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FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

Automate Assembly Cell for LEGO Cars Using a Delta Robot: Mechanical Design and Smart End Effector

THESIS

TO OBTAIN THE ACADEMIC

DEGREE OF

MECHATRONICS

MASTER OF SCIENCE

BY:

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Declaration

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Queretaro, Mexico. February 2017.

Alfonso Castro Medina

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Abstract

The present work comprise the design, construction and implementation of an automated assembly cell with a delta robot as core element. The structure, assembly area, feeding mechanisms and the end effector are explained in detail starting with the conceptualization, design, implementation and tests.

The assembly cell is the second development of its kind on the FH Aachen and its intended for demonstrations on the field of industry 4.0, student practice and future developments.

Content

Chapter I: Introduction

1.1 Problem statement

Assembly operations with automated machinery are didactical and call the attention of the observers, this characteristic makes this applications suitable for trade fairs and other public demonstrations. Furthermore, the technical issues embedded with the process of assembling as, detection, firm grasp, and the correct assembly of the pieces, are particularly challenging and similar to industrial assembly lines, this helps to confront the students with actual industrial problems and obtain valuable experience without the need for robust parts.

For these purposes, the FH Aachen is developing an automated assembly cell using state-of-the-art high speed robotic picking technology and the concepts from Industry 4.0 to assemble parts with high flexibility and easy access to information about the process and machine components.

There are plenty of technical problems that need to be solved to produce an operational prototype, the purpose of this research is to find the proper solution to the problems concerning mechanical design. For instance; the design of a supporting structure, the continuous supply of parts and the assembly area, as well as the design of the end effector to guarantee the correct picking and assembly.

1.2 Justification

This project is intended to help with the necessity for new robotic equipment and will benefit the students providing specialized machinery for flexible manufacturing that is suitable for practice and future projects.

1.3 Aim and objectives

The aim of this project is to develop an automated assembly cell for LEGO cars using a delta robot ABB FlexPicker 340 that is not constrained to a single product model and can be integrated with future machine developments.

Regarding to mechanical design, the following steps are necessary to achieve this aim:

- Design and construction of a structure to support the FlexPicker 340, its controller and the other parts of the machine.
- Design and construction of a smart end effector for the picking and assembling of LEGO parts.
- Design and construction of a supply system for LEGO parts that can be integrated with a LEGO part sorting machine yet to be developed.
- Design and construction of the assembling area.
- Design and construction of safety guards for the safe operation of the machine.

1.4 Hypothesis

Using a Delta robot, the assembling of LEGO based cars can be made in a proper and automatic process.

1.5 Methodology

A traditional engineering design methodology will be followed during the design process [2] [3], essentially:

- Research: Locating information about the existing literature, best practices and available solutions.
- Design requirements: Establishment of the basic design characteristics like the functions, attributes, and specifications based on basic data and end user needs.
- Conceptualization: Generation of ideas and evaluation of the possible alternatives.
- Preliminary design: Further elaboration of the ideas developed during the conceptualization phase, CAD schematics and layouts for adequate evaluation.
- Detailed design: Specifications and construction drawings for the selected solutions.
- Implementation: Fabrication and testing.

Design Process

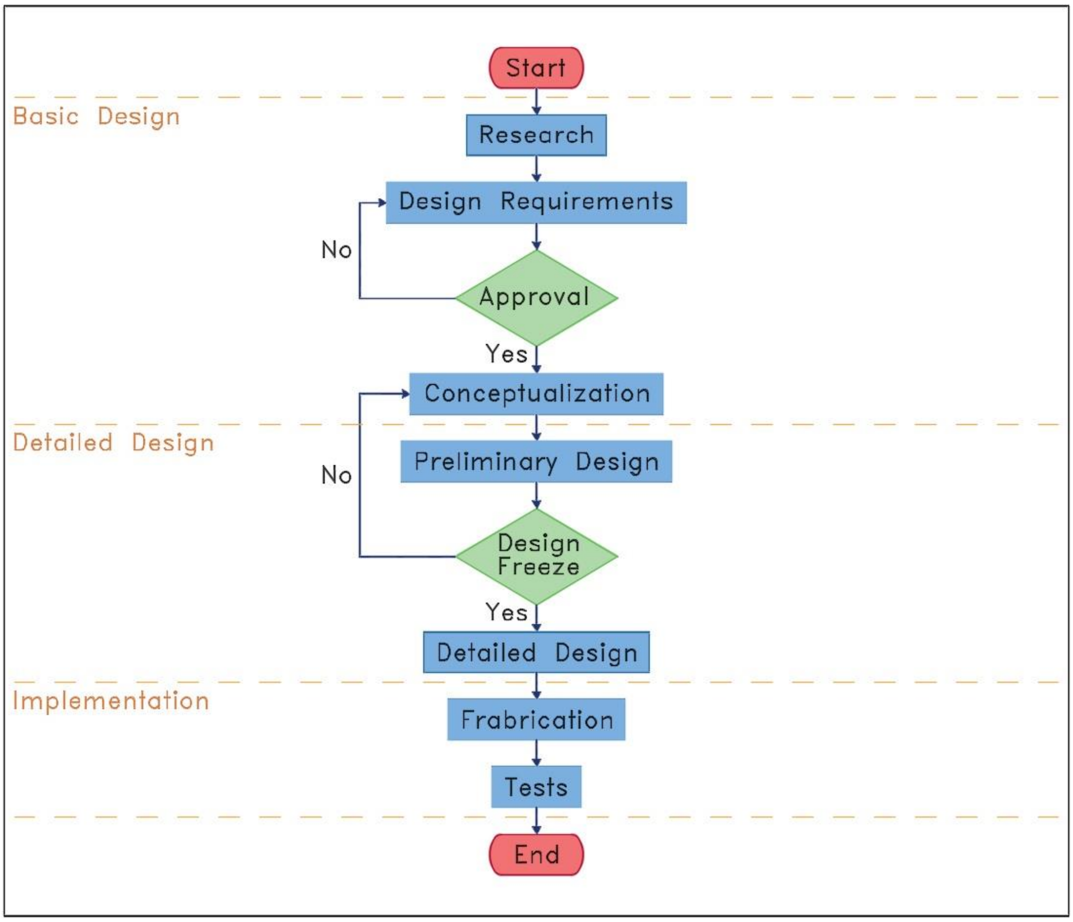

Fig. 1-1: Design Process Flowchart

1.6 Project Background

The idea of using LEGO parts to simulate industrial assembly lines has been growing for some time at the FH Aachen. Last year a fully functional machine was developed with success, this machine was presented with excellent results in national automation trade fairs [1].

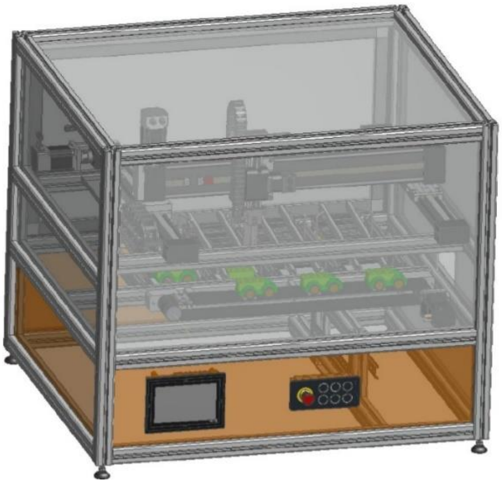

Fig. 1-2: Project cube, LEGO car assembly machine [1]

With this topic in mind the Mechanical and Mechatronics Engineering department acquired 4 ABB FlexPicker 340 intended for different applications with LEGO bricks. The first phase was to use one of the robots to assemble LEGO cars in a fast and flexible way, originating this work.

Fig. 1-3: ABB FlexPicker 340 property of the FH Aachen

Chapter II: Fundamentals

2.1 Automated assembly

The Assembly process is one of the most important for manufacturing. Many efforts are directed every day to improve assembly technology and systems, to make the processes more adaptable and cost effective keeping the pace of the changing markets. [4] Since the beginning of industrial robotics, robots are used in industrial assembly lines. In 1961, General Motors first applied an industrial robot in a manufacturing process. [5] Today, there are millions of robots in assembly operations in different branches of industry like automotive, electronics, aerospace, and others.

The precision and flexibility provided by robots makes them suitable for assembly. SCARA, six-axis and delta robots are preferred for this application. As the most important parameter for most assembly applications is speed, delta robots are increasable being used due to the high speeds this type of robots can achieve.

2.2 Delta robots

"A generalized parallel manipulator is a closed-loop kinematic chain mechanism whose end-effector is linked to the base by several independent kinematic chains" [6].

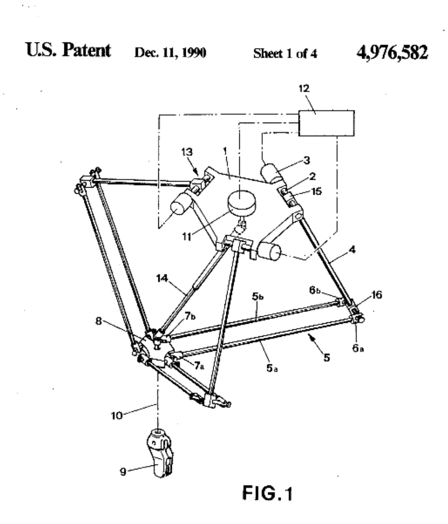

Fig. 2-1: Schematic of a delta robot [7]

Delta robots are mostly used for lightweight pick and place and assembly operations and can be found in different industries like food, pharmaceutical and electronics.

2.3 ABB FlexPicker IRB 340 System Overview

The IRB 340 FlexPicker is a 4-axes delta robot designed for pick and place operations and assembling, the standard version is extremely powerful with an acceleration of 10 G and handling capacity of up to 1 Kg [12].

Fig. 2-2: IRB 340 FlexPicker [13]

The robot is controlled by the IRC5 Robot controller and can be programed with the FlexPendant touch panel or the RobotStudio Software environment.

