POLITECNICO
MILANO 1863

SCHOOL OF INDUSTRIAL AND INFORMATION ENGINEERING

Master of Science in Mechanical Engineering, Advanced Mechanical Design

Design of a new industrial proportional joystick manufactured with 3D printing

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M.Sc. thesis work of:
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“Wisdom is the daughter of experience”

Leonardo da Vinci

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Abstract

Joysticks are often used in construction lifting plants and industries for controlling the cranes and machines thus reducing the need of human intervention. The present work is based on the requirement of TER Tecno Elettrica Ravasi S.r.l., whose object is to design a new small industrial proportional 3D joystick based on customer needs. The principal activities done are the design of smallest joystick in TER using new method of control to achieve infinite life. First time, permanent magnets are used to control the position of the joystick handle and experience the systematic proportional movement of the handle. The Prototype is made using the new concept and tested from the customer experience. The static and fatigue assessments have been performed on the components handle, ball, base which is considered the most critical over the lifetime of joystick. Von Mises criteria are used for the static assessments and Sines used for the fatigue assessment. Moreover, the ball and handle are joined by interference fit coupling, so the appropriate tolerances have been selected. The analysis of all components have been performed with the help of Computer Aided Engineering (CAE), which is widely used for the stress analysis nowadays, allowing to reduce the fatigue testing cost.

2 Introduction

A joystick is an input device that can be used in construction lifting plants and industries for controlling the cranes and machines thus reducing the need for human intervention. The present master thesis work is based on the design of new small industrial proportional 3D joystick whose purpose is to design a smallest 3D joystick in TER by a new conceptual method and improve the limitations of existing types of joysticks, thereby promising infinite fatigue life, above 5 Million load cycles (5x10^6 cycles) in the customer field.

The joystick comprises handle and control elements to send the output signal to a microprocessor board. The uncertainities such as random load conditions, different temperatures limit the achievement of the infinite fatigue life operation of the spring handle zero position. As a result, the unplanned downtime of joystick (which is the main controlling element) in the field incurs a huge loss to the customer. In order to achieve the fatigue life and promise uninterrupted operation of the joystick, a new way of control is designed and tested.

Permanent magnet will likely lose its own persistent magnetic field, less than 1% of their flux density over 100 years. This is 10 times higher than operational cycle time of joystick considering the electrical components and control boards. Axial and Ring magnet is chosen to achieve the zero position of handle from various considerations and tested in real time load application. Ring magnet has magnetization classifications such as axial, radial, diametric, multipolar. Among the types of magnetization, the axial and radial type are chosen by confirming the meeting of operational requirements. The magnet material, geometry, strength, maximum working temperature are appropriately selected considering the environmental application and durability.

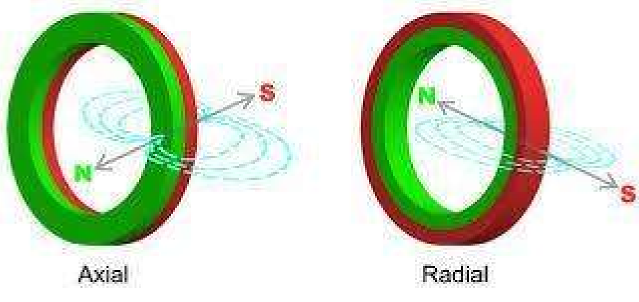


Figure 2.1: Ring Magnets

The analytical and numerical assessment on the critical components are made. This is necessary due to the fact that most of the critical components are novel. The static and fatigue assessments have been performed on the components handle, ball, base which is considered the most critical for the lifetime of joystick. Von Mises and Guest-Tresca criteria are used for the static assessments and Sines used for the fatigue assessment. Moreover, the ball and handle are joined by interference fit coupling, so the appropriate tolerances have been selected. The analysis of all components have also been performed with the help of Computer Aided Engineering (CAE), which is widely used for the stress analysis nowadays, allowing to reduce the fatigue testing cost.

3 State of the art

3.1 Joystick in industries

Since a long time joysticks have a very important task within technical applications as an interface between man and machine, the so called man-machine-interface. The joystick acts as the primary interface between the user and the system, and holds one of the most prominent visual and physical attributes of the system. It can literally make or break the operation of the entire system urging the need to focus on its continual operational satisfaction over the whole life of the system.

Joysticks are used particularly in industrial and construction lifting plants to control gantry cranes, track cranes, jib cranes, wall-mounted jib cranes, tower cranes and winches for construction sites; in the automation industry to command and control systems to manage machines and processes, thus reducing the need for human intervention; in stage technology to control the equipment used to move stage sets, curtains etc.

User studies have shown that an interface that feels well-constructed will be treated as a fine piece of equipment, reducing abuse at the same time that it raises the product's image in the mind of the customer.

3.2 Classification of industrial joysticks

3.2.1 Digital type

Digital joystick is able to give only a single response signal. It has just four switches for four directions (up, down, left, right). Nevertheless, this type of joystick does not have sensitive control, typical example is the joystick buttons in racing games.

3.2.2 Analog type

Analog joystick have the capability to give continuous signal response, but need complex mechanics to convert stick movement in 2 or 3 axis. Analog design of joystick can be done with two potentiometers, or variable resistors to measure the exact position of the handle.

A potentiometer is thereby to translate the stick's physical position into an electrical signal where the signal is totally analog. The potentiometer joystick technology, on the other hand, has limitations in terms of long-term durability and reliability. This problem occurs due to the wearing of moving parts. To activate Z-axis, an additional potentiometer is added which is done by rotating the stick itself. However, the addition of third potentiometer in the joystick, makes the system more robust and complicated.

The technology with a 3D hall sensor implemented can detect x and y axes and bring results that are more precise. With this sensor, lifetime of joystick functionality is extended and more options for future games or industrial implementations of joystick are possible. The hall effect joystick has an advantage over the potentiometer type since it does not have moving parts that will become worn over time. Magnetic field detection in x, y direction allow the sensor to reliably measure two-dimensional movements and for z-axis, an additional sensor is required. The mechanical design plays an important factor to classify the analog type concerning the geometry. They are listed as follows.

3.2.2.1 Thumb Joystick

Thumb joysticks belong according their dimensions and handle heights above the mounting panel to the group of sub miniature joysticks. One or two axes function and maximum one-switch button function is possible with these designs.

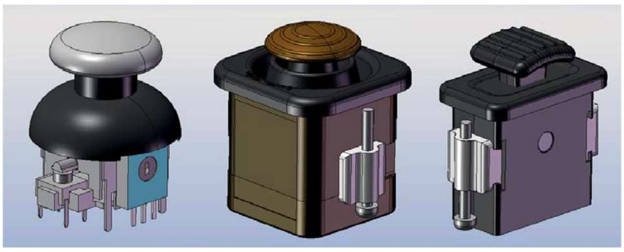


Figure 3.1: Thumb joysticks

3.2.2.2 Finger Joystick

These types are used for precision operating task such as at medical and laboratory devices, precision measurement technology for controlling touch probes, laser welding machines etc. It provides one to three axes function. Using several fingers to grasp the handle knob, the control is done by fingers.

Figure 3.2: Finger joysticks

3.2.2.3 Desktop Joystick

A special variant of finger joysticks represent the desktop joysticks. Within the desktop housing, a finger joystick is incorporated. The housing provides additional functionality like push buttons and the possibility to add an interface like USB.

Figure 3.3: Desktop joystick

3.2.2.4 Handgrip Joystick

These types use handle knob as grip and a complete hand is utilised to control the movement. Due to its size, the handle can be incorporated with additional functions like directional switches, detent mechanisms, switches, thumb joysticks.

Figure 3.4: Handgrip joysticks

3.3 Design of an industrial joystick outline

There are numerous ways to build a joystick, specializing in different areas of desire. Some focus on the range of rotation, control of the handle, or resistive forces within a given direction. The components that contribute to the joystick and the schematic arrangement of all the parts are shown below.

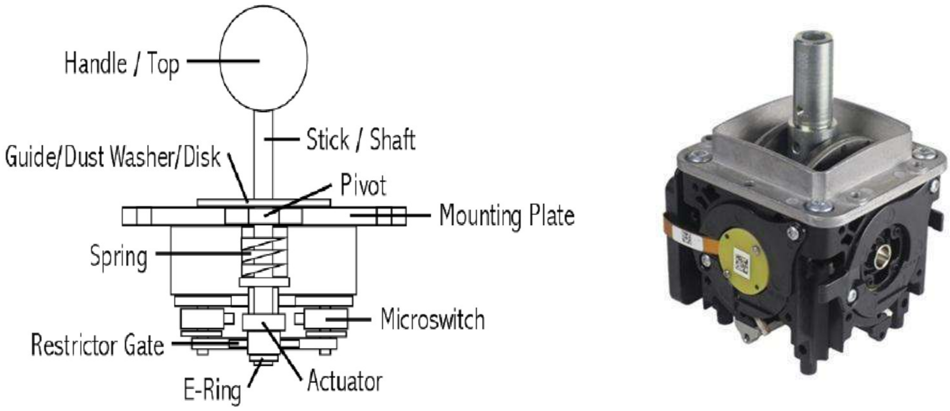


Figure 3.5: Proportional joystick

Handle/top – Where the user handles the joystick usually designed in a ball or bat top.
Stick/Shaft – connects the handle to the body of the joystick in a rod formation.

Figure 3.6: Shaft

Pivot – central point, pin, or shaft on which a mechanism turns or oscillates.

Spring – Used for sending the joystick back to the center position, which is located below the pivot.

Figure 3.7: Spring

Actuator – Gives the bottom of the shaft more area and precision in pressing the switches.

E-ring – This is a type of fastener that attached to the bottom of the shaft, used for aligning and securing parts along it.

Figure 3.8: E-ring

Mounting Plate – connected directly and securely to the control panel in the formation of a plate.

Figure 3.9: Mounting plate

Guide/Dust Washer/Disk/Cover – Surrounding the shaft on top of the control panel, in the formation of a flat disk.

Figure 3.10: Guide

Restrictor Gate – Controls where the joystick can be moved, in the formation of a plate with holes cut within it.

Figure 3.11: Restrictor gate

Other Parts – This include the wire harness which controls the switches around the bottom of the joystick. Other designs include extra plates, different pivot possibilities, or securers along the shaft.

Figure 3.12: Sub-parts

3.3.2 Lever Limiters

The lever provides the mechanical limitation of the lever deflection range. The following types are suggested to customers based on requirements.

- ✔ Square
- ✔ Round
- ✔ Single Axis (X or Y only)
- ✔ + Shape (2 Axes)

The deflection range is purely limited to X and Y axis direction; a deflection in diagonal direction is not possible.

- ✔ X Shape

The deflection is purely limited to diagonal direction, a deflection in X or Y-axis direction only is not possible.

- ✔ Diamond shape.

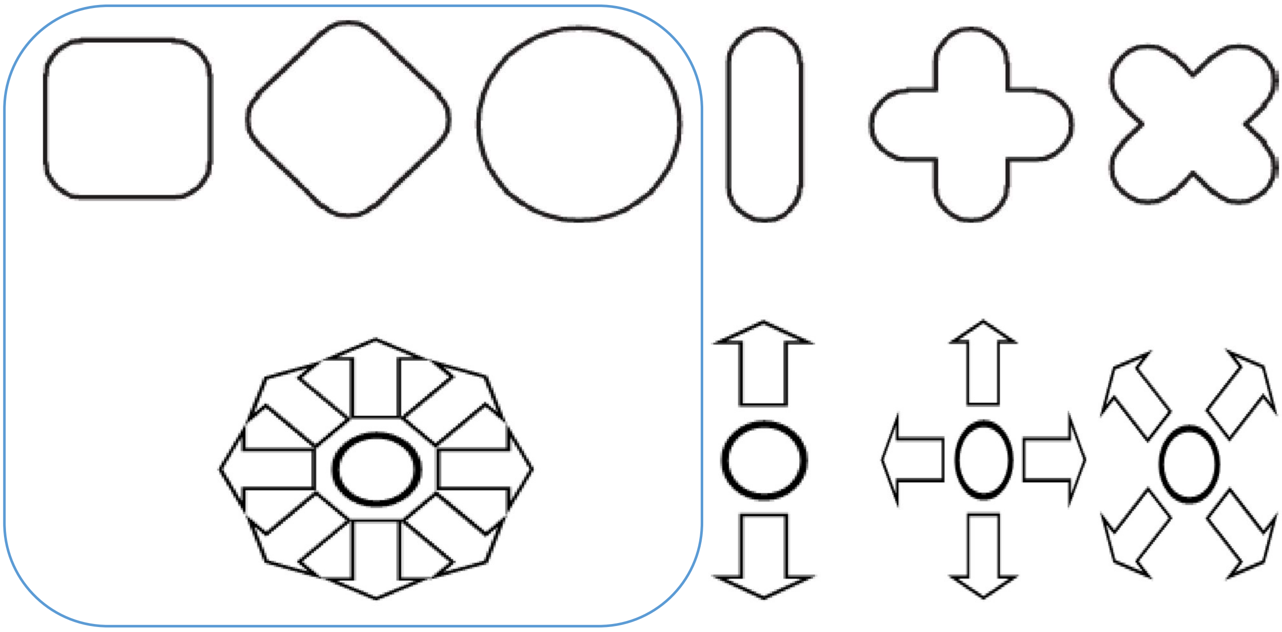


Figure 3.13: Lever profiles

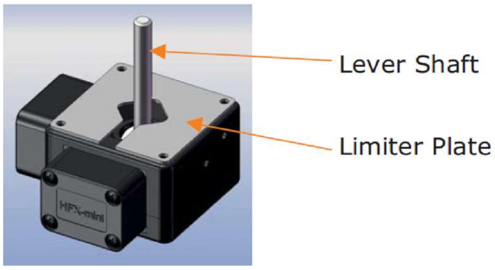


Figure 3.14: Lever guide in joystick

3.3.3 Proportional vs Non-proportional controls

A proportional control is able to provide the user the full control of the system in all travel directions which depends on the amount of force or pressure applied to the control. Proportional drive systems such as joysticks, allow users to increase or decrease the speed gradually depend on the deflection of joystick from neutral position. The proportional movement of joystick handle is monitored by potentiometer or hall sensor and the corresponding response is given.

A non-proportional control will provide either “active” or “not active” (1 or 0) response on the output and does not offer a variable control.

In Industrial joystick, proportional control is generally preferred and it is monitored by potentiometer or hall sensor.

3.3.3.1 Potentiometer and hall sensor

The potentiometers are electromechanical sensors with its function activated by voltage divider principle. In this system, variable resistor is used where an electrical contact moves across conductive plastic element which can be either rotary or linear. During movement of the handle, the physical components of potentiometer increase or decrease the voltage/current which is achieved through the variation of resistance within the electronic circuit. The required variation of voltage/current is realised with a small amount of force applied by the user. Although, the potentiometer technology of joystick created a wide pathway for electronic circuit control, it has the limitations in terms of reliability and long term durability as the moving parts tend to wear over time and minor susceptibility to electromagnetic interference or radio frequency interference.

Figure 3.15: Potentiometer joystick

The hall effect sensor works on the principle of measuring the magnitude of magnetic field and change the output voltage directly proportional to the strength of the magnetic field through it. This technology has the advantage over the potentiometer that there is no physical contact within the sensor which results in no wear. But, the mechanism of bail or gimbal for each magnet move which corresponds to wear over time and thus causing mechanical hysteresis. The other limitation of hall effect joystick is that the nature of ferromagnetic material will lose its magnetic field over time which is directly related to temperatures (< 0°C and 70°C). These variation in the magnetic filed will caue the effect of “drift” which is the variation of output voltge than the preset value for the handle movement and a different response to the user. Thus, the hall effect technology also has the limitation of long term relaibility.

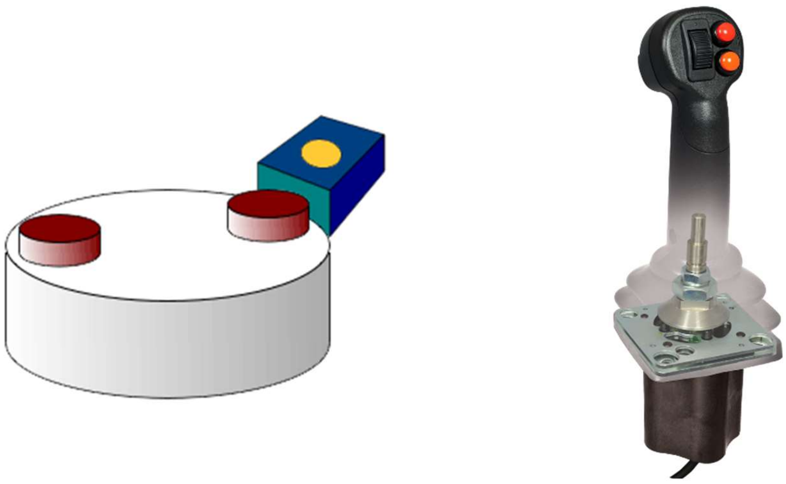


Figure 3.16: Hall effect joystick

3.4 Challenges faced in existing design

An industrial joystick manufacturer is facing the functional issue of spring loaded return to centre design that is used for industrial/high performance tasks which include cranes, excavators, and harvesters. The spring used for centre-return is unable to achieve a minimum of 5 million load cycles which result frequent downtime in construction field.

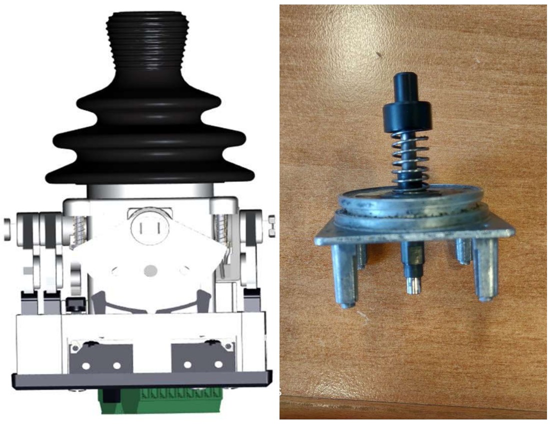


Figure 3.17: Existing joystick

The second challenge is the operation of joystick in extreme temperatures and hostile environments. The main problem is the galling between the zinc surfaces when it is performing at subzero temperatures. A high viscosity synthetic grease is used to lubricate the contact surfaces, but unable to meet the functional life guaranteed by the manufacturer.

Figure 3.18: Spring in joystick

The frequent downtime of centre-return spring and wear due to contact between surfaces causes a stoppage of crane which incur monetary losses to the customer. Consequently, a new way of control which sustain the infinite life is required to develop.

4 Design of new concept joystick for infinite life

The aim of design involves the development of new joystick which is intended to eliminate the problems faced currently and smallest version of all products. When proved, the new concept can also be applied to the existing joysticks in future to meet the minimum functional life of 5 Million load cycles.

The engineering design process realize its product through different phases. They are as follows,

- Identification of need
- Definition of concept
- Preliminary design

- Detailed design
- Realization
- In-service utilization
- Changings
- Obsolescence
- Disposal

Once the demand of a specific product is visualized from the marketing team through various analysis, the property and quantity of the product is chosen. Based on the characteristics of new product, the company involves in three types of design: Regular design, Innovative design, Creative design.

If the number of variables and the ranges of the values remain the same during the design process, this is regular or routine design; If the number of variables remains the same but the range can vary, then this is an innovative design; If the number of variable is changing, this is creative design. This project deals with the innovative design.

In concept development phase, the aim and the structure of function is defined. The research of working principle is done. Based on the aforementioned data, the various concepts are chosen, assessed and selected.

In the preliminary design phase, the layout and shape of the product is developed, the creation of model and the analysis of system is done. Based on the output, the optimization of functions is done and the layout is assessed to choose the suitable one.

In the detailed design phase, the components of the product are subjected to detailed analysis like performance, reliability and durability. The technological processes required to develop the product are evaluated, the performance and cost are optimized through appropriate selection. Finally, the detailed drawings are created.

Once the product is realized, it is subjected to actual working conditions and improvements are made through the user's advise. After the product reached its lifetime, it become obsolete and disposed.

4.1 Specification Study

The project aims at improving the performance related to mechanical with variants of joystick using predefined electrical properties. The specification requirements for the joystick are,

Mechanical:

- Base Dimension: 55 x 55 x 35 (mm)
- Expected life: > 5 million cycles (X,Y and Z axis)
- Mechanical Angle of Movement:
  ±36˚ for X and Y axis (subject to limiter)
  ±50˚ for Z axis (subject to handle)
- No. of steps: 3 - 7
- Breakout Force: 1.3N (2.86lbf)
- Horizontal load maximum: 300 N
- Vertical load maximum: 500 N
- Gate options: square, cross, two axis (A)
- Lever Action (Centering): Magnetic
- Center position tolerance: ± 1°
- Weight: 150g
- Housing: PA12

Environmental:

- Operating Temperature: -40 °C to +85 °C (-40 °F to +185 °F)
- Storage Temperature: -40 °C to +85 °C (-40 °F to +185 °F)
- Above Panel Sealing: Up to IP67 (subject to handle configuration)
- Humidity: IEC 60068-2-38
- Thermal shock: SAE J1455 section 4.1.3.2
- Salt spray: IEC 60068-2-11
- Random vibration: IEC 60068-2-64
- Sinusoidal vibration: IEC 60068-2-6
- EMC Emissions:

- Radiated Emissions Level: ECE/324/Add.9:2012; CISPR 25:2002
- Radiated Emissions Level: CISPR 25:2008

Electrical:

Sensor Type: Hall Effect

Resolution: 12 Bit

Supply Voltage: 5VDC ± 0.01VDC

Output Voltage: See Options

Return To Center Voltage: ± 50MV

Overvoltage Max. 24VDC

Reverse Polarity Max. -12VDC

The proportional handle versions of joystick are,

- Normal
- With mechanical interlock
- With deadman button
- With capacitive deadman button

The lever guide versions are,

- Square with variable width on 4 sides
- Cross with variable width on 4 sides
- Gearbox Type (“H”)
- Circular with variable cone opening

4.2 Concept Development

Based on the functional and specificational requirements, the different concepts are assumed and analysed from various perspectives like cost, ease of handling and fabrication. At first, it is required to understand the schematic of cranes and working of joystick

4.2.1 Schematic of cranes

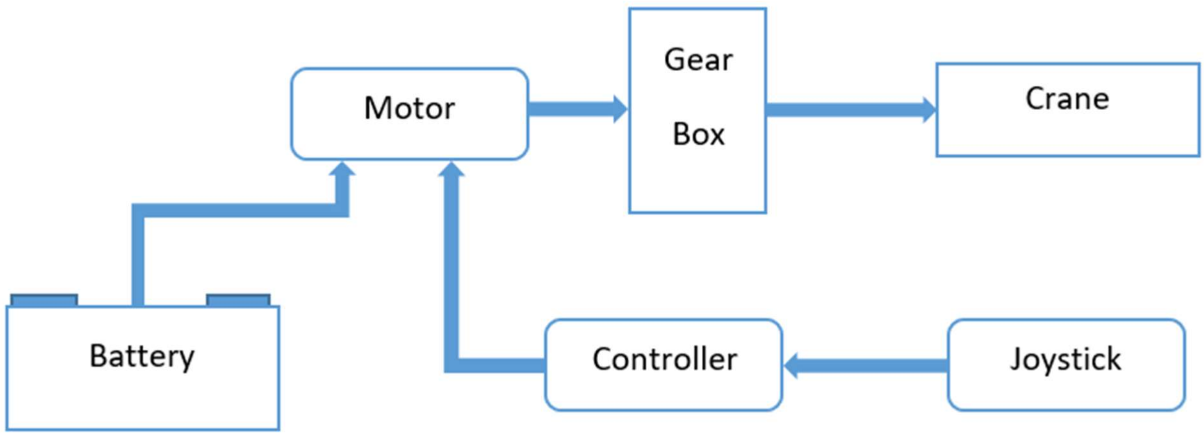


Figure 4.1: Block diagram of crane controller

The figure 4.1 shows the schematic representation of cranes which shows the transmission of energy, when the mechanical force is applied to the joystick, the mechanical energy is converted into electrical energy with the help of potentiometer or hall sensors and these electrical signals run the motor through the controller. The output of motor is connected to the cranes through the transmission.

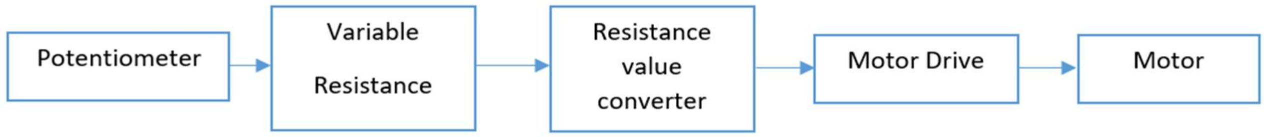


Figure 4.2: Potentiometer control

The process flow diagram of mechanical energy to electrical energy of joystick using potentiometer is shown above. These signals run the motor which propels the vehicle. This is an open loop control system and no feedback. This schematic explains the transmission of energy in the crane, the movement of joystick causes variable resistance and this resistance value is sent to the resistance value converter to convert the signals from analog to digital. As these signals are very low, they are sent to amplifier to amplify these low signals and to the micro controller for signal control.

