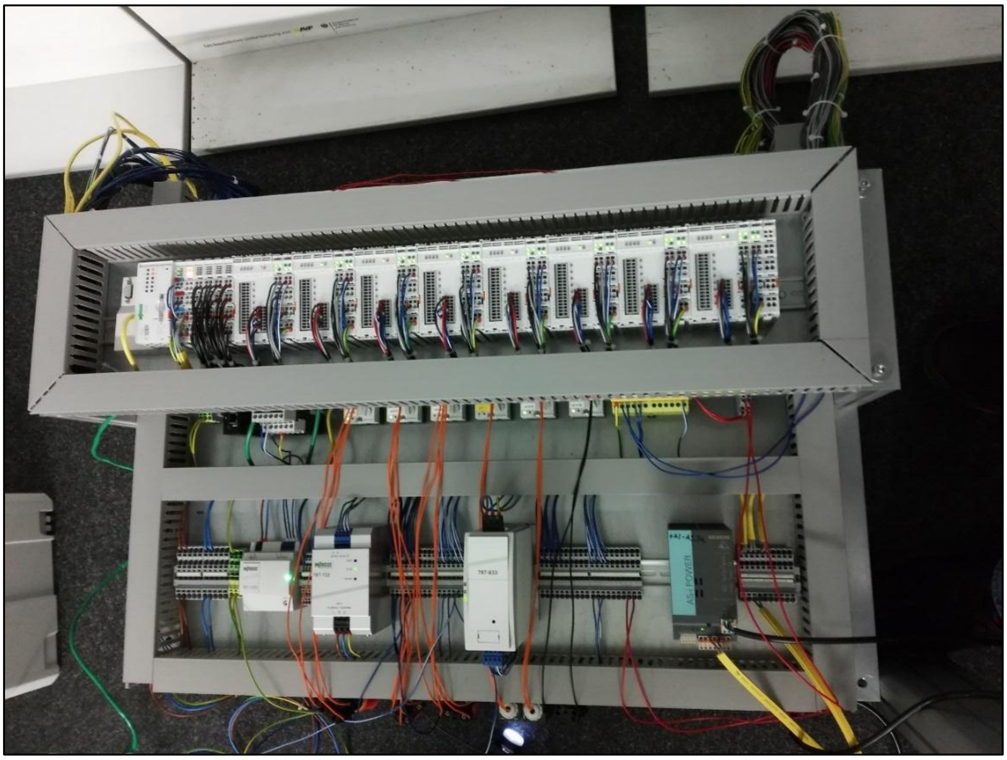

Figure 4.5. Electronic panels with emergency stop buttons and door locks for testing.

Even though the main structure is not there, the elements assembled showed a positive behavior in general, and there are sufficient results to assure that the goals of designing an assembly cell with high mobility, flexibility, and reconfigurability were accomplished. The work left in the set-up of the complete system is now only pending the delivery of the aluminum core structure by its manufacturer.

5. Recommendations and future work

The 3-DOF robot is already assembled but must be added to the central structure along with the electronics and the aluminum slides for feeding the system.

A 5-DOF robot configuration must be defined with the manufacturer and added to the system. The top frame of the structure has a couple of beams to help in this task. After adding the second robotic arm, the corresponding safety system must be designed since it will be most likely placed on top of the cell structure. The safety measures to be taken after the installation of the 5-DOF robot should still allow the mobility of the system.

Another thing to consider when adding the second robot to the system is the total height that would be reached. With the current design for the structure, it should be possible to mount and unmount the robot on the structure easily for mobility reasons. This should be considered in the future implementation of the second robot. Optionally, a resting position for the second robot could also be defined, in which the added height does not affect the transportation of the cell.

As future work, the addition of sensors to have more control over the material handling system is desired. Especially considering that the implementation of sensors is one of the tools that enable the Industry 4.0 concept. The development of a material management system is also one of the purposes of this project, hence its didactical nature.

The design of another gripper is also recommended. A new design that could handle more irregular bricks would enable more flexibility in the system. A gripper that could fit all the systems is also desirable. Additionally, a new design of material feeders would be necessary for the irregular bricks.

6. *Bibliography*

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7. Appendixes

Due to the nature of the documents described in this section, they are contained in a DVD-ROM attached to the back cover of this document. The files are ordered in folders as specified below.

Appendix A	Found in the folder “CAD”. CAD model of the complete assembly, all the subassemblies present in the system and all the individual custom-made parts forming them.
Appendix B	Found in the folder “Datasheets and manuals”. Documentation provided by the manufacturers for the parts contemplated in the construction.
Appendix C	Found in the folder “Technical drawings”. Technical drawings for all the files in the “CAD” folder.
Appendix D	Found in the folder “Electrical”. Contemplates the schematics for wiring the machine.
Appendix E	Found in the folder “Analysis”. Static analysis for parts of the robot and the structure.
Appendix F	Found in the folder “Thesis”. Digital versions of this document in *.docx* and *.pdf* extension files.