Fig. 2-3: IRC5 robot controller + FlexPendant [13]

2.3.1 Working range

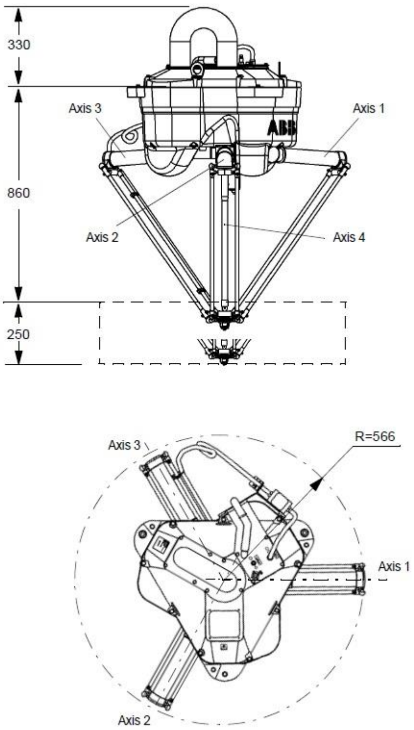

Fig. 2-4: IRB 340 standard version working range (dimensions in mm) [12]

2.4 End effectors

An end effector is the element at the end of a robotic kinematic chain, is the tool used to interact with the work environment. End effectors can be used to grasp objects, take measurements or realize a specialized operation as welding, screwing or sewing.

End effectors used to grasp objects or grippers can be divided on 4 categories [9].

- Impactive: Grasp by direct impact upon the object.
- Ingressive: Physically penetrate the surface of the object.
- Astrictive: Forces applied to the objects surface.
- Contigutive: Requiring direct contact for adhesion to take place.

Fig. 2-5: Example of grippers [14]

2.5 Gripper sensor technology

The current efforts in gripper development go towards the use of multi-sensory systems to improve the capabilities and help the manipulators to achieve the specified tasks. Sensors are used to several applications like, measure position, inclination, piece detection, proximity, applied force-torque, distance, and collision detection [8] [9] [10] [11].

Chapter III: FlexPicker Frame

The first objective to complete was the design of the supporting structure. For this, the engineering team defined the requirements and the IRB 340 product specification was taken as a reference.

3.1 Mounting the Manipulator

The IRB 340 product specification states the following requirements to take into consideration for the design of the robot frame:

- Maximum force in each fixing point is 500 N referring to the z-direction in the base coordinate system.
- Required stiffness of frame: Lowest natural frequency of frame with robot > 17 Hz.

3.2 Frame Requirements

The following requirements were defined with the team during the project meetings.

Structure Frame:

- Maximum deformation of the frame: 0.5 mm.
- Lowest natural frequency of frame with robot > 17 Hz.
- The design must ponder the ABB FlexPicker 340 working area.
- Consider space for IRC5 controller (970 x 725 x 710 mm, 150 Kg).
- Consider mounting for operation panels.
- Standard metallic profiles are preferred.
- Possibility to dismantle.
- Clear visibility to the assembling area from the outside of the machine.
- It must not be possible to introduce extremities while the robot operates.
- Easy to relocate.

3.3 Material Selection

According with the requirement that states the possibility to dismantle the robot frame it was decided to use aluminum profiles from the item MB Building Kit for Mechanical Engineering.

Fig. 3-1: item MB Building Kit for Mechanical Engineering [15]

3.4 Concept

The concept presented in Fig. 3-2 consists of a frame that circumscribes the robot´s working area, a LEGO feeding system based on a conveyor positioned on a certain way that allows a sorting machine to place the bricks on one side and the IRB 340 to pick the pieces form the opposite one, a central assembly area for cars and a slide-tray system for finished product transport and storage. The IRC5 robot controller is positioned on the floor inside the frame area.

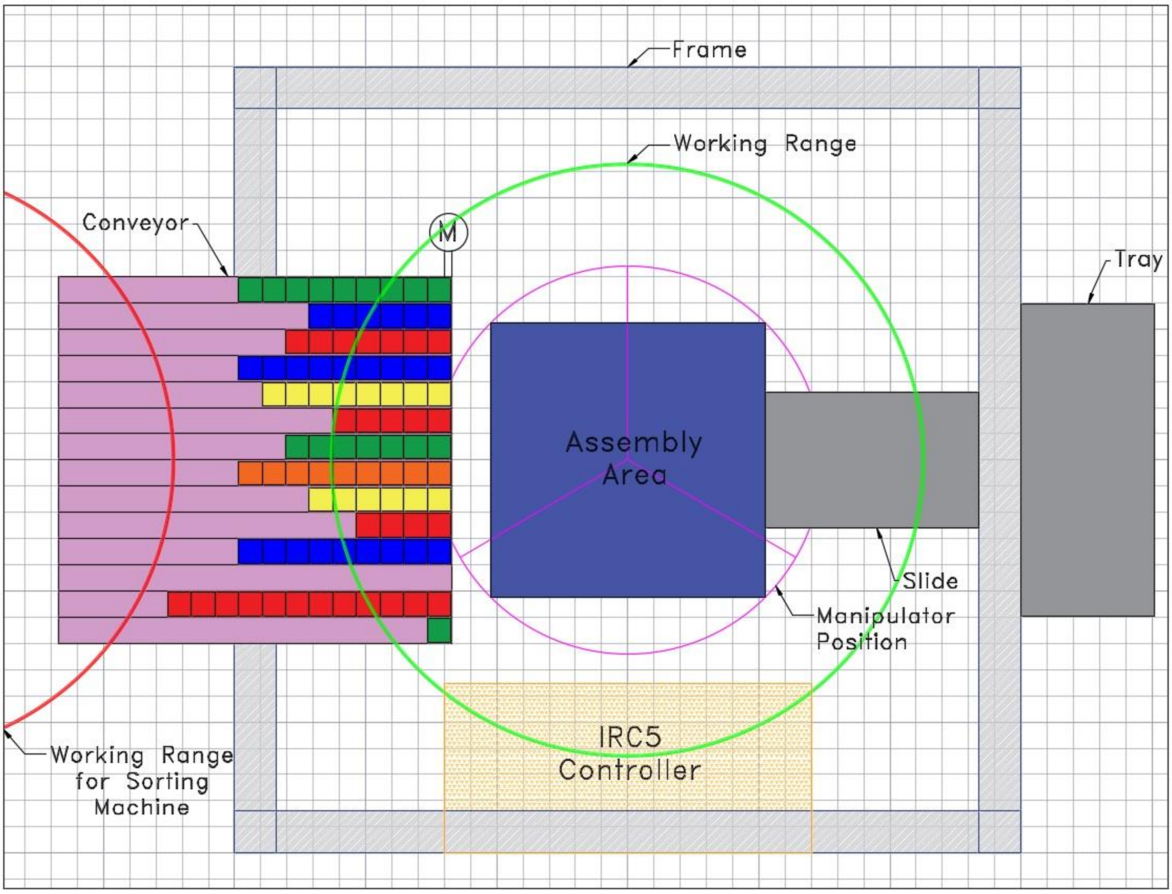

Fig. 3-2: Concept layout for the machine

3.5 Design

After several revisions and the technical support from item's engineers some changes were made to overall design of the frame was approved, the basic characteristics are showed on Fig. 3-3.

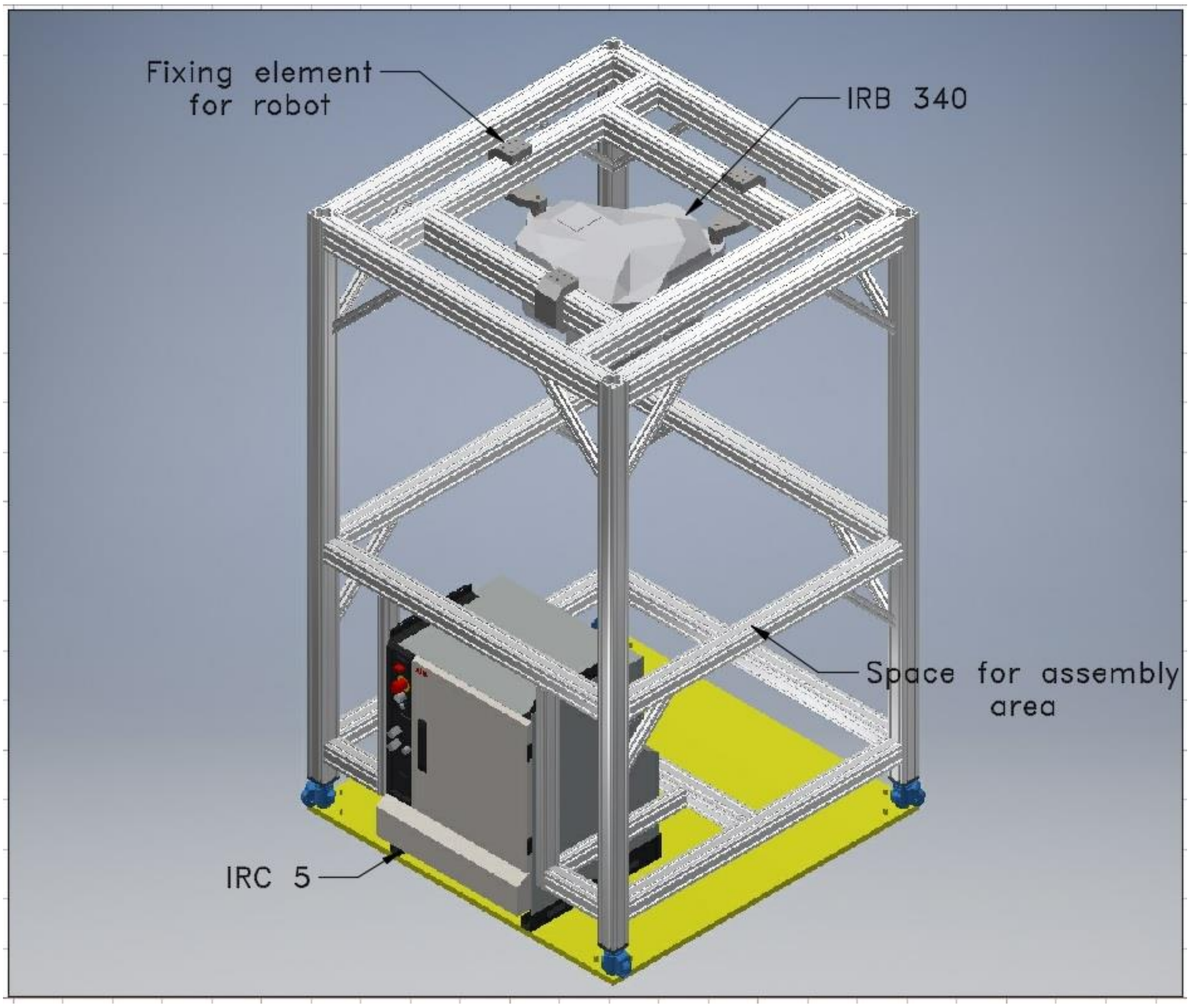

Fig. 3-3: FlexPicker frame version 8

3.5.1 Static Analysis

To determine the principal characteristics of the model such as deformation, stress, etc. a static simulation was performed inside Autodesk Inventor environment.