4.2.2 Requirements for concept generation of joystick

After a series of brainstorming sessions with the technical personnel and with the customer survey, the following requirements are considered.

(1) The joystick must satisfy a minimum functional life of 5-10 million cycles without any interruption.

(2) The joystick must be designed in order to optimize the possibilities for controlling the cranes.

(3) The user control movements are transmitted via the joystick to the cranes in order to guarantee its reliable function with a minimum risk of interruption

(4) The exchange of information takes place between the crane and the user via the joystick in order to facilitate the task of controlling and make it as simple, comfortable and safe as possible.

(5) The operator wants to use only one hand to control the crane.

Based on the above requirements, the following parameters are focussed for concept generation:

(1) Ease of implementation

(2) All functions of speed and direction should be controlled by joystick.

(3) Simple mechanisms to be used

(4) Automatic controlled system

(5) Low price

4.2.3 Concept Development Process

In the concept development phase, the problem is defined and ideas are generated by the interaction with experts from the different departments like design, manufacturing & the user of the product. The concepts were generated & examined to get a promising concept for the fulfil the objectives.

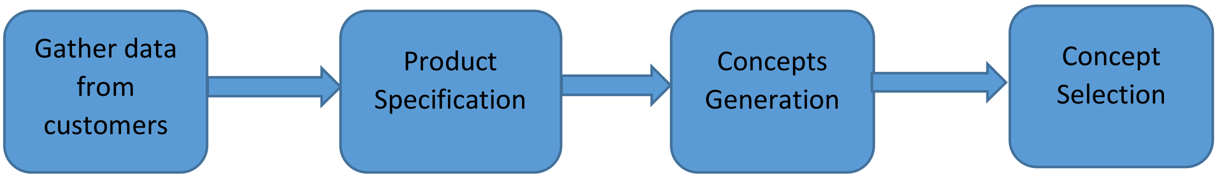


Figure 4.3: Concept development process

4.2.4 Functional analysis

The method of function analysis is used for analysing and developing a function structure of the new product. A function structure is nothing but an abstract model of the product to be developed (new), without any material features such as shape, dimensions and materials of the parts. It describes only the functions of the product with its components and indicates the relation between them.

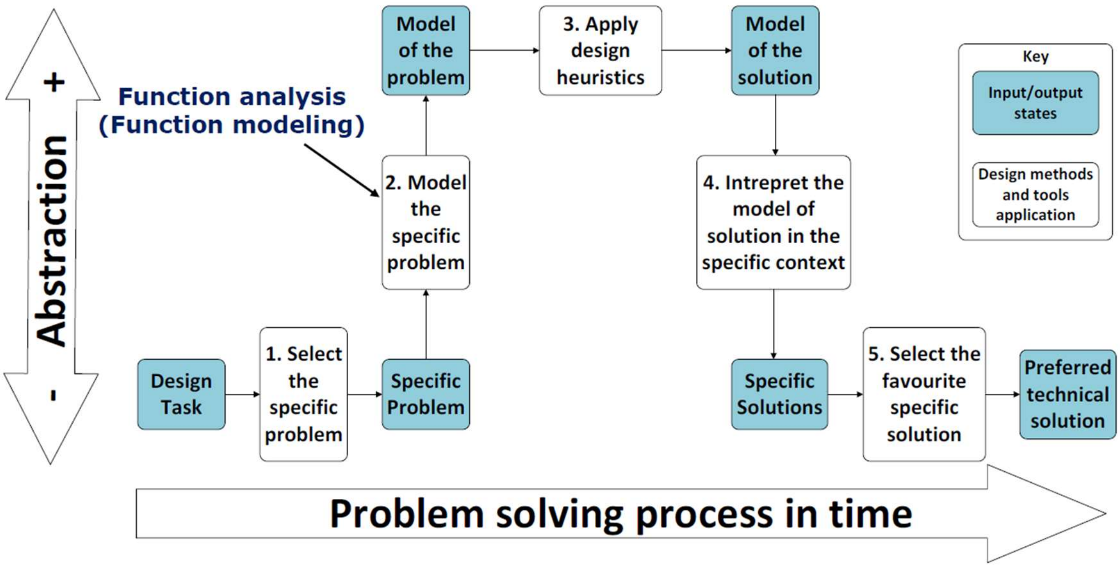


Figure 4.4: Problem solving process

Any technical system can be modeled as a black box channeling or converting energy, material and or signals (information) to achieve a desired outcome.

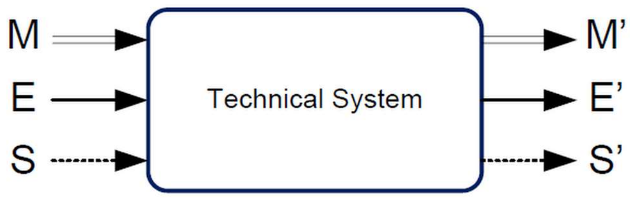


Figure 4.5: Transformation of technical system

4.2.4.1 Law of system completeness (LESE)

The Law of system completeness(LESE) determines the important features to be considered in the model.

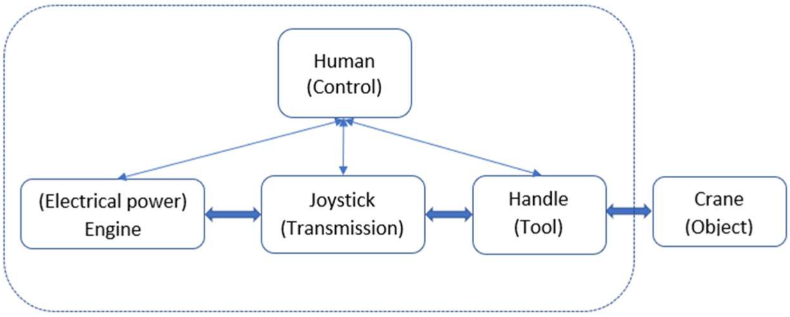


Figure 4.6: Law of system completeness

The TRIZ/OTSM model clarify the functions, the entities composing the system carry out for the overall purpose of the technical system (behaviour and structure).

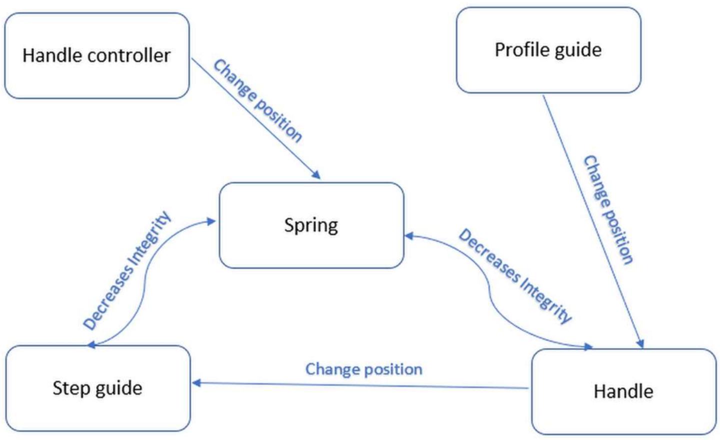


Figure 4.7: TRIZ model

4.2.4.2 Su-field Analysis

Substance-Field (Su-field) Analysis is a TRIZ analytical tool for modeling problems related to existing technological systems. Every system is created to perform some functions.

The desired function is the output from an object or substance (S1), caused by another object (S2) with the help of some means (types of energy, F). The functional interaction shows the insufficient/ harmful function of handle to spring to be analysed and improved.

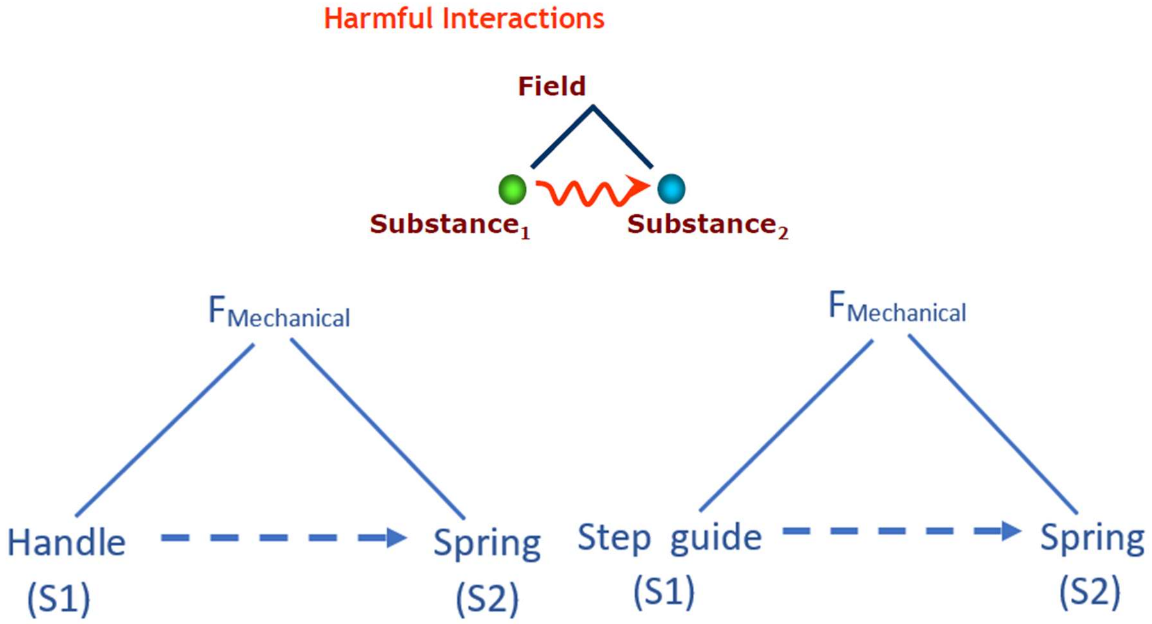


Figure 4.8: Block diagram of Su-field

4.2.4.3 Contradiction model

In any design project, there arise a number of conflicts and constraints due to the number of limitations/contradictions which shows the acceptable and unacceptable solutions in the design process and the one which closes matches the aim of the design. In general, product design is constrained severely as the large number of requirements for a single product are often conflicting during conceptual design as well as problem resolving.

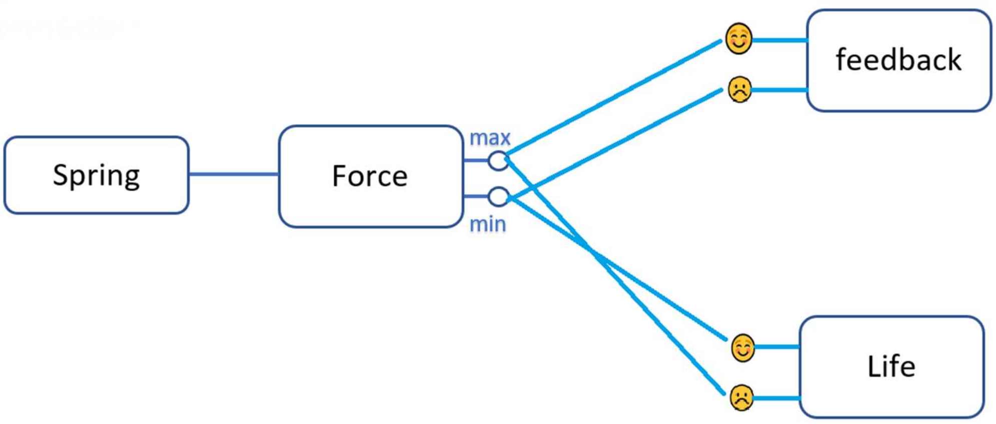


Figure 4.9: Contradiction model

4.2.4.4 Inventive Standard

Inventive standards are techniques to solve a problem by modyfying the physical structure of a system using Su-Field models.

The standards can be classified into 5 classes:

Class 1: Synthesis and decomposition of Su-fields. This class focus on improving the useful interaction of the system or eliminating a harmful function.

Class 2: Evolution of Systems. In this class, the ideality of the system is aiming to be achieved by suggesting other field of control or technologically advanced substances.

Class 3: Transitions towards supersystem or microlevel. These standards will guide us towards multisystems and miniaturization.

Class 4: Measurement and detection. These patterns improve the measurement and detection issues in the studied system.

Class 5: Helpers. The last set of standards will introduce fields and substances in order to obtain better results

Applying the inventive standards, the **standard 1-1-3** introduces a new substance to substance 2 to improve the positive effect of the system.

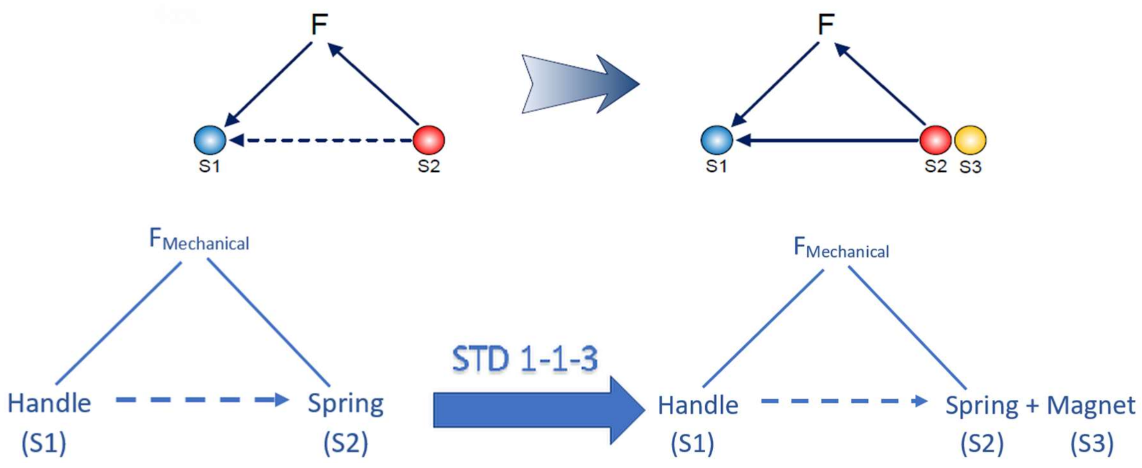


Figure 4.10: Inventive Standard 1-1-3

4.2.5 Concept Generation

Concept generation of a product usually invovles the approximate description of technology used, principle of working and the pattern of the product. It is a brief description of how a product must satisfy the demand of customer. A concept is usually represented by a sketch or three-dimensional model with a brief textual description.

The process of concept generation begins with analysing a set of customer needs, specification target and provides a set of product concepts as an outcome from the team and a final selection is made by comparing all requirements and availabilites. Using the above process, four different concepts are generated by brainstorming and these concepts are explained in detail below.

4.2.5.1 Concept A

In concept A, the spring for the centre return mechanism is replaced with magnets. The two axial magnets are used in rotating ball on two sides to bring the handle to centre zero position in x and y axes. Another two axial disc magnets are used on the case to attract the magnets on the ball thus achieving the centre zero position. The plungers are used on the other two sides to realize the proportional movement of the handle.

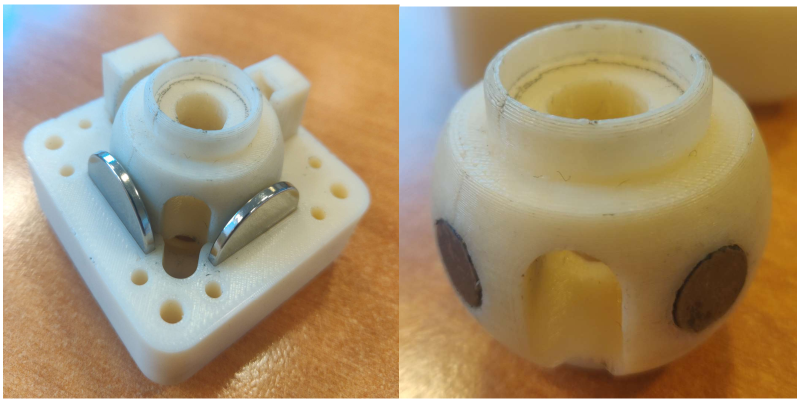


Figure 4.11: Concept A

Drawbacks:

- The magnets are in contact with each other during operation which in turn reduces the expected lifetime of the magnets due to wear.
- The deviation of handle in the centre position due to magnet is higher than allowed tolerance limit level which results in inappropriate feedback to the controller.
- The high friction between the ball and the case makes the interrupted handle movement when the user releases the handle.
- The assembly of magnets in case and ball are complex as the high attraction between the four magnets tend to make possible the wrong alignment during assembly.

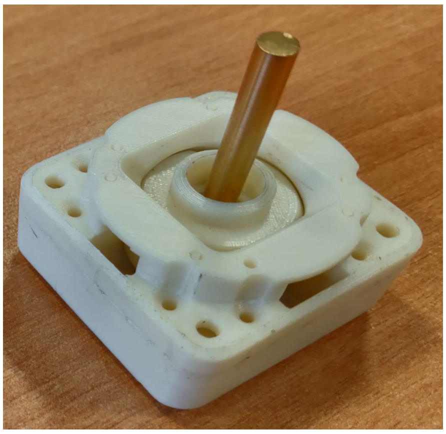


Figure 4.12: Assembly of concept A

4.2.5.2 Concept B

In this concept, the two axial ring magnets are used. One magnet is fixed in the case and the movable magnet is placed on the ball. The magnets are assembled in such a way that the facing poles are different with respect to the centre of disc. As a result, when the position of the handle is changed manually, the repulsion between the magnets makes the handle centred. The magnet is attached to the ball through adhesive. The force required to move the handle is not constant and increases gradually as the handle moves to the extreme position of 42 degree due to high repulsion between the magnets.

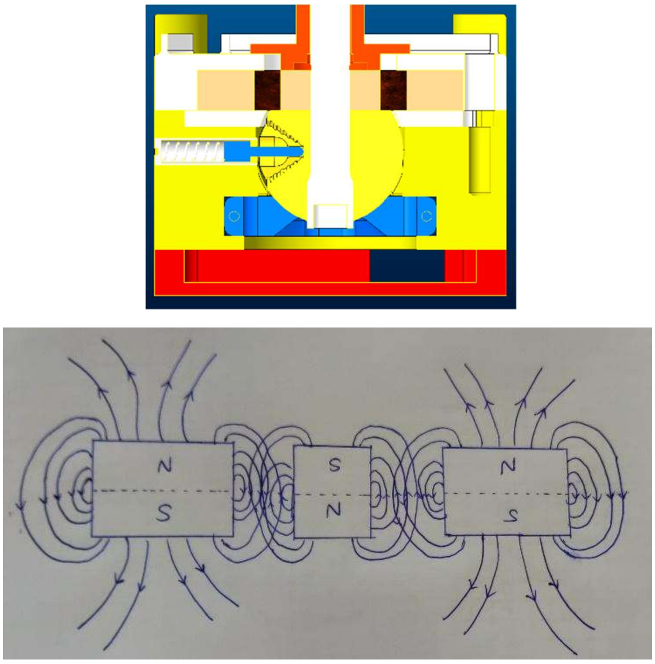


Figure 4.13: Concept B

Drawbacks:

- The high thickness magnets are required to achieve the handle inclination of 42 degrees which results in high cost magnets.

- Due to higher magnet thickness, the overall height of the product increases by approximately double. Since the dimensions of product are limited according to the control station, this dimension is impossible to be passed.
- The magnets may contact at the extreme position of 42 degree which result in reduced lifetime of magnets.

4.2.5.3 Concept C

In this concept, the axial ring magnets are used similar to the previous concept with an alignment of two magnets at different heights on the space. The magnet on the case and the movable magnet is placed on the ball. The magnets are arranged in such a way that the poles are different in any direction. When the handle is moved, the repulsion force creates between the two similar pole magnets which brings the handle to centre after removal of force.

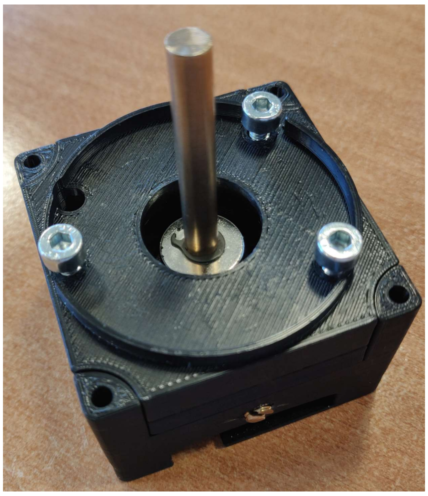


Figure 4.14: Concept C

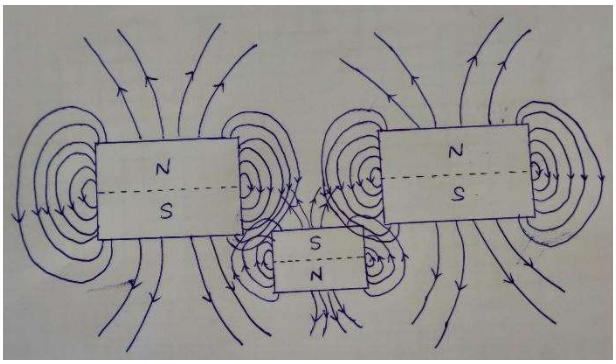


Figure 4.15: Magnet working

The lever limiter is introduced to control the handle movement of two axes or 3D. It is mounted on the bottom section of case and screwed. Depending on the requirement, the user can change the profile of lever limiter.

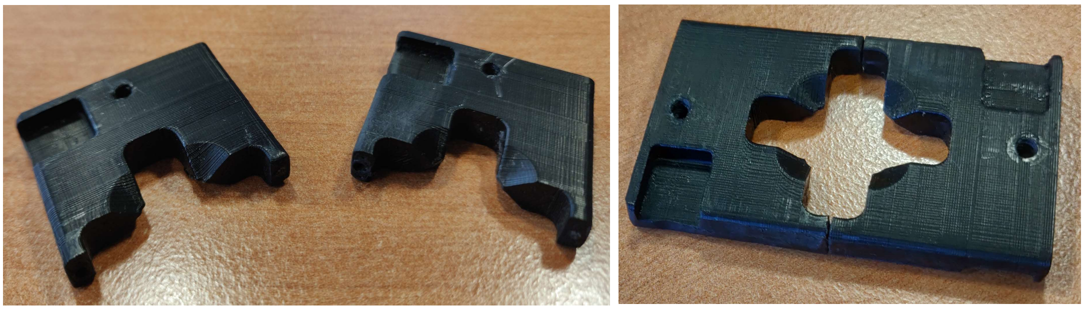


Figure 4.16: Lever limiter

The handle controller is introduced for the mechanical interlock mechanism and the design is made in such a way that cable can pass through the part when the electrical switch is required on the joystick. The spring is used only to return the handle controller instead of two actions (centre-return and vertical handle movement) here.

Figure 4.17: Handle

The proportional movement is integrated in the ball through plunger action. The 5-step profile is introduced on the ball and the plunger is assembled on the case. The piston moves forward and backward when the ball rotates.

