Self-Leveling pedestal for a movable Industrial Robot

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KTH Industrial Engineering and Management

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KTH Industriell teknik och management	**Examensarbete MMK 2016:166 MKN 178** **Självnivellerande piedestal för en mobil industrirobot** **Roshan Arun N.S**

Godkänt	Examinator	Handledare
2016-12-14	Ulf L Sellgren	Kjell Andersson
	Uppdragsgivare ABB	Kontaktperson Daniel Sirkett

Sammanfattning

ABBs kollaborativa robot YUMI, är en industrirobot med sju frihetsgrader. Den har två armar, vilka är avsedda att samverka med människor i arbete. Roboten var ursprungligen avsedd att monteras på ett bord, men olika tillämpningar och krav för förflyttning av sådana samarbetsrobotar motiverade en ny rörlig piedestal.

Avhandlingsarbetet syftar till att utveckla en konceptuell hårdvaruplattform som kan tjäna som en piedestal för ABBs kollaborativa robot. Det föreslagna konceptet bör möjliggöra en korrekt höjdjustering av sittpositionen för olika användare och bör även stödja en självnivellerande funktion . Det föreslagna konceptet ger inte bara förbättrade ergonomiska egenskaper såsom mobilitet, möjlighet att sätta fast tillbehör som skanningsmatare och andra elektriska komponenter, utan är också funktionell i en industriell arbetsmiljö. Olika koncept genererades och en selekteringsverktyg användes för att välja den lämpligaste lösningen. Det valda konceptet analyserades och en prototyp tillverkades. Samtidigt utvecklades nivelleringskonceptet. Den resulterande prototypen tillverkades av aluminiumprofiler med alla nivelleringsfunktioner och själva roboten monterad på den, med fyra linjära ställdonsben. Den resulterande modulen gör det också möjligt att montera ytterligare funktionell utrustning.

Den mekaniska konstruktionen genomfördes med hjälp av SolidWorks 2012. Statisk strukturanalys och modal analys utfördes med hjälp av ANSYS för att säkerställa att produkten fungerar optimalt. MATLAB används för matematisk modellering, medan det självnivellerande logiksystemet utfördes med mjukvaruplattformen Arduino.

De fysiska testerna av strukturen, utformningen av det elektroniska systemets hårdvara och den självnivellerande logiken gav lovande resultat. Dessutom var slutprodukten stabil och styv både under drift och vid transport av roboten från en industriell cell till en annan.

Nyckelord: *kollaborativ robot, nivellerande, piedestal, ställdon, industrirobot.*

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Approved 2016-12-14	Commissioner ABB	Contact person Daniel Sirkett

Abstract

ABB's collaborative robot YUMI is an industrial collaborative robot that has been developed, consisting of seven degrees of freedom with two arms, which is meant to collaborate with humans during working. The robot was originally is meant to be mounted on a table, but considering different applications and requirement of mobility of such collaborative robots motivated a new design of movable pedestal.

The master thesis project aims in the development of a conceptual hardware platform which would function as a pedestal for ABB's collaborative robot. The proposed concept should allow suitable height adjustment in sitting position to different users and also should support a self-leveling feature .The concept proposed not only provided additional ergonomic functions such as mobility, provision for attaching accessories such as scan feeders and other electrical components but also functional in the industrial working environment. Different concepts were generated and a selection tool was used to choose the most feasible solution. Accordingly, the concept was analyzed and the prototype was manufactured. Simultaneously conceptualization for self-leveling was carried out. The resulting prototype was manufactured using aluminum profiles and had all the features of leveling the pedestal and the robot mounted on it, with four independently operational linear actuator legs. The resulting modular product also provided features to mount additional equipment on the setup to deliver the desired functionality.

The mechanical design was carried out using SolidWorks 2012. Static Structural Analysis and MODAL analysis were carried out using ANSYS to ensure that the product works optimally. MATLAB is used for mathematical modeling. And the self-leveling logic for the system is carried out on the Arduino software platform.

The physical tests of the structure, layouts of the electronic hardware system and self-leveling logic seem to be delivering promising results. Furthermore, the final product provided stability and stiffness while operating and transporting the robot from one industrial cell to another.

Keywords: *collaborative robots, self-leveling, pedestal, actuators, industrial robots.*

ACKNOWLEDGMENTS

This chapter includes thanking the people involved during the master thesis project in developing a Self-leveling Pedestal for ABB's industrial collaborative robot.

The master thesis project has been a great learning experience. It introduced a world of robotics and had given a deeper and broader understanding of product development. Firstly I would like to thank ABB Corporate Research Center, Sweden, and manager *"Jonas Larsson"* for having confidence in me and allowing me to work on such an interesting project with freedom and creativity. I would like to thank my supervisor at ABB "*Daniel Sirkett*" for his amazing guidance and support throughout the project. Working under "*Daniel Sirkett"* was truly a knowledgeable experience. I want to especially thank all of my colleagues and peers at ABB, for constantly helping me out in different aspects of the project.

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Roshan Arun

Stockholm, June 2016

NOMENCLATURE

This chapter lincludes a list notations and abbreviations that are used during the thesis project.

Notations

Symbol	*Description*	*Unit*
I	Impluse	[Ns]
K	Stiffness	[N/mm]
M	Moment about a point	[Nm]
m	Mass	[kgs]
F	Force	[N]
H	Height at which forces are acting	[mm]
$R_{a,} R_d$	Reaction forces	[N]
δ	Deformation	[mm]
p	Impulse	[Ns]
v	Velocity	[N/mm]
N	Number of entires	-
gX_{filt}	Filtered accelerometer values	[mm/s^{-2}]
k	Stiffness	[N/mm]

Abbreviations

CAD	Computer Aided Design
FEM	Finite Element Method
YUMI	You and me collaborative robot
QFD	Quality Function Deployment
ANSYS	Analytical System software
QTC	Quantum tunneling composite
PAD	Patented Actuator Device
COG	Center of Gravity
IDE	Integrated Development Environment

TABLE OF CONTENTS

Chapter *Page*

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

CHAPTER 1: Introduction

This chapter includes an introduction to collaborative robots, background; the problem description, delimitations, deliverables and the methodology of the thesis work are defined and stated.

1.1 Background

As the human race steps into the future, a growing trend of technological advancement can be seen. Robots have come a long way since the past decade. From being expensive and scary to work with a skilled workforce, robots now days are safer and simple to work with which can easily take up ergonomically hazardous work. Robots are no longer just present in an industrial workspace but are slowing taking over their human counterparts work with higher productivity and retention rates. Traditional robots are quite unpredictable and dangerous and are so kept in cages and the workers carry out the operations outside, looking in. Collaborative robots, also known as Cobots are robots, on the other hand, are designed to safely work with human counterparts and be more productive . Collaborative robots in this age of Robotic era are considered as on a unique and a frontrunner. These robots are built to work under safe conditions while in collaboration with a human and could soon be an affordable alternative to outsourced labor and fixed automation. These are opening up new opportunities for not only industries and OEMs but also for start-ups, research and potential users alike. These robots are made safer by either limiting the force to avoid injuries or by installing sensors on to the robots which would avoid touching and sometimes by combining both of these technologies. (Lingle, 2015)

Smart, collaborative robot are unique robots which can perform monotonous tasks that free up skilled human labor in certain ways. Integrating these into an industry's workforce would give a competitive advantage to their business in the process of automation. Collabrative robots are intended to help/assist and not replace the worker in an industry. (Lingle, 2015)

1.2 Problem Description.

The master thesis focuses on designing and modeling a self-leveling stable pedestal for ABB's collaborative Robot, YUMI ; see Figure 1, is an industrial collaborative robot that has been developed by ABB. YUMI is a flagship robot which has 7 degrees of freedom with two arms which are meant to collaborate with a human during working (YUMI, 2016). The robot originally is meant to be mounted on a table, but considering the requirement of mobility of such collaborative robots, motivates a new design of movable pedestal with a self-leveling base.

While installing an industrial robot it is absolutely necessary to ensure the robot is stable and is at a right level. Leveling is important since the dynamic model in the controller accurately represents the gravitational loads on the physical robot.

Figure 1: YUMI the collaborative robot

Traditional robots; are usually bolted to a support or base. They are mounted on a permanent fixture which then has to be leveled so that the robot is operable at the right level. This leveling process usually is done once in a while and so is not considered major task by the users. However, a small collaborative robot has to be moved from one place to another while following the process of leveling might be a laborious and time consuming task. Also, the robot should be leveled accurately in order to achieve stable functionality. Since the level of accuracy is dependent on the skill and experience of the operator it can be vulnerable to human induced errors and so measures have to be taken to avoid such errors.

Hence it is very important to have an automated system which would carry out the required and desired features.

1.3 Delimitations

The work under this project is pre-defined in order to ensure all the objectives are achieved in this thesis project. The following were some delimitation which were listed.

- The pedestal should have good mobility so that the robot can be moved easily from one cell to another.
- While working the robot should be stable and fixed at one single position.
- It should be self-adjustable in height while leveling.
- The design should allow fixtures such as Scan-Feeders[2] ; Flex-Feeders[1] and other equipment to be fixed on the pedestal.
- The design of the pedestal should be compactable with the existing robot design.
- The implementation of self-leveling and the prototype testing will be carried out only if time is sufficient.
- The necessary planning to order hardware and materials for the prototype and self-leveling will be carried out but setting up the electrical hardware would not be carried out if time is not sufficient.

1.4 Deliverables

The master thesis project had the following deliverables.

- Design a conceptual solution for a collaborative robotic pedestal.
- Carry out an investigation to observe the latest technologies and solutions available that could be implemented into the pedestal.
- Selection of concept after evaluation of proposed design concepts.
- Generate CAD models and detailed 2D drawings of the final design.
- Analyze the selected concept analytically as well as through Finite element analysis (ANSYS).
- The pedestal must have self-leveling functionalities.
- Features to mount additional accessories as mentioned in the requirements.
- The pedestal should consist of feature which would enable the robot to be mobile quite easily when not in use and to be transported from one working cell to another.
- The design must also integrate ergonomic features which have been discussed.
- Generate concepts, evaluate them and develop analytical analysis for the selected concept (ANSYS will be used for performing finite element analysis).
- Generate CAD models and 2D drawings of the final design
- Generate self-leveling logic on Arduino platform.
- Order necessary hardware equipment and materials (both electrical and mechanical).
- Prototype the final design once approved by ABB.
- Conduct testing of the prototype.
- Implement and demonstrate the self-leveling system on the prototype if time permits.

Flex Feeder[1] – Flex Feeders are systems which are used for separating and presenting parts to the robot.
Scan Feeders[2] – Scan Feeders are systems which are used for presenting a visual image of surface and the orientation of parts to the robot.

1.5 Methodology.

The thesis work tries to adopt 'The Engineering Design Process' method for the development of the pedestal for ABB. The process involves a series of systematic steps to be followed in order to come up with a successful product.

In this section, the method for this thesis is described and the tools that were used to accomplish the deliverables are also presented. The methodology used in this thesis was *The Engineering Method*, the process is illustrated in Figure 2.

In the first stage the problem was defined in order to clearly identify the purpose behind the project. In the second stage a thorough background research was carried out about the existing pedestals and similar products in the market which could assist in the mobility of collaborative robots. Different technologies which could be used in the project where explored through a literature study.

Once a literature survey is carried out, specific customer requirements and technical specifications are listed. A requirement specification from ABB is acquired and based on the needs a Quality Function Deployment (QFD) is used to obtained details for the designing phase.

In the next stage a brainstorming session is carried out in order to generate many possible new ideas for the pedestal. A Morphological tool is used to maximize the number of ideas. The evaluations of these ideas are carried out using a decision matrix tool call Pugh matrix.

In the fifth stage realistic concepts are developed and the chosen concept is future developed and analyzed using software such as Solid Works2012, ANSYS Workbench, Matlab and Arduino coding platform. The chosen concept is later prototyped to realize its working functionality. Later a simple prototype testing is carried out to check if the requirements are satisfied. If it fails to fulfill the above mentioned criteria then the fourth, fifth and sixth stages are carried out again until the requirements are met. And finally the results are efficiently translated through a report.

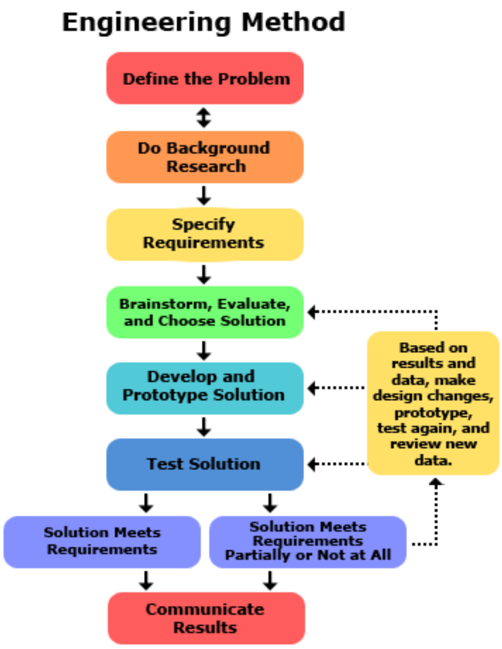


Figure 2: Engineering Design methodology flowchart

CHAPTER 2: Frame of Reference

This chapter includes fundamental background information gathered and existing knowledge relevant to the topic. Knowledge about Robots, pedestals, and other relevant subjects will be covered to have a better understanding of the project.

2.1 Robotics at ABB

Being a part of Discrete Automation group, ABB Robotics has been a leader in providing industrial solutions across different industry verticals. ABB is a strong player in modular manufacturing systems and services and strives to improve productivity, product quality and safety within the area of Robotics. (YUMI, 2016)

There has been an unprecedented growth in the technology industry. Evolution from a cell phone to smartphones, and a similar trend could be seen in automation sector emerging gradually in the market. This was a good sign for robotics since growth in technology which led to huge growth in the production lines. So it was important to address this rapid growth. The current production lines have humans manually assembling small parts which can be cumbersome. So assembly process had to be automated process to deal with this. There weren't many products in the market which truly collaborate with a human while working. It was important to address the short life cycle and scalability of the product which can be easily deployed and re-delayed from one place to another. That was where a collaborative robot could emerge as a game changer. And ABB's answer to this growing requirement was YUMI. YUMI, as illustrated in Figure 1, is a collaborative robot meant to act as a co-worker for a wide range of applications.

It is very hard to replicate an amazing machine called a human being. Although it is almost impossible for a robot to be as flexible or functional as a human and YUMI is a step further to replicate motions of a human with the help of abundant sensory skills. YUMI is a Robotic co-worker with a dual arm which is a small parts assembly robot solution. Its multifunctional hands allow it bridge a gap in the small part assembly sector. It provides an integrated solution to the manufacturing sector. It is an interestedly safe work which allows to be placed anywhere and work with any coworker and can fit any human workspace.

Some of the problems faced in the current small parts assembly sectors are re-configurability, programming and easy to use. So YUMI has functionality lead through programming ability which enables a user to grab the arms and lead it through number positions and manipulate the gripper and thus teaching the robot in a short frame of time. (YUMI, 2016)

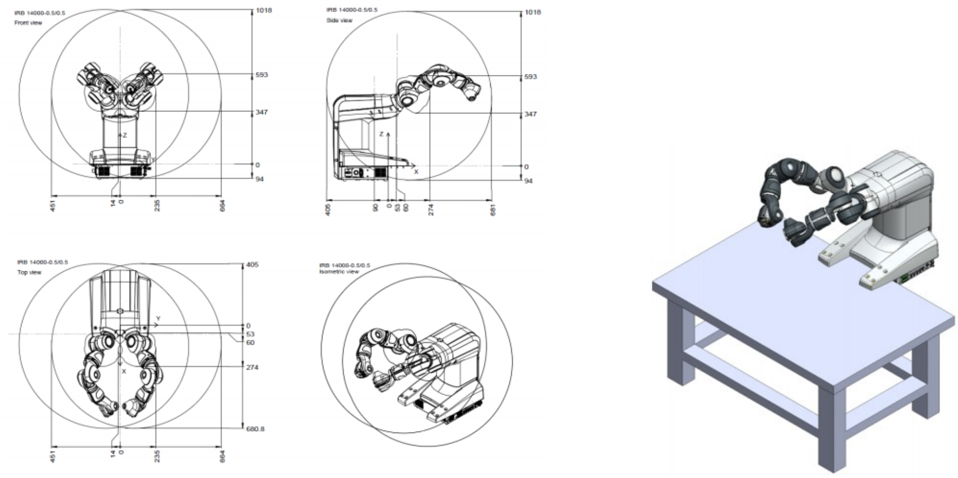
Some of the special features of YUMI also include:

- Speed of 1500mm/s
- Integrated camera-based part location and state-of-the-art robot control.
- Suction
- Integrated vision
- Multitude of connectivity options
- Integrated cables
- Lightweight components

Faster production, better quality, and increased flexibility can be achieved thus providing benefits the whole value chain from manufacturer to the consumer of the product and least impact to the environment.

When conducting thesis at ABB, a lot of technical aspects and design restrictions were observed regarding YUMI. These technical features had to considered have to have a unique feature of clamping on to a support. This can be easily observed from Figure 3(b). So a thorough study was carried out regarding the mounting points and other important features.

According to author Phil (Phil Crowther, 2015), YUMI carries a payload of 0.5kg per arm with a reach of 559mm with a working range as illustrated in Figure 3(a). Considering these factors were very essential for the designing aspects.



a b

Figure 3a & 3b : Working range of YUMI and table mounting

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According to repot YUMI-IRB overview (YUMI, 2016) , the robot has custom I/O interface which were very essential for the designing phase. The customized interfaces can be seen from Figure 4 .

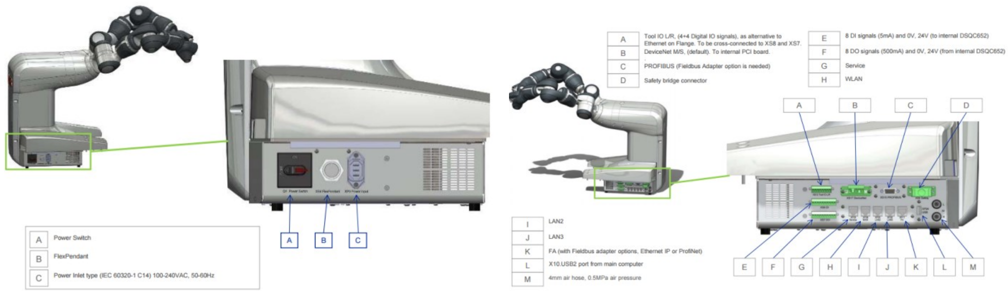

Figure 4: I/O interfaces of YUMI

Considering the above parameters that design phase had to ensure that pedestal design would not affect these moutnings or I/O interfaces in any way .

2.2 Current pedestals in the market.

Being a collaborative robot is it very important to be for it to transition from moveable to stationary mode and leveling of a robot is equally important. There are a lot of existing products in the market which offers movable robot bases. Robots are generally equipped with wheels for transporting it. Their wheels are equipped with brakes which enable the pedestal to be fixed at one position. KUKA's robot on mobile manipulator pedestal called KMR IIWA and KMP 1500 which are illustrated in figure 5 are omnidirectional mobile platform has the feature of movable wheels which provides flexible and autonomous solution when compared to traditional automation in the industry. By introduction of autonomous solution into the industry floors can lead to flexibility, unrestricted maneuverability and works with precision (KUKU Nordics, 2016).

Figure 5: KMR IIWA and KMP 1500 mobile manipulator pedestals from KUKU

From the above article it was concluded that these two mobile platforms provides increased functionality but lacks height adjustable feet. It also lacks self-leveling feature.

Pedestals named Rigid back Baxter from Rethink Robotics (Foote, 2016) illustrated in the Figure 6(a) and "UP-1" from UpDroid illustrated in Figure 6(b) offers complete autonomous mobility solutions which assist the robot with mobility. UpDroid is a dual arm robot like YUMI but is considered more of a personal build and program robot than an industrial robot. Omnidirectional wheels provide precision control for forward, lateral or twisting movements in constrained environments but lacked height adjustment and leveling features as well. These pedestals come with built in IR sensors for microcontroller for controlling the motors but doesn't serve the purpose of leveling for high precision tasks.

While some other pedestals in the market are equipped with both wheels and height adjustable feet which would allow the robot to stand on feet while working.

a b

Figure 6(a) & 6(b) : Rigidback from Rethink Robotics and UP-1 from Updroid

While there is another category of pedestals in the market are equipped with both wheels and height adjustable feet which would allow the robot to stand on feet while working. These are all manually operated which upon arrival at the new location, the feet would be deployed to take the wheels off the ground. Then the operator would use a spirit level to check for alignment of the robot while adjusting the foot height. This is not desirable as it is time consuming although has advantages in terms of pricing and maintenance. Mobile pedestal Baxter from Rethink Robotics (RethinkRobotics, 2016) illustrated in Figure 7(a) and UR5 Pedestal from SICRON (Sicron, 2016) illustrates in figure 7(b) are a few pedestals specimens which work on the above-mentioned principle.

a b

Figure 7(a)&7(b): Mobile pedestal Baxter from Rethink Robotics and UR5 pedestal from SICRON

ABB wanted a movable pedestal for their collaborative robot, and so a working prototype pedestal was developed by a group of KTH Masters students as a part a project. The design consisted of a Rack and Pinion mechanism which used a worm gear, gear rack, linear guides and a plinth solution to achieve a height adjustable, mobile solution. Although successful, the design was never considered a viable solution for ABB due to the unreliable mechanical parts in the system which had issues regarding stability and cranky while in operation. It also lacked the feature of leveling which was an important factor. So, ABB decided to carry out another project in search of a more feasible and reliable solution for the existing problem. Figure 8 illustrates the ABB pedestal designed and prototyped by KTH students. (Ahmed El Shobaki, 2013)

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Figure 8: KTH Pedestal

2.3 Relevant Technology

As a research study was carried out it was for the leveling pedestal, it was certain that a contact feedback system was needed at the legs of the pedestal to ensure all the legs of the pedestal were touching the ground once the leveling is done. So the following new technologies were explored.

2.3.1 QTC

Quantum tunneling composite (QTC) is a smart material which can be using in the project as a force feedback for the feet. It is a smart flexible material with electrical properties. In its normal state it acts as an electrical insulator but when it is deformed it gets metal like conducting properties, and so it can be used as a sensor as a pressure or contact sensing material. (Catarina Mota, Kirsty Boyle, 2016)

QTC is made of metal filler particles combined with an elastomeric binder which is typically a silicone rubber. The electrons tunnel through the material in other words, conduct when their physical structure is slightly changed by pressure. Figure 9 illustrates the working principle of a simple switch using QTC .This material can be installed and designed so as to get some sort of feedback when the feet comes in contact with the ground. (Catarina Mota, Kirsty Boyle, 2016)

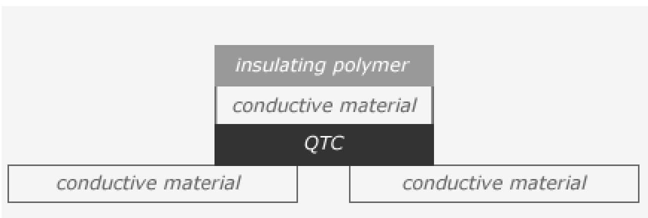


Figure 9: Working principle of a QTC switch

2.3.2 Flat self-leveling system.

FLAT technology is a smart hydraulic technology which will find the level of the table on any uneven surface instantly. The hydraulic PAD (Patented Actuator Device) technology located within the table base instantly reacts to movement or change in environment.

At the contact points with the ground, the FLAT leveling technology consists of a hydraulic cylinder fitted with the leg and all these cylinders are interconnected with fluid hoses as illustrated in Figure 10. When any leg makes contact with the ground the fluid inside hoses is forced through the cylinders to the other legs and thus creating a level. The hose consists of smart valves which would lock until the table moves into the next position and the process continues. (Tony Pike, 2016)

Figure 10: FLAT Leveling feet technology

2.4 Requirement Specification

The first step in developing new products needs a requirement specification. A list of specifications and demands were provided by ABB for the master thesis project which was translated to a simple requirement specification list with testing comments (which are mentioned if needed) that allowed description of the system to be developed along with focusing on the specific problem of the project. Table below illustrates the requirement specification of the master thesis project.

The requirements 1, 2, 3, 7, 8, 9, 10 were functionality requirements needed which were enlisted based the thesis demands put forward by Daniel Sirkett, thesis supervisor at ABB. According to author Klinteskog (Klinteskog, 2011) the horizontal and vertical stiffness had to be at least 40 KN/mm^2 and thus requirement 4 was formulated.