Considering:

- Material: aluminum 6061.
- Maximum force in each fixing point is 500 N referring to the z-direction in the base coordinate system.
- The robot is supported directly in the middle of the main beams.

Name		Minimum	Maximum
Displacement		0.000 mm	0.116 mm
Forces	Fx	-515.066 N	515.360 N
	Fy	-92.238 N	98.873 N
	Fz	-116.305 N	1122.120 N
Moments	Mx	-42572.639 N mm	42081.409 N mm
	My	-29783.234 N mm	203041.681 N mm
	Mz	-39933.866 N mm	40031.437 N mm
Normal Stresses	Smax	-0.389 MPa	2.156 MPa
	Smin	-2.043 MPa	0.017 MPa
	Smax(Mx)	0.000 MPa	0.896 MPa
	Smin(Mx)	-0.896 MPa	-0.000 MPa
	Smax(My)	0.000 MPa	2.158 MPa
	Smin(My)	-2.038 MPa	-0.000 MPa
	Saxial	-0.418 MPa	0.043 MPa
Shear Stresses	Tx	-0.372 MPa	0.372 MPa
	Ty	-0.117 MPa	0.109 MPa
Torsional Stresses	T	0.000 MPa	0.000 MPa

Table 3-1: Static Result Summary

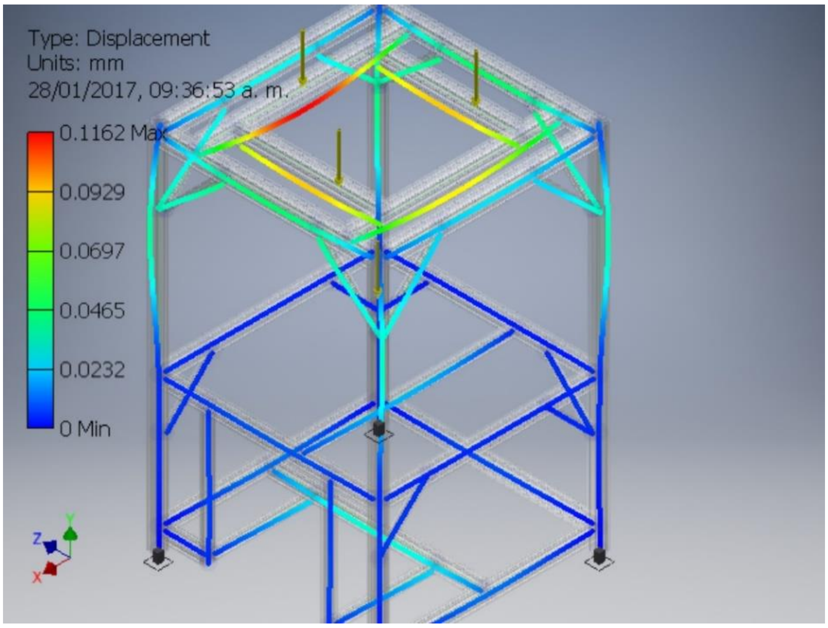

Fig. 3-4: Frame displacement after loading

A maximum displacement of 0.1160 mm is considered acceptable. The displacement is considered so small it will not affect the accuracy of the robot during the assembly process. The frame is strong enough to support the IRB 340 in static conditions.

3.5.2 Modal Analysis

The purpose of this analysis was to determine the natural frequency of the frame to comply with the required frame stiffness that states that the lowest natural frequency of the frame with robot must be > 17 Hz.

Mode	Value
F1	18.31 Hz
F2	20.21 Hz
F3	24.66 Hz
F4	74.18 Hz
F5	77.13 Hz
F6	84.68 Hz
F7	92.12 Hz
F8	104.92 Hz

Table 3-2: Frequency Values

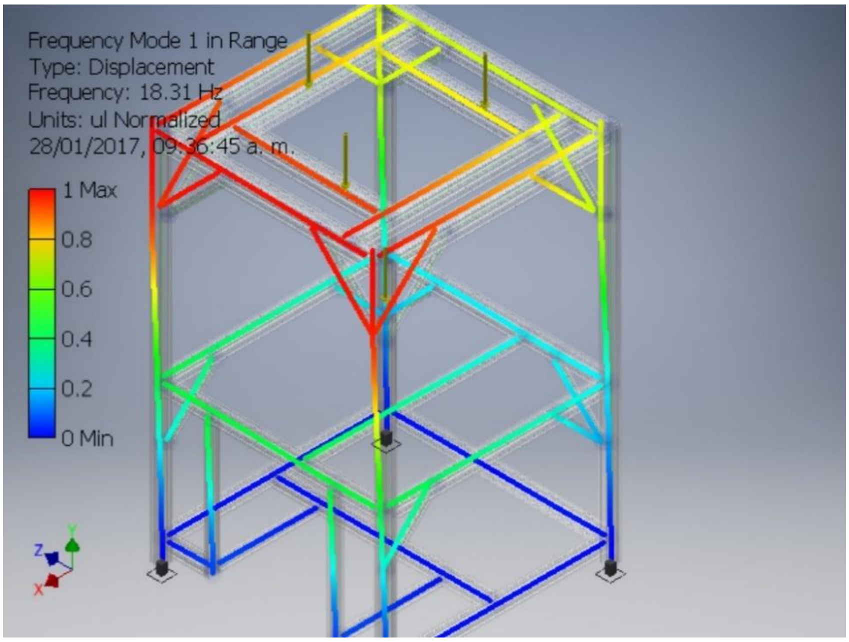

Fig. 3-5: F1 18.31 Hz

As the outputs from the modal analysis are into the desired results, this is necessary to avoid the phenomenon of resonance during normal operation.

3.6 Mounting Brackets

An important task for mounting the manipulator was the design of the principal supports. The FlexPicker IRB 340 has three holes designated for its fastening to a main structure (Fig. 3-6). The area for calibration tool must be considered.

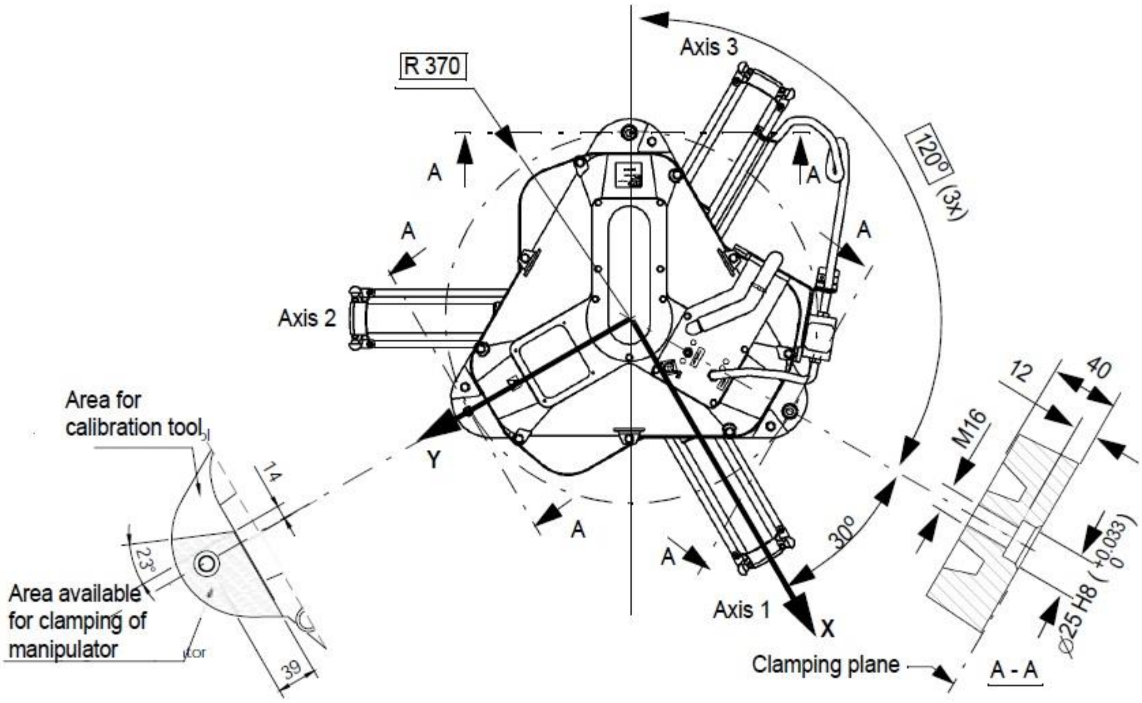

Fig. 3-6: Hole configuration

3.7 Concept

The team was inclined for an intrinsically safe and easy to adjust design. The parts should be C shaped to avoid risk from the robot to fall and to allow sliding along the aluminum profiles to adjust the position, they are screwed to the profiles from the top and bottom and are made of mild steel.