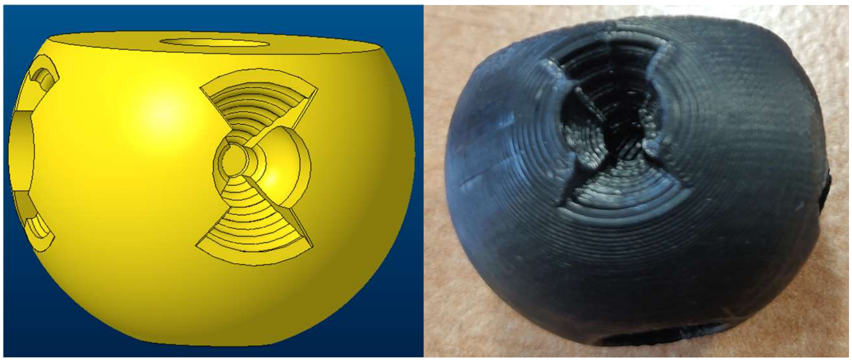


Figure 4.18: Ball

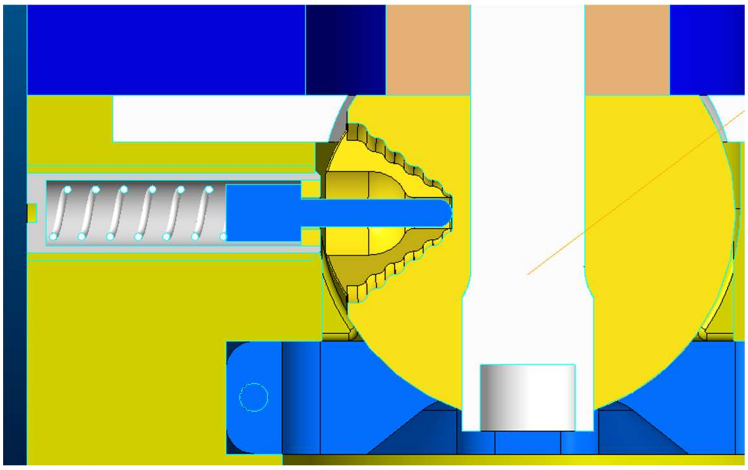


Figure 4.19: Plunger

The assembled view of this concept is shown bellow,

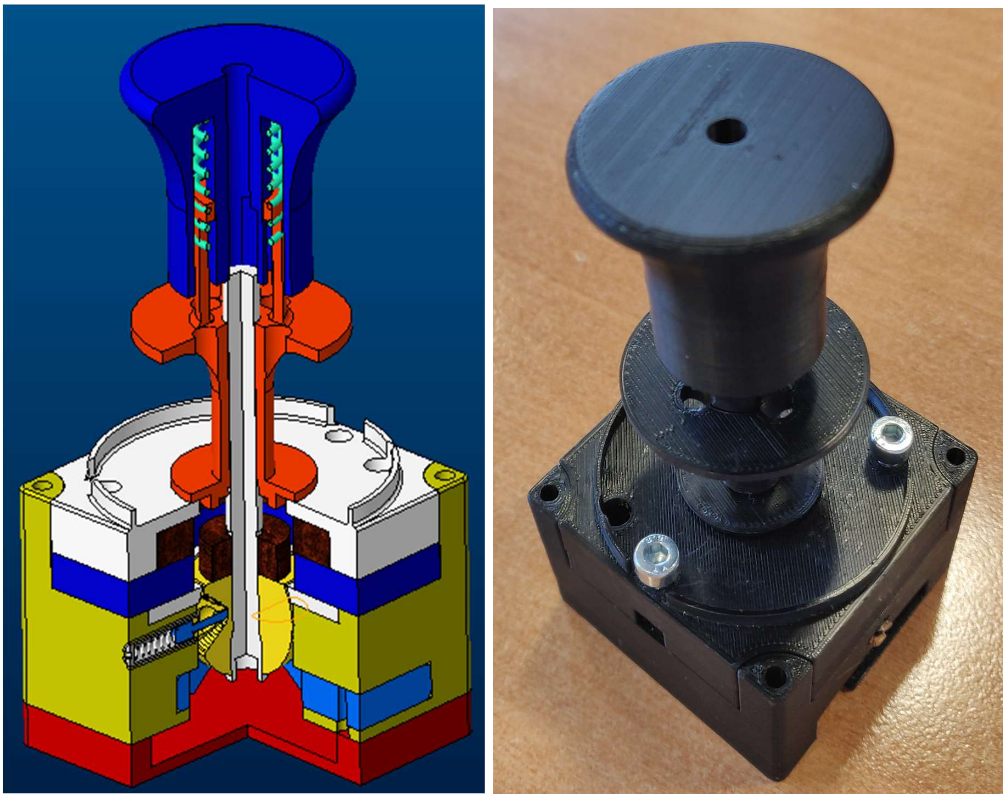


Figure 4.20: Concept C assembly

Advantages:

- The magnet thickness is extensively reduced when compared with the previous concept which greatly results in reduced cost.
- The lever limiter can be easily mounted and dismounted without interrupting the operation of user by their chosen profile.
- The handle controller can be used to pass the cable through it without any alignment problem and it gives a way to connect rubber bellow as protection from water

- The spring life is greatly improved beyond infinite life as the magnet takes responsibility of centre-return position.
- The overall dimension is within the limit of requirement with easy access of table mounting.
- Assembly of parts is easier and poka-yoke is implemented for mass production.
- Standard fasteners are used and low strength plastics are applied for the long term performance.
- The magnet is locked on the ball by e-ring instead of adhesives.
- Hall sensor provision is easily implemented

Drawback:

- Due to high friction between piston and step profile, the handle movement is interrupted during centre-return operation.

4.2.5.4 Concept D

In Concept D, the main modification is on the step profile to overcome the drawbacks faced in concept C. The magnets are assembled similar to the previous concept in an inverted way. The two parts c-section and rectangular section are introduced to rotate the handle in two axes independently. In this concept, a new 3D printing machine is used which is capable of printing the whole mechanism as a single product instead of developing individually with a clearance of 0.3 millimetre between each part. The ball bearing is used at the ends of two parts to transfer the load generated during operation.

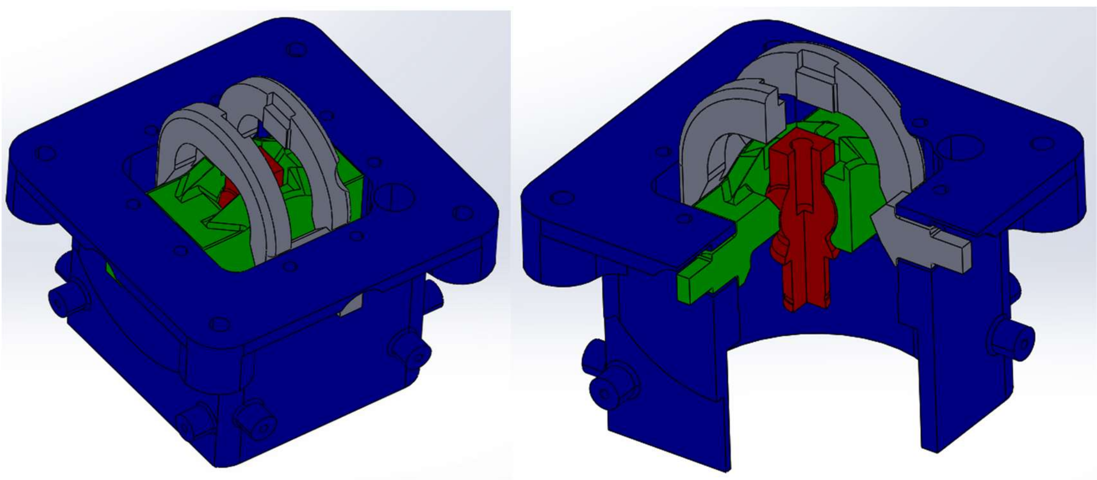


Figure 4.21: Concept D

The step guide with magnets are introduced to realize the proportional feedback while rotating the handle. The small stepped magnets placed on the curved profile attract for each step movement thus give the user feedback about each step.

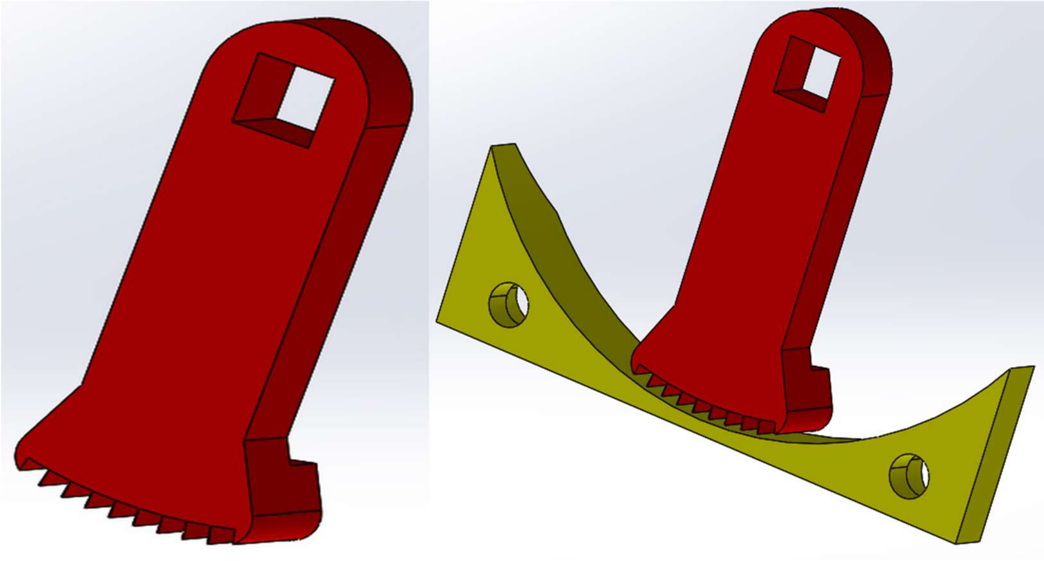


Figure 4.22: Step guide

The handle controller is designed in a way that it provides interlock mechanism for the joystick and the rubber bellow can be mounted on it to ensure protection against water. The legs of handle controller are locked between the c-section and rectangular section after assembly to avoid rotation of handle and degradation of rubber bellow.

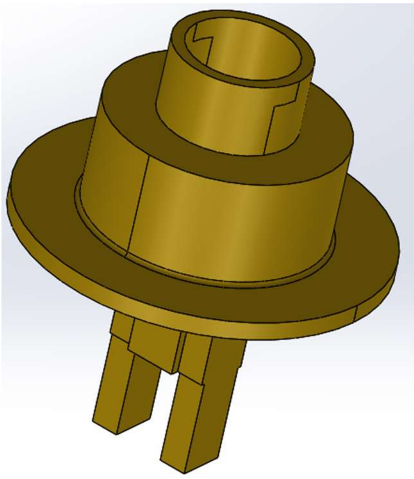


Figure 4.23: Handle controller

The profile guide is introduced at the top of the handle which can be assembled and disassembled indepently depend upon the user's requirement.

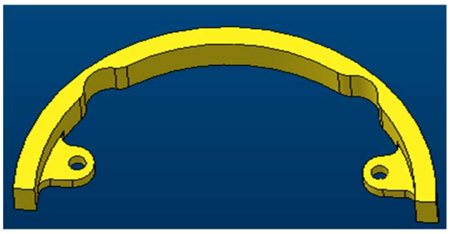


Figure 4.24: Profile guide

The overall concept is shown below,

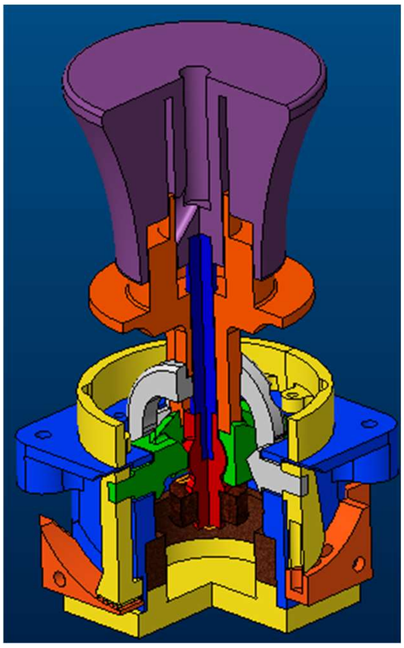


Figure 4.25: Concept D assembly

Advantages:

- The complexity of the proportional feedback from the previous concept is avoided.
- Contactless operation of all magnets which results in infinite life of mechanism.
- Assembly is easier as the majority of mechanism is single printed.
- The spring life is greatly improved beyond infinite life as the magnet takes responsibility of centre-return position.
- The overall dimension is within the limit of requirement with easy access of table mounting.

4.2.5.5 Concept E

In concept E, the centre-return is achieved by introducing two axial cylinderical magnets on two sides by replacing the axial ring magnets used in the previous concept. The magnets are assembled using adhesives and the operation is contactless.

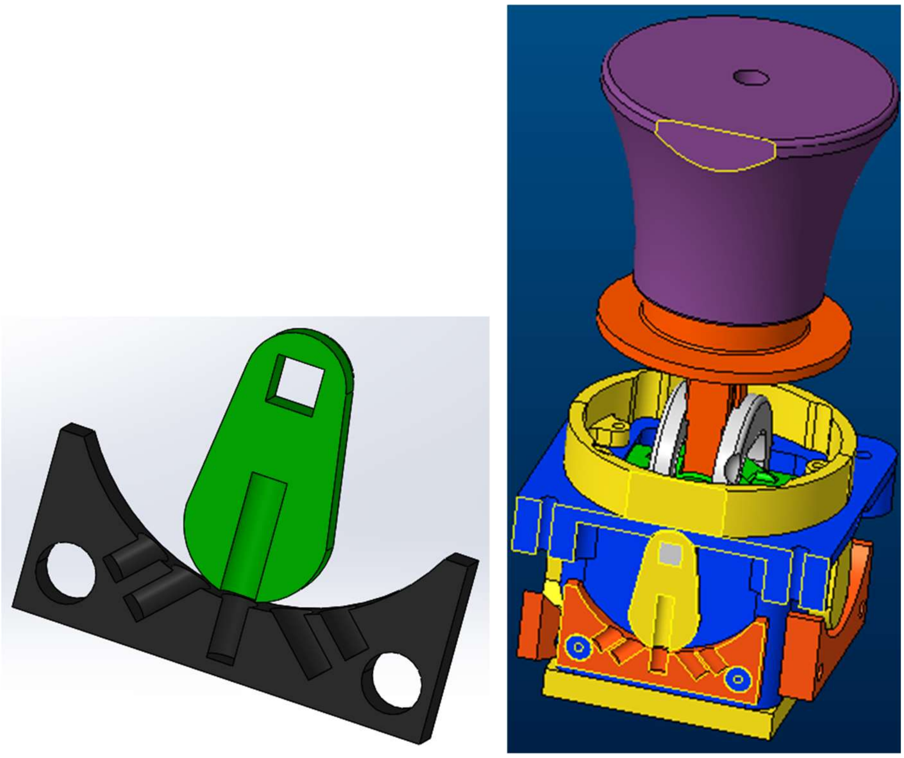


Figure 4.26: Concept E assembly

Advantages:

- Load distribution is uniform along the parts
- The height of product is reduced greatly.
- Easier assembly than previous concept.
- Through process of elimination, a suitable design was selected. The final design was created from all the initial ideas they were analysed and some concepts from the ideas were used to make the final design.

4.2.6 Concept Selection

During concept selection, all the concepts should be presented at the same level of detail for meaningful comparison and unbiased selection. The selection criteria are carefully chosen mainly associating with the objective of design and listed along the left hand side of the screening matrix, as shown in the table 4.1. The objective of design is selected based on the customer needs in the survey as well as on the needs of the enterprise, such as low manufacturing cost or minimal risk of product liability. A relative score of A, B, C and D is to be placed in each cell of the matrix to represent how each concept in comparison to the reference concept relative to the particular criterion.

The concept with highest overall score (top rank) is selected depending on customer survey as well as with the technical experts which are shown in appendix and the outcome of the entire concept development phase is to select the best concept. Therefore, from the the average of all survey, as a conclusion of this phase, the concepts D and E are selected as the final concepts by the survey conducted with the technical experts of the company. Major factors affecting the decision are given below. All team members should be comfortable with the outcome.

- Robust Design
- Ease of handling
- Ease of fabrication
- Ease of operation
- Cost
- Easy to install
- Easy maintenance
- Degrees of freedom

Pugh matrix for concept selection is as follows.

<u>SCORING</u>

1. Poor
2. Not so Good
3. Good
4. Very good
5. Excellent

Sl.No.	Selection criteria	Concepts				
		Concept A	Concept B	Concept C	Concept D	Concept E
1	Robust Design	4	4	5	5	5
2	Ease of handling	2	2	4	5	5
3	Ease of fabrication	5	5	5	4	4
4	Ease of operation	2	4	4	4	4
5	Cost	4	5	5	4	3
6	Easy to install	3	2	4	4	5
7	Easy Maintenance	4	3	4	4	4
8	Degrees of freedom	1	5	5	5	5
	Overall Score	25	30	36	35	35
	Rank	IV	III	I	II	II

Table 4.1: Pugh matrix

The concept selection is made by taking the average of all the concepts. In this Pugh matrix, final selected concept is considered as a reference concept which has the highest score and ranked first. From the matrix, concept C rank first and concepts D & E rank second with the closest score. Consequently, the concepts C, D & E are selected and proceed towards the next phase.

4.3 Detail design of selected concept

The detail design phase includes the complete specification or the detail of the geometry, for all the unique parts in the product. The output of this phase is the controlled documentation for the product, the drawings or computer files describing the detail dimensions of each part and its templates which will acts as tools.

Generally joysticks are operated by using friction and resistive technologies. In this project work resistive technology is used for the joystick. The resistive joystick use potentiometer mounted to spring loaded ball that are moved by a deflection of the joystick handle. Typically one potentiometer is used for each axis(x and y) the output of the potentiometer is read as either a change in velocity or change in electrical resistance depending on how they wired.

4.3.1 Specification

As the specification is already defined from the marketing team based on the demand from the survey, the main properties associated with the project are listed below.

Mechanical		Environmental	
Base Dimension	55 x 55 x 34 (mm)	Operating Temperature	-40 °C to +85 °C (-40 °F to +185 °F)
Expected life	> 5 million cycles (X,Y and Z axes)	Storage Temperature	-40 °C to +85 °C (-40 °F to +185 °F)
Mechanical Angle of Movement	±36° for X and Y axis (subject to limiter) ±50° for Z axis (subject to handle)	Above Panel Sealing	Up to IP67 (subject to handle configuration)
No. of steps	3-7		
Horizontal load maximum	300 N		
Vertical load maximum	500 N		
Gate options	square, cross, two axis (A)		
Center position tolerance	± 1°		
Housing	PA12		

Table 4.2: Specification

The proportional handle versions of joystick are,

- Normal
- With mechanical interlock
- With deadman button
- With capacitive deadman button

The lever guide versions are,

- Square with variable width on 4 sides
- Cross with variable width on 4 sides
- Gearbox Type (“H”)
- Circular with variable cone opening

4.3.2 Development of selected concepts

The concepts C,D & E selected from the pugh matrix are detail developed for service utilization.

4.3.2.1 Concept C

The concept C is developed for the normal handle type with square, cross and circular lever guide versions. The geometry of the concept falls within the requirement and able to be mounted very well within the control station. The parts details are as follows,

Base:

The base component acts as a housing for ball, profile guide and pistons. The overall dimensions are 55*55*32 mm (LxBxH). At the bottom of the base, the profile guides can be screwed and replaced to any profile based on user's choice. The pistons are assembled at the two sides using thread and the proper assembly is ensured by maintaining the surface of piston and base same while screwing. The ball connected with handle is inserted into the base and its rotation for handle movement is enabled in the base.

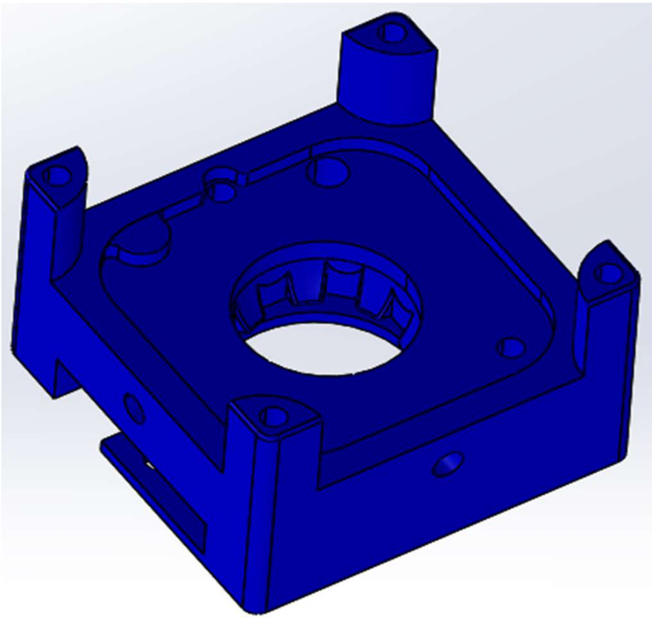


Figure 4.27: Base

Cover box:

The cover box give the space to mount stationary magnet on one end and on the other end, the rubber bellow is screwed to it for the protection against water. The handle controller rest on top of the cover box and while returning from excited position, the handle controller locks automatically into the cover box ensuring the zero position of handle at equilibrium.

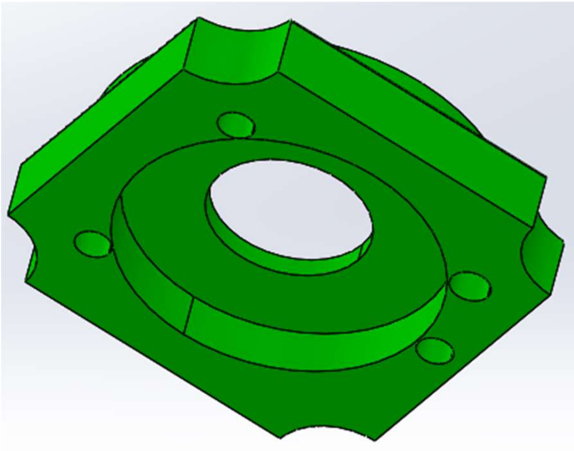


Figure 4.28: Cover box

Ball:

The ball rotates in the base during handle movement and also ensures the proportional feedback by making its contact with pistons. The unique step profile is provided on two sides of the ball which guide the piston during handle movement and also arrest the handle when the extreme position is reached. A ring magnet 15x06x06 (mm) (O.D x I.D x thickness) is assembled on the surface of ball and its motion is arrested using e-ring. A small magnet is inserted at the bottom of ball if hall sensor feedback is required.

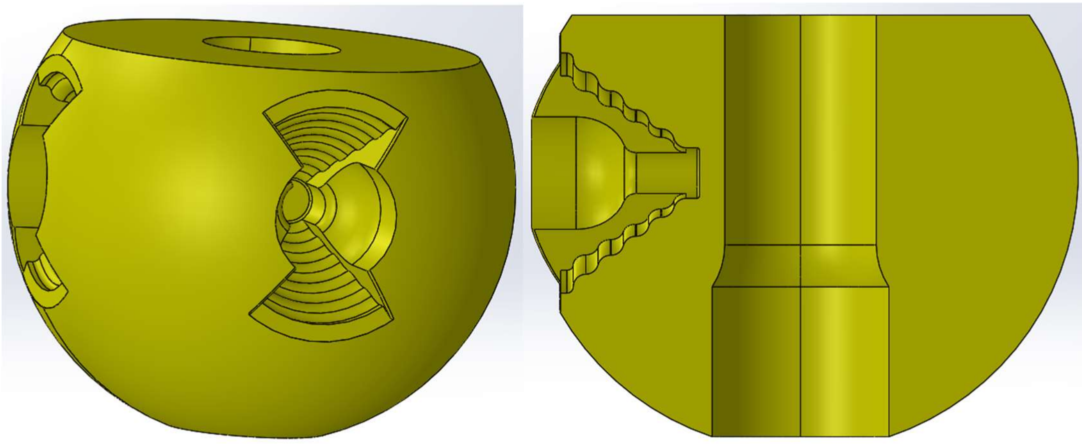


Figure 4.29: Ball

Profile guide:

The profile guide allows the handle to rotate in a predefined path. The path can be square, cross and circular. The component is designed in such a way that no external tool is required to assemble and disassemble from the coverbox. The alignment of the profile guide is ensured by providing the protrusion at one end and extrusion cut at the other end which allow the symmetric parts to get assembled into each other. The symmetric profile guides can be screwed to avoid expulsion during operation. The component top supports the ball and arrest its motion due to protrusion at the end while the handle reaches the extreme position.

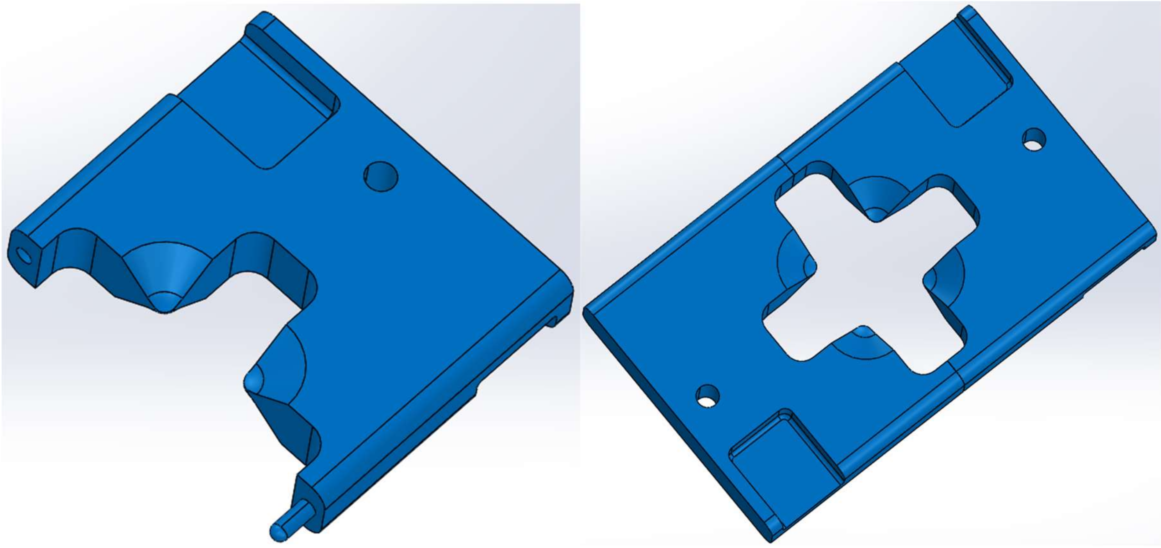


Figure 4.30: Profile guide

Plunger assembly:

The Plunger assembly consists of a spring, piston and housing. The external surface of the plunger assembly is threaded in such a way that it can be assembled into the base ensuring the piston and step profile contact on ball. The piston is in clearance with the housing and the deviation of piston with respect to its axis is less than 1.5 degree and assure the handle centre position with its tolerance.