Table 1:Requirement specification table

Parameter	Sl No	Requirement / specification list	Testing comments
Performance	1	The new mechanism must have a wheel transitioning mode to a stationary stand mode feature installed in the existing interface.	
	2	The new mechanism must have a height adjusting and self-leveling features.(Camera or sensors can be used if needed)	

	3	Moving the pedestal, to which YUMI mounted, must not require too much force or effort from the user.	Force required can be measured using a dynamometer or a scale which can record effort needed by a person to move YUMI around.
	4	Vertical and horizontal stiffness must not be too low. Not Less than 40 KN/mm^2	Check through FEM analysis.
	5	The Pedestal on which the mechanism has been installed must be able to carry a weight of 100kgs (at least the weight of YUMI) where the robot will be installed	A dead weight can be used or a person can be asked to sit on it.
	6	The existing interface should not be hampered. It must be possible to mount YUMI on the existing pedestal. The design should not interfere with the feeder mounting.	
	7	The mechanism with YUMI mounted on it in its non-mobile state should not tip over or wobble.	Analytical calculations and physical testing
	8	Good lifespan of the product, reliable and stable mechanism needed.	Should at least have a life cycle of 2 times per day for 365 days
	9	The self-leveling system must be automated and should have an easy user interface.	
	10	Self-locking mechanism must be provided at the feet	
	11	The pedestal with YUMI mounted on it on its feet should not tip over even at a load of 100-200 N is placed 1500 mm up from ground and 500 mm in front of the center of the pedestal.	Physical testing

	14	The pedestal with YUMI mounted on it should not tip over when a load of 200 N is applied 1500 mm up from the ground and 500 mm in front of the center of the pedestal.	Physical testing
Environment	17	The working temperature range 5 – 40^{o}C	Look at component requirements
Maintenance	18	The components designed and manufactured must be able to mount and demount using standard tools	
	19	The designed components must be simple so that it is easy to mount and dismount and assemble after cleaning.	Able to disassemble parts after assembling.
Budget	20	The cost for manufacturing the pedestal in serial production must be around 4000SEK	
	21	The pedestal must be competitive in quality of the given product cost range	
Transporting	22	The pedestal should not be big enough to restrict easy transporting to the customers. Must be portable.	
Quantity	23	The pedestal design if approved must be easy to mass produce.	
Size	24	Dimensions must be as compact as possible but wide enough to handle 4 feeders along with YUMI mounted.	Measure
Weight	27	Maximum weight of the pedestal 100 kg	Measure
Aesthetics	28	Fillet or chamfer must be given to sharp edges	CAD
	29	The pedestal must have a design that is compatible with YUMI	Approved by Daniel Sirkett
	30	Must be ergonomic and end-users input must be considered.	Speak to end user

Materials	31	The material must be based on its strength and performance and since it's a prototype the pricing must be given a priority as well.	
	32	The material used for building the prototype should be recyclable.	Production specification
Product life span	33	The lifespan should coincide with the lifespan of YUMI. Must have a life cycle to last at least 2 uses*per days* 3 years.	

Ergonomics	35	One person should be able to mount and dismount YUMI on to the pedestal.	Physical testing
	36	The electrical hardware system should harmonize with the YUMI design. The pedestal design must accommodate all the electrical boards and other hardware's	Approved by Daniel Sirkett
Quality	37	Document the production of the prototype for future improvement	Report
Documentation	39	Detailed designs must be documented.	Report
	40	A technical specification of the pedestal and its components must be documented	Report
	41	All calculations and theoretical fail cases must be documented along with the Arduino codes	Report

CHAPTER 3: Implementation

This chapter includes the working process and step by step structured process used to reach the goals of the project thesis. The structured process presented in this chapter is used to reach the goals for the project.

3.1 Idea Generation.

The initial step was to evaluate the entire customer needs and requirement and. A Quality functional Deployment tool was developed. In order to translate these customer requirements into design specifications and to see if these specifications will meet these requirements. Developing a new product needs a lot of new thinking and different ideas. Brainstorming sessions were arranged in order to generate several ideas. Several concepts were idealized and visualized using the morphological chart. However, these concepts were shortlisted and only limited ideas were pursued towards further evaluation.

Customer Profile

Identifying the customer segment or the target set of customers was important to understand the customer demands. This process includes identifying the age, gender, designation of the ends users, along with physical aspects such as height and places where it could be used

Table 2: Customer profile

Variables	Particulars
Gender	Male and female
Age	Between 18 – 60
Designation	Any user in the industry or work floor must able to use it. Must have a simple user interface.
Height	Average Male: 175cm Average female: between 163-164 cm
Location	Europe, Asia, United States and any country where YUMI is planned to be sold.

Quality Function Deployment – QFD

In order to design a quality product it is important to understand the customer requirements and translate these requirements into design or functional parameters. QFD is a methodology which is used in generating information required for the designing phase. QFD methodology helps in transforming the customer requirements into measurable design requirements (G.Ullman, 2010, pp. 148, 169). The QFD leads to the formation of the house of quality which is illustrated in Figure 11. A QFD for the pedestal design can be seen in Appendix A.

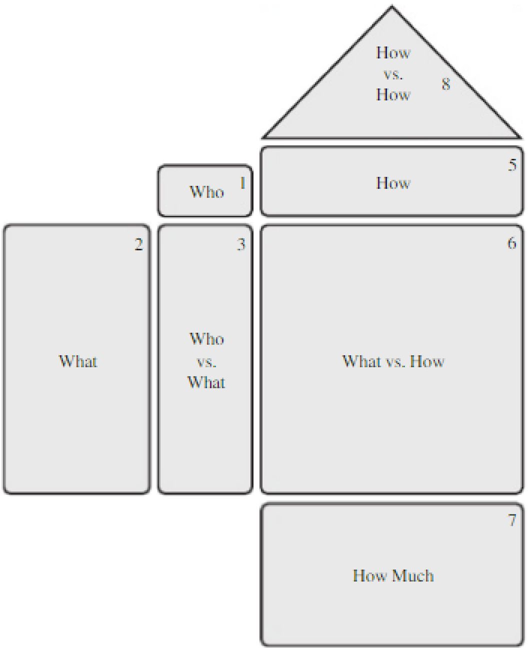


Figure 11: A generalized QFD diagram

The first step is to obtain the desired properties defined by a customer and determine a weightage from one to five to these requirements based on their importance. (G.Ullman, 2010) The most important requirements, in this case, were stability, height adjustment, safety, and self-leveling. Engineering or functional parameters were determined and a thorough evaluation of these parameters with respect to the customer requirements was carried out. A benchmark test was carried out where the existing products from a section in the market mentioned in section 2.2 were rated based on these factors. Studying the competitors during this step helped in understanding the problem better. In the final step, numerical values were obtained which helped to determine the importance of these designs.

All the parameters are evaluated by assigning an absolute value of weightage on a scale of 1, 3, and 9 where 1 represents a weak relationship and 9 represents a strong relationship. In the final step, numerically values were obtained which helped to determine the importance of these designs based on the weightage given to the parameters and the relationship value between them.
QFD is an effective tool to determine technical aspects of the design which are more important than the others. It also helps in determining the importance of a particular the engineering parameters which would help to bring about an effective solution to the customer needs.

Brainstorming

The brainstorming methodology was adopted to generate new and diversified concepts. It was a used a technique was used to trigger new and unique ideas by discussing different ideas with the supervisor. Different propositions were put forward to solve the problem keeping the requirements in mind. No evaluations of concepts were done during this phase. (G.Ullman, 2010). A technique called mind mapping was implemented which helps in generating the main idea by associating with a lot of sub-ideas. This allowed in generating focus areas surrounding the central idea which were essential in building the pedestal.

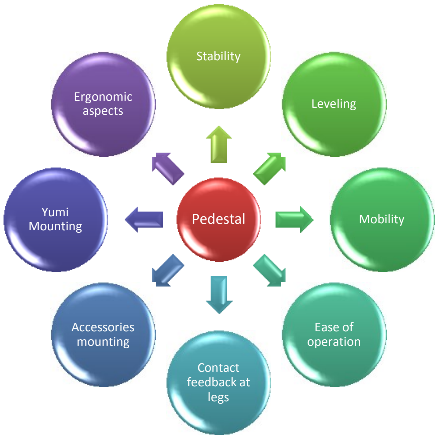


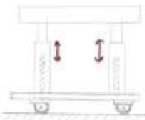
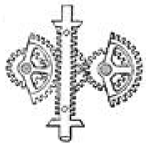
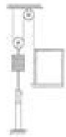
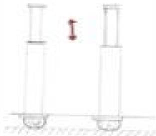
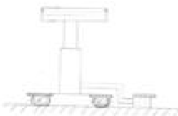
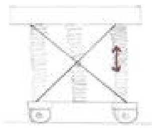
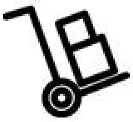
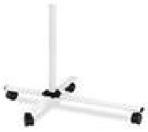
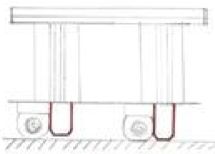
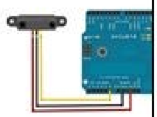
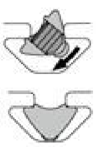
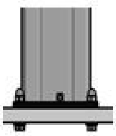
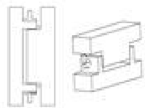
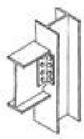
Figure 12: Mind mapping technique used for Brainstorming

Morphological Matrix

Morphological matrix methodology is a powerful technique which allows a designer to foster a number of solutions by considering the functionality requirements from the product. A morphological analysis consists of three major steps. By making a list of all the important functionality requirements, a number of solutions are found out. This leads to the final step where all ideas and combined to obtain the best feasible design solution. (G.Ullman, 2010).

Some of the major functionality are considered for this particular morphological chart as mentioned in Table 2. The functionality is established based on QFD and these are later brainstormed to get multiple concepts. Many of the concepts were then combined to generate four feasible solutions which are discussed in the upcoming sections.

Table 3: Morphological chart

Features	***1***	***2***	***3***	***4***	***5***
Height adjustment					
					
Leveling solution					
Portability					
Contact Feedback					
Robot attachment					

Concepts generated

In this section, the concepts designed will be presented and described briefly. The following section consists of the functionality of the concepts and idea behind the concepts with an illustrated figure.

Concept 1

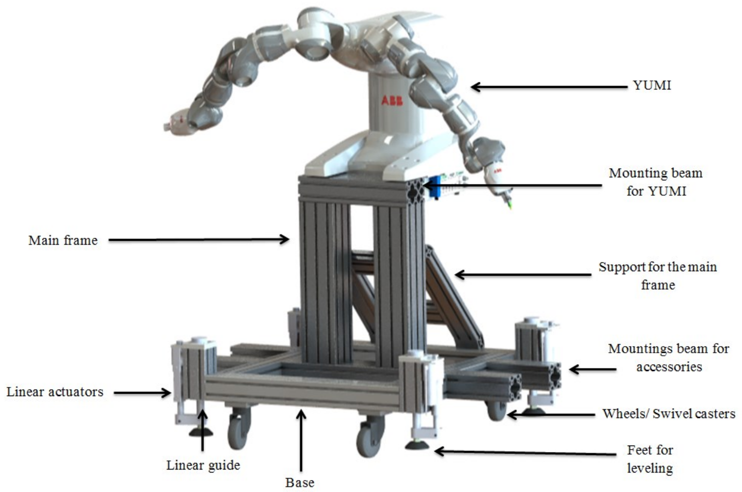


Figure 13: Concept modularity which useslinear actuators

The first concept is designed based on the idea of an electric height adjustment desk. Electric Motorized desk lift systems are tables which are powered by actuators used for height adjustment.

The concept design consists of four linear actuators which facilitates movement linear movements upward and downward and thus ensures the height adjustment of the pedestal.It also facilitates self leveling of the pedestal by controlling each linear actuator individually based on a feedback from an accelerometer sensor which is controlled by a microprocessor. Each leg of the pedestal is powered a DC motor linear actuators and these four motors are controlled by a central controller. Actuators which are used have built in potentiometers that gives feedback on position of these actuators. Based on the reading from the accelerometer the unevenness in the ground is measured and the actuator push tubes move up or down accordingly until the desired outcome is achieved.

The base is also mounted with swivel casters, which enables transitioning it from stationary to mobile mode when the actuator legs are lifted up. This mechanism needs a force feedback system at its legs since a four legged table will never have equal weight on all four legs, due to which leveling might occur with only three legs and thus not letting the fourth leg be in contact with the ground. Hence it is necessary to have a force or contact feedback system in place at the legs. This system not only allows height adjustment and deployment of wheels but also facilitates leveling without a requirement of an additional system.

Concept 2

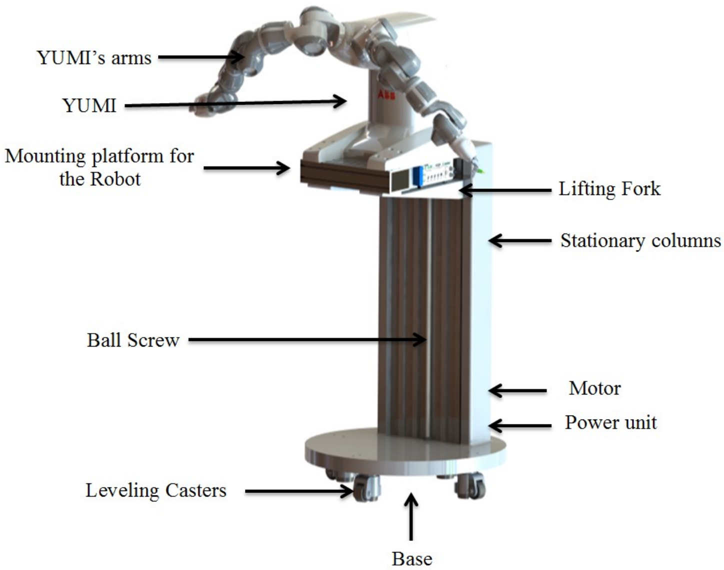


Figure 14: Concept forky which uses lifting forks

The second concept is designed based on the idea of a fork lifter. Fork lifter is powerful tools equipped with machinery which is built to lift a specified maximum weight and a specified maximum center of gravity. The following concept design consists of a lifting fork which is powered by a motor unit which is mounted on the base (not seen in this view). The robot is mounted onto the double sided lifting fork through a mounting platform made from aluflex and is mounted via screws and T-slot nuts. The design also consists of a vertical ball screw and nut which is powered by a gear motor which enables the vertical upward and downward movement of the forks and the braking system installed will ensure the system stayed at the desired position under high loads without external powering.

The base is also mounted with leveling casters , which enable in manually deploying the feet and transitioning it from wheel mode to stationary mode and the casters are mounted with FLAT leveling feet mentioned in section 2.3.2 which allows the system to self-level.

The Screw and ball nut mechanism are bi-directional which allows the robot to move in both directions and thus providing height adjustment. The system can handle high loads with ease and also the mechanism offers high precision movement. But the entire system is comparatively expensive and large and might hinder in easy transportation.

Concept 3

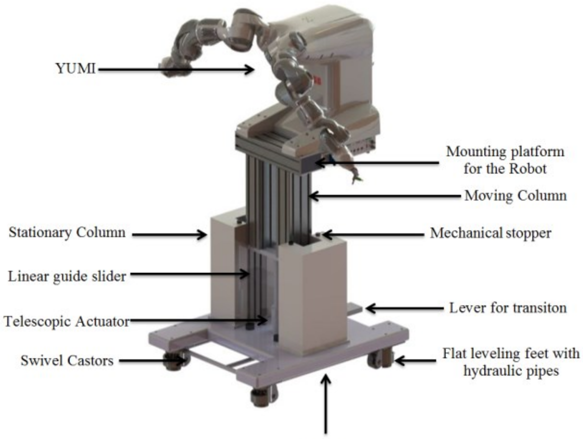


Figure 15: Concept Linearity which uses linear guide columns

The third concept is designed based on the idea of a heavy duty linear slide rails. The stationary column which consists of heavy duty linear slides is coupled with a linear bearing slider block which provides smooth linear guidance under a wide range of speeds and loads (Firgelli, 2016). The following concept design consists of linear slide rails which are powered by a telescopic linear actuator which is electrically powered. This telescopic actuator is mounted onto the base at the bottom. The robot is mounted onto a linear slider block consisting of universal profile guide rails on the side for easy motion. The tension on each side of the carriage can be manipulated so as to adjust the movement of the slide to lose or tight, based on the requirement. The robot itself is fixed on a mounting platform made from Aluflex and is mounted via screws and T-slot nuts. The Telescopic actuator enables the vertical upward and downward movement of these sliding blocks and the self-locking actuator will ensure the system stayed at the desired position under high loads.

The base is also mounted with leveling casters , which enable in manually deploying the feet and transitioning it from wheel mode to stationary mode and the casters are mounted with FLAT leveling feet mentioned in section 2.3.2 which allows the system to self-level.

The system can handle high loads with ease and also the mechanism offers high accurate precision movement. The entire system is quite stable and offers high stiffness. But the entire system has a high initial cost of investment and is quite large compared to the other concepts which might hinder its ability for easy transportation.

Concept 4

The fourth concept is designed based on the idea of a simple hand pushed trolley design. It consists of two fixed feet and two leveling casters at the back. An ergonomic handle has been designed which would allow the entire mechanism to be inclined by pushing the lever provided, making the entire system tilt and rest on the wheels and thus enabling its movement. Once arriving at its new location the system is inclined forward and thus making it rest on its feet. The two leveling casters can be individually manipulated to level the system. Two wheels are mounted in the back of the setup and two support stands are used in the front of the setup. Hand trolley design can be used in this concept to transport/move the setup by tilting it into a certain angle until the two back wheels are in contact with the ground. The following concept design consists of a stationary column which consists of a lifting motor, installed, at the bottom. This motor allows the movement of the robot in both upward and downward direction with the help of a control box (not seen in the figure) with a wide range of speeds and loads. Tension on each side of the carriage can be manipulated so as to adjust the movement of the slide to lose or tight, based on the requirement. The robot itself is fixed on a mounting beam made from Aluflex and is mounted via screws and T-slot nuts. This mounting platform is installed on the motor via a mounting plate.

The system can handle high loads at different loads and offers good height adjustment capability. The entire system is quite stable and offers high stiffness. But the system offers less stiffness and safety compared to the other concepts.

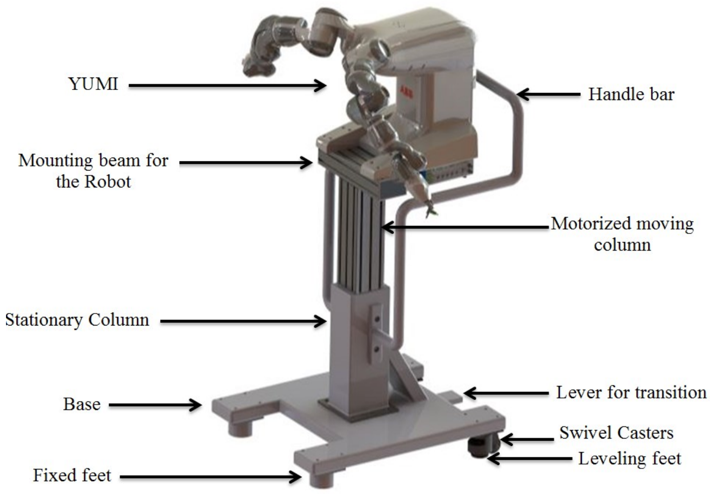


Figure 16 : Concept Simplicity which uses motorized column

3.3 Concept Evaluation

This section illustrates the evaluation of all the designs developed. The generated concepts are compared with a reference using an evaluation tool called Pugh Matrix. The Pugh matrix is a simple technique which allows a designer to use least resources on deciding the most feasible and potential concept but comparison with other concepts. (Ullman, 2010, p. 222).

A Pugh Matrix was generated by listing down important criteria which represent the important properties needed for the final design. On the left most column, the criteria were listed and a suitable weightage was given to each of them based on their importance. The concepts were then evaluated with a reference design. While comparing a value was inserted to judge if the concept is better or worse than the reference. The value 1 refers to better, value -1 refers to worse and 0 refers to the same with respect to the reference. These values are later multiplied with the weightage and summarized to obtain an end score to determine which concept is the best. Two iterations are carried out to adjudge the best concept.

First Iteration.

In the first iteration, pedestal developed by KTH previously was taken as reference and the generated concepts were compared with this. From the result, it was seen that the concept Forky, linearity, and simplicity had a positive result which indicated that the design is better than the reference and had possibilities for further designing and improvement. The concept named simplicity had a negative result which indicated that it is worse than the reference concept.

Table 4: Pugh's matrix second iteration of concepts

Pugh Selection Matrix						
	Alternative Concepts					
Criteria's	**Weightage (1-5)**	**REFERENCE (KTH Pedestal)** 	**Forky** 	**Linearity** 	**Simplicity** 	**Modularity** 
Stability	5	0	1	1	-1	1
Safety	4	0	1	1	1	1
Height Adjustment	4	0	1	1	0	1
Ergonomic Design	3	0	1	1	1	1
Self-1Leveling	4	0	0	1	-1	1
Cost	3	0	-1	-1	1	-1
Portability	2	0	-1	-1	1	1
Compatibility	3	0	1	1	1	1
Accessory Mountings	4	0	-1	-1	-1	1
Weight	4	0	-1	-1	-1	-1
Sum of Positives		0	5	6	5	8
Sum of Negatives		0	4	4	4	2
Sum of Same		0	1	0	1	0
Weighted Sum of Positives		0	19	23	15	29
Weighted Sum of Negatives		0	-13	-13	-17	-7
Total		0	6	10	-2	22

Second Iteration.

In the second iteration, the modularity concept which had the highest positive value was taken as reference and the other generated concepts were compared with this. The KTH concept is not considered during the second iteration. And the same criteria abs weightage were considered. From the result, it was seen that the concept Forky, linearity, and simplicity had a negative result which indicated that the Modularity design is better than the other concepts and hence was chosen for further improvements.

Table 5: Pugh's matrix First iteration of concepts

Pugh Selection Matrix					
	Alternative Concepts				
Criteria's	**Weightage (1-5)**	**REFERENCE (Modularity)** 	**Forky** 	**Linearity** 	**Simplicity** 
Stability	5	0	0	0	-1
Safety	4	0	0	0	-1
Height Adjustment	4	0	0	0	-1
Ergonomic Design	3	0	-1	-1	-1
Self-1Leveling	4	0	-1	-1	-1
Cost	3	0	-1	-1	1
Portability	2	0	-1	-1	1
Compatibility	3	0	-1	0	-1
Accessory Mountings	4	0	-1	0	-1
Weight	4	0	-1	-1	1
Sum of Positives		0	0	0	3
Sum of Negatives		0	7	5	7
Sum of Same		0	3	5	0
Weighted Sum of Positives		0	0	0	9
Weighted Sum of Negatives		0	-23	-16	-27
Total		0	-23	-16	-18

CHAPTER 4: Analysis

This chapter includes the final design including detailed modeling and calculations. An analytical model, describing all the forces and loads acting on the mechanical structure along with verification of analytical model.

4.1 Final Design.

The selected concept 1 – Modularity was the most promising design amongst the rest and was considered for further improvement using Solid works 2012 CAD software. The final designed model was completed with YUMI robot and flex feeder mounting and their accessories to check if the any of the mounting interfered with any designed components.

Figure 17: Final design

The Figure 17 illustrates the final setup for the selected design. It consists of a main frame which acts as a supporting base for YUMI. The dimensions of the main frame is calculate based on the dimensions of YUMI's table mounting feature mentioned in section 2.1. The main frame is also supported by a aluflex structure as illustrated in Figure 17. The base structure is dimensioned and designed keeping in mind the least footprint it the pedestal could occupy at the same time ensuring it not too small which could result in the tipping over of the robot. This is done by considering the center of gravity of YUMI and verified later by finding out the COG of the entire system. It was ensured that the COG was as low as possible and as close to the center as possible. Also it was ensured that the final design did not affect the working range of YUMI's arms. The entire final design was majority based on components which are readily available in the market. Majority of the frame and base has been designed using aluminum profile frames available from Aluflex. This was to ensure easy prototyping of the pedestal at a later stage.

For the height adjustment and leveling mode, four actuators with a linear guide system have been designed, which are attached to the Aluflex base using connectors . The detailed design of the leg is mentioned in section 4.2.1. These four legs extend and retract in the desired direction independently based on the feedback from the electronic system and thus providing leveling and height adjustment features.