3.8 Design

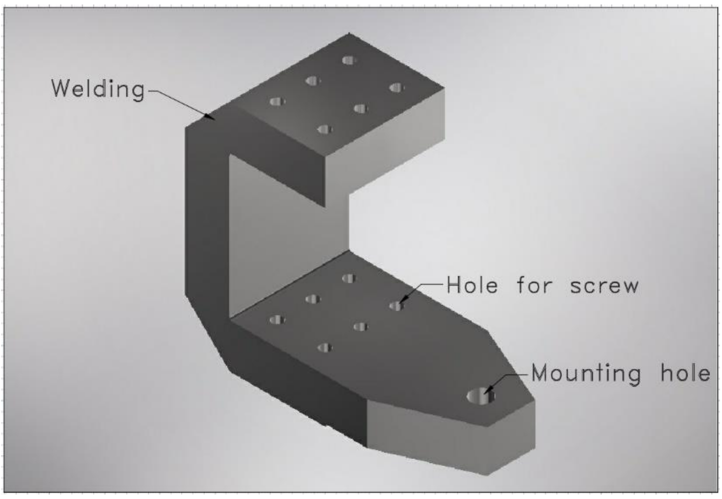

Fig. 3-7: Mounting bracket preliminary design

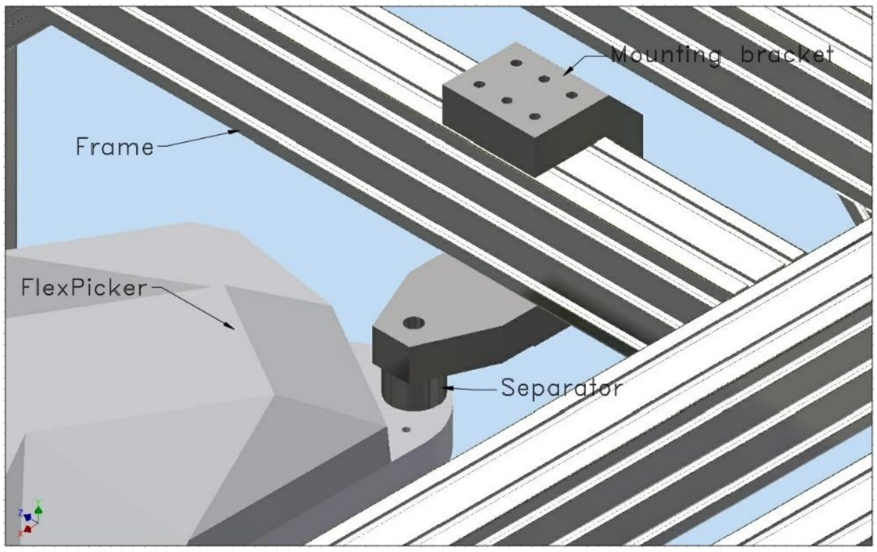

Fig. 3-8: Mounting the FlexPicker to the Frame

3.8.1 Static Analysis

The mounting brackets are one of the most critical parts for the safety of the whole design as they directly support the robot to the aluminum structure. To ensure the good performance of the design a static simulation was performed inside Autodesk Inventor environment.

Considering:

- Material: steel mild.
- Maximum force in each fixing point is 500 N referring to the z-direction in the base coordinate system.

Name	Minimum	Maximum
Volume	1432850 mm^3	
Mass	11.2479 kg	
Von Mises Stress	0.000560802 MPa	18.5374 MPa
1st Principal Stress	-2.19419 MPa	24.6793 MPa
3rd Principal Stress	-9.88735 MPa	5.62808 MPa
Displacement	0 mm	0.00534619 mm
Safety Factor	11.1666 ul	15 ul
Stress XX	-3.91832 MPa	8.87467 MPa
Stress XY	-4.79675 MPa	5.90424 MPa
Stress XZ	-1.99231 MPa	2.44669 MPa
Stress YY	-6.29879 MPa	16.3994 MPa
Stress YZ	-3.75553 MPa	9.31736 MPa
Stress ZZ	-5.70943 MPa	13.6184 MPa
X Displacement	-0.0000941823 mm	0.0000903197 mm
Y Displacement	-0.000255982 mm	0.00524016 mm
Z Displacement	-0.00107948 mm	0.000633598 mm
Equivalent Strain	0.00000000260714 ul	0.000080193 ul
1st Principal Strain	0.000000000576836 ul	0.0000962643 ul
3rd Principal Strain	-0.0000385773 ul	0.0000000333663 ul
Strain XX	-0.00000986473 ul	0.00000939993 ul
Strain XY	-0.0000277994 ul	0.0000342178 ul
Strain XZ	-0.0000115463 ul	0.0000141797 ul
Strain YY	-0.0000276235 ul	0.000049119 ul
Strain YZ	-0.000021765 ul	0.0000539983 ul
Strain ZZ	-0.0000157236 ul	0.0000349083 ul
Contact Pressure	0 MPa	1.5028 MPa
Contact Pressure X	-0.269418 MPa	0.285812 MPa
Contact Pressure Y	-0.838678 MPa	0.96041 MPa
Contact Pressure Z	-1.01969 MPa	1.16154 MPa

Table 3-3: Static Result Summary

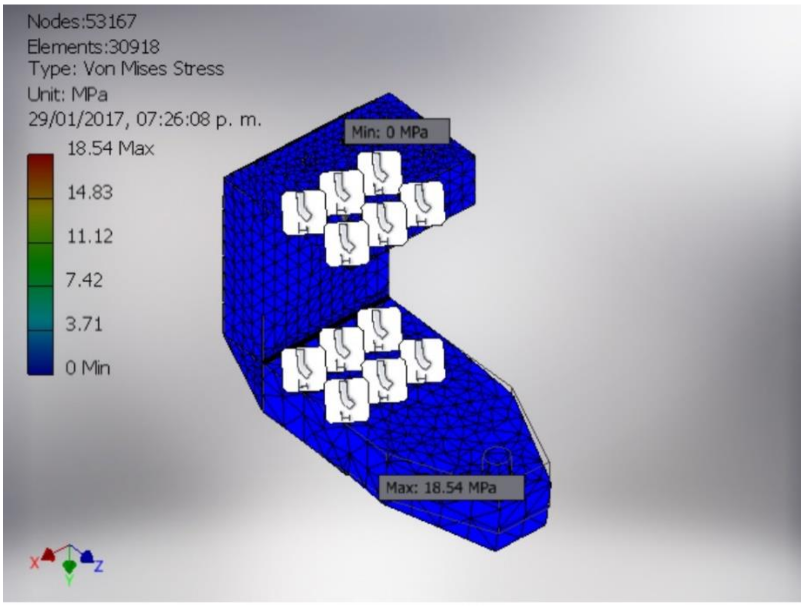

Fig. 3-9: Von Mises stress

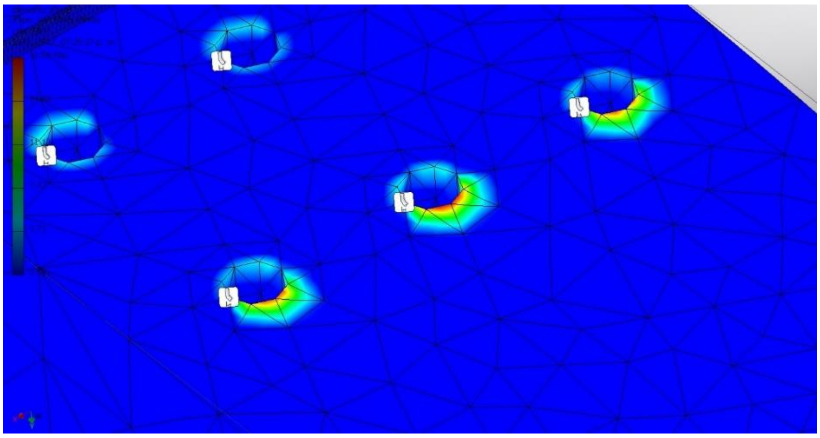

Fig. 3-10: Detailed view for maximum stress

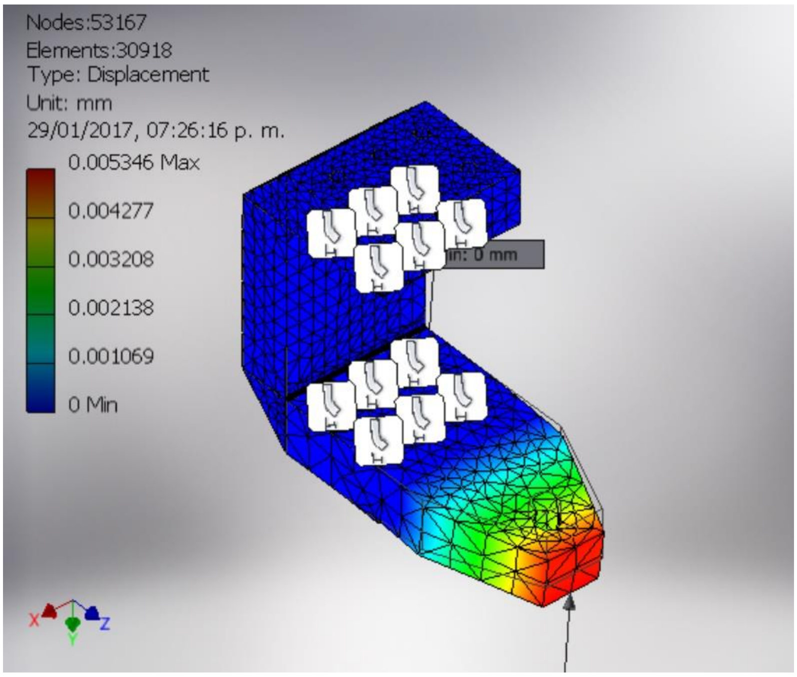

Fig. 3-11: Displacement after load

The static analysis showed that the piece is not compromised by the load having a safety factor around 11 and a depreciable displacement after load.

3.9 Implementation

To build the prototype, aluminum profiles from the company item were selected, Fig. 3-12 shows an early stage of the frame without the Flexpicker.

Fig. 3-12: First works on the frame

Following this it was necessary to mount the IRB 340 FlexPicker on the top part of the frame and place the controller on its position.

Fig. 3-13: IRB 340 FlexPicker mounted on Structure

3.10 Conclusions

The aluminum profiles provided a steady structure with high flexibility for future works and modifications.

Chapter IV: LEGO Feeding

The second principal objective is the design of the feeding system, this system should allow the user, on a first stage, to feed the LEGO bricks without entering the Flexpicker's operation range and, on a future stage of the project, allow a second FlexPicker to feed the LEGO bricks.

4.1 LEGO Feeding Requirements

The following requirements were defined with the team during the project meetings.

LEGO feeding:

- Automatic LEGO feeding.
- Specific place for every type of LEGO part.
- Possibility to join the feeding mechanism with a Lego sorting machine yet to be developed.
- 5 different parts as minimum.

4.2 Concept

The mechanism consists on several bands with a smooth surface, every band is contained between two separator rails to keep the LEGO parts straight during transport. There is a buffer stop at the end side of the band to stop the LEGO parts and form a row with them.