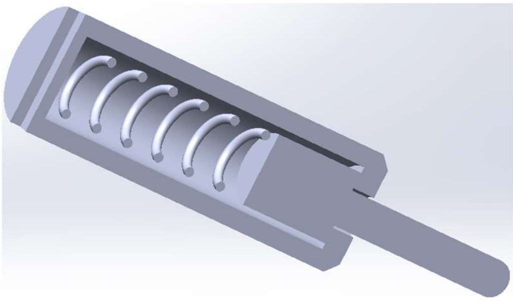


Figure 4.31: Plunger

Handle Controller:

The handle controller is used when there is a requirement of mechanical interlock and also for an electrical switch. The component is assembled through the ball handle and it rests on the cover box thereby allows only the translational movement of handle controller along the ball handle. The provision is given at the top of the component for cable access directly from the top support which reduces the complexity of cable swirling.

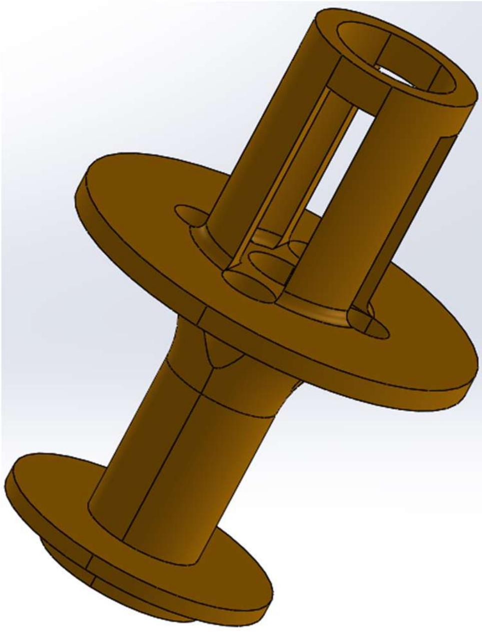


Figure 4.32: Handle

Top support:

The top support is inserted in the handle controller and made fixed by threading it with the ball handle. The spring is assembled inside the component and placed between the top support and the handle controller which returns the component when the handle is released. The cable starts from the top support and reaches the base through handle controller and cover box.

Figure 4.33: Top support

4.3.2.2 Concept D

This concept is developed to print the functional mechanism as a single component instead of printing multiple 3D components and assemble as in traditional additive manufacturing. Since the functional mechanism is printed, the criteria to be maintained is that the independent working parts must have a clearance of 0.35 millimetre between each other which is derived from the printing machine capability. The components details are as follows,

Case:

The case acts as a housing for c-section, rectangular section, ball handle and axial ring magnets. The stationary magnet is assembled in the case. The overall dimension is 55x55x32 mm (LxBxH). The case is table mounted and allows access for cable to pass through it.

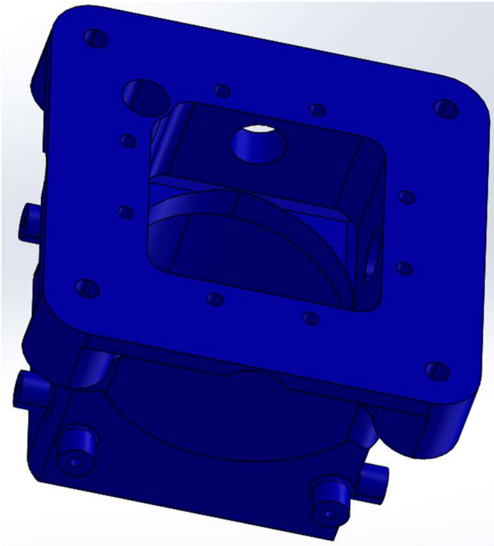


Figure 4.34: Case

C-section:

The c-section allows the movement of the handle in one direction. It is printed inside the case with its two ends enclosed with steel bushes to reduce the relative friction between the part and base during handle movement.

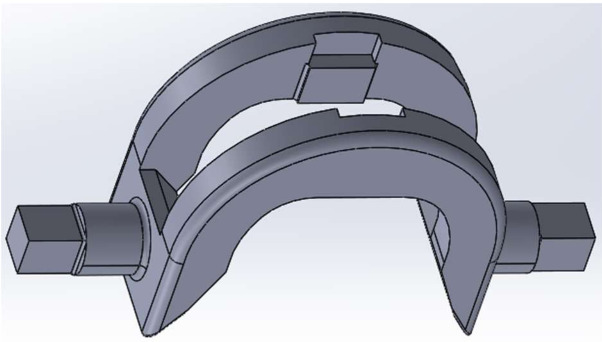


Figure 4.35: C-section

Rectangular section:

The rectangular section is similar to the previous component in terms of function and its ends are enclosed by steel bushes as well. The step guides are assembled at the two ends for proportional feedback.

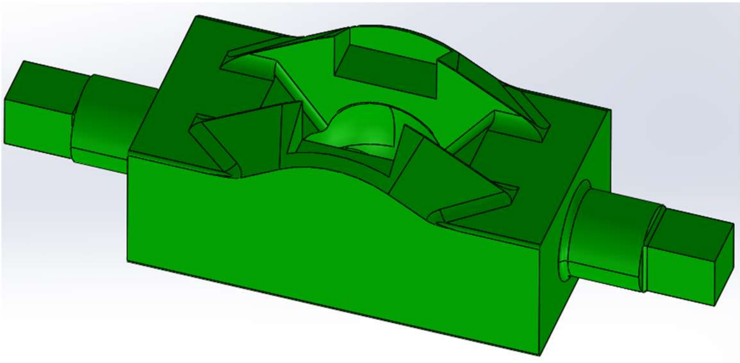


Figure 4.36: Rectangular section

Ball handle:

The ball handle is placed in the rectangular section during printing and it allows the movement handle in various steps. The magnet is assembled at the bottom of ball handle and its translational movement is stopped using e-ring.

Figure 4.37: Ball handle

3D Printed mechanism:

The components case, c-section, rectangular section and ball handle are printed as a single component. This technology enables to print the functional concept with one part inside the other having a clearance of 0.35 millimetre each and allows them to move independently.

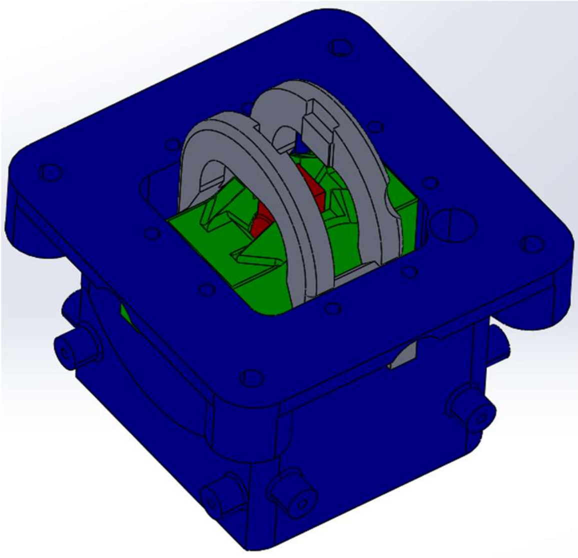


Figure 4.38: Printed Mechanism

Step guide:

The step guide allows the user to realize the proportional feedback while rotating the handle. The foil magnet is stuck to the curved profile of the component and another foil magnet is placed on the bottom plate. The attraction between the opposite poles of magnet gives the user feedback about each step movement.

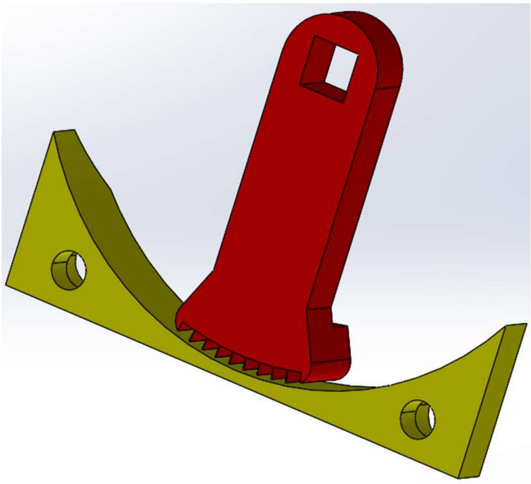


Figure 4.39: Step guide assembly

Metal handle:

The metal handle is introduced in the concept to ensure the infinite life of the joystick. It is assembled in the ball using thread on one end and in the top support on the other end.

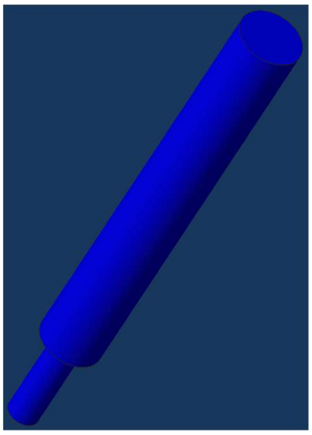


Figure 4.40: Metal handle

Handle Controller:

The handle controller's function is similar to the previous concept with some modifications in the geometry. It is used when there is a requirement of mechanical interlock without an electrical switch. The rubber bellow covers the component and connected on the base against the water protection. The handle controller is removed when there is a requirement of electrical switch.

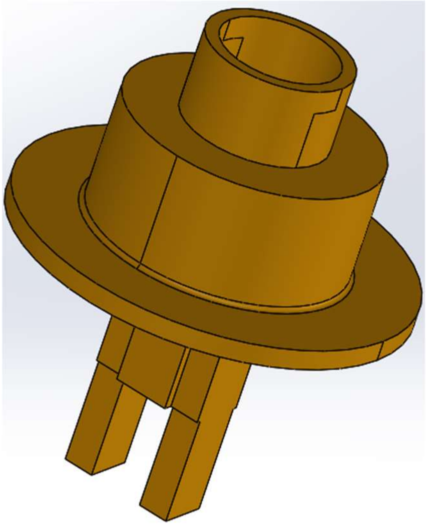


Figure 4.41: Handle controller

Top Support:

The top support is assembled on the top of the handle controller using threaded connection. It allows the cable movement pass through it and spring is inserted in the component which works for the hande controller equilibrium position..

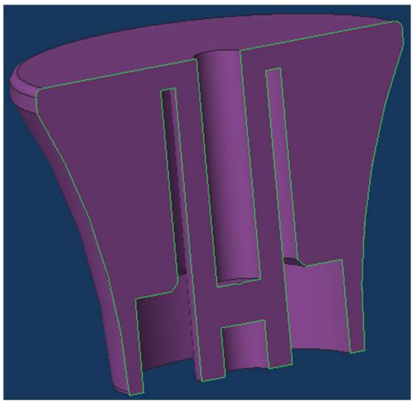


Figure 4.42: Top support

4.3.2.3 Concept E

The concept E is developed as a substitute for the previous concept to create a compact structure by providing the same function and properties. The components are similar to concept D except that the centre-return mechanism is achieved by introducing the axial cylindrical magnets at the sides and removing the axial ring magnets at the case. This concept makes the product compact and the important factor of height is greatly reduced which results in cost improvement. Since the four sides of the case is equally loaded unlike only the two sides in the previous concept, the load distribution is uniform in this case and gives a way for easier assembly.

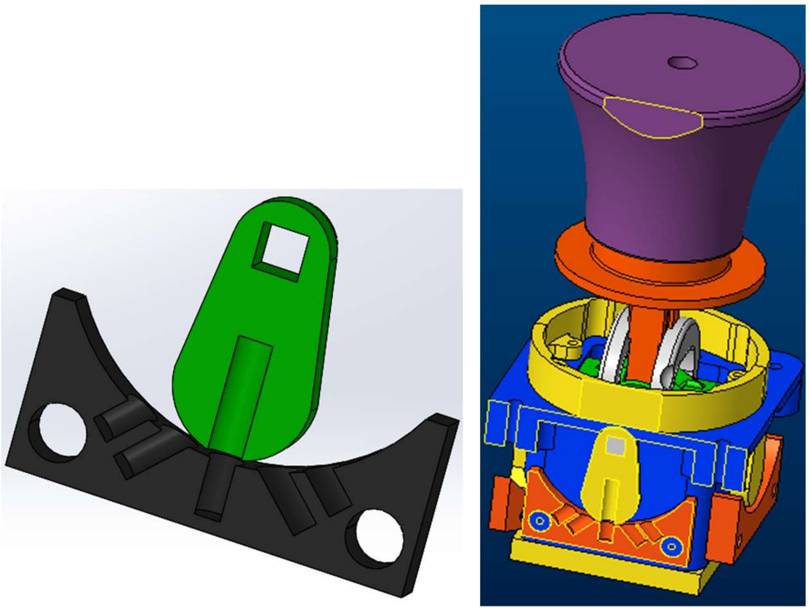


Figure 4.43: Concept E assembly

4.3.3 Assembly details

4.3.3.1 Concept C

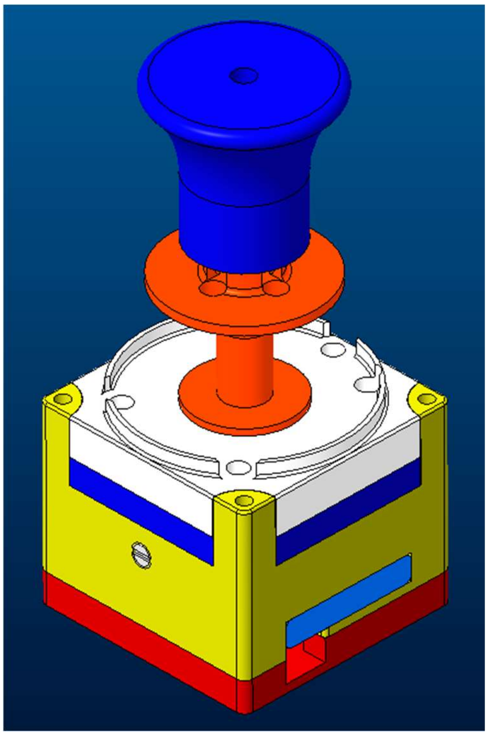


Figure 4.44: Assembled view

The assembly can be carrried out without any special tools which reduces the assembly time extensively. The base is first taken and kept as a fixed component. The ball with metal handle is assembled into the base and arrester plate is inserted to stop the translational movement of handle. The space plate is then inserted and cover box with magnet is assembled on top of it. Now, the handle controller is aligned through the metal handle and top support with spring inside is assembled with the handle controller using threaded connection. The hall sensor magnet is inserted at the bottom of metal handle using adhesive and the conroller board is screwed to the base if required.

Assembly Drawing (Concept-C):

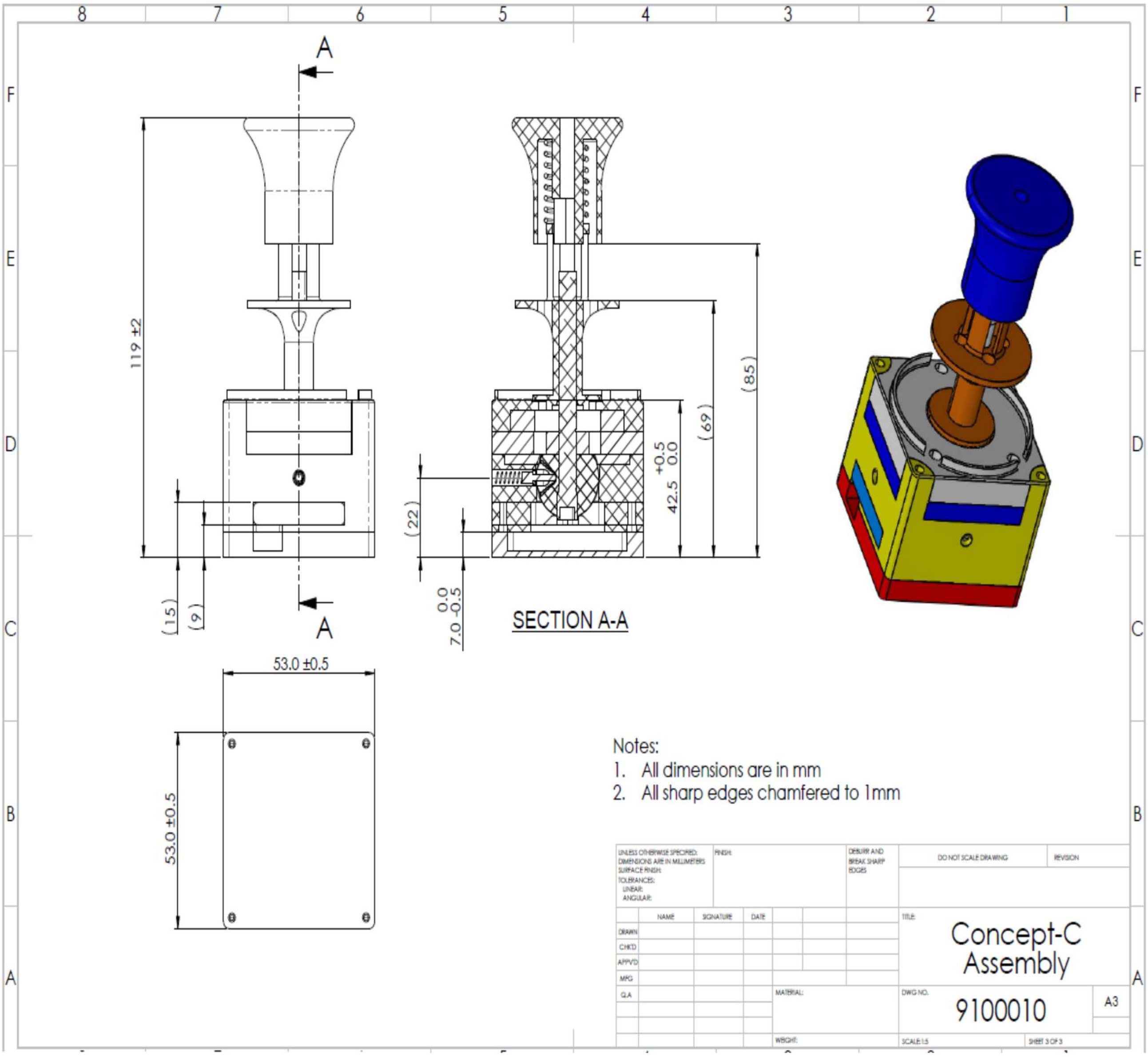


Figure 4.45 Assembly drawing-C

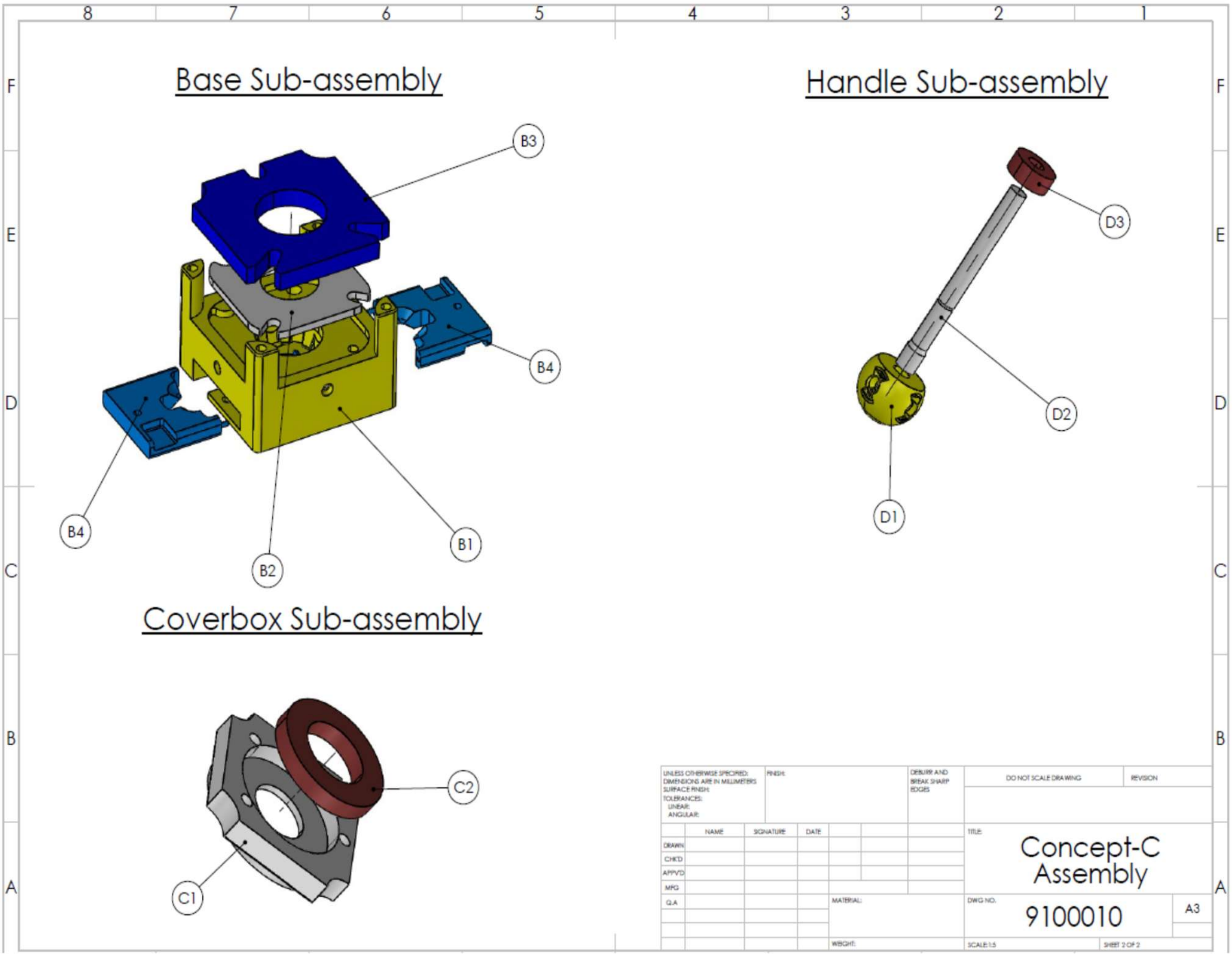


Figure 4.46 Sub-assembly drawing

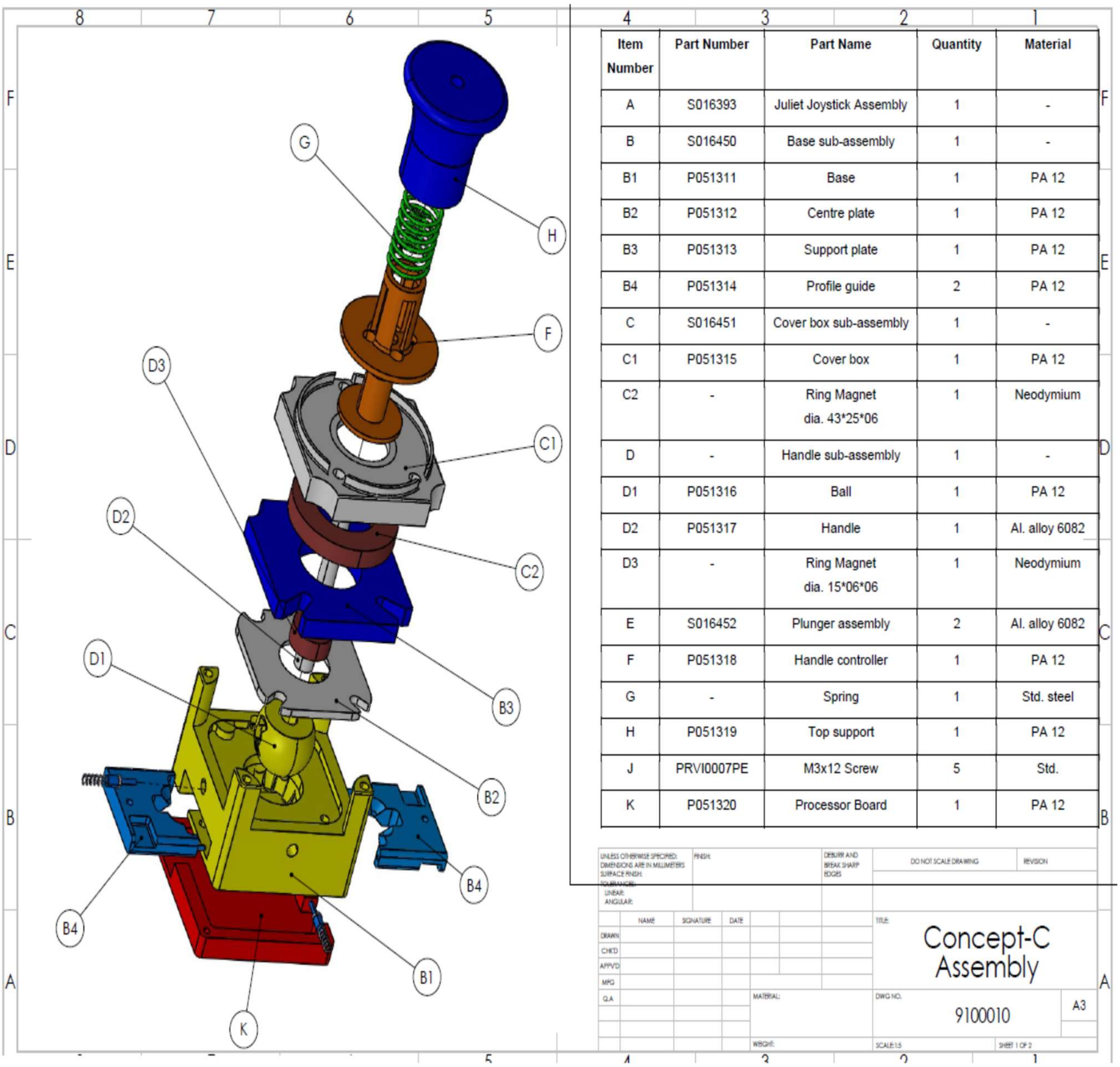


Figure 4.47 Exploded view

Bill of Materials:

Item Number	Part Number	Part Name	Quantity	Material
A	S016393	Juliet Joystick Assembly	1	-
B	S016450	Base sub-assembly	1	-
B1	P051311	Base	1	PA 12

B2	P051312	Centre plate	1	PA 12
B3	P051313	Support plate	1	PA 12
B4	P051314	Profile guide	2	PA 12
C	S016451	Cover box sub-assembly	1	-
C1	P051315	Cover box	1	PA 12
C2	-	Ring Magnet dia. 43*25*06	1	Neodymium
D	-	Handle sub-assembly	1	-
D1	P051316	Ball	1	PA 12
D2	P051317	Handle	1	Al. alloy 6082
D3	-	Ring Magnet dia. 15*06*06	1	Neodymium
E	S016452	Plunger assembly	2	Al. alloy 6082
F	P051318	Handle controller	1	PA 12
G	-	Spring	1	Std. steel
H	P051319	Top support	1	PA 12
J	PRVI0007PE	M3x12 Screw	5	Std.
K	P051320	Processor Board	1	PA 12

Table 4.3 : BOM- concept C

4.3.3.2 Concept D

Figure 4.48: Assembled view

The assembly of components are avoided in this concept. The metal handle is inserted thorugh ball handle and locked using M3 hexagonal nut. The handle controller is aligned with the metal handle and the rotation of handle is locked thorugh insertion. The top support with spring inside is asssembled with the handle controller and locked using thread. The step magnet 1 is connected with extruding sections and step magnet 2 is locked using screws. Finally, the bottom cover plate is assembled to prevent the translational movement of magnet.