For the transportation mode, four swivel casters are being used. These casters are fixed on the base of the Aluflex using a mounting plate and with standard screws. These swivel casters are free to rotate about 360 degrees and consist of a break for emergencies. The wheels and mounting plate are chosen and designed in such a way that when the all the actuator legs are retracted up the pedestal would rest on the wheels and thus enabling the robot to be transported from one position to another.

Perforated aluminum sheets panels are being installed at the base section. This not only provides space for accessories to be placed but also provides screening for floors and allows passage of power chords and thus making the design look cleaner. Other ergonomic features such as handle has been provided for easy handling from the user.

The first concept is designed based on the idea of an electric height adjustment desk. Electric Motorized desk lift systems are tables which are powered by actuators used for height adjustment.

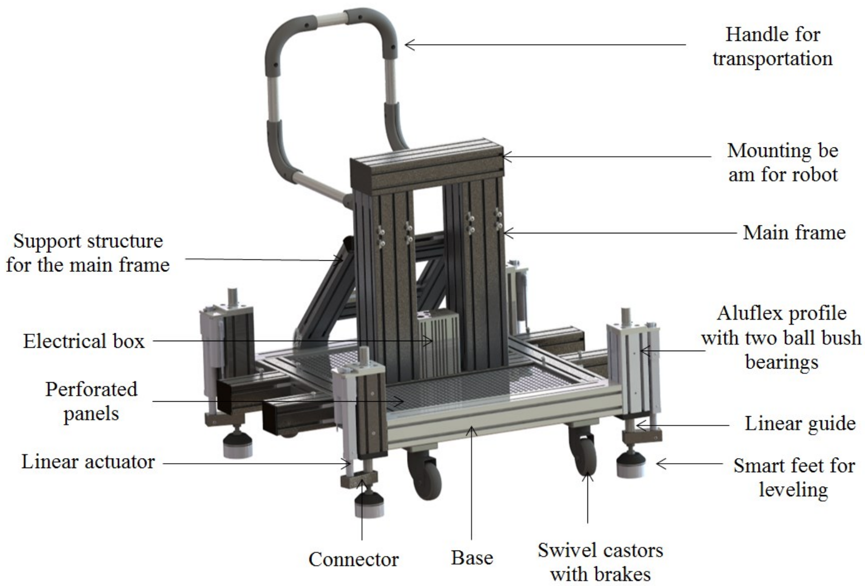


Figure 18: Final pedestal design

4.2 Detailed design

Some of the design aspects and features of important components are discussed in this section.

4.2.1 Smart feet

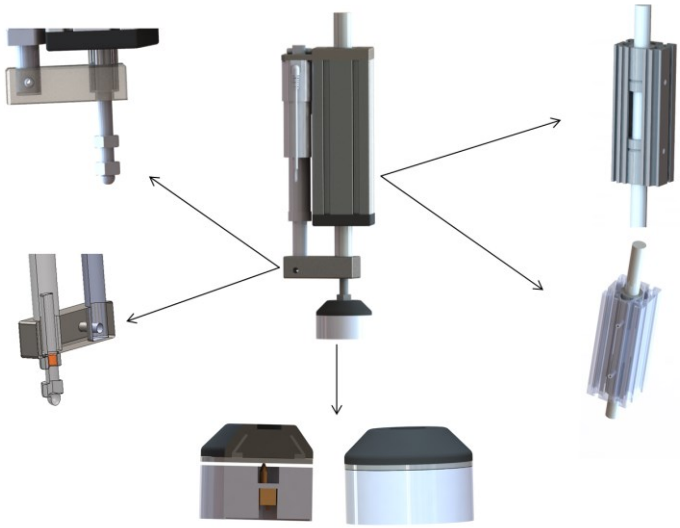


Figure 19: Smart feet

A four legged table will never have equal weight on all four legs. Also there might be a scenario where the pedestal will be leveled using only three legs and the fourth leg not touching the ground. Meanwhile leveling using a three adjustable legged table would result in an incompatible design considering the mounting accessories and current design along with compromising stability. So it was very important to come up with a force feedback mechanism to ensure that all the legs are in contact with the ground when the self-leveling mechanism is triggered. The smart feet consist of three major parts.

Base with Switch

The base of the foot consists of an adjustable foot that is suitable for structures of all kinds. The knuckle foot is used with combination with base plates and is fixed by inserting the threaded knuckle foot through the bore in the guiding shaft. The slope compensation of the knuckle foot is by means of a ball and socket as illustrated in Figure 20.

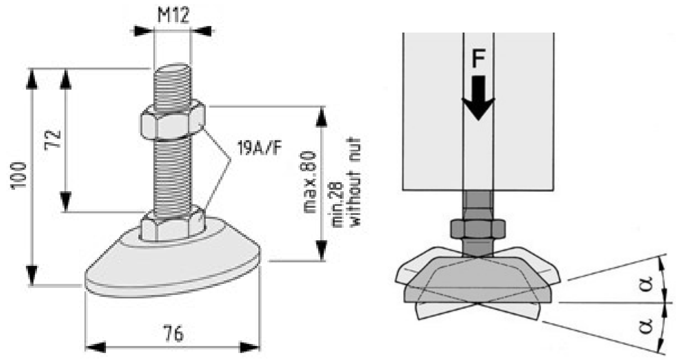


Figure 20: Kunckle foot

Later a fix-on component, as illustrated in Figure 21 is designed which allows a mechanical snap switch to be inserted on to the knuckle foot. The design consists of three slots for springs to be inserted and a main slot for the mechanical switch to be fixed. This is placed in such a way switch is sandwiched between the two parts so that on and off component of the switch is placed underneath the base of the knuckle foot as illustrated in Figure 19.

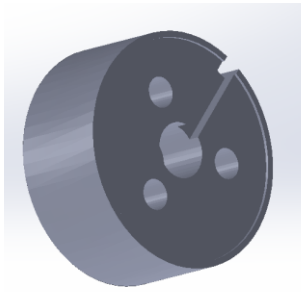


Figure 21: Base of smart feet where a switch is inserted

Aluflex profile with Ball bearing guide.

Ball-Bearing Guide Bush Units consist of sleeves accommodating the Ball Bushes. They form the guide elements for a ball-bearing guide bush. The Ball-Bearing Guide Bush Units are fixed in the cavities of Profiles 8 using grub screw DIN 914-M8. Through this unit a hardened and polished guiding shaft is inserted which acts together as a linear guide system.

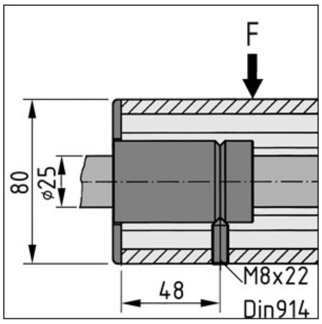


Figure 22: Diagramatic represeantion Ball bush bearing fixed by a grub screw

Bottom connector

The bottom connector is a small metallic component that acts as a clamping system holding the linear guild shaft and linear actuator push tube together. This component tightly clamps both the shaft and tube, thus making it move as one single unit. The shaft is inserted through a 25mm diameter hole with fit tolerances and is fixed axially through a nut. The linear actuator is fixed by inserting through a 21mm diameter hole and locked through but inserting a spring pin.

Figure 23: Bottom connector

4.2.2 Modular Design

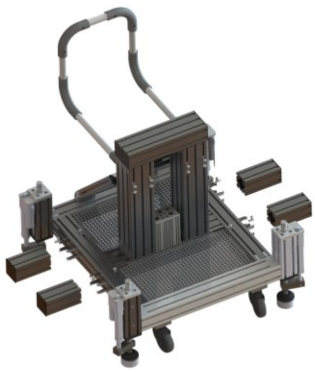


Figure 24: Diagram representing modularity feature of the pedestal

The use of Aluflex frames provides "modularity in design".This provides the the additional support on either side of the main frame structure to be added or removed based on the functionality/ requirement and thus used for multiple robot mountings.The additional support on either side of the pedesatl provides space to mount equipements such as Flex-Feeders and/or Scan-Feeders based on the use and thus it can be said the design is modular.

4.2.3 Spacious Design

Figure 25: Diagram showing spaciousness of the pedestal

The designing was carried out to ensure maximum space optimization. The perforated aluminum panel near the base allows space for accessories to be placed and also provides screening for floors and allows passage of power electric chords. Thus reducing the overall product to be less messy regarding wiring and power chords lying around the robot.

4.2.4 Electrical Box

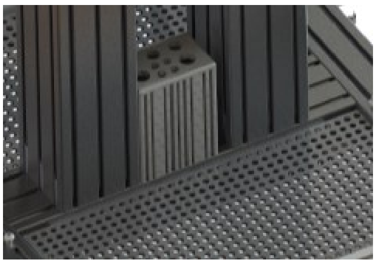


Figure 26: Electric box

Electronic box is designed to house the electronic components. With integrated cooling ribs and Aluflex based profile groove the box not only safeguards the electronic system but also enables easy attachment and fastening. The lid provided with bore grids on the inside ensures cables to be easily pulled out of the box.

4.2.5 Connections

A good amount of research was carried out to find alternatives to avoid welding or drilling on the pedestal. A special set of connectors were then selected from the market to suit the design's application.

Figure 27: Connectors used to fix frame in the pedestal

The special connector consists of a T-slot nut for securing heavy components and fastening two Aluflex frames. T-Slot Nuts are just inserted into the profile groove where they are secured in position by means of thrust pieces. And then standard ISO screws are used to fasten the two structures as illustrated in Figure 27.

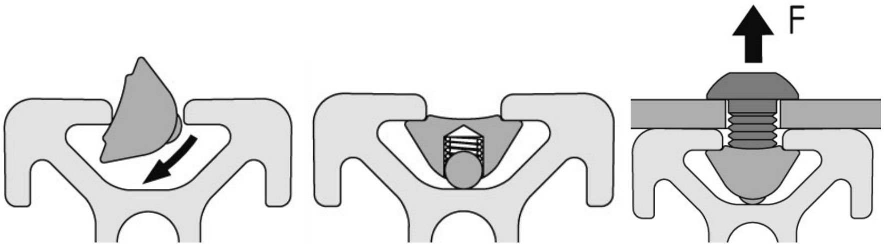


Figure 28: Diagramatic representation of inserting T-slot nut in the Aluflex profile

4.3 Calculations

4.3.1 Theoretical fall cases

The pedestal with smart feet has to be stable and to ensure YUMI's stability, theoretical fall cases were compiled based on the requirements put forward by ABB. For simplicity, YUMI and flex feeders have been hidden from the diagram but are considered for the calculation purposes. COG of the entire pedestal including feeders, and YUMI are obtained through CAD models by assigning the right kind of materials onto it and it is found to be almost near the center from x and y directions of the pedestal. For simplification, the COG is taken to be at the center of (x,y) plane for calculation purposes. Some of the cases are as follows. Each fall cases are calculated over two scenarios.

- When YUMI Robot is mounted on the pedestal.
- When both YUMI and four flex feeders are mounted on the pedestal.

The Robot and Flex feeders are included in all cases for all the calculations. For the equilibrium condition of these cases, it is considered that one of the reaction forces must be zero for the tipping over to occur.

Table 6: Value of parameters for Impluse calculations

Parameter	m_1 The weight from a person causing the force	m_2 YUMI and the pedestal	v_1 The velocity of the impacting force	v_2 The velocity of YUMI and pedestal before impact if force	v_3 The common velocity after collision
Value	20 kg	72 kg	0.5 m/s	0 m/s	0 m/s

A. When a load of 200 N is applied at a height of 1500mm on the Self leveling pedestal mounted on wheels, it must not tip over.
B. When YUMI is acted upon by an impulse of 7.5 Ns at a height of 1500mm sideways and from behind of the Self leveling pedestal mounted on feet, it must not tip over.
C. When YUMI is acted upon by an impulse of 10 Ns at a height of 1500mm and from the side of the Self leveling pedestal mounted on feet, it must not tip over.
D. When a load of 200 N is applied at a distance of 500 mm away the center of the Self leveling pedestal, mounted on feet, it must not tip over.

Impulse is the change of momentum of an object when a force is applied upon the object for an interval of time. With impulse, it is possible to calculate the change in momentum, and thus calculate the average impact force of a collision. This is very important to see if the pedestal with the Robot mounted would tip over, when acted by an impulse force.

From table (6) Impulse value is determined as follows:

$$\Delta p = m_1 v_1 + m_2 v_2 - (m_1 + m_2) v_3$$

(**Error! No sequence specified.**)

$$\Delta p = 10 N / s \qquad (2)$$

Case A:

For this case, it was considered that the pedestal is resting on the wheels and a force F is acting on the side. The requirement for case A is to ensure the pedestal can withstand a maximum force of 200 N. In this case, the moments about D is taken. When the point of contact D tips over, the reaction forces at D would be zero, Rd=0.

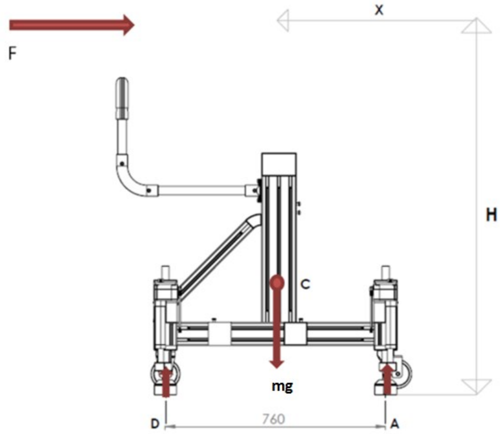


Figure 29: Fail case A where the force F is acting from behind

Considering moment about D, M_d =0

$$R_a = m * g \tag{3}$$

$$M_d = F * H + (m)g * DC - RA * AD \tag{4}$$

$$F_{foot/wheels} = \frac{(R_a * AD) - (m * g * DC)}{H} \tag{5}$$

The above equation can be used in order to find out the maximum allowable force F for the tipping over to occur. Taking into account the following dimensions and the weight of the pedestal, robot and the flex feeders, the following force values were calculated.

With YUMI mounted on:
- When pedestal resting on its feet: 306 N
- When pedestal is resting on its wheels: 210 N

With YUMI and flex feeders mounted on:
- When pedestal resting on its feet: 596 N
- When pedestal is resting on its wheels: 408 N

From the above value of the forces, it can be clear said that the pedestal satisfies the required conditions not to tip over.

Case B:

For this case, it was considered that an impulse acting from behind. The pedestal is assumed to be resting on the wheels. The requirement for case B is to ensure the pedestal can withstand an impulse of 10 Ns. The figure represents impulse acting on the pedestal. In this case, the moments about D is taken. The calculation is shown for the only pedestal mounted with YUMI, since if this case is satisfied, it would definitely satisfy pedestal mounted with YUMI and flex feeders as more the mountings, the heavier the system gets and it would be harder to tip it over. When the point of contact D tips over, the reaction forces at D would be zero, $R_d = 0$. The impulse value is determined by Equation 6.

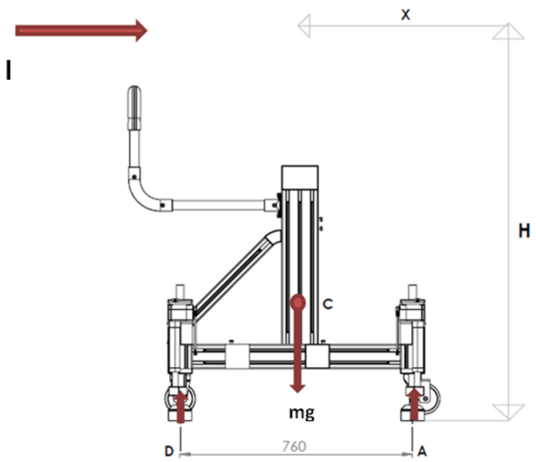


Figure 30: Fail case B where an impluse I is acting from behind

$$I = F * t$$
$$F = \frac{I}{t} \tag{6}$$

$$M_d = F * H_{\text{limit}} + mg * DC - RA * AD \tag{7}$$

$$H_{\text{limit}} = \frac{(-mg * DC) + (mg + AD)}{F} \tag{8}$$

Considering an impulse of 10 Ns for a time period of 0.25 seconds we get force value of 40 N. By calculating the force from the above equation we get the minimum height required for the pedestal to tip over sideways is about 11m which is very high compared to the current height of the pedestal with the robot mounted on it. Hence design is considered safe.

Case C:

For this case, it was considered that impulse was acting from the side and the pedestal was resting on the wheels. The requirement for case C is to ensure the pedestal can withstand an impulse of 10 Ns. The figure represents impulse acting on the pedestal. In this case, the moments about A is taken. The calculation is shown for the only pedestal mounted with YUMI, since if this case is satisfied, it would definitely satisfy pedestal mounted with YUMI and flex feeders. When the point of contact A tips over, the reaction forces at A would be zero, $R_a = 0$. The impulse value is determined by Equation 9.

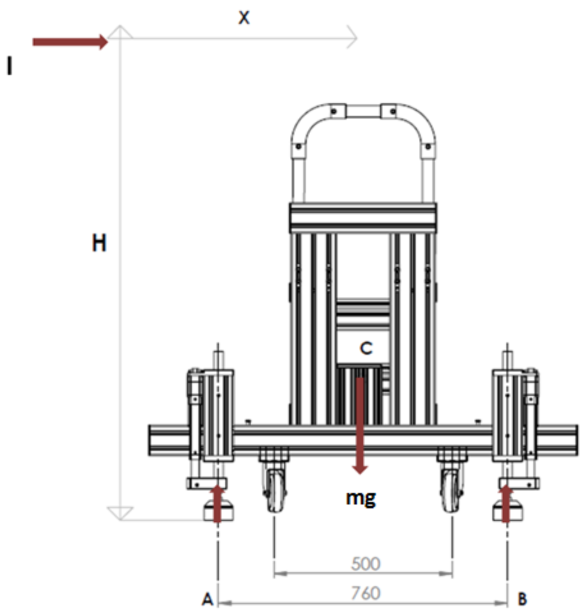


Figure 31: Fail case C where an impluse I is acting sideways

$$I = F * t$$

$$F = \frac{I}{t} \quad (9)$$

$$M_a = F * H_{limit} + mg * \mathrm{AC} - RA * AB \quad (10)$$

Considering an impulse of 10 Ns for a time period of 0.25seconds we get force value of 40 N. By calculating the force from the above equation we get the minimum height required for the pedestal to tip over sideways is about 7m which is very high compared to the current height of the pedestal with the robot mounted on it. Hence design is considered safe and would not tip over in any case.

Case D:

For this case, a load of F was applied at a distance 500 meters away from the center of the pedestal, mounted on feet .It should satisfy a condition of not tipping over. The requirement for case D is to ensure the pedestal can withstand a maximum force F which is basically the due the weight acting on the robots arm when completed in stretched out position. The calculation was shown for only pedestal mounted with YUMI, since if this case was satisfied, it would satisfy pedestal mounted with YUMI and flex feeders. In this case, the moments about D was taken. When the point of contact D tips over, the reaction forces at D would be zero, $R_d = 0$.

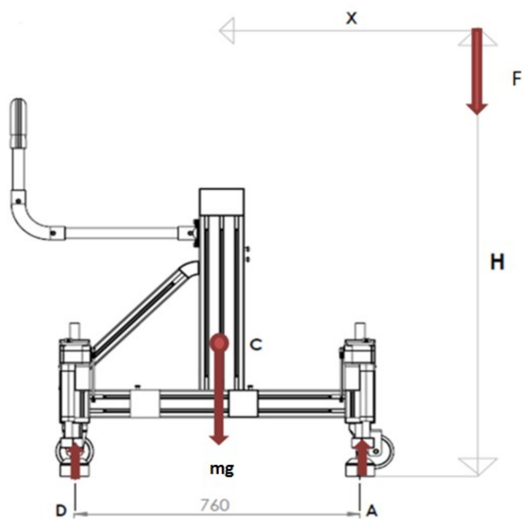


Figure 32: Fail case A where the force F is acting at a distance

Considering force equilibrium we have,

$$F + mg = R_a \quad (11)$$

$$M_d = F*(x + DC) + mg*DC - R_a*AD \quad (12)$$

The reaction force R_a is calculated and applied in the above Equation 11. From that equation the maximum force F needed to tip over the system. It was calculated to be around 500 N which is larger than the actual payload carrying capacity of YUMI which is about 0.5kg per arm (YUMI, 2016) and hence design is considered safe.

4.3.2 Frame design.

The frame designed for a particular purpose should not only provide necessary support to the components placed on it but also be strong enough to withstand shock, twist, vibrations and other stresses (Patel Vijaykumar V, 2012). One of the major requirements for the structure was to have very good horizontal and vertical stiffness along with satisfying criteria of being light weighed.

Another important requirement was to mount YUMI and other accessories on the frame so that it could be moved from one working location to another. The entire frame was built using Aluflex aluminum profiles to realize a modular structure and to avoid welding or drilling, a special set of inserts (mentioned in section 4.2.5). The Aluflex profile allows easy installation of individual frames together with the T-slot inserts provided by the company. The majority of the loads the structure must handle are as follows.

Table 7: Weight parameter Values

Loads	Component	Mass [kg]	Weight/Force [N]
M_1	YUMI	35	344
M_2	One Flex Feeder	27	265
Total			609 N

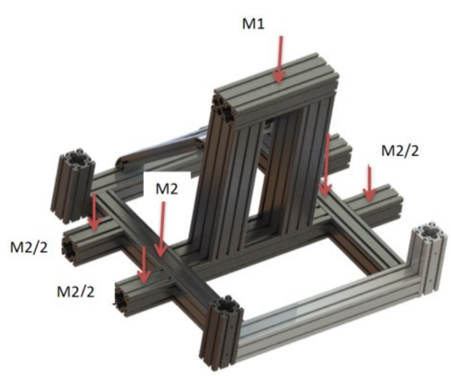
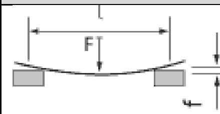
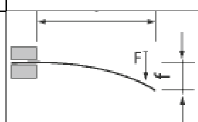
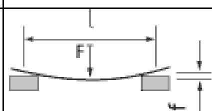


Figure 33: Frame structure of the pedestal

A bending stress analysis was carried out on the frame and by using a bending stress calculator provided on the Aluflex web page (item Industrietechnik, 2016), thus the deflection of the beams and stresses were calculated as shown in the Table 78. From the following table, it can be clearly seen that the obtained values of deflection and stresses are extremely low.

Table 8: Table representing bending stress

Aluflex Profile	Length in mm	Load	Applied force in N	Deflection in mm	Bending Stress X-axis in N/mm²	Bending Stress Y-axis in N/mm²
Profile 8 120x80 Natural E anodized aluminum	380		310	< 0.01	0.43	0.31
Profile 8 80x80 Natural E anodized aluminum	170		172.5	< 0.01	1.16	1.16
Profile 8 80x80 Natural E anodized aluminum	680		345	0.03	2.33	2.33

4.3.3 Connector design

The linear actuator and linear guide are connected through a connector which makes it possible to simultaneously move both of them. So it is important to do a FEM analysis.

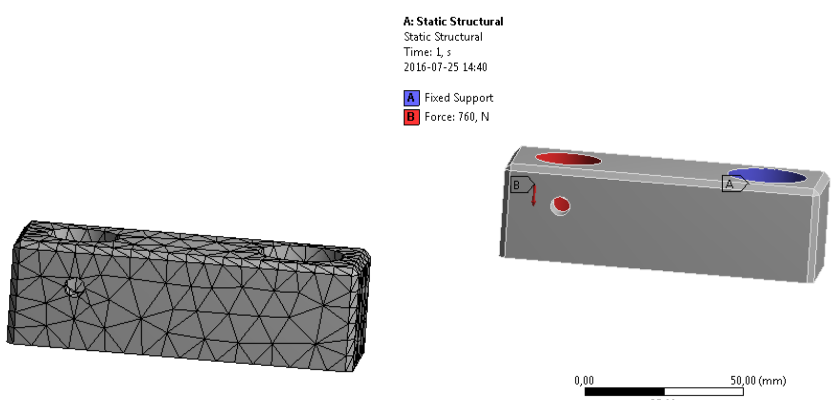


Figure 34(a): Meshing of the connector . (b) Applied forces on the connector

This part was checked for deformation as well as equivalent stress or Von mises stress. The model was imported to ANSYS 14.0. The foot acts as a support and takes all the load of the system, while in stationary mode. This load gets transferred to the linear actuator through the connector. So the walls where the linear guide is mounted through which the feet are connected are considered fixed and a force due to loads is applied on the wall through which the linear actuator is mounted via spring pins.