The LEGO parts are first placed on one side of the conveyor and transported by the belts to the other side, eventually, the bricks will reach the buffer stop so they cannot continue moving forward, as the belts will continue moving, there will be a sliding between the bricks and the belt allowing the bricks to start forming a row and stay still at the same time.

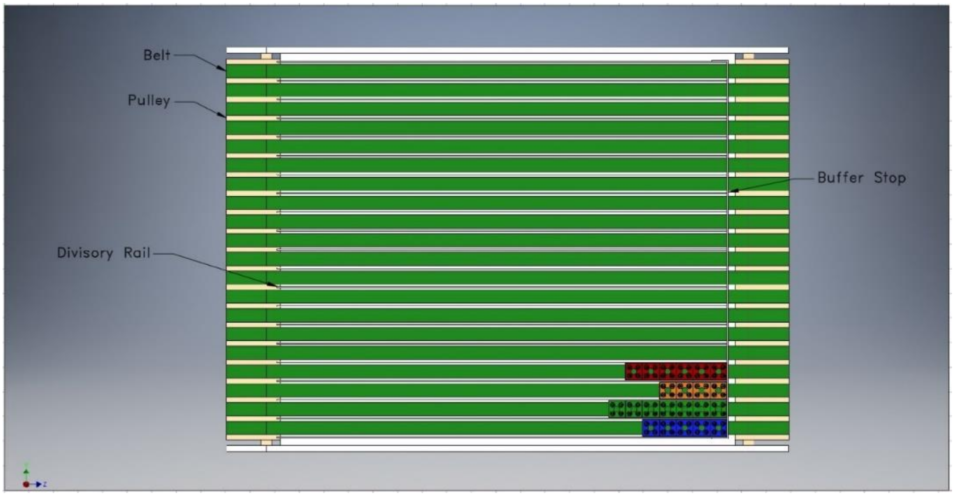

Fig. 4-1: Conveyor belt preliminary design

4.3 Design

Using a set of conveyors available on the laboratory the conceptual idea was taken to propose a design that could take advantage from the existing materials. Some modification was required to use the existing conveyor. The height needed to be modified to give more space to the FlexPicker to move, the top part requires a continuous surface and separation rails are needed between each line of pieces. The conveying belts and mechanism are not modified.

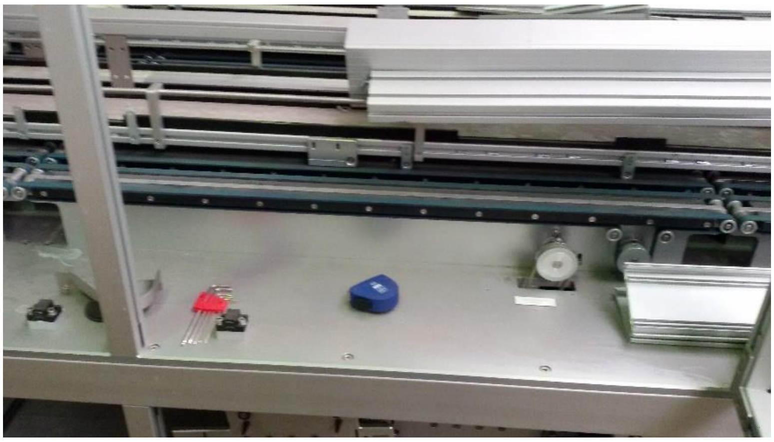

Fig. 4-2: Available conveyors for modification

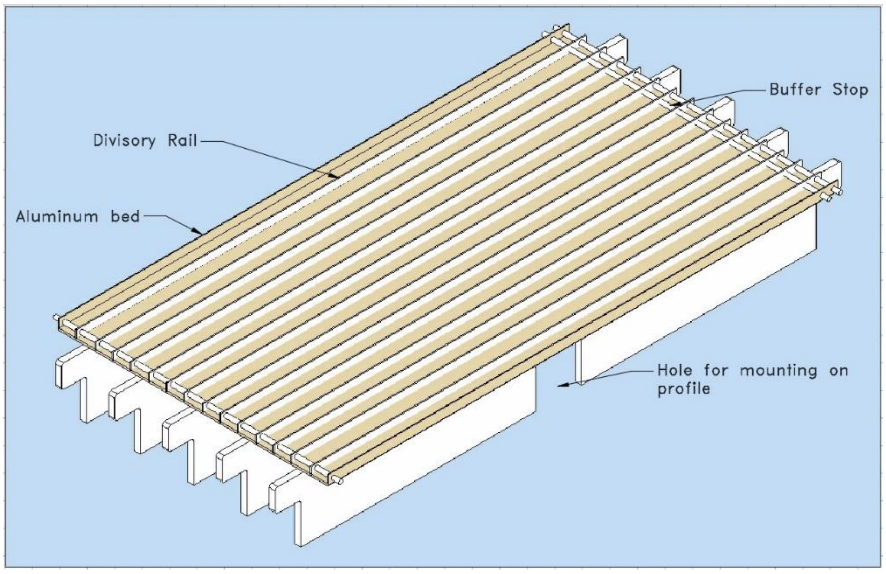

Fig. 4-3: Conveyor for LEGO bricks

4.4 Implementation

After modifying the existing conveyor, the top part and the separation rails were added and adjusted with the help of LEGO pieces.

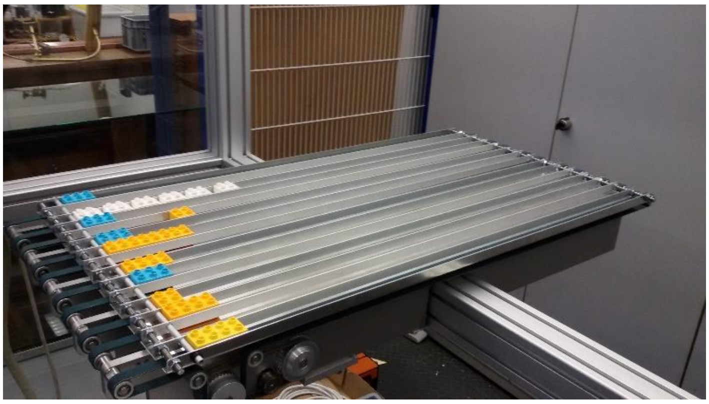

Fig. 4-4: Adjustment of the separation rails

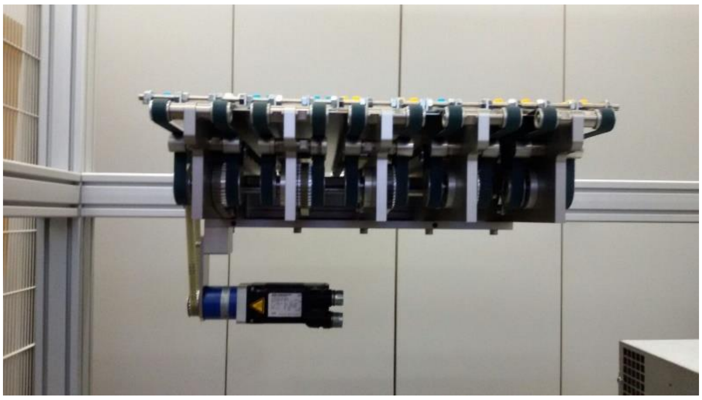

Fig. 4-5: Frontal view of the conveyor

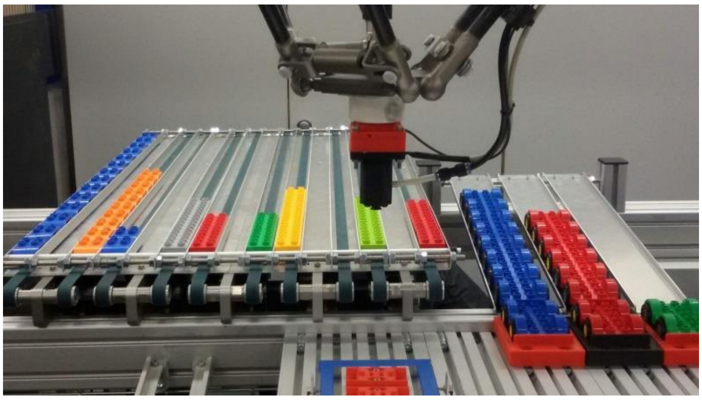

Fig. 4-6: Conveyor with 10 lines of different pieces

4.5 Test

The following tests were performed with the conveyor: Test 1, conveying of a single piece on existing conveyor; Test2, Conveying of pieces with finished conveyor.

Test 1, conveying of a single piece on existing conveyor

This test was performed to validate the capability of the available conveyors to convey the LEGO Duplo pieces and the sliding when reaching the stop buffer. For this, a LEGO piece was placed on the conveying belt and the conveyor was moved manually at different speeds, then a buffer stop was placed to determine the viability of a buffer stop.

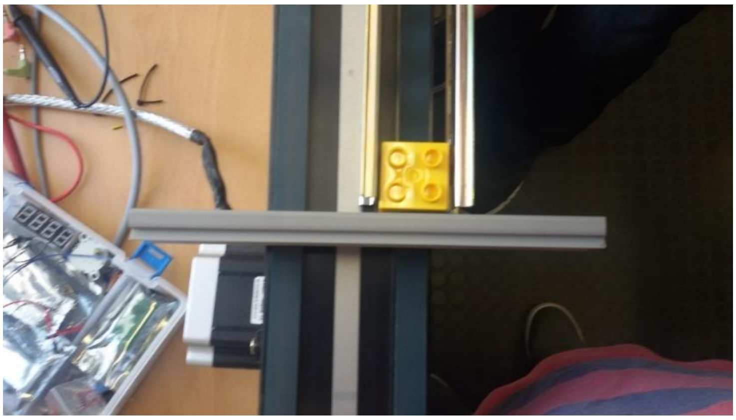

Fig. 4-7: First test for LEGO conveying

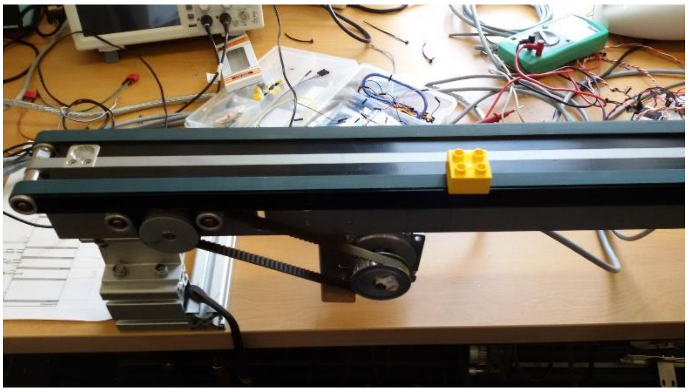

Fig. 4-8: LEGO piece on existing conveyor

Test2, Conveying of pieces with finished conveyor

After the conveyor was finished and the separation rails adjusted, the final test consisted in feeding pieces to the conveyor in all the channels with a continuous movement to validate the correct operation under real conditions, the pieces were retired manually from the stop buffer and fed again to the conveyor to simulate normal operation.