Assembly Drawing (Concept-D):

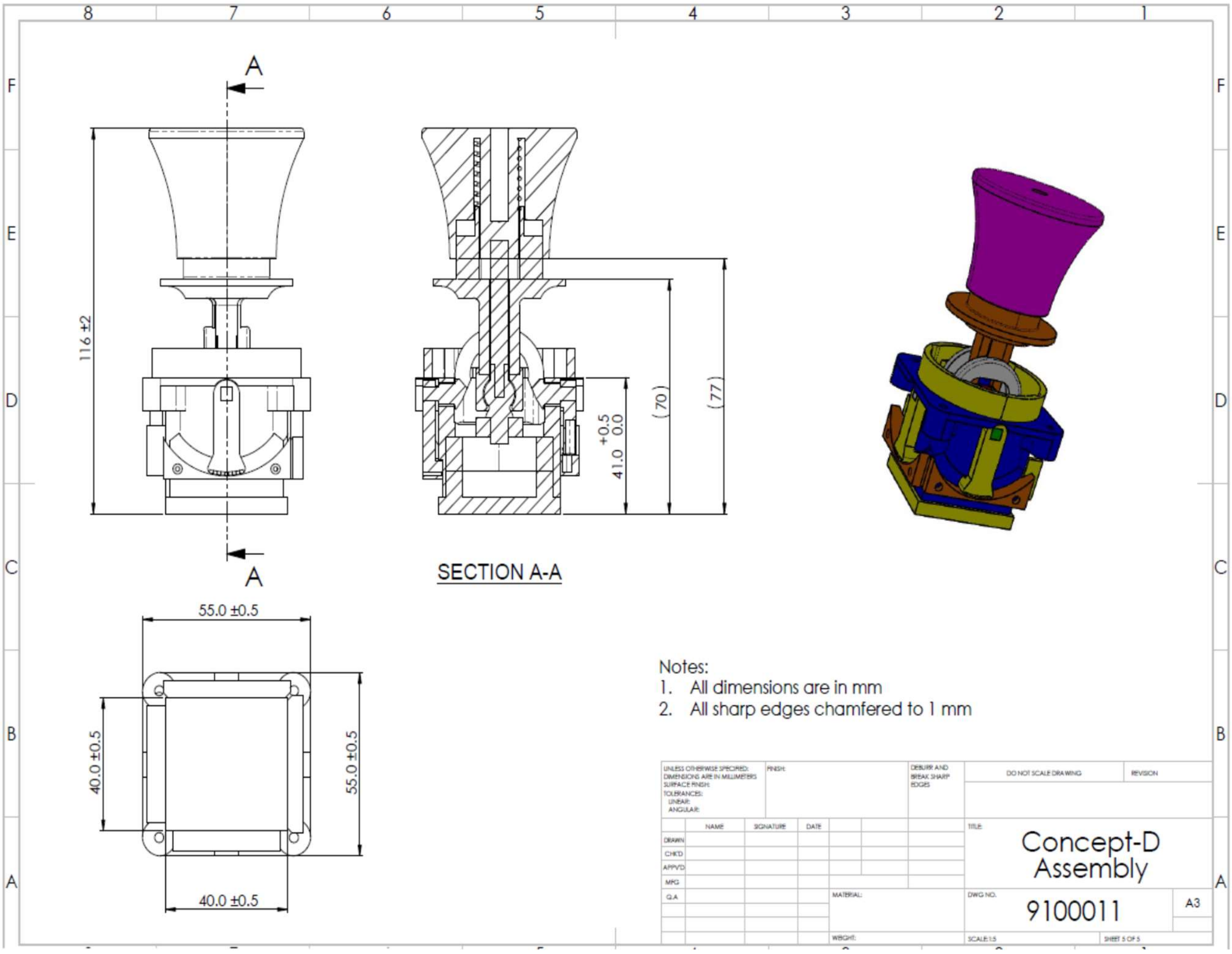
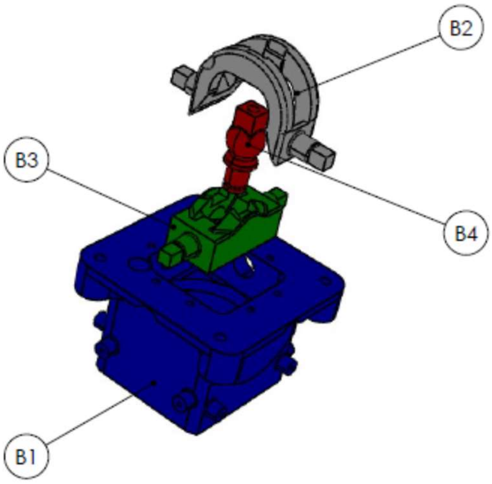
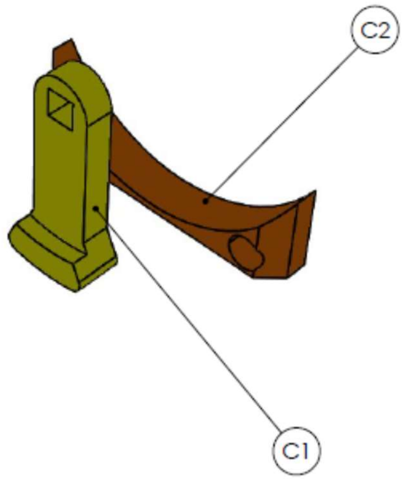


Figure 4.49: Assembly drawing-D





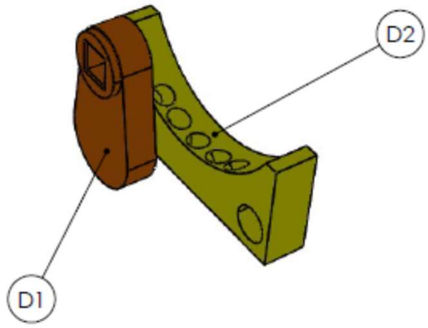
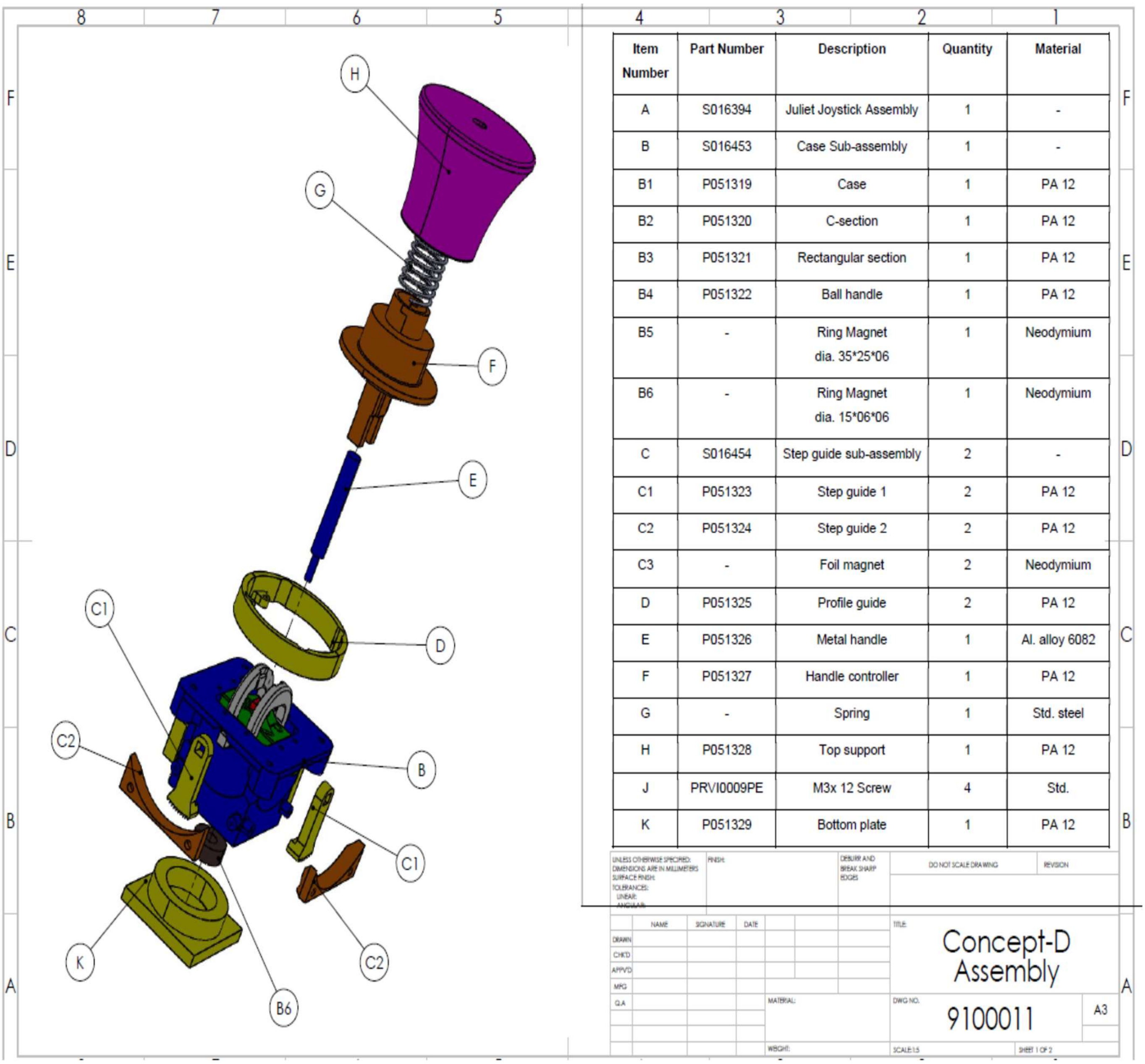


Figure 4.50 Sub-assembly drawing



Item Number	Part Number	Description	Quantity	Material
A	S016394	Juliet Joystick Assembly	1	-
B	S016453	Case Sub-assembly	1	-
B1	P051319	Case	1	PA 12
B2	P051320	C-section	1	PA 12
B3	P051321	Rectangular section	1	PA 12
B4	P051322	Ball handle	1	PA 12
B5	-	Ring Magnet dia. 35*25*06	1	Neodymium
B6	-	Ring Magnet dia. 15*06*06	1	Neodymium
C	S016454	Step guide sub-assembly	2	-
C1	P051323	Step guide 1	2	PA 12
C2	P051324	Step guide 2	2	PA 12
C3	-	Foil magnet	2	Neodymium
D	P051325	Profile guide	2	PA 12
E	P051326	Metal handle	1	Al. alloy 6082
F	P051327	Handle controller	1	PA 12
G	-	Spring	1	Std. steel
H	P051328	Top support	1	PA 12
J	PRVI0009PE	M3x 12 Screw	4	Std.
K	P051329	Bottom plate	1	PA 12

Figure 4.51 Exploded view

Bill of Materials:

Item Number	Part Number	Description	Quantity	Material
A	S016394	Juliet Joystick Assembly	1	-
B	S016453	Case Sub-assembly	1	-
B1	P051319	Case	1	PA 12
B2	P051320	C-section	1	PA 12
B3	P051321	Rectangular section	1	PA 12
B4	P051322	Ball handle	1	PA 12
B5	-	Ring Magnet dia. 35*25*06	1	Neodymium
B6	-	Ring Magnet dia. 15*06*06	1	Neodymium
C	S016454	Step guide sub-assembly	2	-
C1	P051323	Step guide 1	2	PA 12
C2	P051324	Step guide 2	2	PA 12
C3	-	Foil magnet	2	Neodymium
D	P051325	Profile guide	2	PA 12
E	P051326	Metal handle	1	Al. alloy 6082
F	P051327	Handle controller	1	PA 12
G	-	Spring	1	Std. steel
H	P051328	Top support	1	PA 12
J	PRVI0009PE	M3x 12 Screw	4	Std.

K	P051329	Bottom plate	1	PA 12
L	-	Bushing	2	Steel

Table 4.4: BOM- concept D

4.3.3.3 Concept E

Figure 4.52: Assembled view

The assembly is similar to the previous concept except that the centre position ring magnets are replaced by centre guides where the cylinderical magnets are inserted. The centre guides are assmebled on the two sides for x,y axes return.

Assembly Drawing (Concept-E):

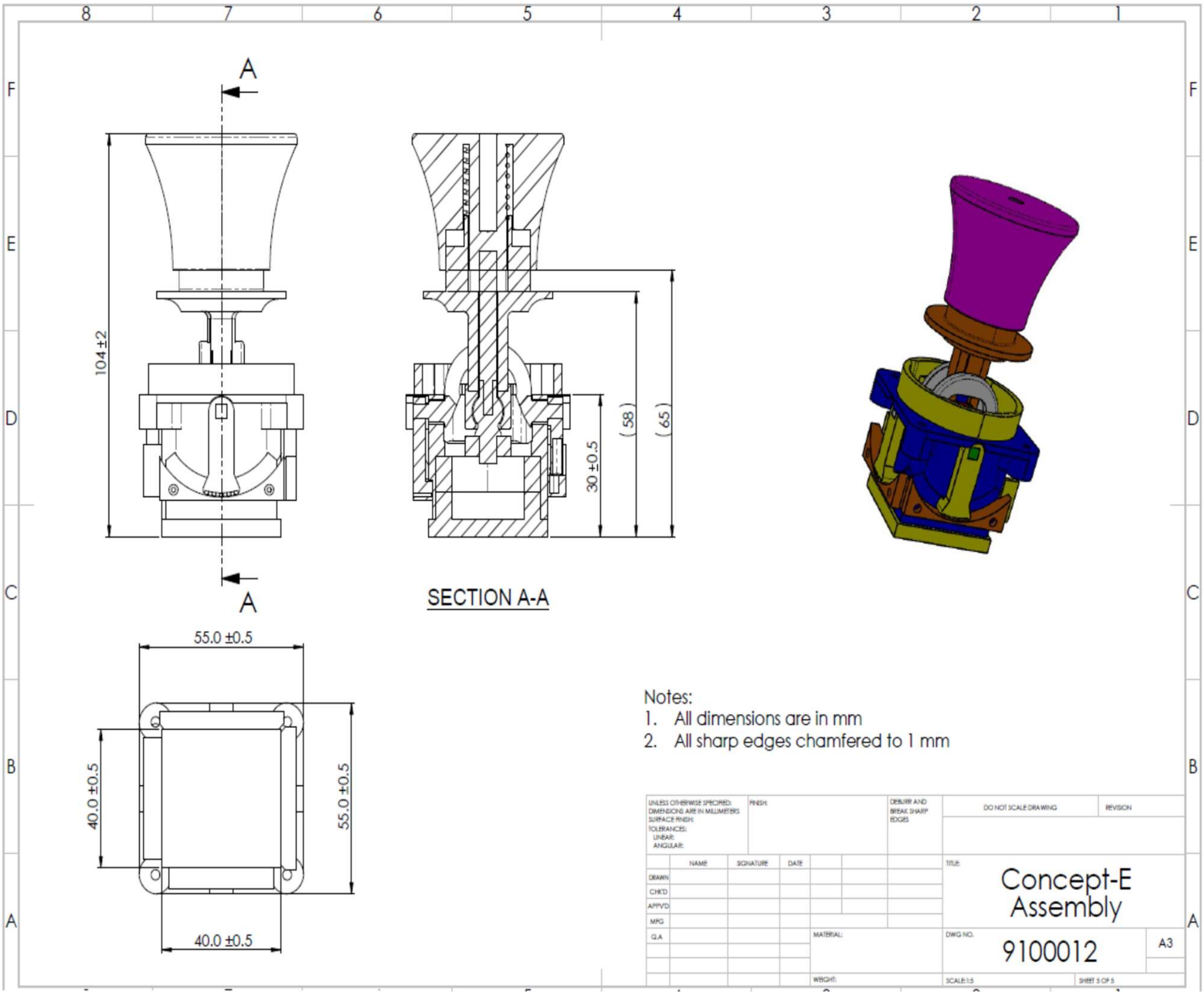


Figure 4.53 Assembly drawing

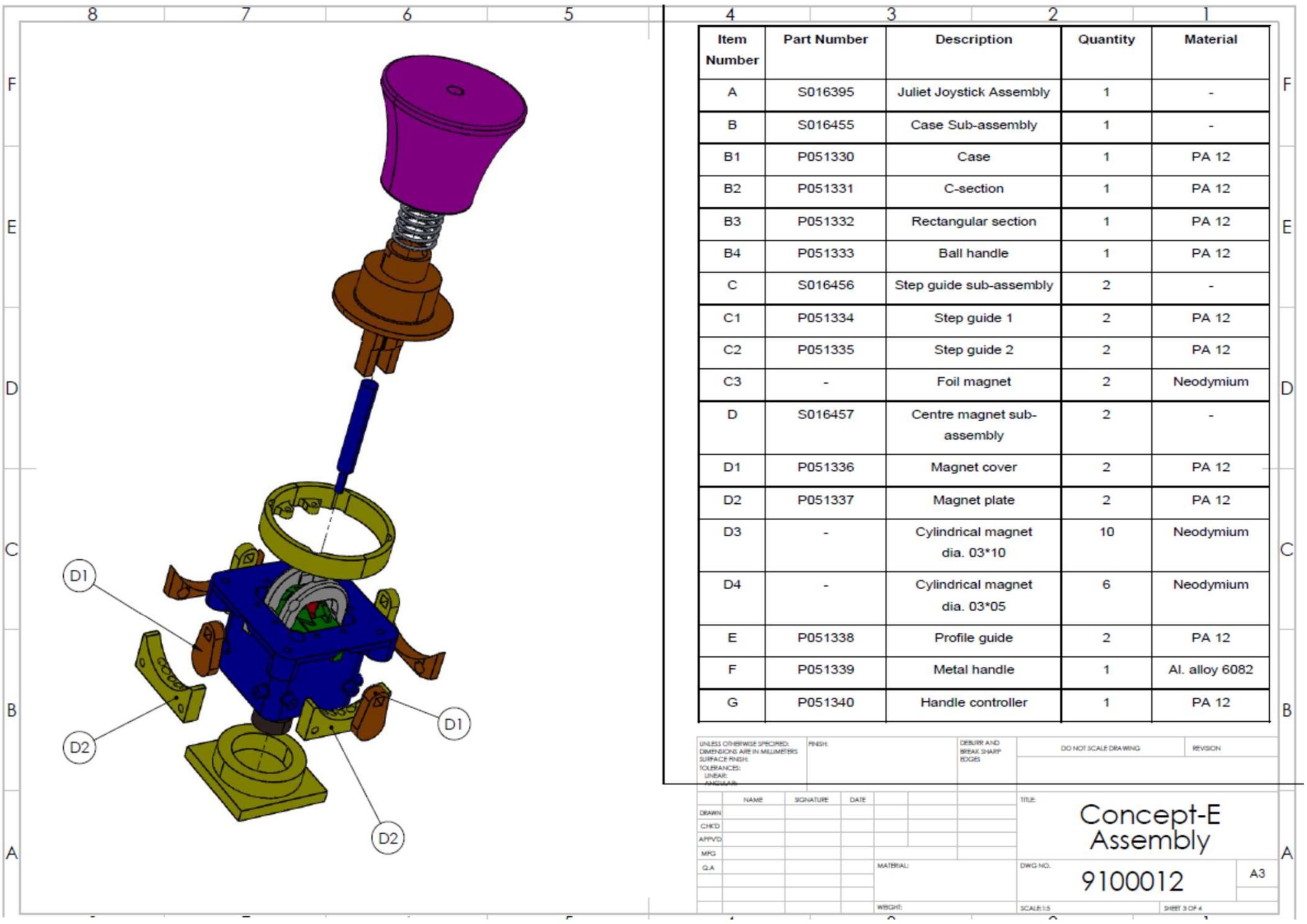


Figure 4.54 Exploded view

Bill of Materials:

Item Number	Part Number	Description	Quantity	Material
A	S016395	Juliet Joystick Assembly	1	-
B	S016455	Case Sub-assembly	1	-
B1	P051330	Case	1	PA 12
B2	P051331	C-section	1	PA 12
B3	P051332	Rectangular section	1	PA 12
B4	P051333	Ball handle	1	PA 12
C	S016456	Step guide sub-assembly	2	-

C1	P051334	Step guide 1	2	PA 12
C2	P051335	Step guide 2	2	PA 12
C3	-	Foil magnet	2	Neodymium
D	S016457	Centre magnet sub-assembly	2	-
D1	P051336	Magnet cover	2	PA 12
D2	P051337	Magnet plate	2	PA 12
D3	-	Cylindrical magnet dia. 03*10	10	Neodymium
D4	-	Cylindrical magnet dia. 03*05	6	Neodymium
E	P051338	Profile guide	2	PA 12
F	P051339	Metal handle	1	Al. alloy 6082
G	P051340	Handle controller	1	PA 12
H	-	Spring	1	Std. steel
J	P051341	Top support	1	PA 12
K	PRVI0009PE	M3x 12 Screw	4	Std.
L	P051342	Bottom plate	1	PA 12
M	-	Bushing	2	Steel

Table 4.5: BOM- concept E

4.3.4 Kinematic considerations

The joystick has to be designed considering kinematic and ergonomic aspects. There is no special tools required to assemble the product and the assembly process is simple using standard tools.

The function of joystick is similar to the lever mechanism. A lever mechanism can be used to exert a large force over a small distance at one end of the lever by exerting a small force over a greater distance at the other end. A lever is a rigid rod or bar capable of turning about a fixed point called the fulcrum and thus it can be used as an effective way of lifting a load by the aplication of a small effort.

The load W and the effort P may be applied to the lever in three different ways. In first-order lever, the fulcrum is positioned between the effort and the load. Since the effort is located far with respect to the load, the effort is smaller than the load. The lever can be considered as a force magnifier. In the second-order levers, the load lies between the fulcrum and effort. The effort and the load are positioned on the same side of the fulcrum but applied in opposite directions. In the third-order levers, the effort lies between the load and the fulcrum. The effort is greater than the load and the lever can be considered as a distance magnifier. The concept C joystick can be approximated as a second type of lever. The concept D & E can be taken as first-order lever.

In concept C, the effort arm is located far from the load arm. Therefore, the mechanical advantage is more than one.