The deformation was analyzed in ANSYS. Seen in Figure 34, the foot acts as a support and takes all the load of the system, while in stationary mode. This load gets transferred to the linear actuator through the connector. So the wall (A) where the linear guide is mounted through which the feet are connected is considered fixed and a force due to loads is applied on the wall (B) through which the linear actuator is mounted. A force of magnitude 760 N was applied.

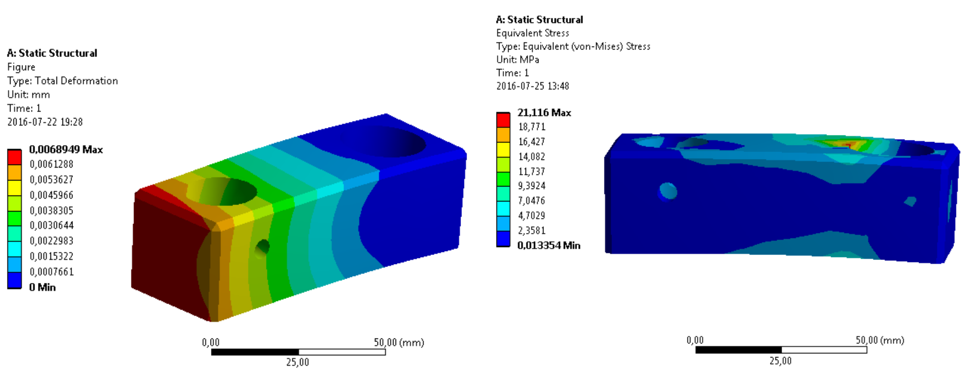


Figure 35(a): Total deformation. (b) Equivalent stress

Stiffness was calculated to be 110.3 kN/mm based on the maximum deformation of 6.8 µm. The max equivalent stress is situated at the wall B and is about 21 Mpa as seen in Figure 35b and the system is considered to be safe and will not deform under applied forces.

CHAPTER 5: Prototyping

This chapter includes the prototyping process of the final design, parts ordered from suppliers.

Prototyping of the design was carried out using different manufacturing processes. Majority of the parts were designed keeping in mind the standard components readily available in the market. In this way it was ensured that only a few components were manufactured from scratch and thus giving higher lead time for assembling the final product. CNC machines, lathe, and drilling tools were used to manufacture the bottom connector and connecting plate.3D printers were used to create smart feet.The majority of the parts were ordered from Aluflex and was assembled together.

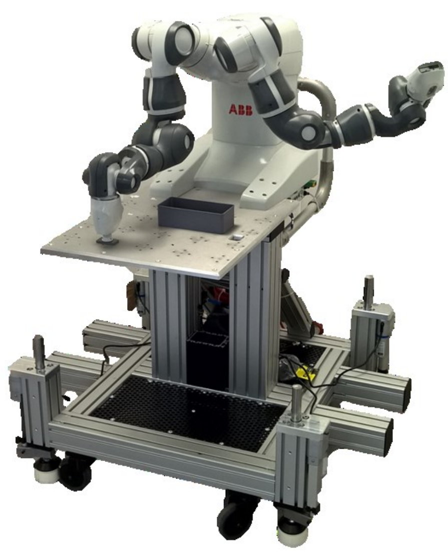


Figure 36: Final prototype of the pedestal

5.1 Smart feet

The smart feet were absolutely necessary to ensure all four legs are in contact with the ground. So instead of outsourcing manufacturing 3D printing was used and high density, high fill material was used to procure strong components. There 3D prints obtained were strong enough to handle the weight of the entire system.

Figure 37: 3D printed smart feet

5.2 Bottom connector

The bottom connector was to ensure the linear actuator tube and shaft move as one component. So the bottom connector acts more like a clamp. The bottom connector was manufactured by a local manufacturer called E-works with an AW-6082-SS4212 stainless steel. The bottom connector manufactured is illustrated in Figure 38.

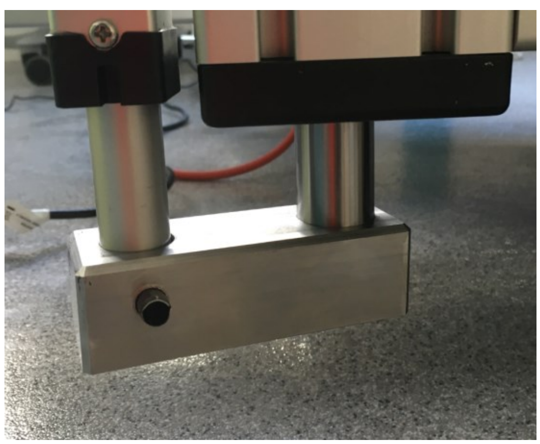


Figure 38: Manufactured bottom connector

5.3 Connecting plate

The connecting plate was to ensure the linear actuator is fixed on the Aluflex frame. So the bottom connector acts more like a clamp. The connecting plate was manufactured by a local manufacture called E-works with a SS-EN-10025-42004 stainless steel material and can be seen in Figure 39.

Figure 39: Manufactured connecting plate

CHAPTER 6: Electronics System

This chapter includes the designing and implementation of the self-leveling system using a microprocessor and complementing electrical hardware circuit. Electrical circuit designing and programming are presented in this section as well.

A self-leveling system is a system which can adjust itself and compensate for inclinations and unevenness on the working floor without any kind of user intervention. The above mechanism assists self-leveling. In this chapter the microprocessor and electrical hardware which would run the self-leveling, transitioning features from wheel to feet and height adjustment features on the pedestal.

6.1 Introduction

Arduino is an open source electronics based platform which is used for prototyping systems. The Arduino processor can take in input from the environment through sensors such as an accelerometer, gyroscopes etc. and convert into usage output by controlling physical elements such as lights, motors, actuators etc. The task in hand was to investigate and bring out a working self-leveling pedestal solution. Some of the tasks carried out are.

- Get an overview of the Arduino platform in general
- Develop an accelerometer reading system using the Arduino platform.
- Develop a motor controlling system using the Arduino platform.
    - Test the Arduino code for functionality.

6.2 Methodology

The entire mechanism is controlled by four motors SKF CAHB-10, self-locking actuators. These actuators consist for 24V DC motors which are run by spur gears are powered by a 24V power supply. The actuators which are mounted onto the bottom base frame consists of an extendable and retractable the push tube. These are controlled by an Arduino microcontroller which determines the movement of the actuators in the upward or downward direction and thus controlling the motors individually. For representation purpose, Arduino UNO is used in Figure 40. These large motors are controlled by the Arduino through motor drivers. A dual axis accelerometer is mounted on to the system as a sensor to measure the tilt of the lower base/platform. The data is read from the accelerometer which in turn is processed by the Arduino microprocessor and thus allowing the Arduino logic to control the motors to rotate in a clockwise or counterclockwise direction and thus moving them upwards or downwards. The potentiometer provided in these actuators help in indicating the position of the linear actuator at any given moment and thus assisting in the height adjustment. A switch is provided to control and initiate the self-leveling and height adjustment process. A schematic representation of the system controlling two motors and thus the actuators is illustrated in Figure 40. The figure is an example representing the schematics of the system and not the final setup of the system itself.

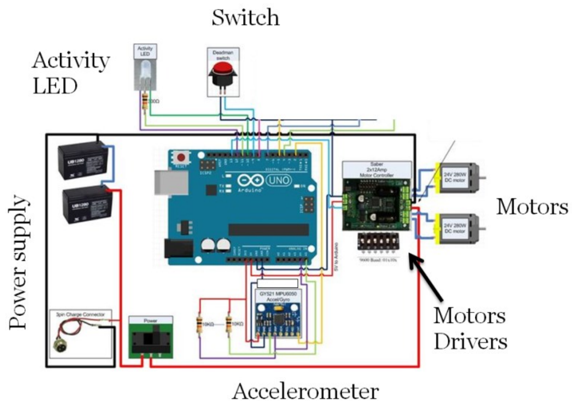


Figure 40: Diagrammatic representation of the circuit components

6.3 Electrical hardware

A simple schematic of the Arduino MEGA board connections to the accelerometer and motor drivers are illustrated in the Figure 41. Arduino (MEGA), voltage regulator, motor drivers (MD1 and MD2), ADXL 345 accelerometer (ACCL), PCB board are some of the major components in the circuit. Arduino MEGA and other accessories are being powered by a 24V, 7.5A power supply since the motors (M1, M2, M3, and M4) used along with this board need a higher power supply. And it is programmed via a universal serial bus (USB) connection. According to the SKF linear actuator data sheet, the motors are rated to 24V max. But the Arduino board itself runs on 5V. So it is important to have a voltage regulator having the capacity to bring down 24V to 5V, as the entire system is powered by the same power supply.

Figure 41 illutrates a simplified schemantics of electronics circuit board. Arduino Mega 2650 is the main processor of this circuit. All connections are made via a PCB board for easy connectivity. There are three major connections that are vital for its working for the system.

1. Accelerometer to MEGA - Accelerometer which is simple sensor which calcualted magnitute and direction of accelaration which can be later interpreted as an angle of tilt and orientation.The acceloremter has 6 pins which are connected to the Arduino Mega through SPI connection accordingly as follows.

Table 9: Pins slots on Accelerometer and on Arduino MEGA

Pins on Accelerometer	***Pins on Arduino***
CS	Pin 10

SDA	MISO - Pin 50
SDO	MOSI - Pin 51
SCL	SCK - Pin 52
VCC	5V
GND	Gnd

Figure 41 : Arduino MEGA SPI connections

2. Motor Driver connections - Two L298N Motor Driver Module Dual H Bridge are used in the circuit. Motor Drivers basically consists of electronic circuits that allows a particular voltage to be applied across a load in either direction. These are used to usually run the DC motors forward and backward. Each motor driver consistes of three power cables connecting to 24V, 5V and GND in the required order, two cables to the DC motors to obtain the desired direction and four communication cables connecting to the Arduino MEGA.

3. Voltage regulators- Voltage regulators are small devices which are designed to automatically maintain a constant voltage level in a system. In ths particular system The voltage regulator/convertor is used to obtain a regular DC voltage of 5V on its output while input is at 24V. For this, three power cables are connected to 24V, 5V and GND to bring down the voltage from power supply from 24V to 5V. The schematics of circuit is illustrated in figure

The potentiometers used in the SKF actuators are powered by 5V from the Arduino MEGA board and these assist in measuring the distance of the front hinge head of the push tube with respect to a reference position. There is a reduction in voltage due to the variation in resistance between two terminals. This reduction in voltage is read by an analog pin which signals the Arduino board to send a signal to the motors. The detailed working principle of the potentiometer is not included since it is out of scope for this thesis and hence excluded. The below figure illustrates the connection of only one potentiometer to the board for simplicity purpose. The final circuit will have four such connections, one for each actuator.

The accelerometer is powered by the onboard 5V power pin on the Arduino board. The accelerometer ADXL 345 is a 3 axis accelerometer which will send signals through the SPI pins on the Arduino board and can take up to 5V in and regulates it to 3.3V.

The contact switches on the smart feet (refer section 4.2.1 for the mechanical design) are connected to the Arduino board and signals of switching ON or OFF of these switches are read as signals through the pins on Arduino board.

Figure 42 illustrates a simplified schemantics of electronics circuit board. Arduino Mega 2650 is the main processor of this circuit. All connections are made via a PCB for easy connectivity.

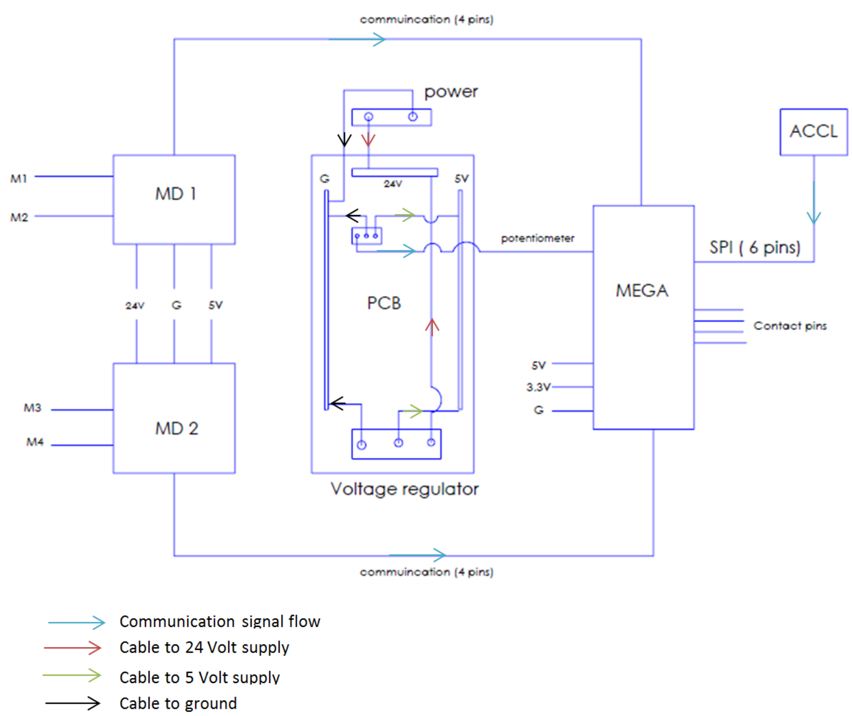


Figure 42: Simplified schematics of the electronic circuit

The flow of power signals within the entire system is illustrated in Figure 42. From the figure, it is clear that the entire system is powered by the 24V power supply and the voltage regulator installed brings down the voltage from 24V to 5V.

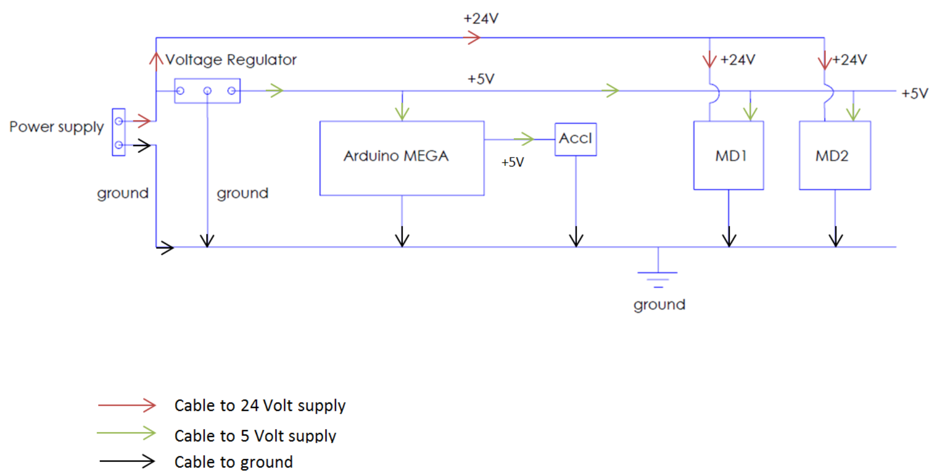


Figure 43 : Simplified power flow schematics in the electronic circuit

6.4 Arduino Platform

Arduino is an open source platform consisting of two components, namely the Arduino MEGA 2560 board and the Arduino IDE (Integrated Development environment). The microcontroller on the board can be programmed using a modified C language and specific Arduino commands. The Arduino MEGA illustrated in Figure 44 is designed to provide easy interaction with the user through interchangeable pin interface.

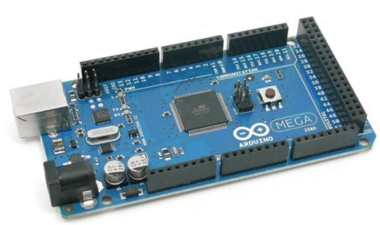


Figure 44: Arduino MEGA

Different classes are created for motors and sensor such as accelerometer on the source code. A simple logic flow chart was made before writing the code in order to form a framework for the logic. The flowchart illustrated in Figure 45 represents the flow of the code. All the libraries used are provided in the appendix along with the self-leveling sketch source code.

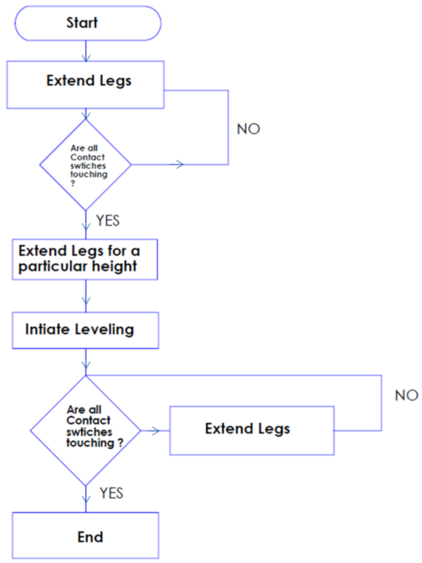


Figure 45: Flowchart of logic code

6.5 Accelerometer

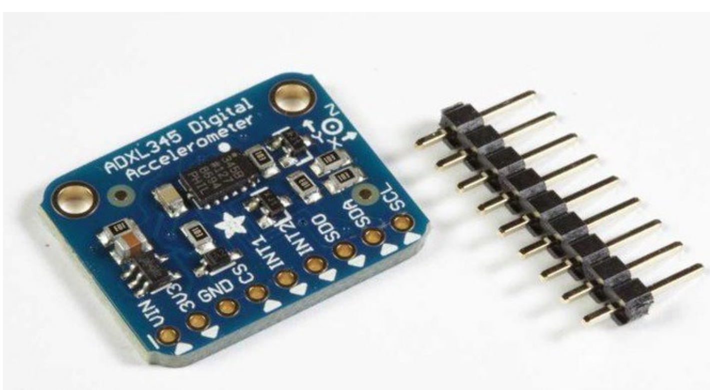


Figure 46 : ADXL 345 accelerometer

A triple axis accelerometer was selected, although only dual axis is needed for this particular logic. So one of the readings amongst the three (Z-axis) on the accelerometer was nullified using the code on IDE. An ADXL 345 accelerometer was chosen since it was relatively inexpensive and had a good sensitivity of about 420 mV/g which is mentioned in Appendix C. A sketch program was coded to read the accelerometer and determine its orientation. The digital data from the accelerometer is read by the Arduino MEGA board and converts it terms of the accelerometer of earth's gravity (G's) and angle of tilt [Appendix C].

The Arduino measures the voltage output of the accelerometer. The sensitivity of the accelerometer is 420mV/g indicates that 1G of acceleration is equal to 420 mV at the accelerometer output pin [Appendix C]. The pins read 5V in integral values between 0 to 1023 units, giving a resolution of:

$$\frac{5V}{1024} = 0.0048\, V\ per\ unit \qquad (13)$$

So the number of counts per G is calculated by the following method:

Simply put, 1g gives:

$$\frac{1024}{5} = 205\ counts \qquad (14)$$

Now,

$$\sin(1) \times 205 = 3.57 \qquad (15)$$

In other words, a tilt of 1 degree from horizontal will give a reading change of 3.57 counts.
Five degrees gives 18 counts.

When the tilting occurs, the measurement of acceleration is either a positive or negative value depending on given notation and can be tilted up to a range of -16G to +16G. The tilting angle can be calculated as a function of the ratio of measured acceleration with the acceleration due to gravity and is covered to degrees. Although the accelerometer has the capacity of measuring values ranging from -16G to +16G, a lower range of -1G to +1G is sufficient for this project and so the readings are limited to this range by manipulating the source code, attached in the appendix. According to author Manuel Juan Zeno (Zeno, 2011), tilting angle is calculated in accordance with the following function.

$$Tilting\ angle\ = \sin^{-1}(\frac{Measured\ acceleration\ in\ G}{1G} \times \frac{180}{\pi}) \qquad (16)$$

The following table illustrates the variation of tilt angle with respect to the acceleration due to gravity.

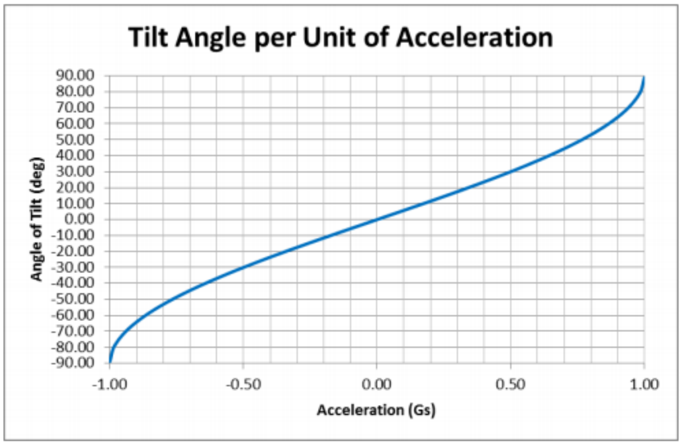


Figure 47: Tilting angle vs. acceleration

Filtering of noise in Data.

It is also very important to filter out the noise out of the 3-axis accelerometer data in real time. The filtering of noise is done by the method of 'Simple moving average'. In this method, the average values of acceleration from a constant number of readings are computed and the old reading is dropped out of numerator as new reading come in. this is done for eliminate unwanted noises in the readings of the accelerometer and to give a smoother curve. The averaging is done based on the following principle.

$$gX_{filt} = \frac{gX_i + gX_{i-1} + \cdots + gX_{i-(n-1)}}{n} \tag{17}$$

Where
N = represents the number of entries.
gX_{filt}= filtered accelerometer value.

Once filtering is done, the accelerometer is programmed to measure the changes in X and Y directions when the device is tilted in their respective axis. The Figure 48 illustrates the change in the reading when the acceleromter is kept on a falt surface. Figure 49a and 49b illustrates data reading when the accelerometer is tilted in x axis (blue) and Y axis (orange) respectively.

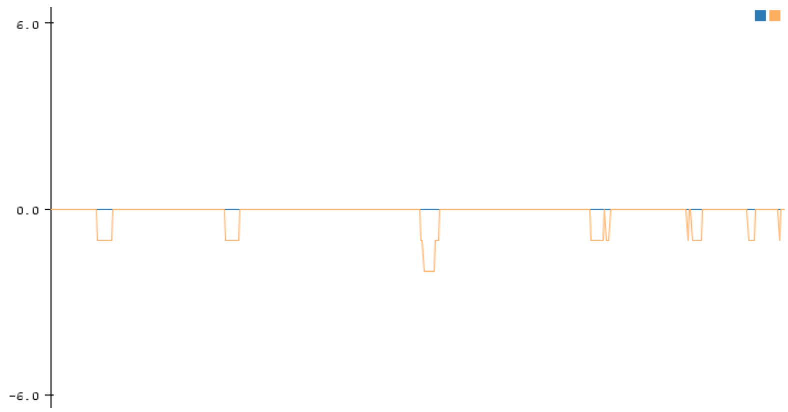


Figure 48: Accelerometer reading when it is kept on a flat surface.

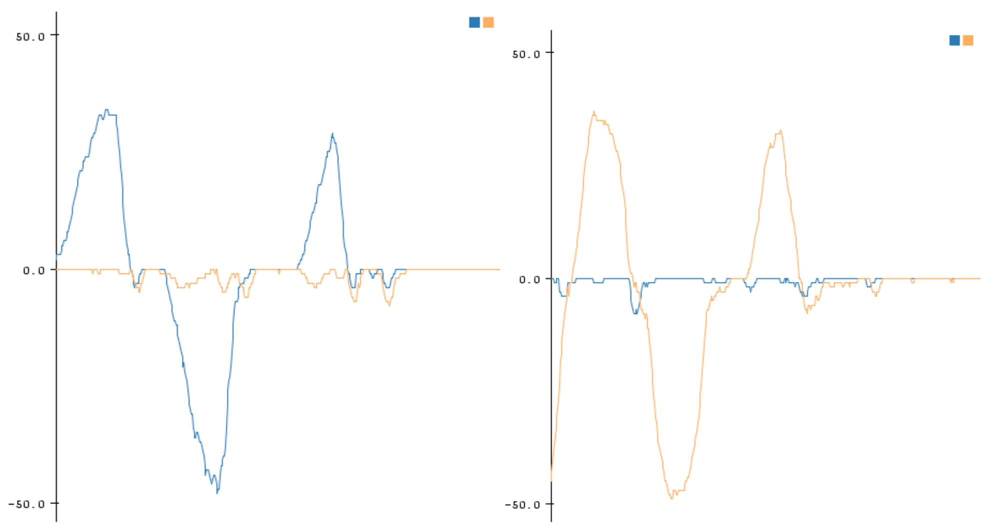


Figure 49a & b : Accelerometer data reading in only X axis and Y axis when it is moved in X and Y axis respectively

6.6 Arduino Sketch codes programming

The sketch logic code was written and revised on the Arduino IDE platform after considering all inputs, motors, accelerometer, mechanical limits, classes, and functions. Simple loops were created to accommodate the working logic of the self-leveling system and a detailed Sketch code is attached in the appendix.