4.6 Conclusions

Using the conveyor during the tests delivered acceptable results, with the proper adjustment of the separation rails the pieces are transported as expected.

Chapter V: Chassis feeder

5.1 Concept

As the conveyor is only used to feed the LEGO bricks, a way to feed the chassis parts was needed. For this, we conceptualized a slide with a counter mold from the chassis at the end, so the chassis could slide easily and when it reaches the end it could have a fixed position to avoid picking problems.

5.2 Design

Using a mold with the form of the inferior part of the chassis, several tests were performed with a rapid prototype to determine the right inclination and a practical design for the mold. In the picture, the final design for the chassis feeder with the possibility for up to tree chassis models is shown in the picture.

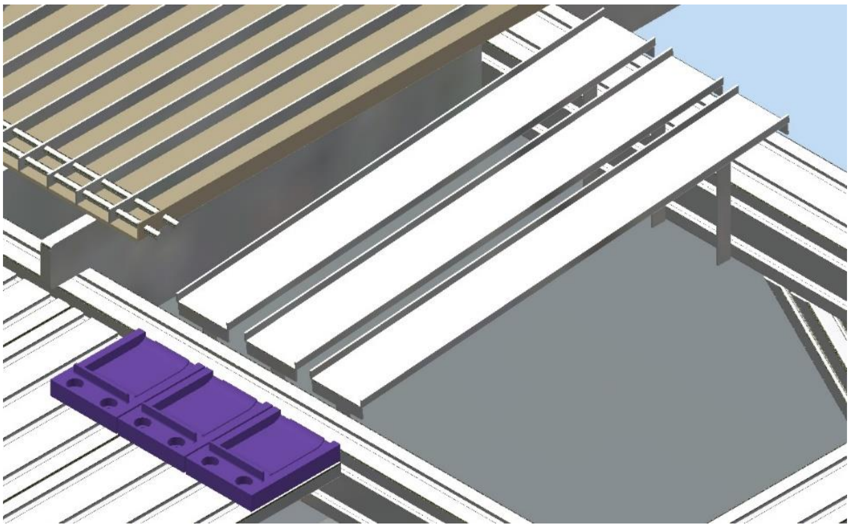

Fig. 5-1: Chassis slide and picking base, final design

5.3 Implementation

The slides were manufactured using 2mm aluminum sheet and the picking bases were 3D printed using PBT plastic.

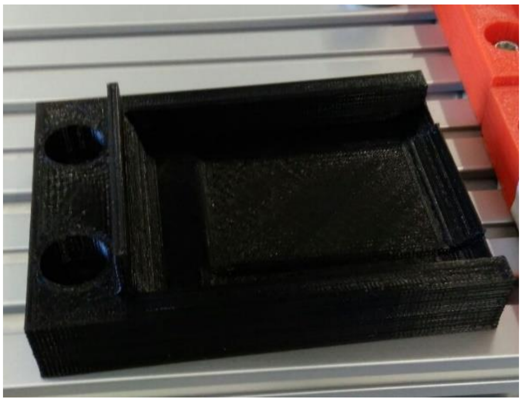

Fig. 5-2: Chassis picking base

Fig. 5-3: Complete chassis feeding system

5.4 Test

For testing, a routine was programed were the chassis is taken from the picking base and moved away to the assembly area and run in a loop. Fig. 5-4 shows the process of picking a chassis from the chassis feeder, first the end effector approaches the chassis, and the end effector takes the chassis and start to lift it, lastly when the end effector lifts the chassis out of the chassis feeder the following chassis is placed on the picking base by gravity.

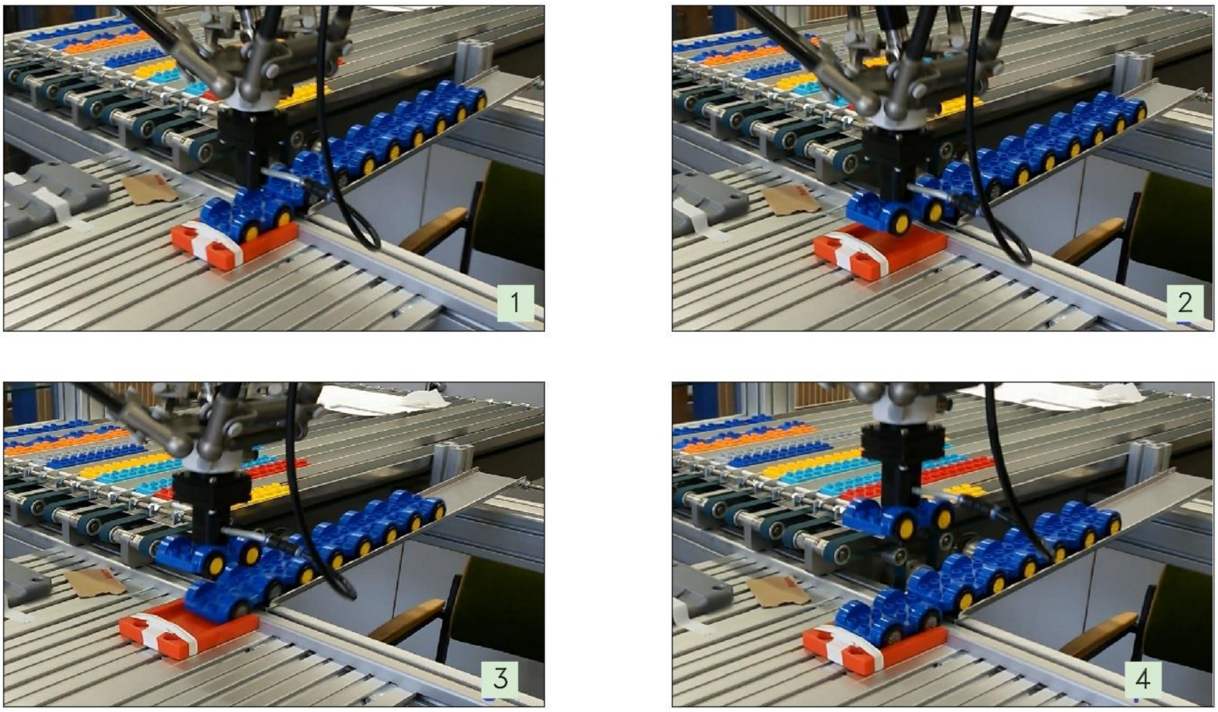

Fig. 5-4: Chassis feeder and picking test

5.5 Conclusions

Although the concept was simple, the chassis system presented several complications and redesign of the picking base, once a functional design was reached the operation became acceptable.

Chapter VI: Assembly area

For the assembly area, we defined the following requirements:

- Firm hold for chassis.
- Fast changing between finished car and new chassis.

6.1 Concept

The assembly area consists on a mold with a counter shape of the chassis that constrains the movement on the XY plane and allows it on Z direction. The design should allow the FlexPicker to place the chassis from above and provide a steady base for the assembly process. When a car is finished the FlexPicker takes the car and moves it to the finished product area.

6.2 Design

The pieces showed in Fig. 6-1 proved a good performance to provide a steady base during the assembly process, the design was taken from the previous works with LEGO during the project cube [1].

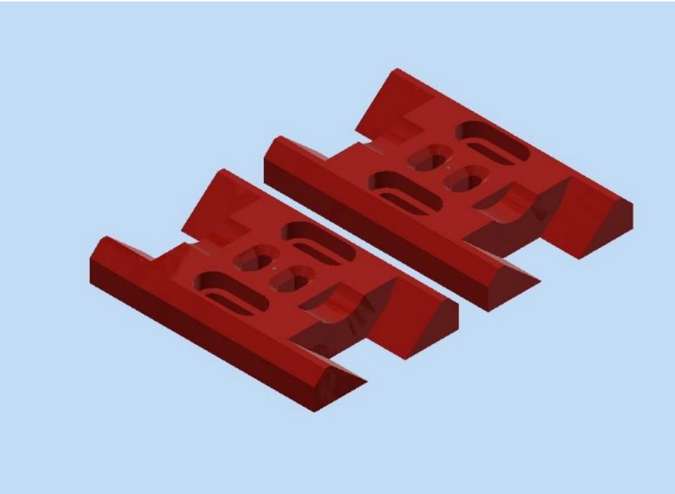

Fig. 6-1: Assembly area, final design

6.3 Implementation

The parts were 3D printed using PBT plastic see Fig. 7-2.

6.4 Test

The parts were tested along with the end effector presenting no inconveniences for the assembly process, see section 8.4.

6.5 Conclusions

This part was already tested on the previous works with car assembly and performed well on the application.

Chapter VII: Finished Product area

7.1 Concept

For the finished product area, it was planned a simplified design consisting on a slide that can take advantage from the rolling of the cars and a tray to store the finished cars.

7.2 Design

Due to manufacturing convenience, the finished product area is simplified to a single slide with a stop where the finished cars are placed and stored in the slide forming a line. The cars can be taken from the stop part as needed.