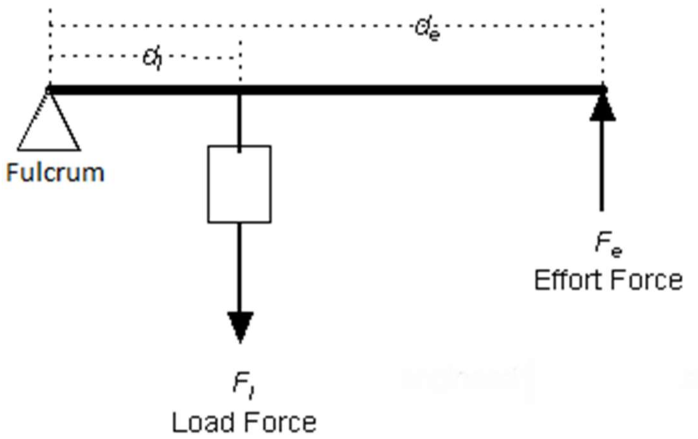


Figure 4.55: Second order lever

The effort force for concept C required to rotate the handle at a distance of 65 mm from the fulcrum is calculated by taking moment action on both sides.

$$Fe * de = Fl * dl$$

$$Fe = Fl * dl / de = (80 * 7) / 55$$

$$Fe = 10.1 \text{ N} = 1 \text{ kg}$$

In concept D, the fulcrum lies between the load and the effort which follows the first-order lever.

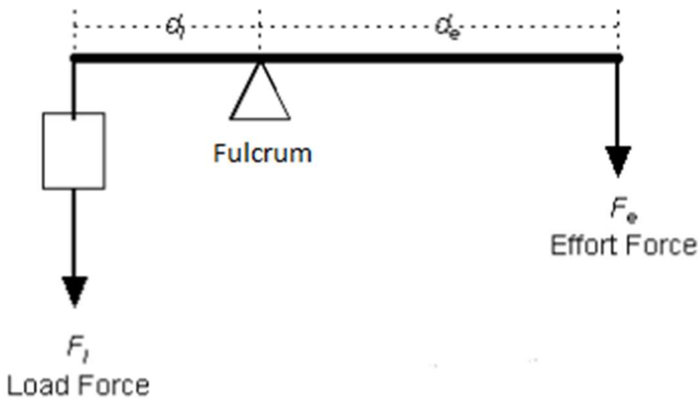


Figure 4.56: First order lever

The effort force for concept D required to rotate the handle at a distance of 65 mm from the fulcrum is calculated by taking moment action on both sides.

$$Fe * de = Fl * dl$$

$$Fe = Fl * dl / de = (70 * 12) / 47$$

$$Fe = 17.87 \text{ N} = 1.8 \text{ kg} \approx 2 \text{ kg}$$

Torque Calculation

The torque is calculated at three situations: at rest, at handle starting position (minimum torque to overcome the friction) and at handle extreme position (maximum torque to hold the handle in 42 degree inclination).

SI.No.	Torque	Force applied (N)	Length (mm)	Torque= FxL (Nmm)
1	No Torque	0	55	0
2	Min. Torque	4.9	55	269.5
3	Max. Torque	9.8	55	539

Table 4.6: Torque values

4.4 Selection of materials

Polyamide 12 (PA12) is commonly used plastic for the injection moulding of parts intended for engineering applications. The PA 12 material has a very fine grain, resulting in parts with higher density and lower porosity than the parts produced with Laser Sintering. This feature also makes PA 12 for multi jet fusion the ideal choice when more detailed surface resolution or thinner walls are required which is complicated in Laser Sintering.

They are accurate, offer excellent chemical and moisture resistance and can be used over a wide temperature range. The mechanical properties are so good and exhibit such stability, that components made in this material are now frequently being used for production applications.Since, parts are accurate and strong, it can be machined, for example parts can be tapped or can carry metal inserts if required, and can be treated in a similar way to injection moulded polyamide components.

The Mechanical Properties are listed below,

- Tensile Modulus: 1500 - 1800 N/mm2
- Ultimate Tensile Strength: 40 - 45 N/mm2
- Elongation at break: 10 - 20%
- Flexural Modulus: 1200 - 1300 N/ mm2
- Hardness, Shore D: 72 - 76

The Thermal Properties are,

- Melting Point: 172 - 180 ^{o}C with recommended temp range of -50 - 100 ^{o}C

4.5 DFX

The term Design for X intend the design criteria finalized at developing a particular aspect, function, characteristic of a product/system in depth. The letter “X” is a generic indication of a particular criterion that will be followed in the design process: Design for Assembly, Design for Environment, Design for Manufacturing, Design for Reliability, Design for Disassembly. DfX must be applied in the first stage of the project development to be really effective and advantageous (after the concept).

According to the general assessment, about 70% of the production cost of a product (materials, process, assembly) is determined by decisions taken during the design stage and that the decisions taken during the production phase (planning of the process activities, choice of the machines/plants to use) are responsible for about 20% of the total costs.

The design of a product considers and strongly orients the technology that will be used and most of the total cost with them. It is necessary to define methodologies able to address soon during the design stage the choices of the engineers toward economically convenient solutions and to involve also the production technicians in the design of a product.

4.5.1 Design for Manufacturing (DFM)

DfM is aimed at minimizing the manufacturing costs while maintaining a suitable product quality and guide the engineers toward the definition of a project with reduced manufacturing difficulties.

1. Reduce the total number of parts
2. Develop a modular project
3. Use standard components
4. Design multifunctional parts
5. Design for an easy processing
6. Avoid screw
7. Minimize the assembly directions
8. Make the assembly easier
9. Minimize the movements

The handle is generally used for the movement of joystick in preferred direction. A rod is used separately which moves vertically and generate the interlock mechanism. The new handle is designed to integrate the two functions which in turn engage in the movement, mechanical interlock and rotational arrest.

Figure 4.57: Handle

The top support is modified to use in all versions of joystick as a single component. When the cable version is not required, the open hole is plugged to avoid entry of dirt particles and water.

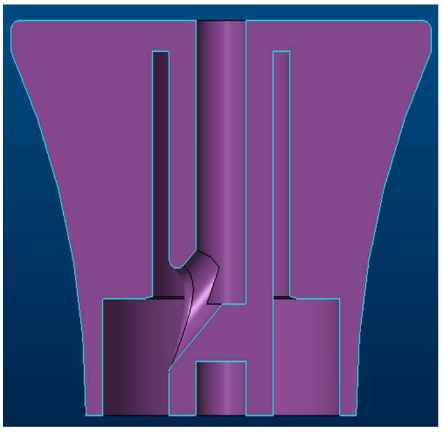


Figure 4.58: Top support

The e-ring groove is integrated in the ball handle during additive manufacturing process which eliminates the machining process.

4.5.2 Design for Assembly (DFA)

Design for Assembly is referred to the design techniques aimed at optimizing the assembly step and at reducing the related costs. DfA requires the revision of the project to make it simpler and to reduce the number of the parts, by answering the following questions.

1. During operation of the product, does the part move relative to all other parts already assembled?

2. Is there any reason why a different material should be used with respect to the other materials already used for the other parts?

3. Should the part to be joined be different from all other parts already assembled because otherwise necessary assembly/disassembly of other separate parts would be impossible?

The above questions yield a minimum number of theoretically necessary parts and to calculate assembly efficiency. The concept is analysed from the above questions.

Base with section: It is the first part to be assembled, there are no other parts that can be merged with it. It is theoretically necessary part.

Bushings: Since they can be made of the same material as base, they are not theoretically necessary.

Stepguide1: This must be separate for making possible assembly and disassembly and considered as theoretically necessary.

Stepguide1 magnets: This must be different material and considered as theoretically necessary.

Stepguide2: This must be separate for making possible assembly and disassembly and considered as theoretically necessary.

Stepguide2 magnets: This must be different material and considered as theoretically necessary.

Stepguide screws: Theoretically not necessary.

Magnet 15*06: This must be of separate material and for possible assembly and disassembly. Theoretically necessary.

Bottom Cover Plate: This must be separate for possible assembly and disassembly. Theoretically necessary.

Bottom Cover Plate screws: Theoretically not necessary.

Metal Handle: It can be combined with ball handle. Theoretically not necessary.

Handle controller: It allows the movement of handle during locking and unlocking. Theoretically necessary.

Interlock handle: It can be combined with above part. Theoretically not necessary.

Top support: This part closes the system and support the handle controller. Theoretically necessary.

Spring: It guarantees the translational movement of handle controller, but it does the same movement. It is theoretically not necessary.

Profile guide: It allows to guide the handle in variable defined path. Theoretically necessary.

Profile guide screws: Theoretically not necessary.

The analysis shows that the minimum number of theoretically necessary parts are 10. To calculate the effective total time, the effect of the symmetry during the assembly phase and the general diculty of the entire assembly are evaluated.

Handling Code Table	Time						
	Type	No Handling Difficulties			Part Tangles or Nests		
	Thickness	>2 mm		<2 mm	>2 mm		<2 mm
	Size	>15 mm	6-15 mm	<6 mm	>15 mm	6-15 mm	<6 mm
Symmetry Degree (α+β)	Code	0	1	2	3	4	5
<360	0	1.13	1.43	1.69	1.84	2.17	2.45
360-539	1	1.5	1.8	2.06	2.25	2.57	3
540-719	2	1.8	2.1	2.36	2.57	2.9	3.18
720	3	1.95	2.25	2.51	2.73	3.06	3.34

Insertion Code Table	Time						
	Security Type	Separate Operation or Part				Snap Fit	
	Holding Down?	Not Required		Required			
	Alignment	Easy	Hard	Easy	Hard	Easy	Hard
Difficulties	Code	0	1	2	3	4	5
None	0	1.5	3	2.6	5.2	1.8	3.3
Access or Vision	1	3.7	5.2	4.8	7.4	4	5.5
Access and Vision	2	5.9	7.4	7	9.6	7.7	7.7

Table 4.7: Assembly times

The two main factors that influence the assembly cost of a product or subassembly are,

- The number of parts in a product.
- The ease of handling, insertion, and fastening of the parts.

The DFA index,E_A (assembly efficiency) is

$$E_A=(t_{min} \times N_{min}) / T_{eff}$$

t_{min} is the basic estimated assembly time (generally 3 s) without any particular related

N_{min} is the minimum number of theoretically necessary parts

T_{eff} is the effective total time needed to assemble the system.

The efficiency of assembly for initial concept is as follows,

Parts (Initial concept)	Amount	Handling Code	Handling Time	Insertion Code	Insertion Time [s]	Penalties [s]	Total [s]
Case + section	1	2-0	1.8	-	0	0	1.8
Bushing	4	0-1	1.43	0-0	1.5	0	11.72
Step guide1	2	3-0	1.95	0-0	1.5	0	6.9
Step guide1 magnets	30	1-2	2.06	1-1	5.2	1.5	262.8
Step guide2	2	3-0	1.95	0-0	1.5	0	6.9
Step guide2 magnets	14	1-2	2.06	1-1	5.2	1.5	122.64
Step guide screws	4	1-0	1.5	0-2	2.6	1.5	22.4
Magnet 15*06	1	1-1	1.8	0-0	1.5	0	3.3
E-ring	1	0-2	1.69	1-2	4.8	1.5	7.99
Magnet 35*24	1	1-1	1.8	0-0	1.5	0	3.3
Bottom Cover plate	1	1-0	1.5	0-0	1.5	0	3
Bottom Cover plate screws	4	1-0	1.5	0-2	2.6	1.5	22.4
Metal handle	1	1-0	1.5	0-1	3	0	4.5
Interlock rod	1	0-0	1.13	0-0	1.5	0	2.63
Handle Controller	1	1-0	1.5	0-0	1.5	0	3
Top Support	1	1-0	1.5	0-0	1.5	0	3
Spring	1	0-0	1.13	0-0	1.5	0	2.63
TS + S	1	1-0	1.5	0-0	1.5	0	3
Profile guide	2	2-1	2.1	0-0	1.5	0	7.2
Profile guide screws	4	1-0	1.5	0-2	2.6	1.5	22.4
					t_eff		523.51
					N_min		10
					t_min		3
					E		5.7%

Table 4.8: Initial Assembly efficiency

The proposals are made to improve the assembly performance. The stepguide magnets are integrated into stepguide and purchased as a standard subassembly. The interlock road is combined with handle controller. The new assembly efficiency is evaluated and found to be enhanced greatly due to elimination of a step which contributes more than 50% of the initial assembly time.

Parts (Initial concept)	Amount	Handling Code	Handling Time	Insertion Code	Insertion Time [s]	Penalties [s]	Total [s]
Case + section	1	2-0	1.8	-	0	0	1.8
Bushing	4	0-1	1.43	0-0	1.5	0	11.72
Step guide1 + magnets	2	3-0	1.95	0-0	1.5	0	6.9
Step guide2+ magnets	2	3-0	1.95	0-0	1.5	0	6.9
Step guide screws	4	1-0	1.5	0-2	2.6	1.5	22.4
Magnet 15*06	1	1-1	1.8	0-0	1.5	0	3.3
E-ring	1	0-2	1.69	1-2	4.8	1.5	7.99
Magnet 35*24	1	1-1	1.8	0-0	1.5	0	3.3
Bottom Cover plate	1	1-0	1.5	0-0	1.5	0	3
Bottom Cover plate screws	4	1-0	1.5	0-2	2.6	1.5	22.4
Metal handle	1	1-0	1.5	0-1	3	0	4.5
Handle Controller	1	1-0	1.5	0-0	1.5	0	3
Top Support	1	1-0	1.5	0-0	1.5	0	3
Spring	1	0-0	1.13	0-0	1.5	0	2.63
TS + S	1	1-0	1.5	0-0	1.5	0	3
Profile guide	2	2-1	2.1	0-0	1.5	0	7.2
Profile guide screws	4	1-0	1.5	0-2	2.6	1.5	22.4
					t_eff		135.44
					N_min		8
					t_min		3
					E		17.7%

Table 4.9: Improved Assembly efficiency

4.5.3 Design for Environment

In order to improve the product and guarantee a lower environmental impact, the Ten Golden Rules have been followed. In particular:

1. Don't use toxic substances and arrange closed loops for necessary but toxic ones.

In this project no toxic substances are needed

2. Minimize energy and resource consumption in production phase and transport through house-keeping.

The purchasing parts are reduced by eliminating the secondary parts and thereby the resource consumption is mitigated

3. Use structural features and high quality materials to minimize weight in products,if not interfering with necessary flexibility, impact strength or functional priorities.

Plastics are used in major to reduce weight while maintaining the structural integrity.

4. Minimize energy and resource consumption in the usage phase, especially for products with most significant aspects in the usage phase

The energy consumption is significantly reduced as the long life permanent magnets are used.

5. Promote repair and upgrading, especially for system dependent products

All the "level" of the system could be easily dismounted and replaced.

6. Promote long life for products, especially for products with most significant environmental aspects OUT of usage phase

The life of the product is enhanced by permanent magnets and high structural strength with respect to the applied load. No maintenance intervals are needed

7. Invest in better materials, surface treatments or structural arrangements to protect products for dirt, corrosion and wear, giving longer and minimize maintenance

Materials and surface treatments are constrained by the low required cost. The cases are thought to protect the system by dirt.

8. Prearrange upgrading, repair and recycling trough access ability, labeling, modules, breaking points, manuals

9. Promote upgrading, repair and recycling by using few, simple, recycled, not blended materials and no alloys

The parts are made by PA 12, aluminium and neodymium.

10. Use as few joining elements as possible and use screws, adhesives, welding, snap fits, geometric locking, according to the life cycle scenario

Except for the bottom plate and step guide, all the parts are joined by means of simple insertion and locking.

4.5.4 Design for Reliability

The concept of reliability is quite different from endurance, a product can be designed to last long and can be not reliable at the same time. And a product designed to work in limited and short periods can be very reliable.

The Design for reliability aims to increase the reliability of the component and to evaluate the possible effect of the different failures. In this project, the Failure Modes and Effects Analysis (FMEA) has been used as qualitative (and only partially quantitative because of the usage of tables for the occurrence, detection and severity of the failure taken from literature) method in order to evaluate (and improve) the reliability of product.

It is quantitatively assessed how dangerous is a failure in terms of the three factors mode-cause-effect. The index RPN (Risk Priority Number) is defined: it is the value of the product of the three characteristics cause-mode-effect: Occurrence (O), Detection (D) and Severity (S)

$$RPN=OxDxS$$

with values ranging from 1 and 10.

Occurrence: index of the probability that the cause of the failure take place;
Detection: measures the probability that the control procedures and tools are able to detect the possible failure mode.
Severity: measures the gravity and how dangerous is the failure mode.

The FMEA for the existing concept and improved version are given below,

Components	Failure Mode	Effect	Cause	Occurrence	Detection	Severity	RPN
Handle controller	Leg1 breaking	No handle movement on one side	Material failure, fatigue	9	10	8	720
	Leg2 breaking	No handle movement on one side	Material failure, fatigue	9	10	8	720
	Finger Support breaking	Total Handle movement blocked	Material failure, fatigue	8	10	8	640
Ball handle	Head breaking	Total Handle movement blocked	Material failure, fatigue	9	10	8	720
	Groove failure	No zero return function	Material failure	3	9	8	216
Rectangular Section	Wall breaking	Devation of handle on rest	High load, material	4	8	4	128
	Leg breaking	High handle movement	High load, material	3	8	1	24
	Extended edge breaking	No proportional feedback	Excessive load, material	5	8	8	320
C-section	Internal protrusion breaking	Handle misalignment	Excessive load	7	8	5	280
	Side wall breaking	Part misalignmnet to axis	Excessive load	9	9	8	648
	Extended edge breaking	No proportional feedback	Excessive load, material	5	8	8	320
Step guide	Interference fit failure	No proportional feedback	Wrong tolerance, Excessive load	5	8	8	320
	Magnet detachment	Partial movement of handle blocking	Poor adhesive	3	6	8	144
Case	Bolt extrusion breaking	Step guide misalignment	Material failure, fatigue	2	6	9	108
Metal handle	Thread failure	Improper handle feedback	High stress	3	6	9	162
Top support	Thread failure	Improper handle feedback	High stress	3	6	9	162
Profile guide	Wall breaking	No guide control	Contact with handle	3	6	7	126

Table 4.10: FMEA First version

Components	Failure Mode	Effect	Cause	Occurrence	Detection	Severity	RPN
Handle controller	Leg1 breaking	No handle movement on one side	Material failure, fatigue	3	10	8	240
	Leg2 breaking	No handle movement on one side	Material failure, fatigue	3	10	8	240
	Finger Support breaking	Total Handle movement blocked	Material failure, fatigue	4	10	8	320
Ball handle	Head breaking	Total Handle movement blocked	Material failure, fatigue	2	8	8	128
	Groove failure	No zero return function	Material failure	3	9	8	216
Rectangular Section	Wall breaking	Devation of handle on rest	High load, material	4	8	4	128
	Leg breaking	High handle movement	High load, material	3	8	1	24
	Extended edge breaking	No proportional feedback	Excessive load, material	5	8	8	320
C-section	Internal protrusion breaking	Handle misalignment	Excessive load	7	8	5	280
	Side wall breaking	Part misalignmnet to axis	Excessive load	4	9	8	288
	Extended edge breaking	No proportional feedback	Excessive load, material	5	8	8	320
Step guide	Interference fit failure	No proportional feedback	Wrong tolerance, Excessive load	5	8	8	320
	Magnet detachment	Partial movement of handle blocking	Poor adhesive	3	6	8	144
Case	Bolt extrusion breaking	Step guide misalignment	Material failure, fatigue	2	6	9	108
Metal handle	Thread failure	Improper handle feedback	High stress	3	6	9	162
Top support	Thread failure	Improper handle feedback	High stress	3	6	9	162
Profile guide	Wall breaking	No guide control	Contact with handle	3	6	7	126

Table 4.11: FMEA Improvements

5 Design for Injection Molding

5.1 Introduction

Injection molding is a processing technology primarily used for the thermoplastic polymers. This method is utilised by heating the thermoplastic material to its melting point and the molten polymer is flown into the solid mold where it gets cooled and solidifed according to the shape of the mold. Since the cost of mold and tooling are expensive in injection molding, it is essential to calculate these costs at the earliest stages of design. This is the best way to ensure the choice of the process and obtaining maximum economic advantage from the process for a design team (this method is suggested for mass production requirement).

The thermoplastic polymers are chosen in most of the applications using injection molding. The reason is that these polymers can be subjected to heating (soften) and cooling (harden) several without any change in the properties. The long chain molecules in the polymer always remain as separate entities without any formation of chemical bonds to one another.

5.2 Molding cycle

The injection molding process cycle consists of three major stages for thermoplastics: (1) injection or filling, (2) cooling, and (3) ejection and resetting. During the injection or filling stage, the molten material is highly nonlinear viscous fluid. It flows through the complex mold passages and is subjected to rapid cooling from the mold wall, on the one hand, and internal shear heating, on the other. The polymer melt then undergoes solidification under high packing and holding pressure of the injection system. Finally the mold is opened, the part is ejected, and the machine is reset for the next cycle to begin.

5.2.1 Injection or filling stage

The injection stage consists of the forward stroke of the plunger or screw injection unit to facilitate flow of molten material from the heating cylinder through the nozzle and into the mold. The amount of material to be transferred into the mold is referred to as the shot. The injection stage is accompanied by a gradual increase in pressure. As soon as the cavity is filled, the pressure increases rapidly, and packing occurs. During the packing part of the injection stage, flow of material continues, at a slower rate, to account for any loss in volume of the material due to partial solidification and associated shrinkage. The packing time depends on the properties of the materials being molded. After packing, the injection plunger is withdrawn or the screw is retracted and the pressure in the mold cavity begins to drop. At this stage, the next charge of material is fed into the heating cylinder in preparation for the next shot.

5.2.2 Cooling or freezing stage

Cooling starts from the first rapid filling of the cavity and continues during packing and then following the withdrawal of the plunger or screw, with the resulting removal of pressure from the mold and nozzle area. At the point of pressure removal, the restriction between the mold cavity and the channel conveying material to the cavity, referred to as the gate of the mold, may still be relatively fluid, especially on thick parts with large gates. Because of the pressure drop, there is a chance for reverse flow of the material from the mold until the material adjacent to the gate solidifies and the sealing point is reached. Reverse flow is minimized by proper design of the gates such that quicker sealing action takes place upon plunger withdrawal.

Following the sealing point, there is a continuous drop in pressure as the material in the cavity continues to cool and solidifies in readiness for ejection. The length of the sealed cooling stage is a function of the wall thickness of the part, the material used, and the mold temperature. Because of the low thermal conductivity of polymers, the cooling time is usually the longest period in the molding cycle.

5.2.2 Ejection and Resetting stage

During this stage, the mold is opened, the part is ejected, and the mold is then closed again in readiness for the next cycle to begin. Considerable amounts of power are required to move the often massively built molds, and mold opening and part ejection are usually executed by hydraulic or mechanical devices. Although it is economical to have quick opening and closing of the mold, rapid movements may cause undue strain on the equipment, and if the mold faces come into contact at speed, this can damage the edges of the cavities. Also, adequate time must be allowed for the mold ejection. This time depends on the part dimensions, which determine the time taken for the part to fall free of moving parts between the machine platens. For parts to be molded with metal inserts, resetting involves the reloading of inserts into the mold. After resetting, the mold is closed and locked, thus completing one cycle.

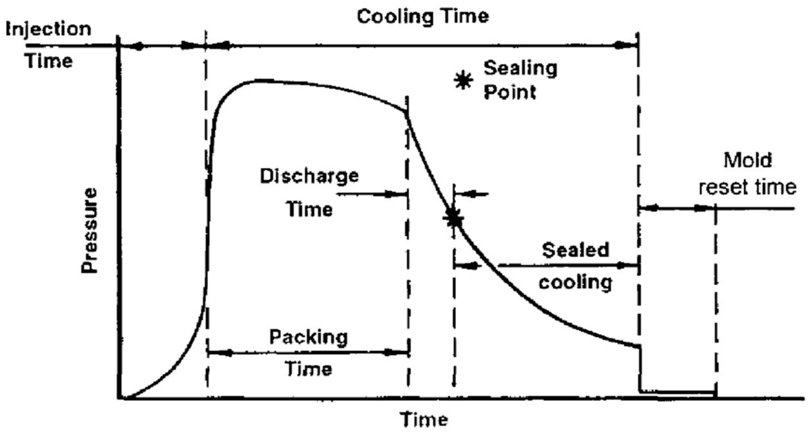


Figure 5.1: Molding cycle times

5.3 Injection Molding Analysis

In this section, the molding is designed for individual parts and the cost related to the manufacturing of parts are calculated.

5.3.1 Material Selection

As explained earlier, the material selected for the components is Polyamide 12 (PA12). Being a thermoplastic, it is very well suited for injection molding. The processing data for the selected polymer is

- Injection temperature: 260 ^{o}C
- Mold temperature: 54 ^{o}C
- Ejection temperature: 82 ^{o}C
- Injection pressure: 1000 bar

5.3.2 Selection of molding machine

Determination of the appropriate size of an injection molding machine is based primarily on the required clamp force. This in turn depends upon the projected area of the cavities in the mold and the maximum pressure in the mold during mold filling. The size of the runner system depends upon the size of the part. Typical runner volumes as a percentage of part volume are shown in the figure.