A simple Sketch flow chart representing the flow of logic in the code is illustrated in the below figure.

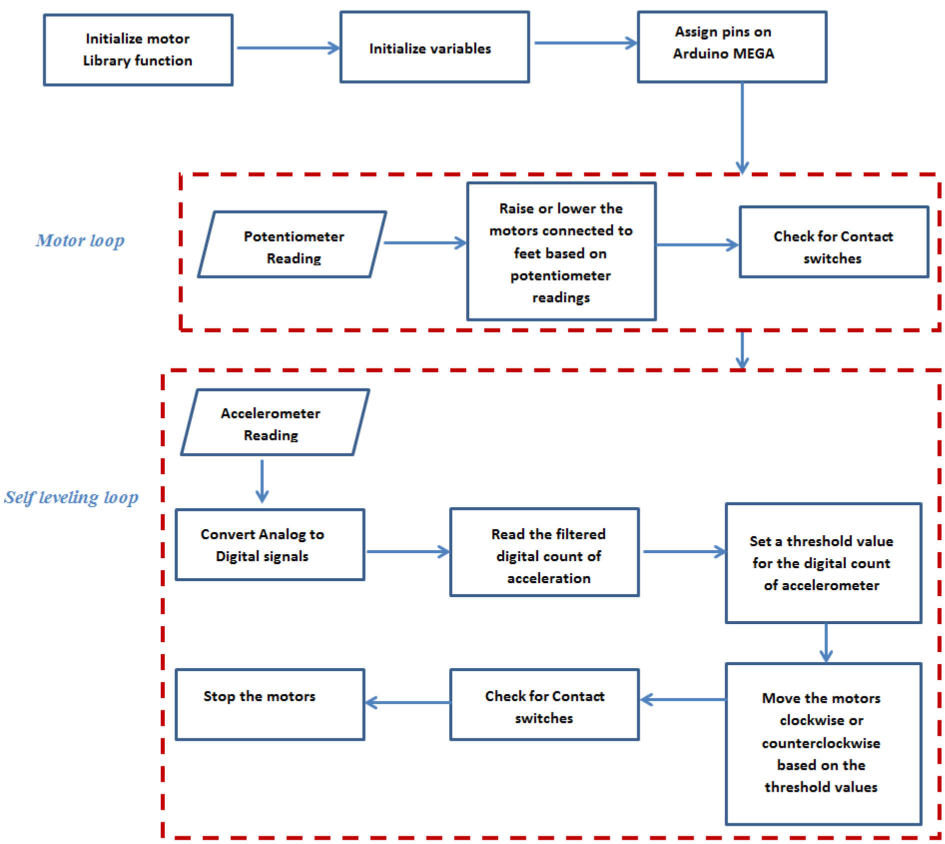


Figure 50 :Flowchart of logic in the entire self leveling syste

CHAPTER 7: Results

This chapter includes verification and analysis of the design model using and thus the results obtained.

7.1 Finite model analysis (FEM)

The next step was to carry out a structural statically analysis to understand the vertical and horizontal stiffness of the designed pedestal along with carrying out a modal analysis to understand the vibration natural frequency characteristics of the system. All the results were simulated on ANSYS 15.0 software and results are interpreted as follows.

Two main cases are considered and are as follows.

- The first case considered was when the pedestal is standing on its feet and all four legs are in contact with the floor and a static structural analysis was carried out to calculate the total deformation of the system along with Von Mises stress.
- The second case considered was when the pedestal is still on its feet with all four legs are in contact with the floor and a modal analysis was carried out in order to understand the natural frequency of the system.

Modal analysis is used to determine/study the response of the structure for a particular load. It can be used to determine the natural frequency of vibration of any structure. The natural frequency is the frequency of the structure at which it tends to vibrate when it is disturbed. And a mode shape is a specific pattern of a vibration of a structure to a specific frequency.

Dynamic analysis is not considered during the thesis, as the robotic arms are the only moving part when the Robot is functional .So considering the light weight of the dual arms compared to other components and actual payload carrying capacity of the arms (0.5 kilograms), it was decided under supervision that dynamic motion of the robot would not have a major impact on the pedestal itself and so was decided to be omitted from the thesis work.

In the case of the pedestal, vertical forces such as the weight of the robot, the weight of flex feeders, and the force due to the payload on the gripper are considered during analysis. Geometrical simplification of the model was done and a couple of features in the design was simplified. The pedestal was considered to be resting on its feet. The feet profile and the actuators were simplified for analysis, where complicated parts were replaced by simple rectangular profiles with no fillets or chamfers or other complications. The aluflex frame was kept as it is its oversimplification of the frame might not give accurate results considering the entire frame of the pedestal is made up of aluflex frames.

The pedestal is made up of different Aluflex aluminum profiles. And the feet assembly consisting of a bottom connector, linear actuator, connecting plate, linear guides and feet are simplified. The same material and structural properties are assigned to the simplified version.

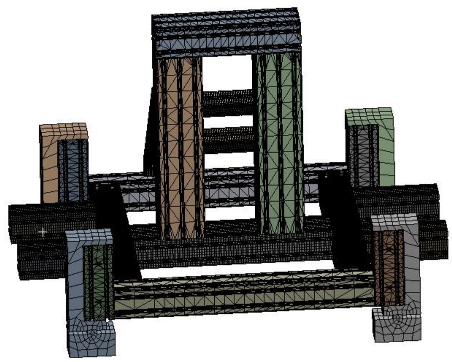


Figure 51: Meshing of the simplified pedestal for analysis

The simplified setup of the pedestal then meshes with tetrahedral shaped elements and the two cases was analyzed.

Case A: In this case, the pedestal is considered to be in standing mode. The feet are lowered causing the wheels to rise up. Thus the wheels have no contact with the ground. Thus the feet are considered to be fixed as illustrated in Figure 52. Furthermore, weight from the robot, weight due to the flex feeders is considered. An additional remote load at the grippers of the robotic arm due to payload is considered. All the values of loads acting are considered with a predefined value of 'Factor of a Safety' just as a precautionary step.

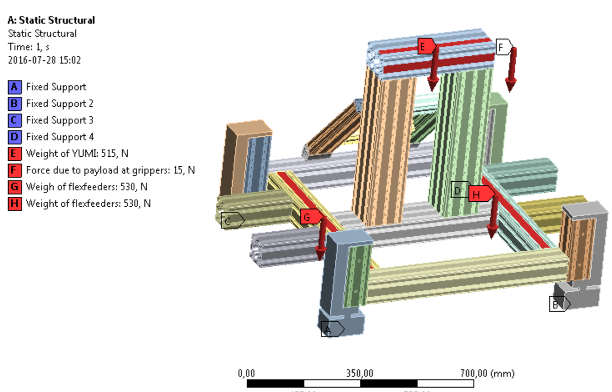


Figure 52: Applied forces on the simplified version of the pedestal

Interesting results were obtained showing a max deformation of about 0.05 mm and is principally found on the base where the Robot is mounted. Considering how small the value of deformation was, the design was considered safe. Figure 53 illustrates the deformation of the simplified pedestal for the applied load and force conditions.

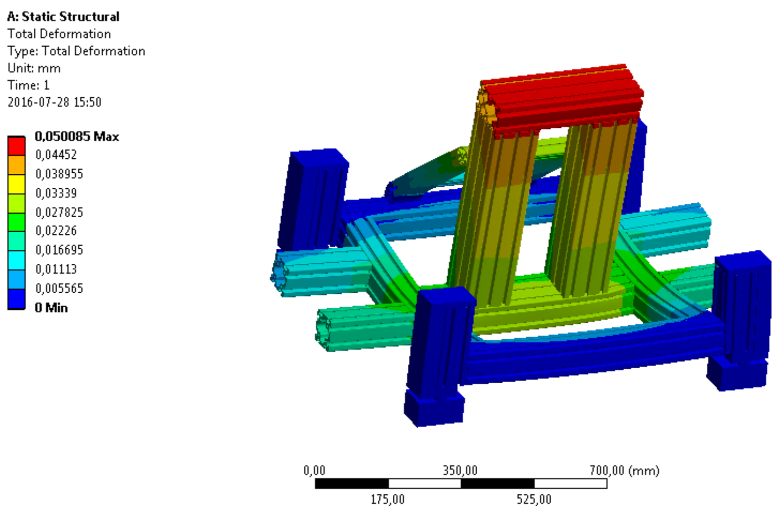


Figure 53: Total deformation of the simplified pedestal

Directional deformation in X and Y axis were calculated and were found to be at a max value 0.03mm and 0.001 mm which are extremely low and design cam be considered safe.

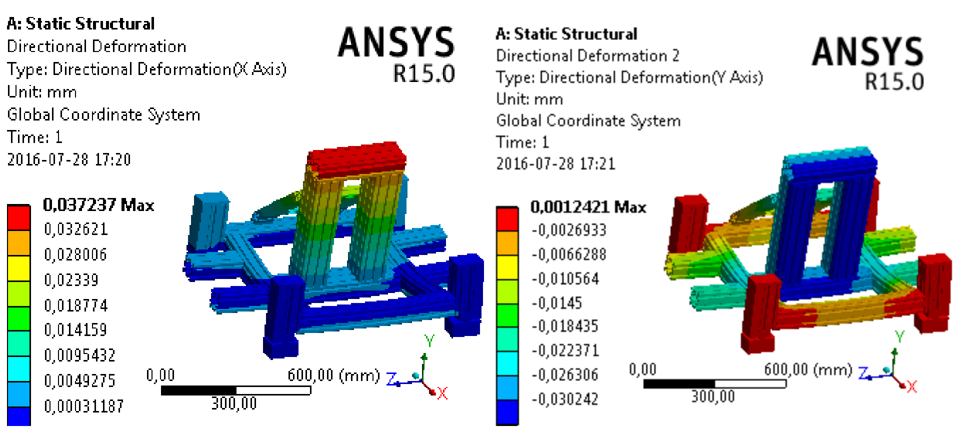


Figure 54(a): Directional deformation in x axis. (b) : Directional deformation in y axis

Stiffness has been an important criterion of the project. Good stiffness is an absolute necessity for the pedestal. Stiffness can be defined as the rigidity of an object or structure. It can be also explained as the extent to which an object resists deformation in response to an applied force.

$$Stiffness = k = \frac{F}{\delta} \qquad (6)$$

Where
F= Force applied.
δ = Deformation.

From the above equation horizontal and vertical stiffness were calculated and were found to be at a value of 53 KN/mm and 159 KN/mm when a force of 1590 N is applied. These values are far better than the requirement and therefore can be considered stable and stiff.

Case B: In this case, the pedestal is again considered to be in standing mode. The feet are lowered causing the wheels to rise up. Thus the wheels have no contact with the ground. Thus the feet are considered to be fixed. It is important to calculate the fundamental natural frequency. The mode of the fundamental/first natural frequency is illustrated in Figure 55. If a disturbance frequency of around the pedestal is 135Hz then the system will reach resonance. Resonance must be avoided to avoid failure. It was informed that the fundamental frequency of the robot was around ~ 5Hz since the robot while working is very stiff and is well built. Since the difference is the natural frequencies is quite high it can be concluded that the potential failure of the pedestal structure cannot be observed.

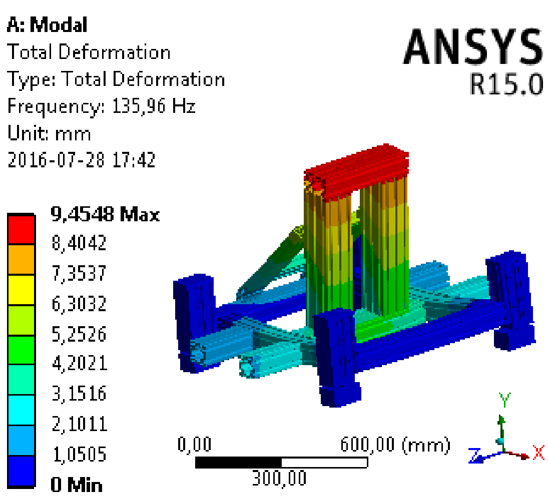


Figure 55: Fundamental Frequency

Different modal shapes (number of modes - six) were obtained to understand the behavior of the pedestal at different modes and can be observed from the Figure 56. And the values of these different modes can be seen from Figure 57.

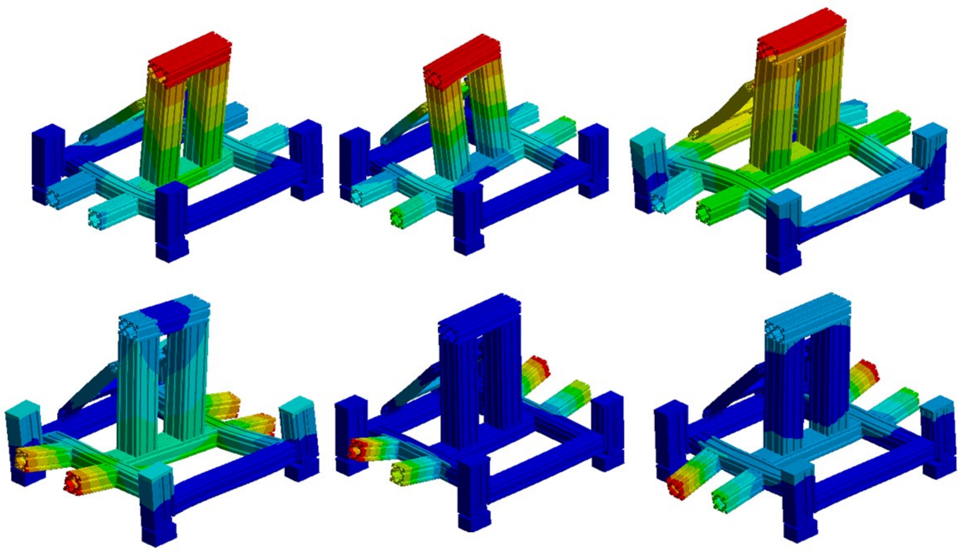


Figure 56: Modal Analysis for six different extracted modes

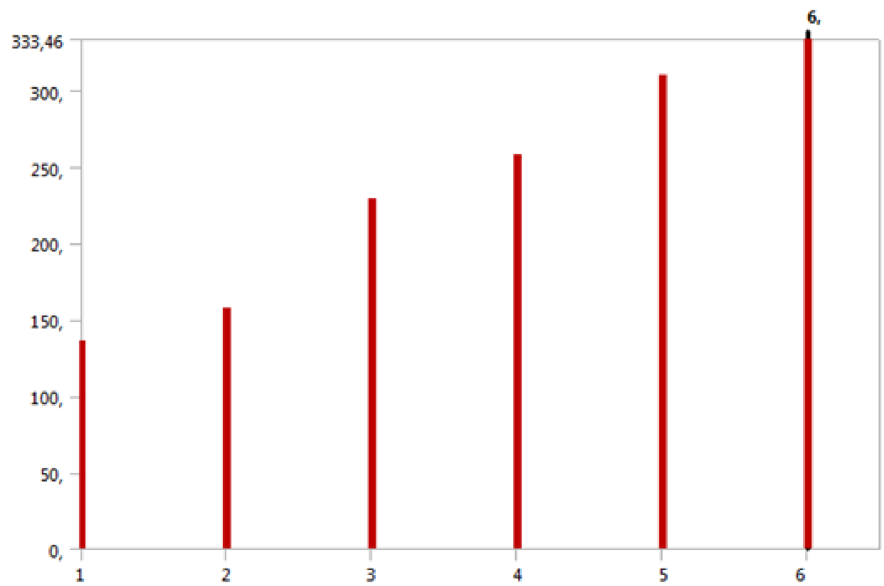


Figure 57: - Chart representing calculated mode frequencies

7.2 Results from the Physical testing.

The results from the prototype are illustrated in this section. One person was able to mount YUMIon the pedestal quite easily as per requirement and then some of the important criteria were tested.

Since a sophisticated equipment wasn't available, a bathroom weighing scale was used to measure force for the load cases. Factor of gravity $g = 10\ m/s^2$ was used for calculation purposes. Some of the observations and results were as follows:

- With the help of the Arduino system, the movements of the linear actuators were tested and found to be quite smooth and functional.
- It was possible to move around the pedestal quite easily by a single user as per requirement. It was found out that a force of 40N (corresponding to 4 kgs of on the scale) was sufficient to move it around.
- The pedestal with YUMI mounted on it was subjected to forces from behind and sideways as illustrated in Figure 58a & 58b, both when the system was on its feet and then on its wheels and satisfactory results were obtained. It was observed that the user wasn’t able to tip it over and thus confirming good stability and sturdiness.
- A higher payload was installed to the grippers of the robotic arm and was given a

sudden impulse to see if it would tip over. At no point did the pedestal tip over or lose contact and thus satisfying majority the requirements.

- Some minor tests were not possible to conduct on the pedestal due to time constraints and lack of availability of the robot and pedestal itself.

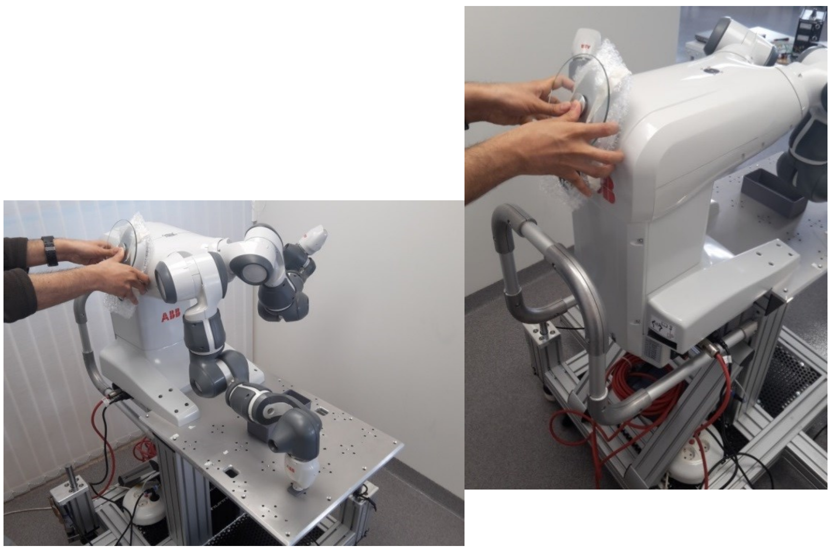


Figure 58a & 58b: Physcial testing of the prototype

7.3 Test results of the electronics system

In order to determine the self-leveling ability of the system, wiring was carried out and test runs were made. The time taken to accomplish leveling was never a criterion. Different sets of tests were conducted to check the height adjustment feature, automatic deployment of feet when in stationary mode along with the leveling feature.

A bubble leveler illustrates in Figure 59 was used to validate the outcome. The bubble leveler was initially used to check for the flatness of the floor on which the pedestal with YUMI was mounted on. Care was taken to ensure that the accelerometer mounting was tight and rigid, to secure unnecessary disturbances in the accelerometer reading. Also, it was made certain that the accelerometer was mounted to the pedestal in parallel so that when the pedestal with the circuit and accelerometer is placed on a flat surface it would give a flat reading.

Figure 59: Bubble leveler

It was found out that one of the potentiometers in the actuator was defective so another sketch code was generated where the motors were controlled based on delays and thus able to trigger motor and leveling loops based on time rather than position.

During the testing phase, positive results were obtained. Both the self-leveling system and deployment of feet when in stationary mode seems to be working. But multiple tests weren’t conducted due to time constraints. Once the leveling process was carried out, the bubble leveler was taken to check for the accuracy of the system. It was found to be around 90% accurate after a couple of trails where the bubble remained within the limit provided.

The results were satisfactory and the tests proved that the pedestal functions as it was intended.

CHAPTER 8: Discussions and Conclusion

8.1 Discussions

This master thesis project involved in the development of a complete functioning prototype. There are several interesting topics to be discussed. One major interesting aspect is the design of the mechanism itself. There was a debate to choose a three-legged actuator system over four legged in the concept evaluation phase. The three-legged actuating design would have been more stable; especially on an uneven floor over a four-legged design. In that scenario, there was no requirement for contact feedback smart feet, which is meant for giving a contact feedback. But the three-legged design had to be wide enough to ensure it would not tip over. If a three-legged design is considered, supporting a round top (assumption) there is a 120-degree space without any support and if weight is applied on a section with no support points, it would easily tip over. On the other hand, the four-legged design has more support points and forces acting would be proportionally smaller and has more advantage when it comes to tipping over. It also provided better options for placing accessories on the pedestal and a four-legged design was chosen.

Another important aspect to discuss is the use of linear guides along with the linear actuators. Linear guides provided unmatched stiffness and straightness to the movement of linear actuators. Using ball bush bearing not only assisted in the linear movement but also provided good friction for the rod movement. The design allowed good stiff motion which not only reinforced movement of feet up and down but also facilitated leveling. The setup was later checked for the good user interface, where users were asked to operate the setup and positive feedback in terms of mobility, mounting the robot and using the system were obtained. The perforated panel at the bottom allowed inserting the messy wiring, router, and cables which made the YUMIsetup cleaner and less messy. The robust handle allowed easy movement of the robot from one working station to another. The pedestal also gave a good ground clearance.

A modular design was achieved which allowed the easy dismantling of components based on requirement and functionality. A height adjustment of about 80mm was able to be achieved. Mounting facilities were provided for a wide range of equipment and accessories. The pedestal with the YUMIand flex-feeders has final dimensions of about 1100 x 830 x 1400 (in mm) and has final dimensions of about 1100 x 830 x 1400(in mm) without the flex-feeders. The pedestal can pass through the majority of the doorways since the dimensions are within the industrial doorway standards.

The 3D printed feet were quite strong and stiff but since it is made up of plastic material it will deform after continued usage. So it would be advisable to order metallic machined components in order to ensure durability during the course of usage.

The design could have been improved by connecting the feet linearly aligning with the actuator push tube rather than the linear guide tube. This would have been a good feature as it would not have any impact on the bottom connector which might be subjected to bending. But due to manufacturing constraints and time restrictions it was decided to go with the current method of mounting the feet. This is something which can be carried forward for newer versions of the pedestal. By eliminating minor faults in the design a more compact design can be achieved.

The calculations proved that the pedestal with the robot mounted can indeed withstand forces and an impulse of 10 Ns. These values were decided based on discussions with the project supervisors, but a further investigation is needed to clearly analyze what kind of impulse and forces can be expected in the real working scenario. The MATLAB calculations also prove that the pedestal will not tip over for different cases and thus verify the results.

The results from analysis were satisfactory. The ANSYS static structural analysis and MODAL analysis gave insights into the behavior of the pedestal under different simulated conditions. A maximum deformation of about 0.04 mm was observed which gave good stiffness, both vertically as well as horizontal and thus confirming the stability of the pedestal. A large gap was discovered with the fundamental natural frequency of the system and robot and thus confirming no possible scenario to reach resonance.

There were a lot of issues while setting up electronics hardware. Since the author was not experienced in the field of electronics it was hard to check for errors and debug them. Due to which a couple of microprocessors were burnt. It was observed that the reason behind these failing Arduino boards and motor drivers were because of short circuiting and also weak heat transfer capability of motor drivers. Also, an interesting error was found in one of the SKF actuators, where the mechanical limit switch was found to be defective which led to overheating in the circuit. When the push tube of the actuator reached the limit upward, failed to stop causing the motor to push further causing a max current of 4A to flow through it but the motor drivers can handle 2A, does burning the motor drivers. Since it was a factory defect, it was sent to SKF for replacement and so only limited tests were conducted before the actuators were sent.

A robust and compact prototype was built which ensured all desired functionalities established during the thesis work.

8.2 Conclusions

YUMI is a collaborative robot which allows a user to perform collaborative work while working on industrial floors. The master thesis project aimed to design a height adjusting and self-leveling system with deployable feet mechanism. Although the main focus of the thesis was revolving around the mechanical design aspect, work was carried out in the electronics system as well to achieve a functioning prototype. For this proposal, a conceptual working prototype was manufactured and analyzed. The pedestal designed met all the requirements. The design also ensured that it was compatible with the design of YUMI. Tests were conducted to ensure results matches the requirements and it satisfies all the requisites of the customer. The design of the pedestal is stable and robust and had very good stiffness.

CHAPTER 9: Future Work

This chapter includes the future work and recommendations for improvements and thus for better outcomes.

The master thesis is concluded with the good outcome but there is always scope for improvements. There are a lot more opportunities and areas where improvements can be expected for better versions of the product and some of them are mentioned below.