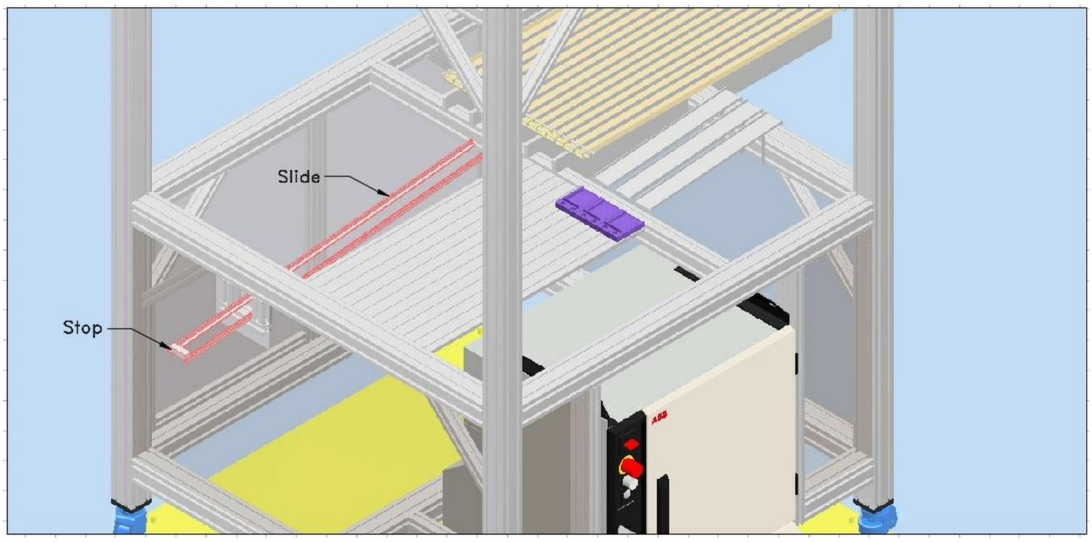

Fig. 7-1: Finished product area, first design

7.3 Implementation

The construction of the storage slide was made with 15 mm aluminum L profiles and a squared aluminum profile as stop, the placement can be observed in Fig. 7-2.

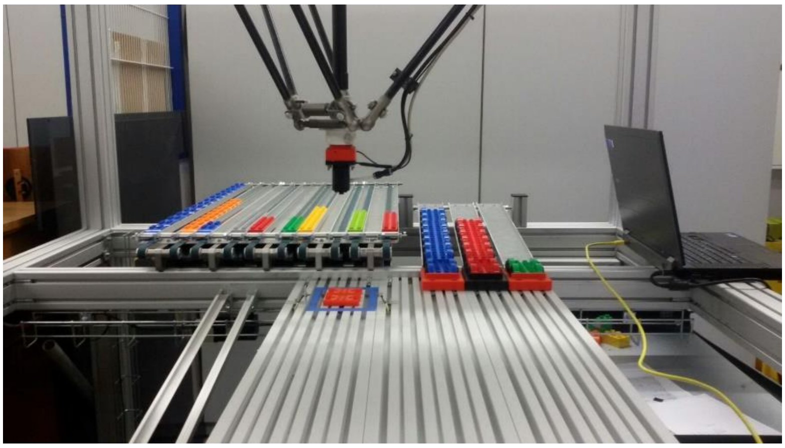

Fig. 7-2: Complete assembly area

7.4 Test

The inclination of the slide was adjusted during the installation to allow a smooth sliding for the finished cars and avoid damage or disassembly of parts.

7.5 Conclusions

The simplicity of the part exceeded the initial expectative on functionality and was approved.

Chapter VIII: End effector

A critical objective for this work is the design of the end effector, a way to grab LEGO bricks from different size and weight including the chassis, see Fig, 8-1.

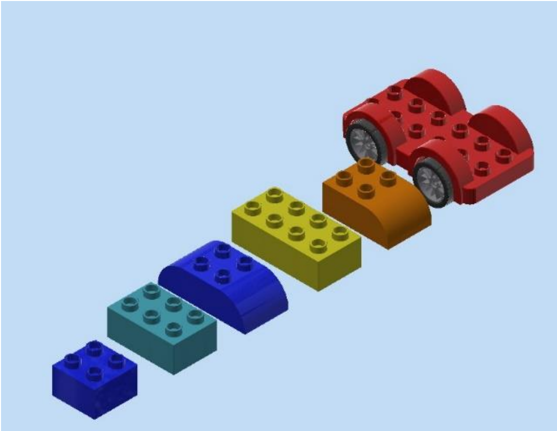

Fig. 8-1: Different types of LEGO Duplo

The following requirements where defined for the end effector:

- For using with different LEGO Duplo blocks.
- Must be capable to lift a complete assembled car.
- Pressure sensor to avoid LEGO crushing.
- Presence sensor to detect tool.
- Steady LEGO picking and assembly.

8.1 Concept

The decided idea to follow is using the existing vacuum system from the IRB 340 to pick the bricks. The design should include a suction cup and a mechanism to force the right orientation of the pieces avoiding its rotation during de picking.

Fig. 8-2: Suction cup used for LEGO picking

8.2 Design

For testing purposes, a prototype was built using rapid prototyping. The End effector consists of a suction cup covered by a rigid body with 4 alignment inserts at the end that get inserted in the holes situated on the top part of the LEGO (Fig. 8-3).

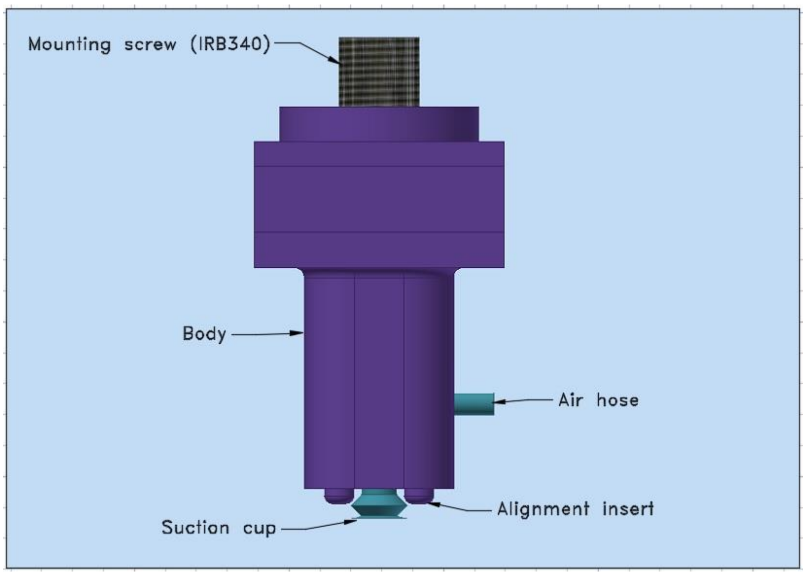

Fig. 8-3: End effector, first design

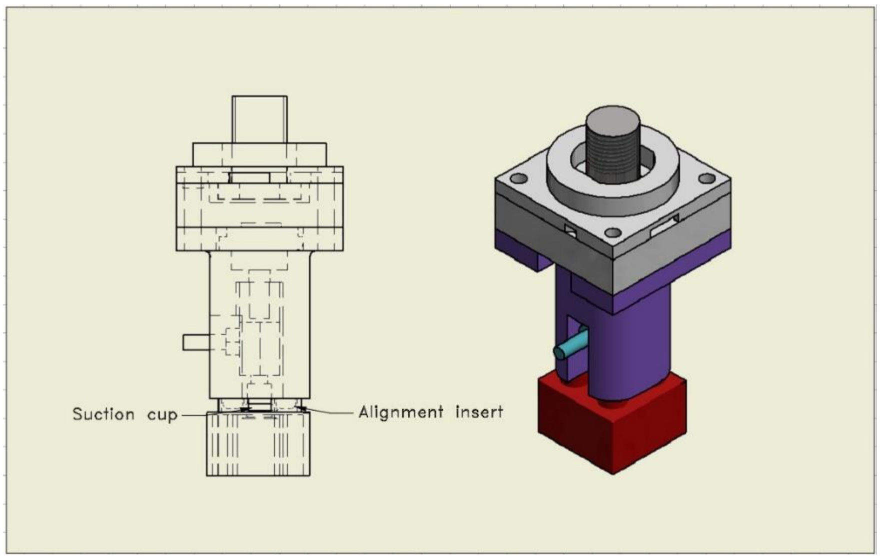

Fig. 8-4: Detail, end effector picking a LEGO

The tandem configuration allows the fixed installation of the base to the robot allowing to remove or install the body in case of maintenance or modifications.

For the final design, it was added space for a pressure sensor FS20 from TE Connectivity and a magnetic field sensor from Balluff. The pressure sensor gives feedback about the applied force so the assembly process could be performed without damaging the robot end effector or the LEGO pieces. The magnetic field sensor is used to detect if the end effector is attached to the robot so no operation can occur without the tool.

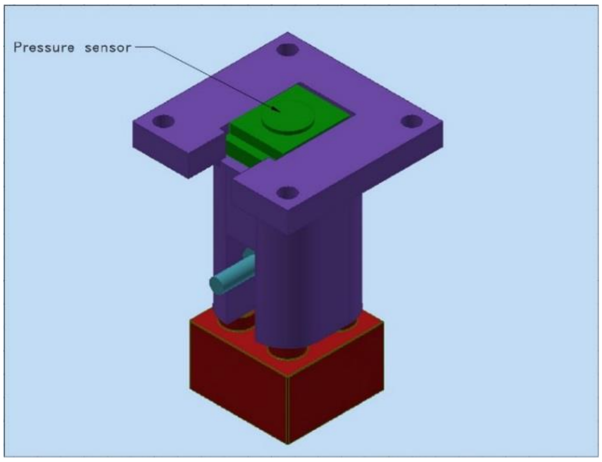

Fig. 8-5: Pressure sensor for end effector

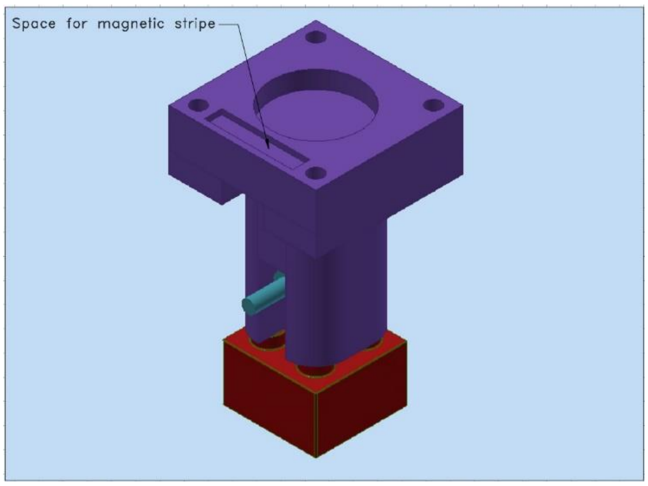

Fig. 8-6: Magnetic stripe for end effector

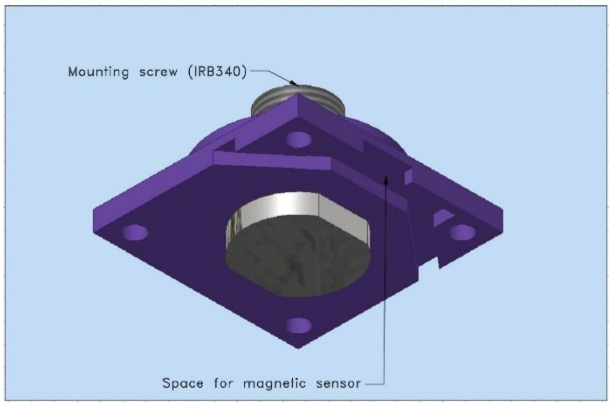

Fig. 8-7: Magnetic field sensor for end effector

8.3 Implementation

For validation purposes a prototype was made using 3D printing technology with PBT plastic as material.