Part volume (cm^3)	Shot size (cm^3)	Runner %
16	22	37
32	41	28
64	76	19
128	146	14
256	282	10
512	548	7
1024	1075	5

Table 5.1: Runner %

A major economic advantage of injection molding is its ability to make multiple parts in one machine cycle through the use of multi cavity molds. The motivation is to reduce processing cost through an initially higher mold investment. The effect of the chosen number of cavities on part cost can be dramatic. This means that the cost of alternative designs of a particular part can only be estimated if the appropriate number of cavities is known.

When a multi cavity mold is used, three principal changes occur:

1. A larger machine with a greater hourly rate is needed than for a single-cavity mold.
2. The cost of the mold is clearly greater than for a single-cavity one.
3. The manufacturing time per part decreases in approximately inverse proportion to the number of cavities.

An optimal number of cavities is calculated for each part and it depends upon the cavity area, total processing time for one part and number of required parts. The expression for the optimum number of cavities (n) is

$$n = (N_t k_1 t/(m C_{c1}))^{1/(m+1)}$$

N_t = Number of parts produced

k_1 = machine rate($/hr)

t = Total cycle time (s)

m = machine rate coefficient

C_{c1} = Cost of single cavity

k1 [$/h]	Single Cavity Mold Area [cm2]	Single Cavity Cost [$]	Optimal Number Of Cavities
74	373.1	1562.00	3.2
74	330	1459.04	3.0
41	337.225	1465.72	2.2
41	278.4	1379.78	4.1
33	387.366	1569.82	2.5
30	379.89	1567.74	1.3
28	316.012	1446.31	2.5
33	361	1496.13	2.9

Table 5.2: Optimal number of cavities

The total projected area (A_t) of the part is calculated from the area of single part(As), runner volume and number of cavities.

$$A_t = n * R * A_s$$

The maximum separating force (F) is,

$$F = A_t * p_{rec}$$

p_{rec} = Recommended pressure for material

$$\text{Shot size, } V_s = V\ R\ N$$

The available machine and power is selected by taking the required maximum separating force and shot size from the table.

Clamping force (kN)	Shot size (cc)	Operating cost ($/h)	Dry cycle times (s)	Maximum clamp stroke (cm)	Driving power (kW)
300	34	28	1.7	20	5.5
500	85	30	1.9	23	7.5
800	201	33	3.3	32	18.5
1100	286	36	3.9	37	22.0
1600	286	41	3.6	42	22.0
5000	2290	74	6.1	70	63.0
8500	3636	108	8.6	85	90.0

Table 5.3: Availability of machines

From the available data, the parameters for all components are calculated below,

Parts	Material	Parts Per Product	N cavities	Single Part Projected Area [cm2]	Runner %	Total Projected Area [cm2]
Case	PA12	1	6	157.20	10	1037.54574
C-Section	PA12	1	6	25.49	37	209.5278
Rectangular Section	PA12	1	4	26.08	37	142.9184
Ball Handle	PA12	1	8	7.95	37	87.132
Handle Controller	PA12	1	6	69.89	37	574.4958
Top Support	PA12	1	2	120.99	28	309.7344
Profile Guide	PA12	2	6	18.63	37	153.1386
Bottom Cover Plate	PA12	1	6	54.82	37	450.6204

Max Separating Force [kN]	Machine Selection 1	Single Part Volume [cm3]	Shot Size [cm3]	Machine Selection	Injection Power [W]
5187.7287	7	25.96	171.3096	7	90000
1047.639	4,5,6,7	28.30	232.626	4	22000
714.592	3,45,6,7	3.43	18.7964	3	18500
510.59352	3,4,5,6,7	9.78	107.1888	3	18500
3366.545388	6,7	13.78	113.2716	6	63000
1815.043584	6,7	38.94	99.6864	6	63000
765.693	3,4,5,6,7	1.65	13.563	3	18500
2253.102	6,7	12.07	99.2154	6	63000

Table 5.4: : Selection of machines

5.3.3 Molding cycle time

After the appropriate machine size for a particular molded part has been established, the molding cycle time can next be estimated. The molding cycle can be effectively divided into three separate segments: injection or filling time, cooling time, and mold-resetting time.

The filling time is found by,

$$t_f = 2.V_s.p_j/P_j \qquad \text{(sec)}$$

Vs = required shot size (m3)

p_j= recommended injection pressure (N/m2)

P_j = Injection power (W)

It is assumed that cooling in the mold takes place almost entirely by heat conduction. The cooling time (tc) is given by

$$t_c = \frac{h_{max}^2}{\pi^2 \alpha} \log_e \frac{4(T_i - T_m)}{\pi(T_x - T_m)} \text{ s}$$

h_{max} = maximum wall thickness, mm

T_x = recommended part ejection temperature, °C

T_m = recommended mold temperature, °C

T_i = polymer injection temperature, °C

$\boldsymbol{\alpha}$ = thermal diffusivity coefficient, mm^2/s

The dry cycle time and ejection-rest time is found from the table below. The dry cycle time depends upon the machine size and the ejection-rest time depends on the shape of the part. The table of values are given below,

	Flat	Box	Cylindrical
Mold open	2	2.5	3
Part eject	0	1.5	3
Mold close	1	1	1

Table 5.5: Eejection time

The total time calculated for all components are given in the table

Filling Time [s]	Max Thickness [mm]	Corrective Factor	Cooling Time [s]	Dry Cycle [s]	Ejection-Reset Time [s]	Total Time [s]
0.85	3	1.00	19.45	3.3	5	27.75
2.40	3	1.00	19.45	3.3	5	27.75
1.66	11.925	1.00	307.25	6.1	5	318.35
1.91	5.5	0.67	43.57	3.9	7	54.47
0.97	13	0.67	244.65	1.7	5	251.35
1.67	9	0.67	116.67	1.9	7	125.57
6.00	8	0.67	92.65	1.9	5	99.55
5.36	3	1.00	19.45	6.1	3	28.55

Table 5.6: Total time

5.3.4 Mold cost estimation

The mold cost can be broken down into two major categories: the cost of the prefabricated mold base consisting of the required plates, pillars, guide bushings, etc., and cavity and core fabrication costs

The mold base cost (C_b) is a function of the surface area of the selected mold base plates and the combined thickness of the cavity and core plates. It is given by the formula,

$$C_b = 1000 + 0.45\, A_c h_p^{0.4}$$

C_b = cost of mold base, $

A_c = area of mold base cavity plate, cm^2

h_p = combined thickness of cavity and core plates in mold base, cm

The part must have adequate clearance from the plate surfaces (and from each other) to provide the necessary rigidity against distortion from the cavity pressure during molding and to allow space for cooling channels and any moving core devices. Typically, the minimum clearance between adjacent cavities and between the cavity surface and the edges and rear surfaces of cavity plates should be 7.5 cm. The mold base area is found by assuming a rectangle with cavity and allowance of 7.5 cm on all sides of cavity.

In addition to the manufacture of the cavities and cores, a substantial amount of work has to be performed on the mold base in order to transform it into a working mold. The main tasks are the deep hole drilling of the cooling channels and the milling of pockets in the plates to receive the cavity and core inserts. Additional tasks are associated with custom work on the ejector plate and housing to receive the ejection system, the insertion of extra support pillars where necessary, and the fitting of electrical and coolant systems. A rule of thumb in mold manufacture is that the purchase price of the mold base should be doubled to account for the custom work that has to be performed on it. The mold cost considering the projected area and combined thickness is given in the table.

Mold Array		Total Mold Area [cm2]	Max Width [mm]	hp [cm]	Mold Base Cost [$]	Mold Fabrication Cost [$]	Total Mold Cost [$]	Final Mold Cost [$]
2	3	1326.60	55	20.5	2998.27	2998.27	5996.54	40996.54
2	3	1121.25	18	16.8	2559.69	2559.69	5119.38	40119.38
2	2	850.90	15	16.5	2175.13	2175.13	4350.25	39350.25
2	4	1132.95	10	16	2545.51	2545.51	5091.02	40091.02
2	3	1400.50	43.2	19.32	3060.14	3060.14	6120.28	41120.28
2	1	609.03	51	20.1	1910.18	1910.18	3820.37	38820.37
2	3	1054.27	24.5	17.45	2488.96	2488.96	4977.92	39977.92
2	3	1281.00	13	16.3	2760.50	2760.50	5521.01	40521.01

Table 5.7: Mold cost

5.3.5 Total cost

The cost estimated based on the design decision of a product contributes 70% of the production cost (materials, process, assembly) and decision during production phase contributes to 20% of the total cost. The overall cost estimated shows the approximate price considering various factors. The material cost of PA12 is 7 euros per kg. To calculate the operating cost, the total time product is subjected in the machine, machine rate, number of products produced per year is required. The unit cost of joystick through injection molding is estimated as 113.58 euros.

Weight [kg]	Single Part Material Cost[$]	Total Material Cost [$]	Operating Cost [$]
0.0267	0.1869	560.7	1314.806122
0.003	0.021	189	552.2344132
0.0032585	0.0228095	205.2855	484.3992476
0.0138876	0.041801676	376.215084	1303.074756
0.0195676	0.058898476	530.086284	442.5364275
0.0552948	0.166437348	1497.936132	178.4740747
0.002343	0.00705243	126.94374	405.418795
0.0171394	0.051589594	464.306346	1064.849564

Table 5.8: Material cost

OVH cost [$]	Total time of 3,000 piece (hr)	Labour Cost [$]	Total cost [$]	Single Part Cost [$]	Single Part Cost [eur]
152.02	17.77	239.86	44825.93	14.94	13.60
32.33	2.49	33.58	42385.57	14.13	12.86
41.79	3.94	53.17	41600.62	13.87	12.62
94.83	10.59	143.02	43387.93	14.46	13.16
77.15	4.47	60.35	43800.22	14.60	13.29
160.50	1.98	26.77	42251.79	14.08	12.82
38.76	4.83	65.16	42060.51	14.02	12.76
104.51	10.76	145.21	43796.01	14.60	13.28
					1
					1.5
					1.5
					0.4
					2
					2.5
					0.1
					0.2
			Cost of Joystick (eur)		113.58

Table 5.9: Unit Part cost- concept C

6 Design for additive manufacturing

Additive Manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing or growing solid material, with no dedicated tools. It is a completely digital technology, as it is computerised and requires starting from a 3D CAD model of a part. The CAD model is then sliced into a stack of layers. Each layer is converted into a path or trajectory, which is followed by the AM machine while building the part. The current and potential success of AM relies on 3 key factors.

1. It is a completely digital technology
2. It requires no dedicated tools
3. It allows great geometrical complexity (undercuts, optimized topology)

6.1 Processes of AM

Although the term “3D Printing” is used as a synonym for all Additive Manufacturing processes, there are actually lots of individual processes which vary in their method of layer manufacturing. Individual processes will differ depending on the material and machine technology used. The American Society for Testing and Materials (ASTM) formulated a set of standards that classify the range of Additive Manufacturing processes into 7 categories.

1. Vat photopolymerization (SLA): It is a process that utilizes a liquid photopolymer that is contained in a vat and processed by selectively delivering energy to cure specific regions of a part cross-section.

2. Powder bed fusion (SLS/SLM): Process that utilizes a container filled with powder that is processed selectively using an energy source, most commonly a scanning laser or electron beam.

3. Material extrusion (FDM/FFF): Deposition of material by extruding it through a nozzle, typically while scanning the nozzle in a pattern that produces a part cross-section is realized in this process.

4. Material jetting: Ink-jet printing processes - droplets of build material are jetted to form an object.

5. Binder jetting: This is a process where a binder is printed into a powder bed in order to form part cross-sections.

6. Sheet lamination (LOM): Sheets are bonded to form an object.

7. Directed energy deposition (LENS): Process that simultaneously deposit a material (usually powder or wire) and provide energy to process that material through a single deposition device.

FDM is the most economic and diffused technology for the consumer market. Plastic filaments are extruded through a heated nozzle and deposited over the platform or over the as built materials. PA 12 (also known as Nylon 12) is a good general-use plastic with broad additive applications and is known for its toughness, tensile strength, impact strength and ability to flex without fracture. PA 12 has long been used by injection molders due to these mechanical properties. And more recently, PA 12 has been adopted as a common material in additive manufacturing processes for creating functional parts and prototypes.

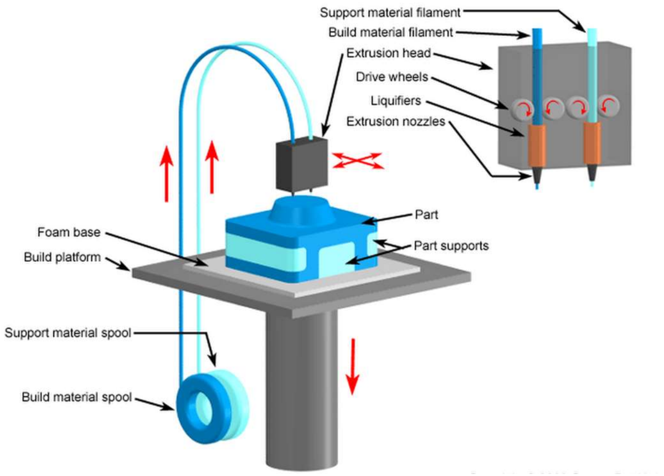


Figure 6.1: Fused Deposition Modeling

6.2 Strength parameters

To understand the comparative performance of AM parts to traditional injection molded specimens, the researchers generated a standard stress-strain curves. A stress-strain curve shows the relationship between the deformation (strain) of a material exhibited as a result of tensile loading (stress). The first chart shows the stress-strain relationship of test specimens printed with FDM versus the same test specimen manufactured with injection molding. The injection molded data is represented by the blue line, and the solid red line represents FDM data from a sample oriented in the X-direction during printing.

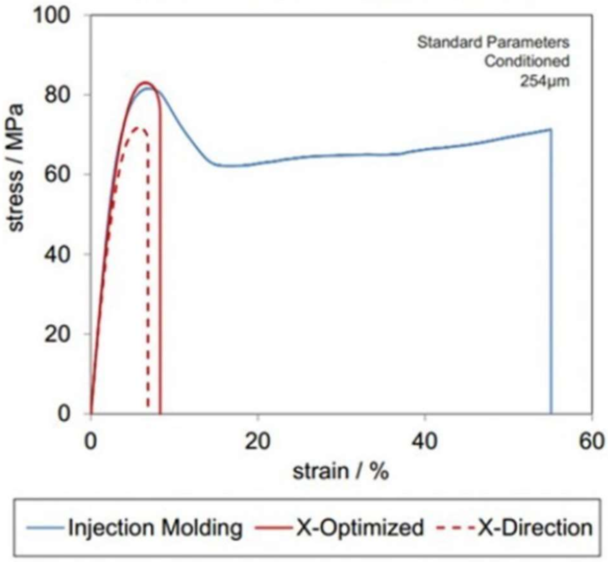


Figure 6.2: Stress-strain curve

The FDM part printed in the X-direction performed equivalently to the injection molded part in stress, but fractured at a much lower strain. Compared to AM processes, injection molding typically has lower porosity and greater homogeneity, leaving fewer imperfections in the structure of the material to encourage crack propagation. From the experimental observations of various materials, it is found that the tensile strength of FDM on the X-Y plane is approximately around 70-85% of injection moulded parts and of the same material along the Z-axis it is around 30-50%.

6.3 Design rules for AM

Although AM process is generally considered capable of producing parts with high geometrical complexity, still many limitations must be considered when designing the part and the process:

- Maximum allowed overhang
- Presence of thermal stresses and/or distortions

The risk of distortions due to gravity or thermal effects creates the need for anchors and supports, or fillets and radii. This is true not only for laser based processes but for nearly all AM processes except LOM processes, where the material is deposited and bonded already at solid and consolidated state. The risk of distortions and bad surface quality is present also for low angles (<45°) of walls. A minimum gap of 0.3 mm can be left between parts before they become merged together. Many part quality issues depend on proper design of toolpaths (roads).

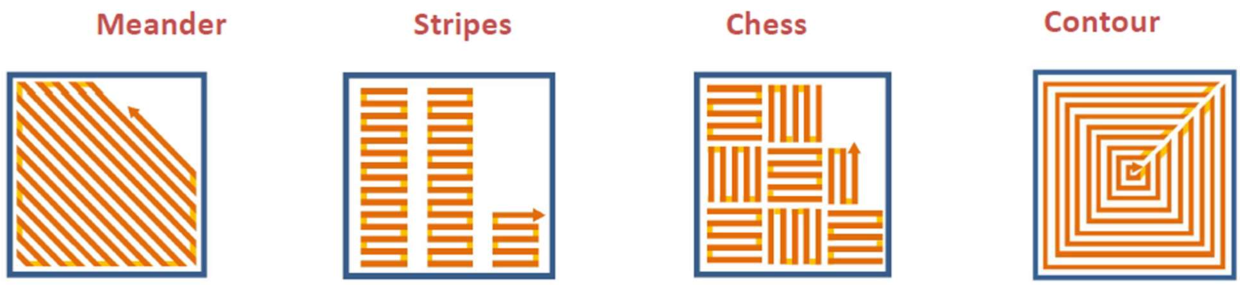


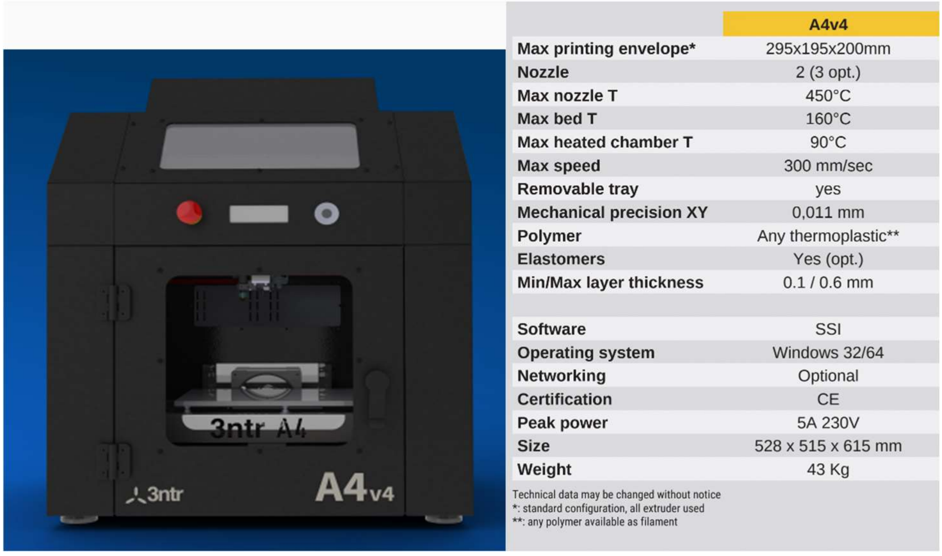
Figure 6.3: Nozzle patterns

While designing a part for additive manufacturing of polymers, the four important considerations are derived based on the above discussions:

- The print orientation of a part is critical to tensile strength.
- FDM test specimens have much higher tensile strength when printed in the X or Y direction than the Z-direction.
- SLS printed parts demonstrate far greater isotropy than the FDM printed parts.
- FDM and SLS parts can exhibit similar tensile strength to injection molded parts, but fracture at much lower strains.

6.4 Printer specification and challenges

The 3D printer used for the concept realization is 3ntr A4 v4 with maximum build size of 295 x 195 x190 mm. The printer uses FDM technology and various materials like PLA, High performance (PEEK, ULTEM), ABS. It is able to print upto three different materials simultaneously like gears with integrated bushing, two different rubber hardness. The surface roughness of the printed component is 11 microns(μm) with a filament thickness of 0.1-0.6 mm.The specification details are listed.



	A4v4
Max printing envelope*	295x195x200mm
Nozzle	2 (3 opt.)
Max nozzle T	450°C
Max bed T	160°C
Max heated chamber T	90°C
Max speed	300 mm/sec
Removable tray	yes
Mechanical precision XY	0,011 mm
Polymer	Any thermoplastic**
Elastomers	Yes (opt.)
Min/Max layer thickness	0.1 / 0.6 mm
Software	SSI
Operating system	Windows 32/64
Networking	Optional
Certification	CE
Peak power	5A 230V
Size	528 x 515 x 615 mm
Weight	43 Kg

Technical data may be changed without notice
*: standard configuration, all extruder used
**: any polymer available as filament

Figure 6.4: 3ntr A4 printer

The product has been designed primarily based on functions and also considering the constraints of 3D printing. The part orientation in the build space has a strong influence on many quality characteristics. In order to use the full potential and to consider the restrictions from the start, a design guideline is necessary to support the whole design process. It is a relevant problem since the determination of part orientation is complex and time consuming due to many contradictory trade off which have to be considered, including surface quality and build time. The bottom surface of the printed part has poor quality as it is the first layer of deposition and the orientation of parts is aligned in such a way that assembly between components of first layer is avoided. A poor surface at the first layer is shown.

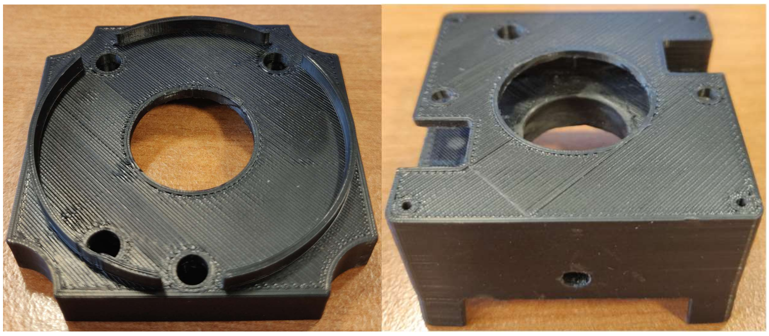


Figure 6.5: Surface profile

6.5 Total cost

The general idea is that AM costs are convenient at low batches and are insensitive to the volumes. Apart from the initial investment, the material and energy consumption is constant for multiple number of parts.

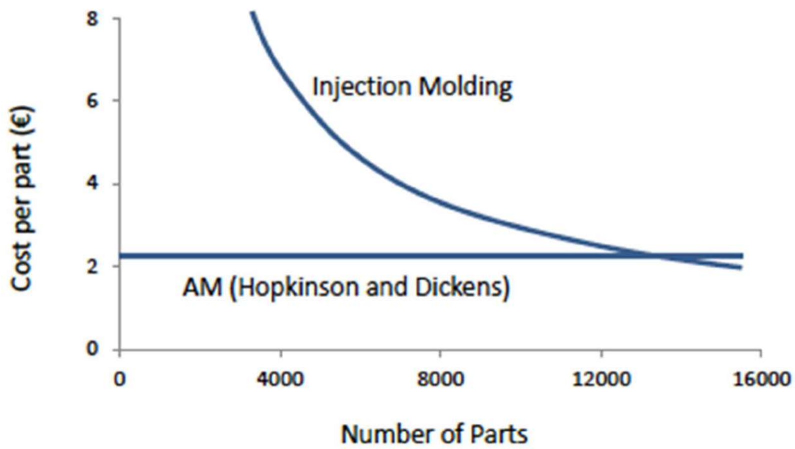


Figure 6.6: Cost curve

The concept C is developed using 3ntr A4 printer. The initial investment of the machine is 14,000 euros(€) and the building speed is 24,100 mm^3/hr with a machine utilization rate of 0.8. The actual capacity of printing volume considering support material and utilization rate is 579852000 mm^3/yr. The required total volume of material is 98557000 mm^3/yr which is 17% of the actual machine capacity per year. The material cost is 30 euro/kg. The overhead cost is the sum of 10% of material and 10% of labour. The total cost is the sum of machine, material, labour and overhead. The post-processing for the components is required to remove the solid support material using special grinding tools. So, the labour cost to this printer is reasonably higher than MJF 580 printer. The unit cost of concept C joystick through 3ntr A4 printer is 35.74 euros.

	3ntr A4				
For 1,000 Parts per year, for 3ntr machine Investment: 50,000 euros					
Replace to Concept C Parts					
Parts	Machine Inv. (eur)	Part Volume (mm3)	Machine Print Volume (mm3)	Machine Printing Time (hr)	Machine Cost (eur)
Base	50,000	39978.80	39978800	2764.8	1723.66
Support plate		12230.50	12230500	845.8	527.31
Centre plate		3475.00	3475000	240.3	149.82
Cover box		13629.50	13629500	942.6	587.63
Handle Controller		5525.00	5525000	382.1	238.21
Top Support		12786.30	12786300	884.3	551.27
Profile Guide		6880.60	6880600	475.8	296.65
Ball		4051.30	4051300	280.2	174.67
Metal handle	---				
Plunger pin					
Magnet 15*06					
Magnet 40*23					
E-ring					
Spring					
Total			98557000	6815.8	4249.2
Machine Print Rate (cm3/hr)	24.1				
Ideal Machine Print Rate (mm3/hr)	24100				
Actual Machine Print Rate (mm3/hr)	14460				
Full build job time for 248 mm height (hrs)	20				
Ideal Machine Print Rate (mm3/day)	11505000				
Ideal Machine Print Rate (mm3/yr)	2416050000				
Actual Machine Print Rate (mm3/yr)	724815000				
Machine utilization rate	0.8				
Actual Machine Print Rate with utilization (mm3/yr)	579852000	0.170			
Cost to actual machine print rate per year	25000	Return on investment, 2 years			
Cost of machine for total parts volume	4249.2				

Table 6.1: 3ntr costs

Material (eur/kg)	Material cost (eur)	Labour (eur)	OVH (eur)	Total cost (eur)	Single Part Cost (eur)
130	6240	1666.67	790.67	10421.00	10.42
130	1950	333.33	228.33	3038.98	3.04
130	520	100.00	62.00	831.82	0.83
130	2119	100.00	221.90	3028.53	3.03
130	910	1666.67	257.67	3072.54	3.07
130	2600	166.67	276.67	3594.61	3.59
130	1300	666.67	196.67	2459.99	2.46
130	650	1000.00	165.00	1989.67	1.99
					1
					1.5
					2
					2.5
					0.1
					0.2
				Cost of Joystick (eur)	35.74

Table 6.2: Unit part cost – concept C

7 Multi Jet Fusion Printing

In Multi Jet Fusion (MJF), parts are built by jetting a binding agent onto thin layers of polymer powder particles (typically nylon) and then sintering them using an IR heat source. MJF produces functional plastic parts with isotropic mechanical properties that can be used for detailed prototyping or end-user low-volume production.