- Perform a rigid dynamic model analysis for better results.
- Replace the 3D printed parts with metallic components for more durability.
- Professional electrical hardware installation would ensure there are not issues regarding the wiring and thus would fix unexpected errors in the electronics system.
- Setup a better electrical hardware on a PCB panel, making it more compact.
- The operation of the system with tablet PC application / flex pendent.
- Scope for further optimization of structural design for improved compactness.
- Thorough testing of the prototype on tilted surfaces.
- Provide instructions manual for the end user for easy installation and for operating the system.

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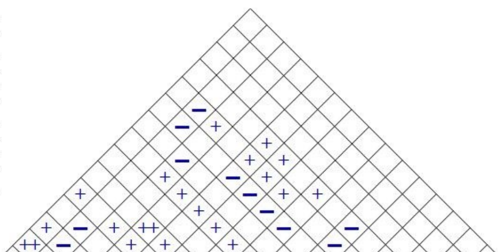
Appendix A- QFD

This section includes an appendix which includes QFD – Quality Functional deployment which presents information used to build a house of quality that translated customer requirements to functionality requirements.

Title: ABB Self Leveling mobile Pedestal for Robots
Author: Roshan Arun N.S
Date: 2016-02-20
Notes:

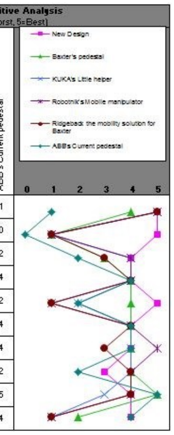
Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



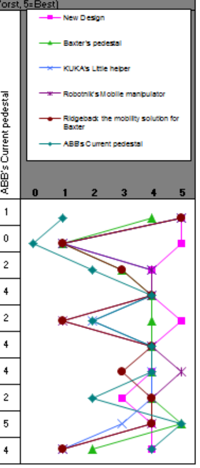
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Height adjustment of Pedestal	Weight of pedestal	Width of Pedestal	Material selection	Ergonomic Design	Easy manufacturability or mass productability	Safety	Design compatible with the design of Robot	Self leveling features on the pedestal	Number of moving parts	Manual power for moving the pedestal	Modular Design for addtional mountings			
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▼	▼	x	x	x	▲	x	x	▼	▼	x			
1	9	12,5	5,0	Mobility	Θ	Θ	O	O	Θ	O	▲	Θ	Θ	Θ	O	Θ			
2	9	12,5	5,0	Self Leveling	O	Θ			▲	▲	Θ	O	Θ	O		▲			
3	9	12,5	5,0	Stability and safety	O	O		O	O		Θ	O		Θ	Θ				
4	9	7,5	3,0	Easy to operate	▲				▲		▲	Θ	Θ	O	Θ	▲			
5	9	10,0	4,0	Easy installation of Robot and other accessories					Θ	O	O	Θ				Θ			
6	9	10,0	4,0	Safe to use	O	▲			O		Θ	O		O	O				
7	9	7,5	3,0	Spaceoptimized	Θ	O	Θ		Θ		Θ	Θ	Θ	▲	O	▲			
8	9	7,5	3,0	Ergonomic	O			O	Θ			Θ	Θ	O		O			
9	9	10,0	4,0	Portability/ Easy shipment	O	Θ	O		O					O					
10	9	10,0	4,0	Height Adjustment	Θ	▲			O			O							
				Target or Limit Value															
				Difficulty (0=Easy to Accomplish, 10=Extremely	4	4	3	5	6	6	5	4	6	7	2	4			
				Max Relationship Value in Column	9	9	9	3	9	3	9	9	9	9	9	9			
				Weight / Importance	435,0	395,0	135,0	97,5	485,0	80,0	432,5	540,0	427,5	375,0	270,0	252,5			
				Relative Weight	11,1	10,1	3,4	2,5	12,4	2,0	11,0	13,8	10,9	9,6	6,9	6,4			

Competitive Analysis (0=Worst, 5=Best)

Row #	New Design	Baxter's pedestal	KUKA's Little helper	Robotnik's Mobile manipulator	Ridgeback the mobility solution for Baxter	ABB's Current pedestal
1	5	4	5	5	5	1
2	5	1	1	1	1	0
3	4	3	4	4	3	2
4	4	4	4	4	4	4
5	5	4	2	1	1	2
6	4	4	4	4	4	4
7	4	4	4	5	3	4
8	3	4	4	4	4	2
9	4	5	3	4	4	5
10	4	2	1	1	1	4



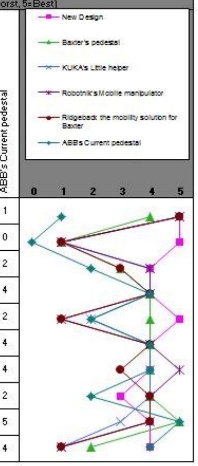
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Height adjustment of Pedestal	Weight of pedestal	Width of Pedestal	Material selection	Ergonomic Design	Easy manufacturability or mass productability	Safety	Design compatible with the design of Robot	Self leveling features on the pedestal	Number of moving parts	Manual power for moving the pedestal	Modular Design for addtional mountings				New Design	Baxter's pedestal	KUKA's Little helper	Robotnik's Mobile manipulator	Ridgeback the mobility solution for Baxter	ABB's Current pedestal
				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitive Analysis (0=Worst, 5=Best)					
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▼	▼	x	x	x	▲	x	x	▼	▼	x									
1	9	12,5	5,0	Mobility	Θ	Θ	O	O	Θ	O	▲	Θ	Θ	Θ	O	Θ				5	4	5	5	5	1
2	9	12,5	5,0	Self Leveling	O	Θ			▲	▲	Θ	O	Θ	O		▲				5	1	1	1	1	0
3	9	12,5	5,0	Stability and safety	O	O		O	O		Θ	O		Θ	Θ					4	3	4	4	3	2
4	9	7,5	3,0	Easy to operate	▲				▲		▲	Θ	Θ	O	Θ	▲				4	4	4	4	4	4
5	9	10,0	4,0	Easy installation of Robot and other accessories					Θ	O	O	Θ				Θ				5	4	2	1	1	2
6	9	10,0	4,0	Safe to use	O	▲			O		Θ	O		O	O					4	4	4	4	4	4
7	9	7,5	3,0	Spaceoptimized	Θ	O	Θ		Θ		Θ	Θ	Θ	▲	O	▲				4	4	4	5	3	4
8	9	7,5	3,0	Ergonomic	O			O	Θ			Θ	Θ	O		O				3	4	4	4	4	2
9	9	10,0	4,0	Portability/ Easy shipment	O	Θ	O		O					O						4	5	3	4	4	5
10	9	10,0	4,0	Height Adjustment	Θ	▲			O			O								4	2	1	1	1	4



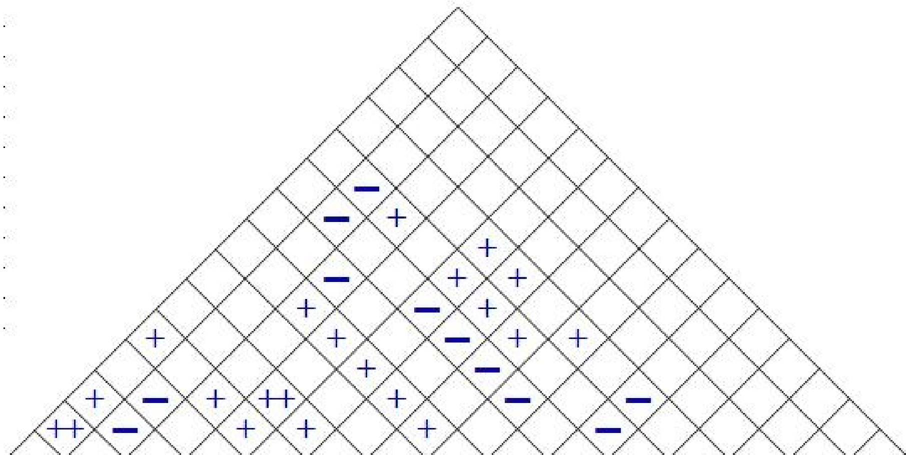
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column # → / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▼	▼	x	x	x	▲	x	x	▼	▼	x			
				Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Height adjustment of Pedestal	Weight of pedestal	Width of Pedestal	Material selection	Ergonomic Design	Easy manufacturability or mass productability	Safety	Design compatible with the design of Robot	Self leveling features on the pedestal	Number of moving parts	Manual power for moving the pedestal	Modular Design for addtional mountings			
1	9	12,5	5,0	Mobility	Θ	Θ	O	O	Θ	O	▲	Θ	Θ	Θ	O	Θ			
2	9	12,5	5,0	Self Leveling	O	Θ			▲	▲	Θ	O	Θ	O		▲			
3	9	12,5	5,0	Stability and safety	O	O		O	O		Θ	O		Θ	Θ				
4	9	7,5	3,0	Easy to operate	▲				▲		▲	Θ	Θ	O	Θ	▲			
5	9	10,0	4,0	Easy installation of Robot and other accessories					Θ	O	O	Θ				Θ			
6	9	10,0	4,0	Safe to use	O	▲			O		Θ	O		O	O				
7	9	7,5	3,0	Spaceoptimized	Θ	O	Θ		Θ		Θ	Θ	Θ	▲	O	▲			
8	9	7,5	3,0	Ergonomic	O			O	Θ			Θ	Θ	O		O			
9	9	10,0	4,0	Portability/ Easy shipment	O	Θ	O		O					O					
10	9	10,0	4,0	Height Adjustment	Θ	▲			O			O							
				Target or Limit Value															
				Difficulty (0=Easy to Accomplish, 10=Extremely	4	4	3	5	6	6	5	4	6	7	2	4			
				Max Relationship Value in Column	9	9	9	3	9	3	9	9	9	9	9	9			
				Weight / Importance	435,0	395,0	135,0	97,5	485,0	80,0	432,5	540,0	427,5	375,0	270,0	252,5			
				Relative Weight	11,1	10,1	3,4	2,5	12,4	2,0	11,0	13,8	10,9	9,6	6,9	6,4			

Competitive Analysis (0=Worst, 5=Best)

Row #	New Design	Baxter's pedestal	KUKA's Little helper	Robotnik's Mobile manipulator	Ridgeback the mobility solution for Baxter	ABB's Current pedestal
1	5	4	5	5	5	1
2	5	1	1	1	1	0
3	4	3	4	4	3	2
4	4	4	4	4	4	4
5	5	4	2	1	1	2
6	4	4	4	4	4	4
7	4	4	4	5	3	4
8	3	4	4	4	4	2
9	4	5	3	4	4	5
10	4	2	1	1	1	4



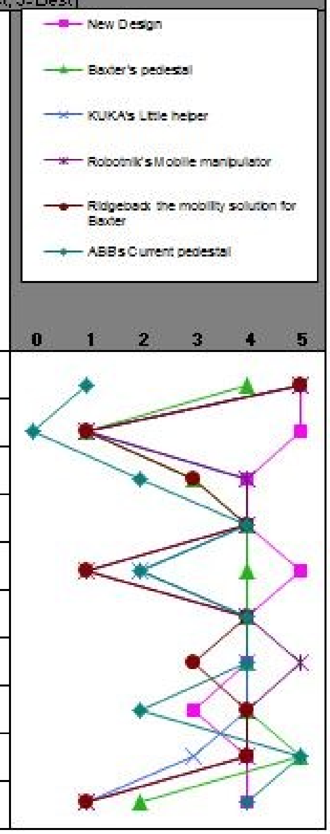
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Height adjustment of Pedestal	Weight of pedestal	Width of Pedestal	Material selection	Ergonomic Design	Easy manufacturability or mass productability	Safety	Design compatible with the design of Robot	Self leveling features on the pedestal	Number of moving parts	Manual power for moving the pedestal	Modular Design for addtional mountings
1	9	12,5	5,0	Mobility	Θ	Θ	O	O	Θ	O	▲	Θ	Θ	Θ	O	Θ
2	9	12,5	5,0	Self Leveling	O	Θ			▲	▲	Θ	O	Θ	O		▲
3	9	12,5	5,0	Stability and safety	O	O		O	O		Θ	O		Θ	Θ	
4	9	7,5	3,0	Easy to operate	▲				▲		▲	Θ	Θ	O	Θ	▲
5	9	10,0	4,0	Easy installation of Robot and other accessories					Θ	O	O	Θ				Θ
6	9	10,0	4,0	Safe to use	O	▲			O		Θ	O		O	O	
7	9	7,5	3,0	Spaceoptimized	Θ	O	Θ		Θ		Θ	Θ	Θ	▲	O	▲
8	9	7,5	3,0	Ergonomic	O			O	Θ			Θ	Θ	O		O
9	9	10,0	4,0	Portability/ Easy shipment	O	Θ	O		O					O		
10	9	10,0	4,0	Height Adjustment	Θ	▲			O			O				



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
▲	▼	▼	x	x	x	▲	x	x	▼	▼	x			
Height adjustment of Pedestal	Weight of pedestal	Width of Pedestal	Material selection	Ergonomic Design	Easy manufacturability or mass productability	Safety	Design compatible with the design of Robot	Self leveling features on the pedestal	Number of moving parts	Manual power for moving the pedestal	Modular Design for additional mountings			
Θ	Θ	O	O	Θ	O	▲	Θ	Θ	Θ	O	Θ			
O	Θ			▲	▲	Θ	O	Θ	O		▲			
O	O		O	O		Θ	O		Θ	Θ				
▲				▲		▲	Θ	Θ	O	Θ	▲			
				Θ	O	O	Θ				Θ			
O	▲			O		Θ	O		O	O				
Θ	O	Θ		Θ		Θ	Θ	Θ	▲	O	▲			
O			O	Θ			Θ	Θ	O		O			
O	Θ	O		O					O					
Θ	▲			O			O							

Competitive Analysis
(0=Worst, 5=Best)

New Design	Baxter's pedestal	KUKA's Little helper	Robotnik's Mobile manipulator	Ridgeback the mobility solution for Baxter	ABB's Current pedestal
5	4	5	5	5	1
5	1	1	1	1	0
4	3	4	4	3	2
4	4	4	4	4	4
5	4	2	1	1	2
4	4	4	4	4	4
4	4	4	5	3	4
3	4	4	4	4	2
4	5	3	4	4	5
4	2	1	1	1	4



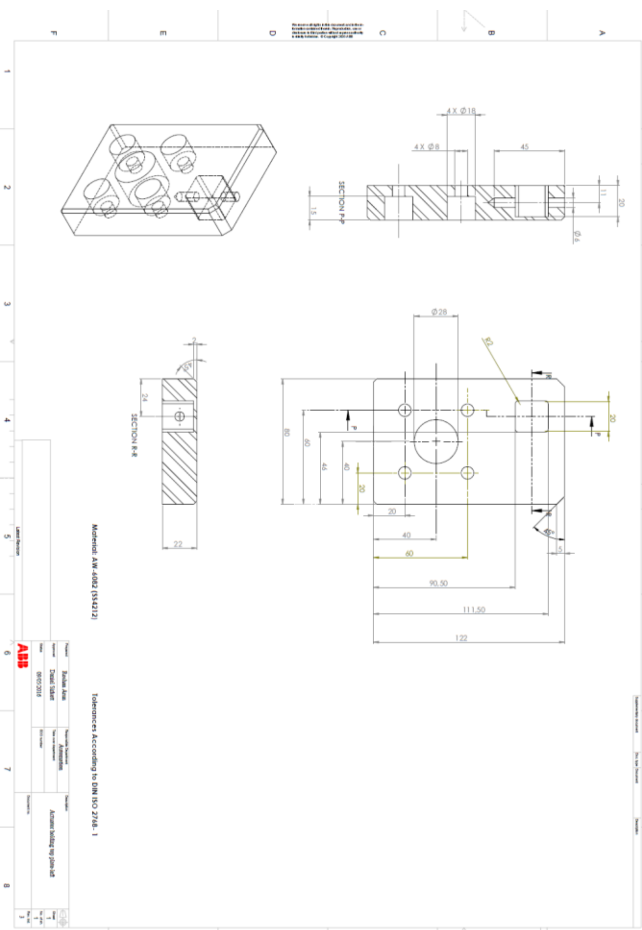
Target or Limit Value															
Difficulty (0=Easy to Accomplish, 10=Extremely	4	4	3	5	6	6	5	4	6	7	2	4			
Max Relationship Value in Column	9	9	9	3	9	3	9	9	9	9	9	9			
Weight / Importance	435,0	395,0	135,0	97,5	485,0	80,0	432,5	540,0	427,5	375,0	270,0	252,5			
Relative Weight	11,1	10,1	3,4	2,5	12,4	2,0	11,0	13,8	10,9	9,6	6,9	6,4			

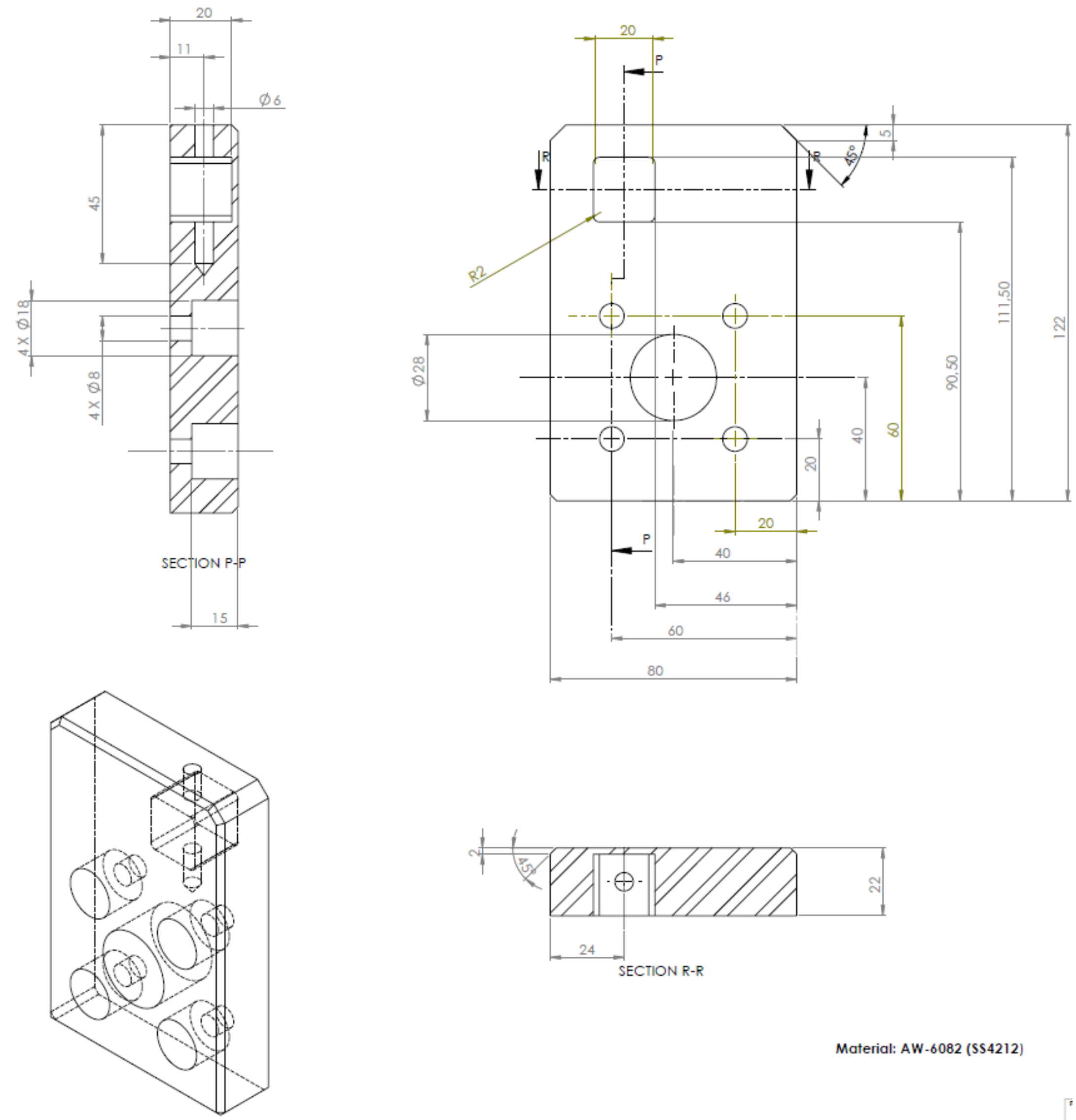
Legend		
⊝	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
▬	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Appendix B- Manufacturing drawings

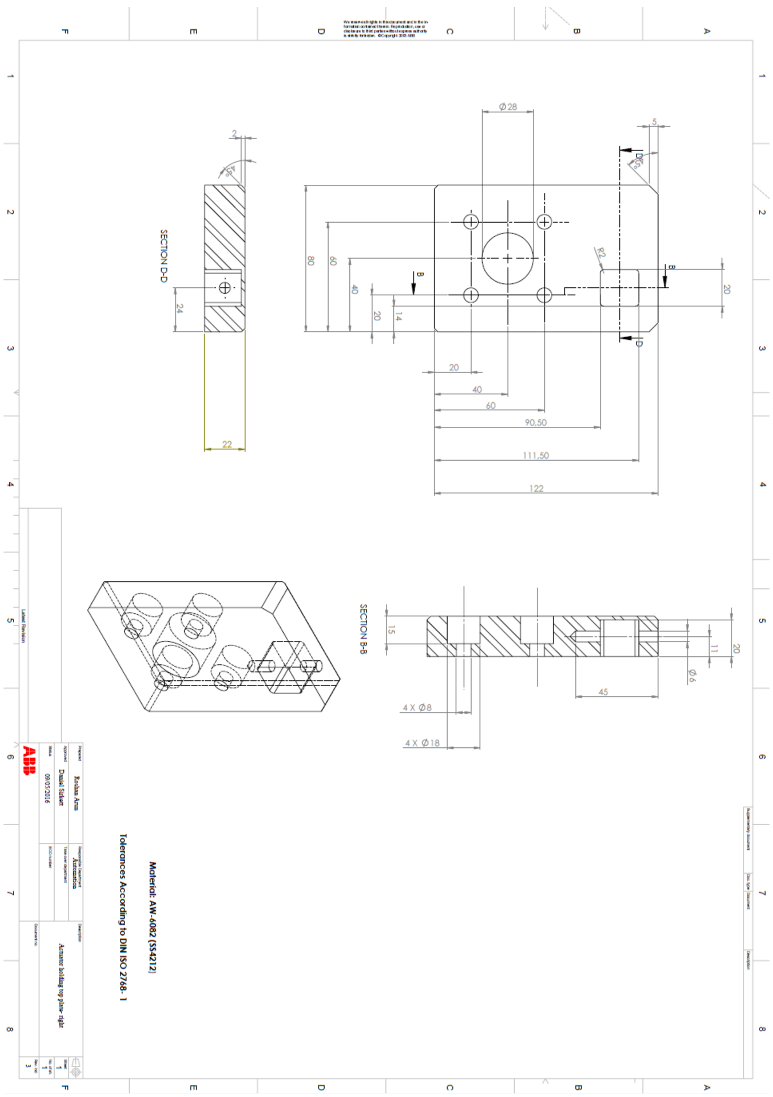
This section contains an appendix which includes manufacturing drawings which were passed on to the manufacturing department.