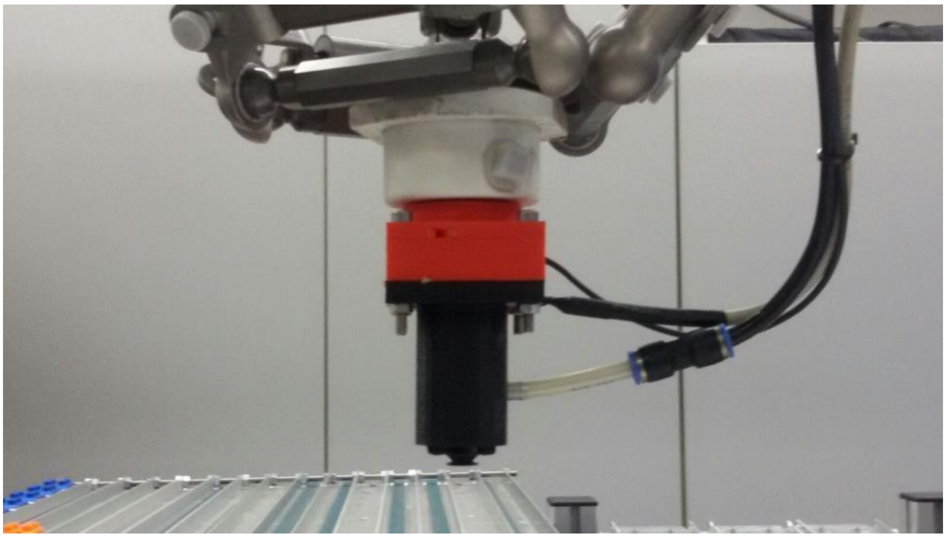

Fig. 8-8: End effector prototype

8.4 Test

The following tests where designed to validate the operation: Test 1, Picking of a 2x2 LEGO part and assembly on a fixed chassis; Test2, Picking of a chassis from the chassis feeder; Test 3, Assembly of cars in serial production.

The purpose of the tests is to evaluate the performance of the end effector under real operation conditions

Test 1, Picking of a 2x2 LEGO part and assembly on a fixed chassis.

The first test consisted in picking a LEGO piece and assemble it on a fixed chassis, the purpose was to evaluate the basic functionalities of the end effector.

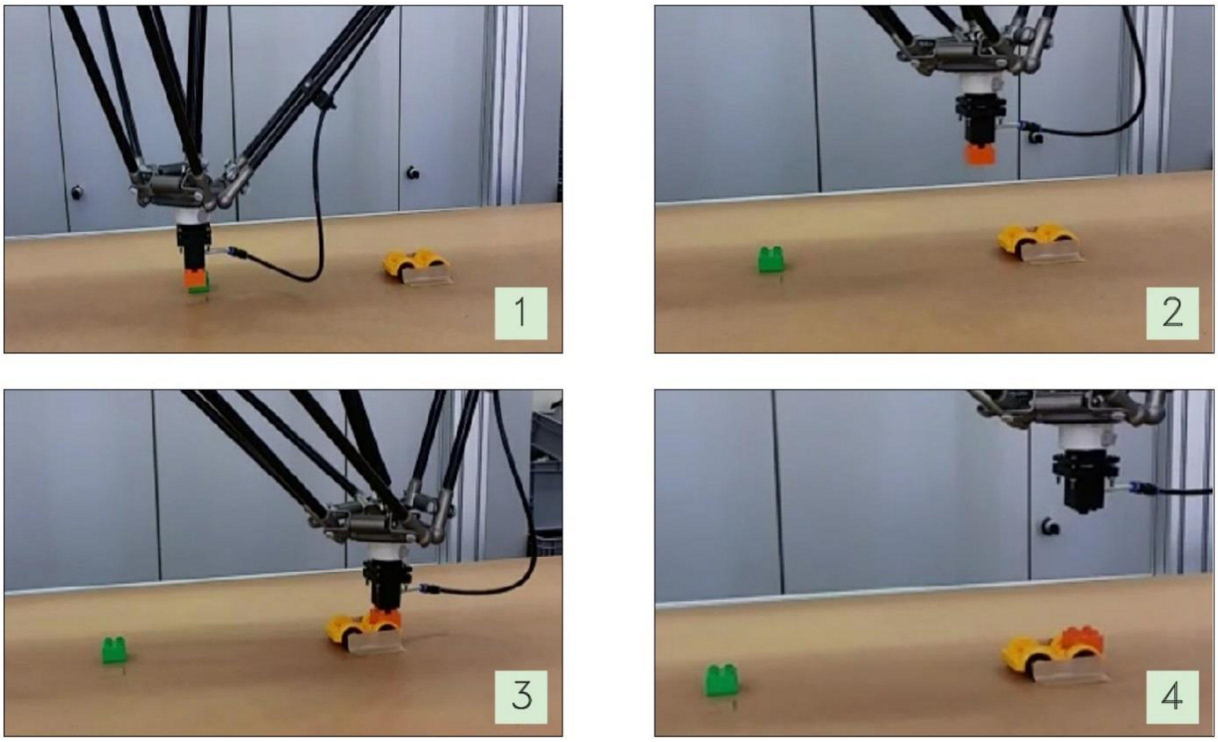

Fig. 8-9: Picking and assembly test

Test2, Picking of a chassis from the chassis feeder.

This test was discussed previously on section 5.4.

Test 3, Assembly of cars in serial production.

With this test the combination of several variables where tried at the same time. First, a model of car consisting of two parts and a chassis was defined, the robot put on automatic mode started the assembly of the cars taking the finished products to the finished product area and starting a new one as the next step until the chassis feeder was empty.

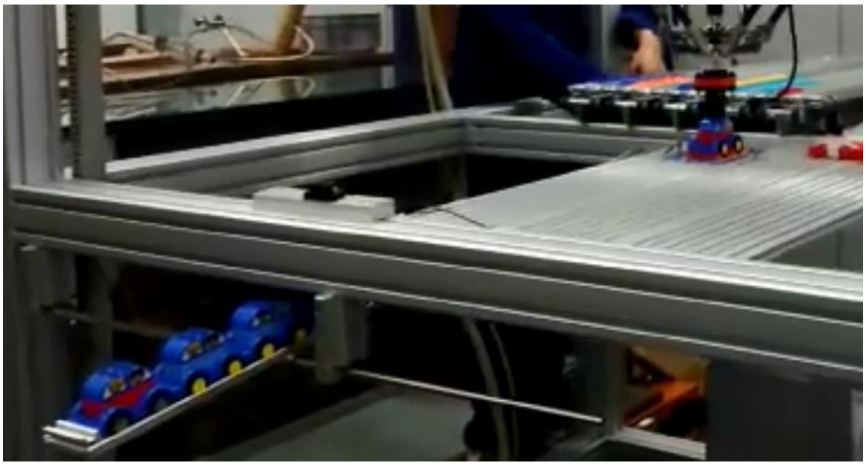

Fig. 8-10: Serial production

8.5 Conclusions

The end effector performed well during the tests but during operation the programing team detected some inconveniences on the design, during the grasping of pieces with eccentric center of mass the pieces have a small tilt that increases with the fast moving of the manipulator and cause problems when assembling at high speed. Apart from this, there were commentaries about repeatability problems caused by the gaps between the alignment inserts and the holes on the top part of the pieces.

Chapter IX: Recommendations and future works

The design with sensors was not proved due to shortage of time and the early development of the control system, so is proposed for future works on the assembly cell. Also, the overall design of the end effector needs to be revised to make front to the problems encountered during the extensive utilization of the part.

Bibliography

[1] F. König, Konstruktion, Fertigung und Inbetriebnahme eine Industrie 4.0 Anlage, FH Aachen, 2016.

[2] N. Cross, Engineering Design Methods, Strategies for Product Design. Chichester, England.: WILLEY, 2000.

[3] A. Risitano, Mechanical Design, Boca Raton FL: CRC Press, 2011.

[4] H. ElMaraghy Smart Adaptable Assembly Sytems, Elsevier B.V., 2016.

[5] M. Wilson, Implementation of Robot Systems, Elsevier B.V., 2015.

[6] V. Poppeová, Delta Robots-Robots for High Speed Manipulation, University of Žilina, 2011.

[7] R. Clavel, "Device for the Movement and Positioning of an Element in Space", U.S. Patent No. 4,976,582. 1990.

[8] P. V. Prasad Reddy, A Review on the Importance of Universal Gripper in Industrial Robot Applications, IJMERR, 2013.

[9] G. J. Monkman, Robot Grippers, WILEY-VCH, 2007.

[10] O. Prakash Sahu, Development of Robotic End-Effector Using Sensors for Part Recognition and Grasping, International Journal of Materials Science and Engineering, 2015.

[11] O. Prakash Sahu, Multiple Sensor Integrated Robotic End-effectors for Assembly, Elsevier B.V., 2014.

[12] ABB, Product Specification IRB 340 M2000, ABB Automation Technologies, 2000.

[13] ABB, "www.abb.com", 2016. [Online].

[14] Schunk, "www.schunk.com", 2017. [Online].

[15] Item, "www.item24.com", 2017. [Online].

List of tables and figures

Tables

Figures