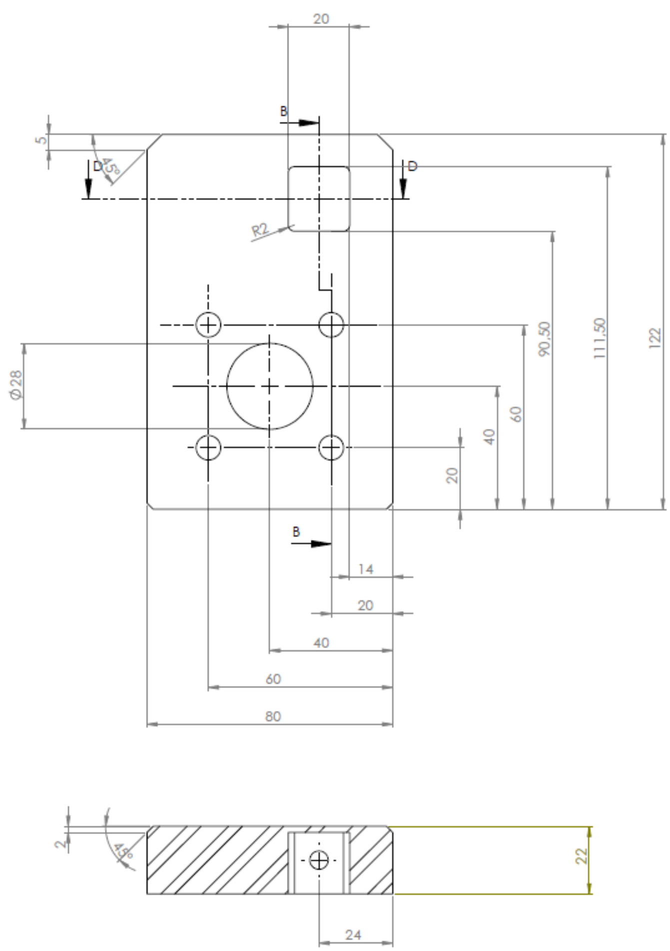
1. Connecting plate - Left


SECTION P-P
SECTION R-R
Material: AW-6082 (SS4212)
Tolerances According to DIN ISO 2768-1

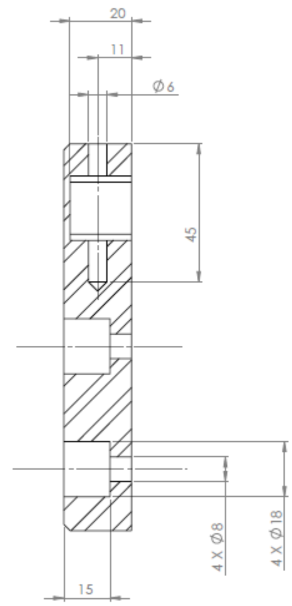

SECTION P-P
SECTION R-R
Material: AW-6082 (SS4212)

2. Connecting plate – Right

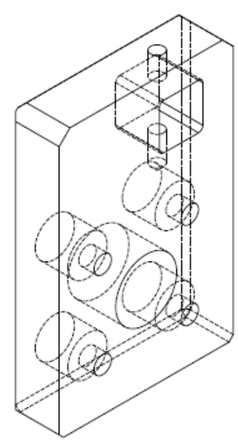

SECTION D-D
SECTION B-B
Material: AW-6082 (SS4212)
Tolerances: According to DIN ISO 2768- 1



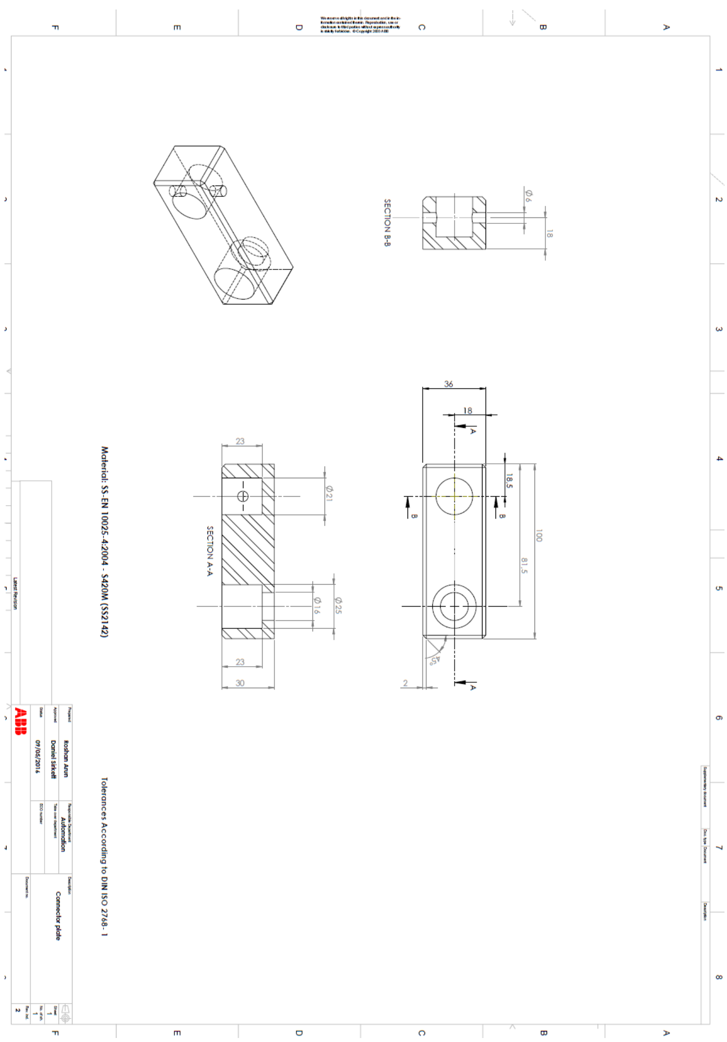
SECTION D-D

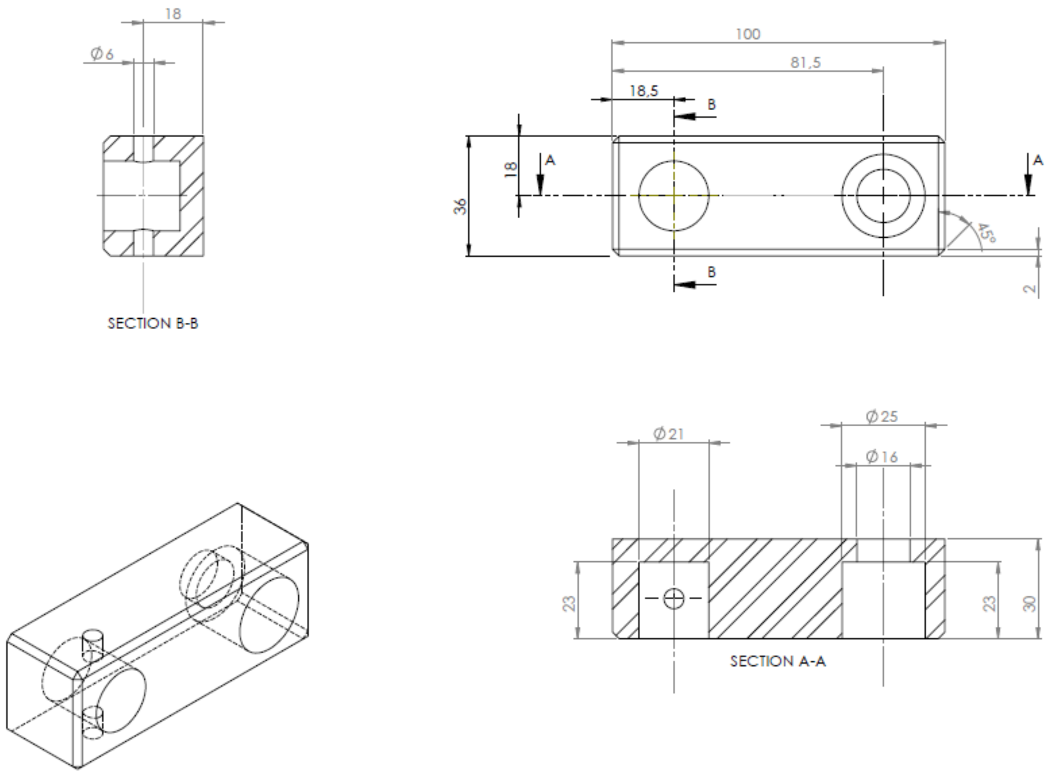


SECTION B-B



3. Bottom Connector

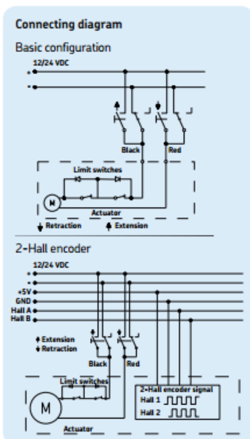


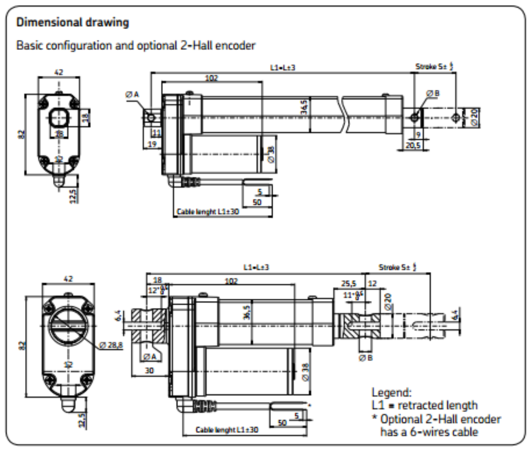

18
Ø6
SECTION B-B
100
81,5
18,5
B
A
18
36
45°
2
Ø21
Ø25
Ø16
23
23
30
SECTION A-A

Appendix C- Data Sheets

This section contains an appendix which includes all the important data sheets used during the project.

1. SFK Linear Actuators





Stroke (mm)	50	100	150	200	250	300
Retracted length (L1)	158	209	260	311	362	413
Retracted length with fork head	179	230	281	332	383	434

Encoder resolution

Gear ratio	5:1	10:1	20:1	30:1	40:1
Mm/pulse	0,3	0,15	0,075	0,05	0,038

Technical data

	Unit	CAHB-10... 1	CAHB-10... 2	CAHB-10... 3	CAHB-10... 4	CAHB-10... 5
Push load	N	120	240	500	750	1 000
Pull load	N	120	240	500	750	1 000
Speed (full load to no load)	mm/s	45 to 56	24 to 30	13 to 16	8 to 10	6 to 8
Stroke	mm	50 to 300	50 to 300	50 to 300	50 to 300	50 to 300
Retracted length	mm	–*	–*	–*	–*	–*
Voltage	V DC	12 or 24	12 or 24	12 or 24	12 or 24	12 or 24
Power consumption	W	N/A	N/A	N/A	N/A	N/A
Current consumption 12 V DC	A	4	3,5	3,2	3	2,8
24 V DC	A	2,2	2,0	1,8	1,8	1,6
Duty cycle	%	25	25	25	25	25
Ambient temperature	°C	–40 to +85	–40 to +85	–40 to +85	–40 to +85	–40 to +85
Type of protection	IP	66s	66s	66s	66s	66s
Weight (at 300 mm stroke)	kg	1,5	1,5	1,5	1,5	1,5
Color	–	Silver	Silver	Silver	Silver	Silver
Limit switches	–	Yes	Yes	Yes	Yes	Yes
Thermal protection	–	Yes	Yes	Yes	Yes	Yes

* See above table

2. ADXL 345 accelerometer

ANALOG DEVICES

3-Axis, ±2 *g*/±4 *g*/±8 *g*/±16 *g* Digital Accelerometer

ADXL345

FEATURES

Ultralow power: as low as 40 µA in measurement mode and 0.1 µA in standby mode at V_S = 2.5 V (typical)
Power consumption scales automatically with bandwidth
User-selectable resolution
- **Fixed 10-bit resolution**
- **Full resolution, where resolution increases with *g* range, up to 13-bit resolution at ±16 *g* (maintaining 4 m*g*/LSB scale factor in all *g* ranges)**

Embedded, patent pending FIFO technology minimizes host processor load
Tap/double tap detection
Activity/inactivity monitoring
Free-fall detection
Supply voltage range: 2.0 V to 3.6 V
I/O voltage range: 1.7 V to V_S
SPI (3- and 4-wire) and I²C digital interfaces
Flexible interrupt modes mappable to either interrupt pin
Measurement ranges selectable via serial command
Bandwidth selectable via serial command
Wide temperature range (−40°C to +85°C)
10,000 *g* shock survival
Pb free/RoHS compliant
Small and thin: 3 mm × 5 mm × 1 mm LGA package

APPLICATIONS

Handsets
Medical instrumentation
Gaming and pointing devices
Industrial instrumentation
Personal navigation devices
Hard disk drive (HDD) protection
Fitness equipment

GENERAL DESCRIPTION

The ADXL345 is a small, thin, low power, 3-axis accelerometer with high resolution (13-bit) measurement at up to ±16 *g*. Digital output data is formatted as 16-bit twos complement and is accessible through either a SPI (3- or 4-wire) or I²C digital interface.

The ADXL345 is well suited for mobile device applications. It measures the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration resulting from motion or shock. Its high resolution (4 m*g*/LSB) enables measurement of inclination changes less than 1.0°.

Several special sensing functions are provided. Activity and inactivity sensing detect the presence or lack of motion and if the acceleration on any axis exceeds a user-set level. Tap sensing detects single and double taps. Free-fall sensing detects if the device is falling. These functions can be mapped to one of two interrupt output pins. An integrated, patent pending 32-level first in, first out (FIFO) buffer can be used to store data to minimize host processor intervention.

Low power modes enable intelligent motion-based power management with threshold sensing and active acceleration measurement at extremely low power dissipation.

The ADXL345 is supplied in a small, thin, 3 mm × 5 mm × 1 mm, 14-lead, plastic package.

FUNCTIONAL BLOCK DIAGRAM

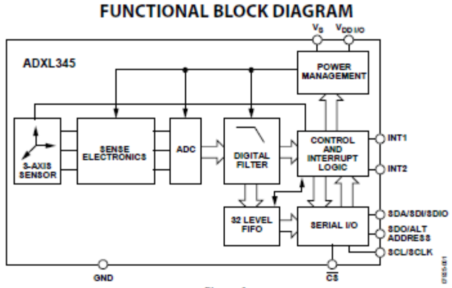


Figure 1.

One Technology Way, P.O. Box 9106, Norwood, MA 02062-9106, U.S.A.
Tel: 781.329.4700 www.analog.com
Fax: 781.461.3113

SERIAL COMMUNICATIONS

I²C and SPI digital communications are available. In both cases, the ADXL345 operates as a slave. I²C mode is enabled if the $\overline{CS}$ pin is tied high to $V_{DD\,I/O}$. The $\overline{CS}$ pin should always be tied high to $V_{DD\,I/O}$ or be driven by an external controller because there is no default mode if the $\overline{CS}$ pin is left unconnected. Therefore, not taking these precautions may result in an inability to communicate with the part. In SPI mode, the $\overline{CS}$ pin is controlled by the bus master. In both SPI and I²C modes of operation, data transmitted from the ADXL345 to the master device should be ignored during writes to the ADXL345.

SPI

For SPI, either 3- or 4-wire configuration is possible, as shown in the connection diagrams in Figure 3 and Figure 4. Clearing the SPI bit in the DATA_FORMAT register (Address 0x31) selects 4-wire mode, whereas setting the SPI bit selects 3-wire mode. The maximum SPI clock speed is 5 MHz with 100 pF maximum loading, and the timing scheme follows clock polarity (CPOL) = 1 and clock phase (CPHA) = 1.

$\overline{CS}$ is the serial port enable line and is controlled by the SPI master. This line must go low at the start of a transmission and high at the end of a transmission, as shown in Figure 5. SCLK is the serial port clock and is supplied by the SPI master. It is stopped high when $\overline{CS}$ is high during a period of no transmission. SDI and SDO are the serial data input and output, respectively. Data should be sampled at the rising edge of SCLK.

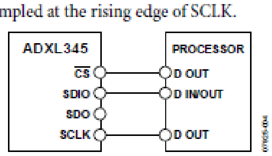


Figure 3. 3-Wire SPI Connection Diagram

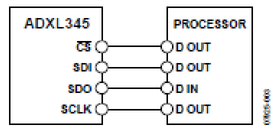


Figure 4. 4-Wire SPI Connection Diagram

To read or write multiple bytes in a single transmission, the multiple-byte bit, located after the R/$\overline{W}$ bit in the first byte transfer (MB in Figure 5 to Figure 7), must be set. After the register addressing and the first byte of data, each subsequent set of clock pulses (eight clock pulses) causes the ADXL345 to point to the next register for a read or write. This shifting continues until the clock pulses cease and $\overline{CS}$ is deasserted. To perform reads or writes on different, nonsequential registers, $\overline{CS}$ must be deasserted between transmissions and the new register must be addressed separately.

The timing diagram for 3-wire SPI reads or writes is shown in Figure 7. The 4-wire equivalents for SPI writes and reads are shown in Figure 5 and Figure 6, respectively.

Table 8. SPI Digital Input/Output Voltage

Parameter	Limit[1]	Unit
Digital Input Voltage		
Low Level Input Voltage (V_{IL})	0.2 × $V_{DD\,I/O}$	V max
High Level Input Voltage (V_{IH})	0.8 × $V_{DD\,I/O}$	V min
Digital Output Voltage		
Low Level Output Voltage (V_{OL})	0.15 × $V_{DD\,I/O}$	V max
High Level Output Voltage (V_{OH})	0.85 × $V_{DD\,I/O}$	V min

[1] Limits based on characterization results, not production tested.

Table 9. SPI Timing (T_A = 25°C, V_S = 2.5 V, $V_{DD\,I/O}$ = 1.8 V)[1]

	Limit[2, 3]			
Parameter	**Min**	**Max**	**Unit**	**Description**
f_{SCLK}		5	MHz	SPI clock frequency
t_{SCLK}	200		ns	1/(SPI clock frequency) mark-space ratio for the SCLK input is 40/60 to 60/40
t_{DELAY}	10		ns	$\overline{CS}$ falling edge to SCLK falling edge
t_{QUIET}	10		ns	SCLK rising edge to $\overline{CS}$ rising edge
t_{DIS}		100	ns	$\overline{CS}$ rising edge to SDO disabled
$t_{CS,DIS}$	250		ns	$\overline{CS}$ deassertion between SPI communications
t_S	0.4 × t_{SCLK}		ns	SCLK low pulse width (space)
t_M	0.4 × t_{SCLK}		ns	SCLK high pulse width (mark)
t_{SDO}		95	ns	SCLK falling edge to SDO transition
t_{SETUP}	10		ns	SDI valid before SCLK rising edge
t_{HOLD}	10		ns	SDI valid after SCLK rising edge

[1] The $\overline{CS}$, SCLK, SDI, and SDO pins are not internally pulled up or down; they must be driven for proper operation.
[2] Limits based on characterization results, characterized with f_{SCLK} = 5 MHz and bus load capacitance of 100 pF; not production tested.
[3] The timing values are measured corresponding to the input thresholds (V_{IL} and V_{IH}) given in Table 8.

AXES OF ACCELERATION SENSITIVITY

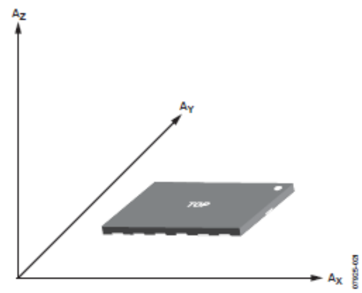


Figure 16. Axes of Acceleration Sensitivity (Corresponding Output Voltage Increases When Accelerated Along the Sensitive Axis)

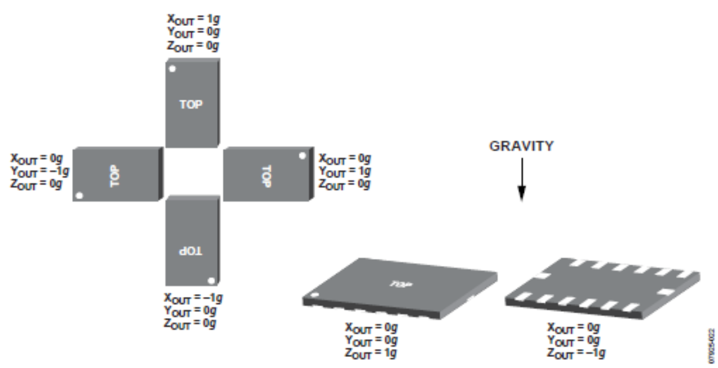


Figure 17. Output Response vs. Orientation to Gravity

Table 11. I^2C Timing ($T_A = 25°C$, $V_S = 2.5$ V, $V_{DD I/O} = 1.8$ V)

	Limit[1, 2]			
Parameter	**Min**	**Max**	**Unit**	**Description**
f_{SCL}		400	kHz	SCL clock frequency
t_1	2.5		µs	SCL cycle time
t_2	0.6		µs	t_{HIGH}, SCL high time
t_3	1.3		µs	t_{LOW}, SCL low time
t_4	0.6		µs	$t_{HD, STA}$, start/repeated start condition hold time
t_5	350		ns	$t_{SU, DAT}$, data setup time
t_6[3, 4, 5, 6]	0	0.65	µs	$t_{HD, DAT}$, data hold time
t_7	0.6		µs	$t_{SU, STA}$, setup time for repeated start
t_8	0.6		µs	$t_{SU, STO}$, stop condition setup time
t_9	1.3		µs	t_{BUF}, bus-free time between a stop condition and a start condition
t_{10}		300	ns	t_R, rise time of both SCL and SDA when receiving
	0		ns	t_R, rise time of both SCL and SDA when receiving or transmitting
t_{11}		250	ns	t_F, fall time of SDA when receiving
		300	ns	t_F, fall time of both SCL and SDA when transmitting
	$20 + 0.1 C_b$[7]		ns	t_F, fall time of both SCL and SDA when transmitting or receiveing
C_b		400	pF	Capacitive load for each bus line

[1] Limits based on characterization results, with $f_{SCL} = 400$ kHz and a 3 mA sink current; not production tested.
[2] All values referred to the V_{IH} and the V_{IL} levels given in Table 10.
[3] t_6 is the data hold time that is measured from the falling edge of SCL. It applies to data in transmission and acknowledge times.
[4] A transmitting device must internally provide an output hold time of at least 300 ns for the SDA signal (with respect to $V_{IH(min)}$ of the SCL signal) to bridge the undefined region of the falling edge of SCL.
[5] The maximum t_6 value must be met only if the device does not stretch the low period (t_3) of the SCL signal.
[6] The maximum value for t_6 is a function of the clock low time (t_3), the clock rise time (t_{10}), and the minimum data setup time ($t_{5(min)}$). This value is calculated as $t_{6(max)} = t_3 - t_{10} - t_{5(min)}$.
[7] C_b is the total capacitance of one bus line in picofarads.

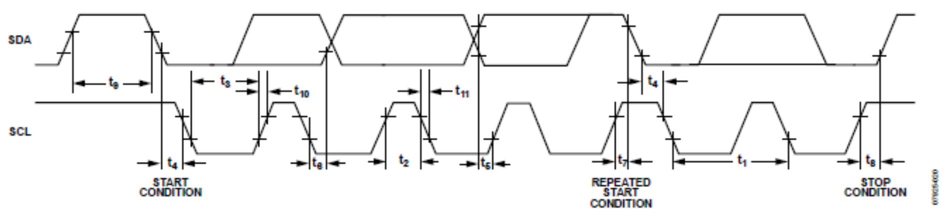


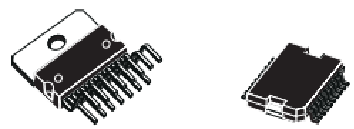
Figure 10. I^2C Timing Diagram

3. Motor Drivers – L298n Dual H bridge

L298

DUAL FULL-BRIDGE DRIVER

- OPERATING SUPPLY VOLTAGE UP TO 46 V
- TOTAL DC CURRENT UP TO 4 A
- LOW SATURATION VOLTAGE
- OVERTEMPERATURE PROTECTION
- LOGICAL "0" INPUT VOLTAGE UP TO 1.5 V (HIGH NOISE IMMUNITY)



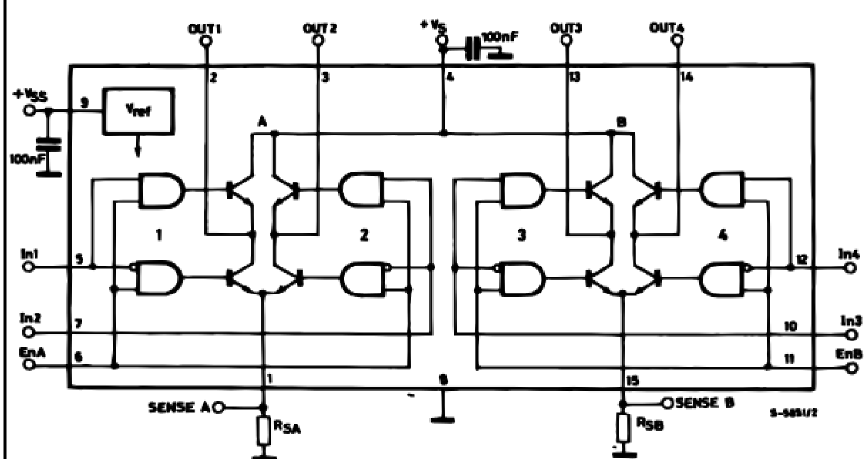
Multiwatt15 **PowerSO20**

ORDERING NUMBERS : L298N (Multiwatt Vert.)
L298HN (Multiwatt Horiz.)
L298P (PowerSO20)

DESCRIPTION

The L298 is an integrated monolithic circuit in a 15-lead Multiwatt and PowerSO20 packages. It is a high voltage, high current dual full-bridge driver designed to accept standard TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors. Two enable inputs are provided to enable or disable the device independently of the input signals. The emitters of the lower transistors of each bridge are connected together and the corresponding external terminal can be used for the connection of an external sensing resistor. An additional supply input is provided so that the logic works at a lower voltage.

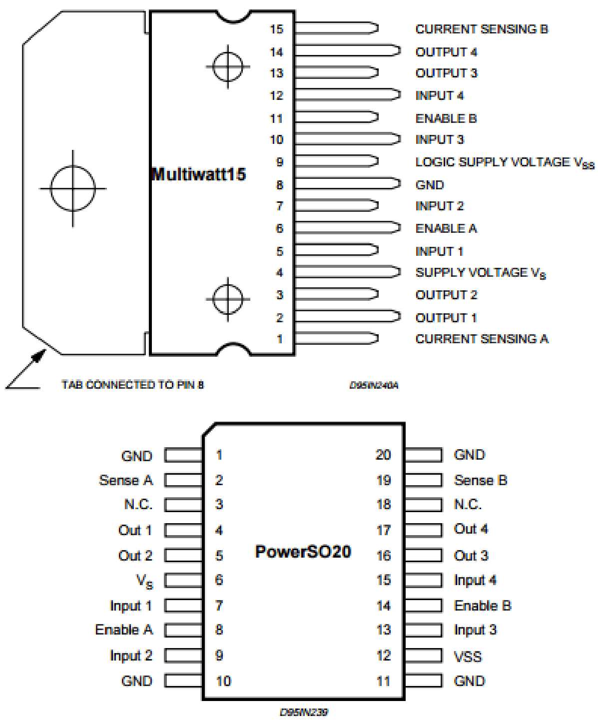
BLOCK DIAGRAM



ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Value	Unit
V_S	Power Supply	50	V
V_{SS}	Logic Supply Voltage	7	V
V_I, V_{en}	Input and Enable Voltage	–0.3 to 7	V
I_O	Peak Output Current (each Channel) – Non Repetitive (t = 100µs) –Repetitive (80% on –20% off; t_{on} = 10ms) –DC Operation	 3 2.5 2	 A A A
V_{sens}	Sensing Voltage	–1 to 2.3	V
P_{tot}	Total Power Dissipation (T_{case} = 75°C)	25	W
T_{op}	Junction Operating Temperature	–25 to 130	°C
T_{stg}, T_j	Storage and Junction Temperature	–40 to 150	°C

PIN CONNECTIONS (top view)



THERMAL DATA

Symbol	Parameter		PowerSO20	Multiwatt15	Unit
$R_{th\ j\text{-}case}$	Thermal Resistance Junction-case	Max.	–	3	°C/W
$R_{th\ j\text{-}amb}$	Thermal Resistance Junction-ambient	Max.	13 (*)	35	°C/W

(*) Mounted on aluminum substrate

PIN FUNCTIONS (refer to the block diagram)

MW.15	PowerSO	Name	Function
1;15	2;19	Sense A; Sense B	Between this pin and ground is connected the sense resistor to control the current of the load.
2;3	4;5	Out 1; Out 2	Outputs of the Bridge A; the current that flows through the load connected between these two pins is monitored at pin 1.
4	6	V_S	Supply Voltage for the Power Output Stages. A non-inductive 100nF capacitor must be connected between this pin and ground.
5;7	7;9	Input 1; Input 2	TTL Compatible Inputs of the Bridge A.
6;11	8;14	Enable A; Enable B	TTL Compatible Enable Input: the L state disables the bridge A (enable A) and/or the bridge B (enable B).
8	1,10,11,20	GND	Ground.
9	12	VSS	Supply Voltage for the Logic Blocks. A100nF capacitor must be connected between this pin and ground.
10; 12	13;15	Input 3; Input 4	TTL Compatible Inputs of the Bridge B.
13; 14	16;17	Out 3; Out 4	Outputs of the Bridge B. The current that flows through the load connected between these two pins is monitored at pin 15.
–	3;18	N.C.	Not Connected

ELECTRICAL CHARACTERISTICS (V_S = 42V; V_{SS} = 5V, T_j = 25°C; unless otherwise specified)

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
V_S	Supply Voltage (pin 4)	Operative Condition	V_{IH} +2.5		46	V
V_{SS}	Logic Supply Voltage (pin 9)		4.5	5	7	V
I_S	Quiescent Supply Current (pin 4)	V_{en} = H; I_L = 0 V_i = L V_i = H		13 50	22 70	mA mA
		V_{en} = L V_i = X			4	mA
I_{SS}	Quiescent Current from V_{SS} (pin 9)	V_{en} = H; I_L = 0 V_i = L V_i = H		24 7	36 12	mA mA
		V_{en} = L V_i = X			6	mA
V_{iL}	Input Low Voltage (pins 5, 7, 10, 12)		–0.3		1.5	V
V_{iH}	Input High Voltage (pins 5, 7, 10, 12)		2.3		VSS	V
I_{iL}	Low Voltage Input Current (pins 5, 7, 10, 12)	V_i = L			–10	µA
I_{iH}	High Voltage Input Current (pins 5, 7, 10, 12)	Vi = H ≤ V_{SS} –0.6V		30	100	µA
V_{en} = L	Enable Low Voltage (pins 6, 11)		–0.3		1.5	V
V_{en} = H	Enable High Voltage (pins 6, 11)		2.3		V_{SS}	V
I_{en} = L	Low Voltage Enable Current (pins 6, 11)	V_{en} = L			–10	µA
I_{en} = H	High Voltage Enable Current (pins 6, 11)	V_{en} = H ≤ V_{SS} –0.6V		30	100	µA
$V_{CEsat\,(H)}$	Source Saturation Voltage	I_L = 1A I_L = 2A	0.95	1.35 2	1.7 2.7	V V
$V_{CEsat\,(L)}$	Sink Saturation Voltage	I_L = 1A (5) I_L = 2A (5)	0.85	1.2 1.7	1.6 2.3	V V
V_{CEsat}	Total Drop	I_L = 1A (5) I_L = 2A (5)	1.80		3.2 4.9	V V
V_{sens}	Sensing Voltage (pins 1, 15)		–1 (1)		2	V

Main Features

Module L298N double H bridge dc stepper motor drive controller board for Arduino
features
good chip: L298N as main chip, pc corporation production. low heat, outstanding anti-interference performance. high working power to 46V, the high current reach 3a max and continue current is 2a, the power to 25W. can drive a 2-phase stepper motor, a 4-phase stepper motor or two DC motors.
built 78m05, get power from the drive power, but when driving power over12v, use an external 5V power supply.
large capacity filter capacitance after the protective flow diode, more stable and reliable .
specification:
Name: Double H bridge motor driver
work mode: drivers of h bridge (double lines)
control chip L298N (st)
logic voltage: 5V
driving voltage: 5V - 35V
logic current: 0mA-36mA
drive current: 2a (maximum single bridge)
storage temperature : -20 ℃ --- + 135 ℃
maximum power: 25W
note:
this module has a built-in 5V power supply, then the drive voltage is 7V-35V, this supply suitable for power, not input voltage to + 5V power supply interface, but ledding out 5v for external use is available.
when ENA enable IN1 IN2 control OUT1 OUT2
when ENB enable IN3 IN4 control OUT3 OUT4.

Specifications

listing	2014-07
Type	Accessories
Used for	Universal
accessory Function	Current
Model	L298N
Dimension (cm)	4.4 x 4.4 x 2.5
Net Weight (kg)	0.026

4. Voltage regulator.

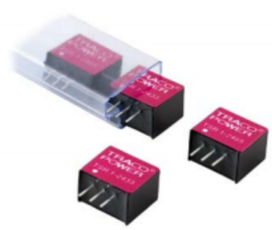
TRACO® POWER

DC/DC Converters

TSR-1 Series, 1 A

Features

- Up to 96 % efficiency
  - No heat-sink required
- Pin compatible with LMxx linear regulators
- SIP-package fits existing TO-220 footprint
- Built in filter capacitors
- Operation temp. range –40°C to +85°C
- Short circuit protection
- Wide input operating range
- Excellent line / load regulation
- Low standby current
- 3-year product warranty



The new TSR-1 series step-down switching regulators are drop-in replacement for inefficient 78xx linear regulators. A high efficiency up to 96 % allows full load operation up to +60°C ambient temperature without the need of any heat-sink or forced cooling.
The TSR-1 switching regulators provide other significant features over linear regulators, i.e. better output accuracy (±2 %), lower standby current of 2 mA and no requirement of external capacitors. The high efficiency and low standby power consumption makes these regulators an ideal solution for many battery powered applications.

Models

Order code	Input voltage range	Output voltage	Output current max.	Efficiency typ. @ Vin min.	Efficiency typ. @ Vin max.
TSR 1-2412	4.6 – 36 VDC*	1.2 VDC	1.0 A	74 %	62 %
TSR 1-2415	4.6 – 36 VDC*	1.5 VDC		78 %	65 %
TSR 1-2418	4.6 – 36 VDC*	1.8 VDC		82 %	69 %
TSR 1-2425	4.6 – 36 VDC*	2.5 VDC		87 %	75 %
TSR 1-2433	4.75 – 36 VDC*	3.3 VDC		91 %	78 %
TSR 1-2450	6.5 – 36 VDC*	5.0 VDC		94 %	84 %
TSR 1-2465	9.0 – 36 VDC*	6.5 VDC		93 %	87 %
TSR 1-2490	12 – 36 VDC*	9.0 VDC		95 %	90 %
TSR 1-24120	15 – 36 VDC*	12 VDC		95 %	92 %
TSR 1-24150	18 – 36 VDC*	15 VDC		96 %	94 %

* For input voltage higher than 32 VDC an input capcitor 22 µF / 50 V is required. See application notes (page 3)

Input Specifications

Maximum input current (at Vin min. and 1 A output current)	1 A
No load input current	1 mA typ.
Reflected ripple current	150 mA
Input filter	internal capacitors, see application notes for to meet EN55022 class A

Output Specifications

Voltage set accuracy		±2 % (at full load)
Regulation	– Input variation – Load variation (10 – 100 %) 1.2 & 1.5 VDC models: other models:	0.2 % 0.6 % 0.4 %
Overshoot startup voltage		1.0 % max.
Minimum load		not required
Ripple and noise (20 MHz Bandwidth)	1.2 – 6.5 VDC models: 9 – 15 VDC models:	50 mV max. 75 mV max.
Temperature coefficient		±0.015 % / °C max.
Dynamic load response 50% load change (upper half)		150 mV max. peak variation 250 µS max. response time
Startup rise time 10 % to 90 % Vout		2 mS
Short circuit protection		continuous, automatic recovery
Current limitation		at 2.5 A typ.
Capacitive load		470 µF max.

General Specifications

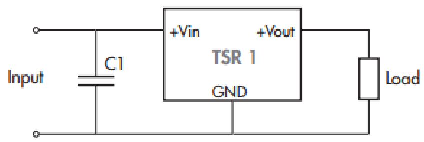
Temperature ranges	– Operating – Storage	–40°C to +85°C (–40°F to +185°F) –55°C to +125°C (–67°F to +257°F)
Derating		2.4 %/K above 60°C
Thermal shock		acc. MIL-STD-810F
Humidity (non condensing)		95 % rel H max.
Reliability, calculated MTBF (MIL-HDBK-217F, at +25°C, ground benign)		>5'350'000 h
Isolation voltage		none
Switching frequency		500 kHz ±10 % (pulse width modulation)

Physical Specifications

Casing material	non-conductive plastic
Potting material	silicon (flammability to UL 94V-0 rated)
Package weight	1.9 g (0.07 oz)
Soldering profile	max. 265°C / 10 sec. (wave soldering)

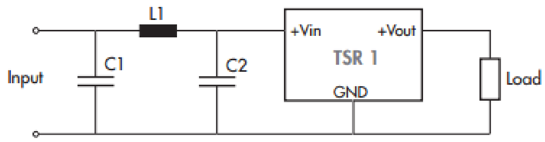
Applications notes

For input voltage higher than 32 VDC (max. 36 VDC)



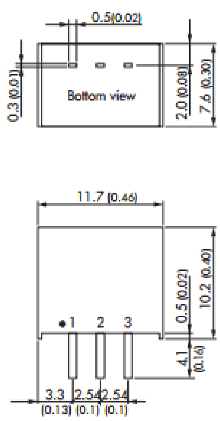
C1 = 22 µF / 50 V

Input filter to meet EN 55022 class A



C1 = 4.7 µF / 50 V
C2 = 4.7 µF / 50 V
L1 = 8.2 µH / 1.5 A / 0.08 Ohm

Outline Dimensions



Pin-Out	
1	+Vin
2	GND
3	+Vout

Dimensions in [mm], () = Inch
Pin pitch tolerances: ±0.25 (±0.01)
Pin profile tolerance: ±0.1 (±0.004)
Other tolerances: ±0.5 (±0.02)

Appendix D- Matlab Code

This section contains an appendix which includes the Matlab script used during the thesis.

```
% Testcases
% YUMI

cc
clear all
close all

width_feet =0.76;       % width between feet
distance_feet=0.76;     % distance between feet
distance_wheels= 0.52;  % distance between wheels
width_wheels=0.76;      % width between wheels
m1=240;                 % mass with pedestal YUMIand Flexfeeders
m2=124;                 % mass with pedestal and YUMIonly
x=1.5;                  % Height at which force is acting
g=9.81;


%impluse calculations


%COOG
cog_x=0.138;
cog_y=0.237;
cog_z=0.005;




F=[0:200];

%% moment about linear actuators
% Estimate 40% on front feet 60% back feet

mrod = ((m1*g*0.76/2)-200*0.12+(m1*g*0.6*0.76) - (m1*g*0.4*(0.05)))/4 ;

disp('Torque');
disp ('mrod');
%% CASE A
% On wheels. F has its impact from behind, worst case.

disp('CASE A');
disp('F requirement at the feet and wheels when applied at a height of
1.5m with YUMIand flexfeeders mounted ') ;
Ra= m1*g;
```

```
F_foot1 =((m1*g*distance_feet)- (m1*g*(distance_feet/2)))/x ;
F_wheel1 = ((m1*g*distance_wheels)- (m1*g*(distance_wheels/2)))/x;
F_foot2 =((m2*g*distance_feet)- (m2*g*(distance_feet/2)))/x ;
F_wheel2 = ((m2*g*distance_wheels)- (m2*g*(distance_wheels/2)))/x;

disp('Force at foot');
disp(F_foot1);
disp('Force at wheel');
disp(F_wheel1);

disp('F requirement at the feet and wheels when applied at a height of
1.5m with just YUMImounted ') ;
disp('Force at foot');
disp(F_foot2);
disp('Force at wheel');
disp(F_wheel2);


%% CASE B
% Impulse acting backside
I=10;
h=1.5;
t=0.25;

F_I=I/t;

F_maxback=(m2*g*(distance_feet/2))/h;

h_limitback=(-m2*g*(distance_feet/2)+m2*g*distance_feet)/F_I;
disp('CASE B');
disp('The minimum height required for the pedesatl to tip over in the
front or back');
disp (h_limitback);


disp('Requirement 8,max force to withstand the impulse on the backside');
disp(F_maxback);


%% CASE C
% Impulse acting sideways when YUMIon its wheels
I=10;
h=1.5;
t=0.25;

F_I =I/t;

F_maxside=(m2*g*(distance_wheels/2))/h;

disp('CASE C');
h_limitback=(-m2*g*(distance_wheels/2)+m2*g*distance_wheels)/F_I;
disp('The minimum height required for the pedesatl to tip over
sideways');
```

```
disp (h_limitback);


disp('Max force to withstand the impulse acting sideways to the pedestal
');
disp(F_maxside);

%% CASE D
% Force acting at a distance of 0.5 meters

F_at_hands=(m2*g*(distance_feet/2))/((1.260-distance_feet/2));
disp('CASE D');
disp('Max force acting at 0.5 mts away from center');
disp(F_at_hands);
```

Appendix E – Arduino Code

This section contains an appendix which includes the Arduino Code used to run the Self-Leveling system.

```
#include <SoftwareSerial.h>
#include "Accelerometer.h"
#include "Motor.h"

#define PIN_MTL_DOWN  6
#define PIN_MTL_UP    7
#define PIN_MTL_POT   1
#define PIN_MTL_SW    A0

#define PIN_MTR_DOWN  4
#define PIN_MTR_UP    5
#define PIN_MTR_POT   2
#define PIN_MTR_SW    A1

#define PIN_MBL_DOWN  9
#define PIN_MBL_UP    10
#define PIN_MBL_POT  3
#define PIN_MBL_SW    A3

#define PIN_MBR_DOWN  11
#define PIN_MBR_UP    12
#define PIN_MBR_POT   4
#define PIN_MBR_SW    A2

#define TH_BAL        10
#define EXTEND_POS    50

Motor MTL;
Motor MTR;
Motor MBL;
Motor MBR;
Accelerometer Acc;
volatile int currentState = LOW;
volatile int changed = LOW;
int LED=13;
int interruptPin = 2;

void setup(void)
{
```

```
  //Create a serial connection to display the data on the terminal.

  MTL.setup(PIN_MTL_DOWN, PIN_MTL_UP, PIN_MTL_POT, PIN_MTL_SW);
  MTR.setup(PIN_MTR_DOWN, PIN_MTR_UP, PIN_MTR_POT, PIN_MTR_SW);
  MBL.setup(PIN_MBL_DOWN, PIN_MBL_UP, PIN_MBL_POT, PIN_MBL_SW);
  MBR.setup(PIN_MBR_DOWN, PIN_MBR_UP, PIN_MBR_POT, PIN_MBR_SW);

  Acc.setup();

  Serial.begin(9600);

  pinMode(LED,OUTPUT);
  digitalWrite(LED, 1);

  pinMode(interruptPin, INPUT_PULLUP);
  attachInterrupt(digitalPinToInterrupt(interruptPin), interruptButton,RISING);
}


//****************test motors**********************


//***************//raise feet logic//*************

void downLegs()
{
  bool finished = false;
  int comTL,comTR,comBL,comBR;

  while(!finished)
  {
    finished = true;
    //Check is feet in contact

    if(MTL.hasContact()) comTL = 0;
    else
    {
      comTL = -1;
      finished = false;
    }

    if(MTR.hasContact()) comTR = 0;
    else
    {
      comTR = -1;
      finished = false;
```

```
    }

    if(MBL.hasContact()) comBL = 0;
    else
    {
      comBL = -1;
      finished = false;
    }

    if(MBR.hasContact()) comBR = 0;
    else
    {
      comBR = -1;
      finished = false;
    }
  }
  if(MTL.hasContact()) comTL = -1;
  if(MTR.hasContact()) comTR = -1;
  if(MBL.hasContact()) comBL = -1;
  if(MBR.hasContact()) comBR = -1;

  //apply commands to motors
  MTL.runMotor(comTL);
  MTR.runMotor(comTR);
  MBL.runMotor(comBL);
  MBR.runMotor(comBR);

  delay (2000);

  MTL.runMotor(0);
  MTR.runMotor(0);
  MBL.runMotor(0);
  MBR.runMotor(0);

  leveling();
}
  void upLegs()
  {

    int comTL,comTR,comBL,comBR;

     comTL = 1;
     comTR = 1;
     comBL = 1;
     comBR = 1;
```

```
    //apply commands to motors
    MTL.runMotor(comTL);
    MTR.runMotor(comTR);
    MBL.runMotor(comBL);
    MBR.runMotor(comBR);
    delay (3000);
    MTL.runMotor(0);
    MTR.runMotor(0);
    MBL.runMotor(0);
    MBR.runMotor(0);
}

//*******************************//levelinglogic//**************************

void leveling()
{
  int x,y;
  bool finished = false;
  int balX,balY;
  int comTL,comTR,comBL,comBR;

  while(!finished){
    //Get feedback from accelerometer
    Acc.update_values();
    x = Acc.get_filtered_value(ORI_X);
    y = Acc.get_filtered_value(ORI_Y);

    if      (x >  TH_BAL) balX = 1;
    else if (x < -TH_BAL) balX = -1;
    else                  balX = 0;

    if      (y >  TH_BAL) balY = 1;
    else if (y < -TH_BAL) balY = -1;
    else                  balY = 0;

    //Process commands for motors
    comTL = - balX + balY;
    comTR = - balX - balY;
    comBL =   balX + balY;
    comBR =   balX - balY;

    //Check is feet in contact
    if(!MTL.hasContact()) comTL = -1;
    if(!MTR.hasContact()) comTR = -1;
    if(!MBL.hasContact()) comBL = -1;
```

```
    if(!MBR.hasContact()) comBR = -1;

    //apply commands to motors
    MTL.runMotor(comTL);
    MTR.runMotor(comTR);
    MBL.runMotor(comBL);
    MBR.runMotor(comBR);

    // Update finished state
    finished = (balX == 0) && (balY == 0) && MTL.hasContact() && MTR.hasContact()
&& MBL.hasContact() && MBR.hasContact();
  }
}

double x,y,z;

void loop(void)
{
  ///Acc.update_values();
  //x = Acc.get_filtered_value(ORI_X);
  //y = Acc.get_filtered_value(ORI_Y);
  //z = Acc.get_filtered_value(ORI_Z);

  //Serial.print(x);
  //Serial.print("\t");
  //Serial.println(y);
  //Serial.print("\t");
  //Serial.println(z);


  MTL.runMotor(0);
  MTR.runMotor(0);
  MBL.runMotor(0);
  MBR.runMotor(0);
  if (changed == HIGH)
  {
    noInterrupts();
    //noInterrupts(); //detachInterrupt(digitalPinToInterrupt(interruptPin));
    changed = LOW;
    if (currentState == HIGH)
    {
      digitalWrite (LED, 1);
      downLegs();
      interrupts();                              //attachInterrupt(digitalPinToInterrupt(interruptPin),
interruptButton,RISING);
    }
```

```
    else if (currentState == LOW)
    {
      digitalWrite (LED, 0);
      upLegs();
      interrupts();                                   //attachInterrupt(digitalPinToInterrupt(interruptPin),
interruptButton,RISING);
    }
  }
}

//**********//switch on or off button//*********************


void interruptButton()
{
  changed = HIGH;
  currentState = !currentState;
  noInterrupts();
}
```

BIBLIOGRAPHY[1]

Roshan Arun Nagappa Sundaraswamy

Candidate for the Degree of

Master of Science

Thesis: TYPE FULL TITLE HERE IN ALL CAPS

Major Field: Type Field Here

Biographical:

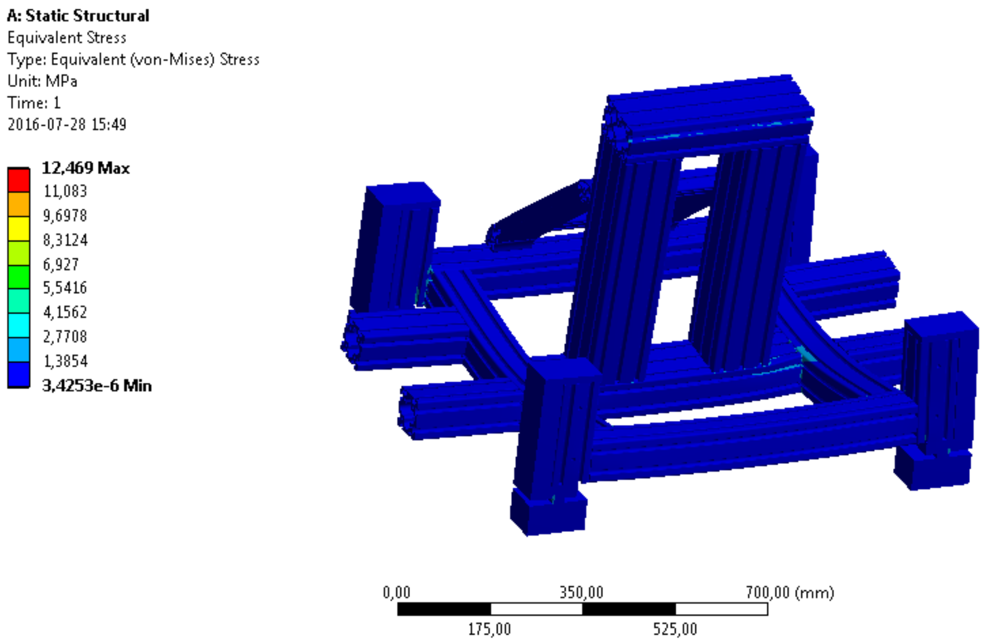
Personal Data:

Education: (prior degrees)

Fill in your own words, though, Completed the requirements for the Master of Science in Environmental Chemistry at Clarkson University, Potsdam, New York in September 2008.

ADVISER'S APPROVAL: Type Adviser's Name Here

[1] IF NECESSARY (should not exceed one page except for PhDs)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