The build begins by laying down a thin layer of powdered material across the working area. The material recoater carriage scans from top-to-bottom. Next, the printing and fusing carriage with a thermal inkjet (printhead) array and energy sources scans from right-to-left across the working area. The leading energy source preheats the working area immediately before printing to provide consistent and accurate temperature control of each layer as it is printed. The printheads now print functional agents in precise locations onto the material to define the part’s geometry and its properties. The printing and fusing carriage now returns left-to-right to fuse the areas that were just printed. At the ends of the scans, supply bins refill the recoater with fresh material and service stations can test, clean, and service the printheads on the printing and fusing carriage as needed to ensure reliable operation.

After finishing each layer, the surface of the work area retracts about the thickness of a sheet of office paper, and the material recoater carriage scans in the reverse direction for optimum productivity. The process continues layer-by-layer until a complete part, or set of parts, is formed in the build unit.

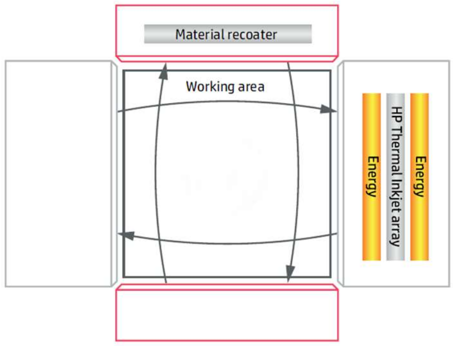


Figure 7.1: Injection process

7.1 Specification

It is capable of printing the working mechanism of system in a single build with a gap of 0.35 mm between adjacent moving parts. The maximum build size is 332 x 190 x 248 mm. The build speed is 1817 cm^3/hr with a layer thickness of 0.08 mm.

Printer performance	Technology	HP Multi Jet Fusion technology
	Effective building volume	Up to 332 x 190 x 248 mm (13.1 x 7.5 x 9.8 inches)
	Building speed[3]	1,817 cm^3/hr (111 in^3/hr)
	Full build job time for 248-mm (9.8-in) buildable height[4]	As fast as 20 hours
	Layer thickness	0.08 mm (0.003 inches)
	Printhead resolution	1200 dpi
Dimensions (w x d x h)	Printer	1565 x 955 x 1505 mm (61.6 x 37.6 x 59.3 inches)
	Shipping	1770 x 1143 x 2013 mm (69.7 x 45 x 79.3 inches)
	Operating area	2785 x 2530 x 2440 mm (109.6 x 99.3 x 96 inches)
Weight	Printing	650 kg (1433 lb)
	Shipping	850 kg (1874 lb)
Environmental ranges	Operating temperature	20-30° C (68-86° F)
	Operating humidity	20-70% RH without condensation
Acoustics[5]	Front operating position	72 dB (without muffler) / 70 dB (with muffler)
	Rear bystander position	80 dB (without muffler) / 75 dB (with muffler)
Network[6]	Gigabit Ethernet (10/100/1000Base-T), supporting the following standards: TCP/IP, DHCP (iPv4 only), TLS/SSL)	
Hard disk	HDD 1TB (AES-256 encrypted, disk wipe DoD 5520M) & SSD 1TB (AES-256 encrypted)	
Software	Included software	HP SmartStream 3D Build Manager
		HP SmartStream 3D Command Center
	Supported file formats	3MF, STL, OBJ, VRML v.2
Power	Consumption	4.5-6.3 kW (typical)
	Requirements	One dedicated circuit configuration: input voltage 200 - 240 V (line-to-line), 36 A max, 50/60 Hz

Figure 7.2: HP MJF 580 printer

The concept D and E is developed using the printer. As indicated earlier, the working mechanism is produced in a single build. The metal handle is inserted through PA12 ball and locked using M3 nut. The sub-components are build separately and assembled as the external operations like threading is required.

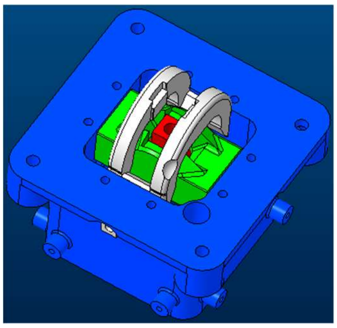


Figure 7.3: Printed mechanism

7.2 Cost estimation

The initial investment is almost half when compared with the injection molding due to high number of components whereas the raw material is 18 times costlier than injection molding.

The cost for additive manufacturing is calculated considering to develop 3,000 parts for three years and 1000 parts per year as same as injection molding. The initial investment of machine is 1,50,000 euros. Assuming the return on investment of machine as 3 years, the investment share of machine per year is 50,000 euros. The machine prints at a building speed of 1817 cm^3/hr. The typical material volume occupied during a block printing is 20-30% of the total volume.

The actual capacity of printing volume considering support material and utilization rate is 985561920 mm^3/yr. The required total volume of material is 51372050 mm^3/yr which is 9%

of the actual machine capacity per year. The material cost is 130euro/kg. The overhead cost is the sum of 10% of material and 10% of labour. The total cost is the sum of machine, material, labour and overhead.The labour cost to this printer is lower than 3ntr A4 printer due to its easy separation of parts from support material (powder). The unit cost of the concept D joystick through HP MJF 580 printer is 40.58 euros.

HP MJF 580

For 1,000 Parts per year

Parts	Machine Inv. (eur)	Part Volume (mm3)	Machine Print Volume (mm3)	Machine Printing Time (hr)	Machine Cost (eur)	Material (eur/kg)	Material cost (eur)
Case	1,50,000	2595.60	2595600	4.8	219.47	130	3471
C-Section		2796.20	2796200	5.1	236.43	130	390
Rectangular Section		3401.50	3401500	6.2	287.61	130	416
Ball Handle		1025.20	1025200	1.9	86.68	130	1794
Handle Controller		13709.50	13709500	25.2	1159.19	130	2535
Top Support		16163.15	16163150	29.7	1366.66	130	7176
Profile Guide		1642.00	1642000	3.0	138.84	130	299
Bottom Cover Plate		10038.90	10038900	18.4	848.83	130	2223
Metal handle	---						
Stepguide1+Magnets							
Stepguide2+Magnets							
Bushing							
Magnet 15*06							
Magnet 35*24							
E-ring							
Spring							
Total			51372050	94.2	4343.7		

Machine Print Rate (cm3/hr)	1817	
Ideal Machine Print Rate (mm3/hr)	1817000	
Actual Machine Print Rate (mm3/hr)	545100	
Full build job time for 248 mm height (hrs)	20	
Ideal Machine Print Rate (mm3/day)	15643840	
Ideal Machine Print Rate (mm3/yr)	3285206400	
Actual Machine Print Rate (mm3/yr)	985561920	
Machine utilization rate	0.6	
Actual Machine Print Rate with utilization (mm3/yr)	591337152	0.087
Cost to actual machine print rate per year	50000	**Return on investment, 3 years**
Cost of machine for total parts volume	4343.7	

Table 7.1: HP MJF 580 costs

Labour (eur)	OVH (eur)	Total cost (eur)	Single Part Cost (eur)
666.67	413.77	4900.90	4.90
666.67	105.67	1528.76	1.53
666.67	108.27	1608.54	1.61
666.67	246.07	2923.42	2.92
666.67	320.17	4811.03	4.81
666.67	784.27	10123.59	10.12
666.67	96.57	1331.07	1.33
666.67	288.97	4157.46	4.16
			1
			1.5
			1.5
			0.4
			2
			2.5
			0.1
			0.2
		Cost of Joystick (eur)	**40.58**

Table 7.2: Unit part cost- concept D

7.3 Comparison between 3ntr and MJF 580

The investment of 3ntr printer is almost ten times lesser than MJF 580. But, the MJF 580 can develop the functional product which is not possible by 3ntr and the build speed, capacity is better. Assuming the development of 1000 products per year, the unit cost of concept C joystick through 3ntr is 35.74 euros and the unit cost of concept D joystick through MJF 580 is 40.58 euros. It is found that concept C can be developed by 3ntr which is cheap and easy to fabricate and concept D & E should be developed by MJF 580 to realize the functional product.

8. Static and fatigue strength assessment

The components selected from the concepts C,D & E should withstand the average and maximum load during service. The static strength is the basic requirement to verify and once all the components are safe in static analysis, the critical parts are verified for the infinite life.

8.1 FEM static strength assessment

The static strength assessment is aimed to assess the globa failure of the structure when the extreme load conditons are expected and rarely happening phenomena. Some of the possible failures are the yileding of high stress components, fracture of material (when the fracture toughness is reached) and stability loss, the latter occur mainly due to compressive stresses in thin walled structures well below the yield stress.

The stress and buckling load can be applied to the structure and the static proof strength can be verified using linear finite element methods. Using this approach, the limit load can be calculated by considering the structure reaching plastic section and however with the limitation of unable to capture the significant effects such as large deformations, complex sections yielding, and contact.

Due to its limitations, the accurate determination of limit load is not possible using linear methods. Generally, the elasto-plastic behavior as wells as the deformation limit have to taken into account. During static strength assessment, the linear behavior of ductile material upto yielding plays a major role. For brittle material, there is no yielding and the material failure is sudden, all notches have to be considered due to its material fracture behavior. Brittle material fails for elongation at break less than 6% and ductile material fails for elongation at break greater than 6%.

The finite element method is a numerical method to solve engineering problems. The analytical method is not possible in case of complicated geometries, loadings and variable material properties. The analytical solution works on the principle of mathematical expressions to find the desired unknown quantities at any location in the structure for a given load conditions and eligible for any quantities of locations in the structure.The ordinary or partial differential equations are employed to find the unknown quantity in this method and it is usually impossible in the complex geometries,loadings and variable material properties. Therefore, the analytical solution proves to be the effective method with acceptable solutions in such cases. The average safety factor for the static strength is 1.25 and 4 and it can be assumed higher if the unexpected load conditions occur.

8.1.1 Concept C

Preventing the static failure and high plasticization constitutes the aim of the static design. High safety factors should be used because of the seriousness of the possible failure. The components are verified for the maximum stress using Solidworks Cosmos.

Base:

The base acts as a housing for ball, profile guide and pistons. It is mounted under the table like controller with its upper surface mounted through screw holes. The maximum load applied on the sections will be transferred to the base radially and it is verified for its maximum stress. The maximum stress acting on the material is far less than the limit strength and the safety factor associated with this stress is around 20. The high safety factor is purposefully given considering the unexpected load conditions in the harsh working environment.

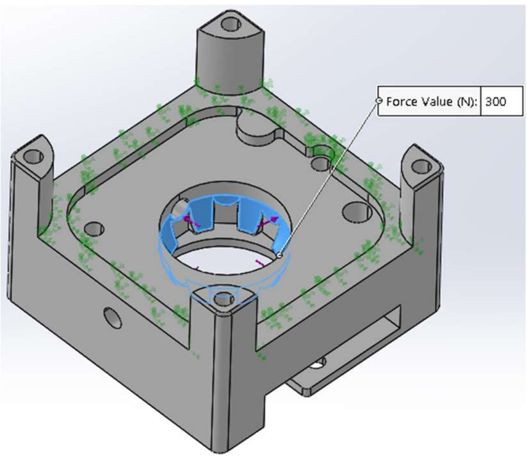


Figure 8.1: Base showing force direction

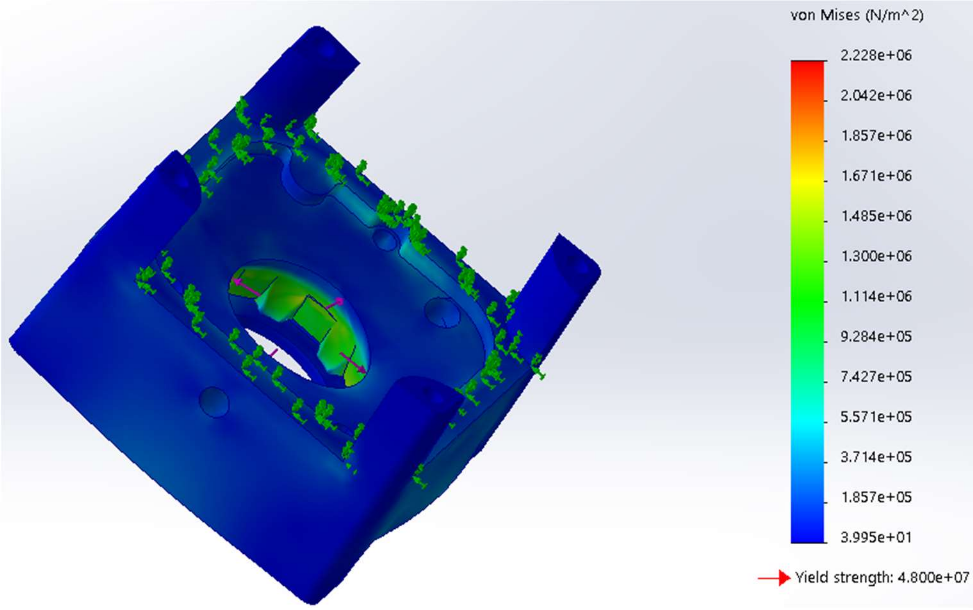


Figure 8.2: Base FEA

Cover box:

The cover box accommodates the stationary magnet and rubber bellow with its one end connected to it for the protection against water. The load from the handle during return position acts on the cover box and the safety factor is as high as 20.

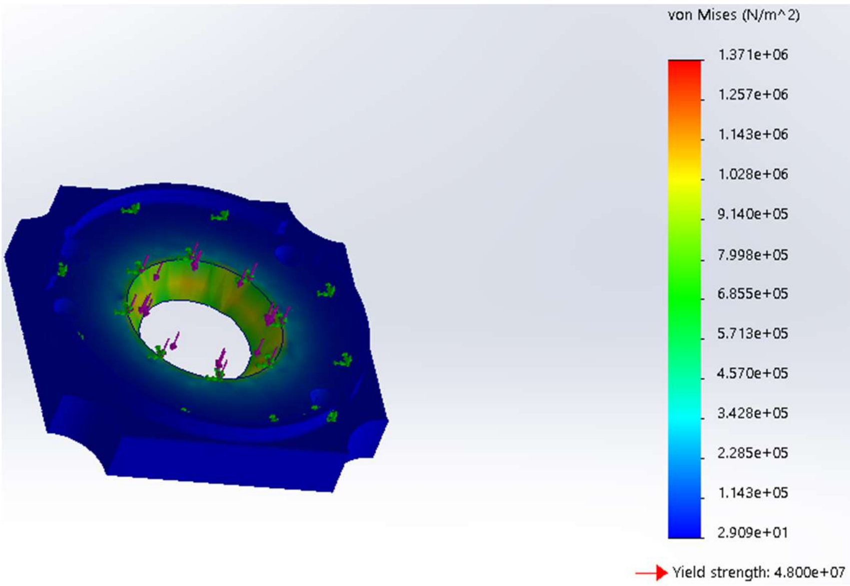


Figure 8.3: Cover box FEA

Ball:

The ball rotates inside the cover box during handle movement and expects the high load acting on it. The reaction force due to 30 kg acting on the contact area of the part and the safety factor is 5.2.

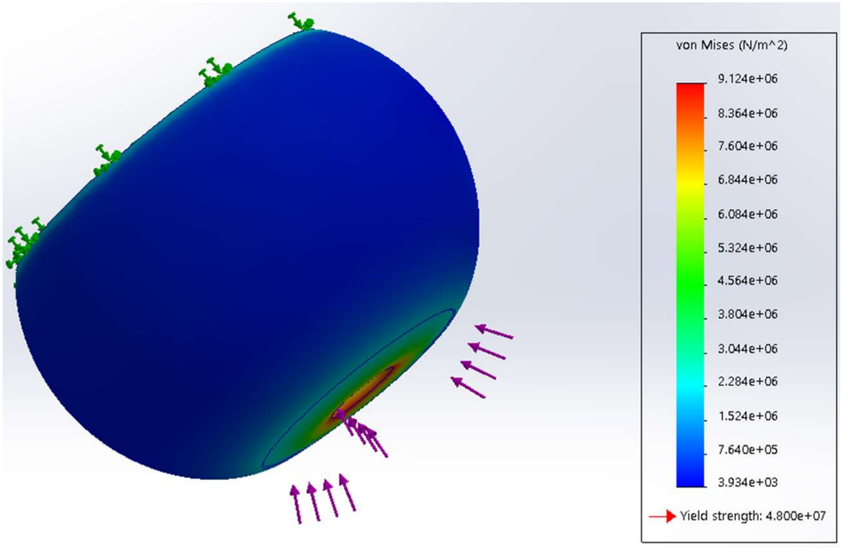


Figure 8.4: Ball FEA

Profile guide:

The profile guide allows the handle to rotate in a predefined path. The path can be square, cross and circular. The cross profile will be highly stressed component as the maximum load of 30 kg acts on the smaller surface area. The safety factor is 3.4 which is in acceptable limit.

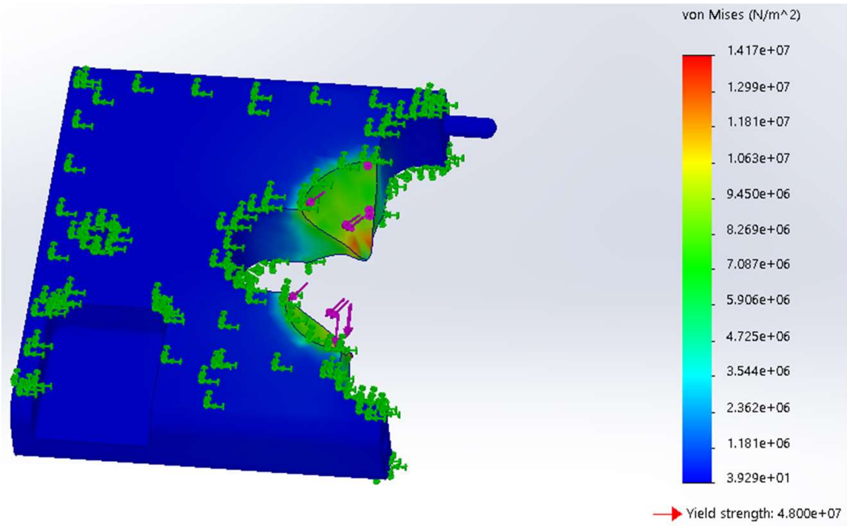


Figure 8.5: Profile guide FEA

Handle Controller:

The handle controller is used when there is a requirement of mechanical interlock and also for an electrical switch requirement. The load of 30 kg acts on the wall of the component when it reaches the extreme position of handle rotation. The safety factor is 3.

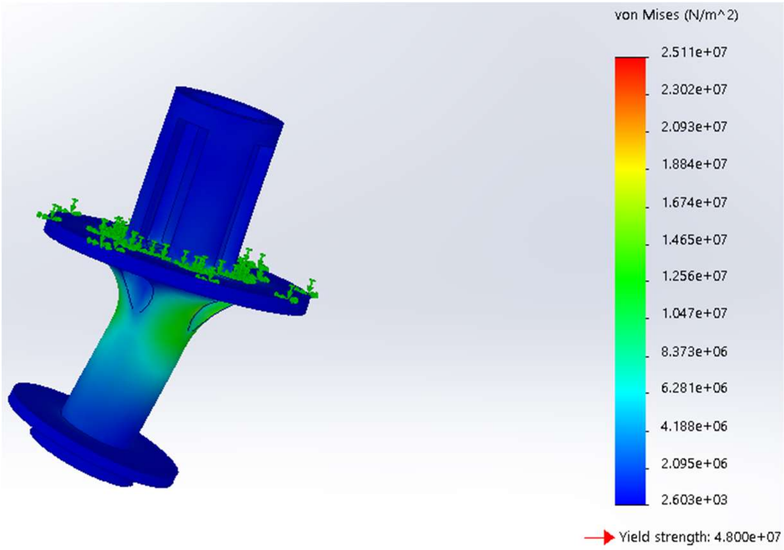


Figure 8.6: Handle controller FEA

Top support:

The top support is inserted in the handle controller and fixed by threading it with the ball handle. The load of 1.5 kg acts on the bottom surface and 30 kg acts on the handle connection surface. The safety factor is 2.3.

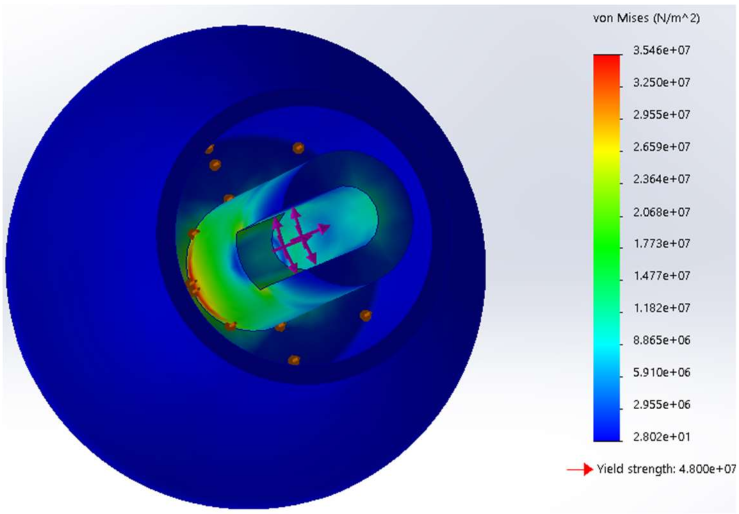


Figure 8.7: Top support FEA

Ball handle:

The component support the radial load of 30 kg when the handle reaches the extreme position. The material chosen is 6082 Aluminium alloy which is easily available and commonly used. The safety factor is as high as 15, since this is one of the critical components.

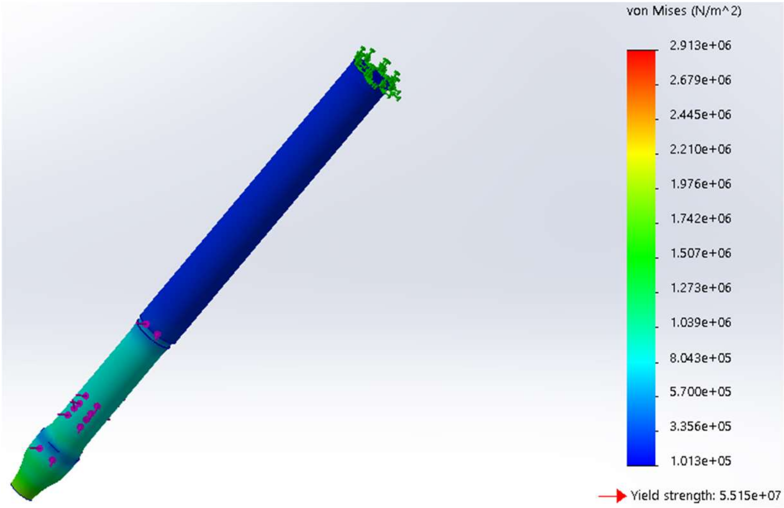


Figure 8.8: Handle FEA

8.1.2 Concept D

The loaded components used in concept D & E are the same except the two additional magnets are added on the side wall.

Case:

The case acts as a housing for c-section, rectangular section, ball handle and axial ring magnets. The radial load of 30 kg acts on the mounting hole of the case and the safety factor is as high as 20 due to unexpected load conditions.

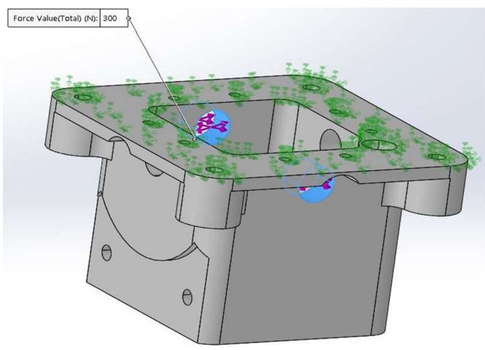


Figure 8.9: Base load direction

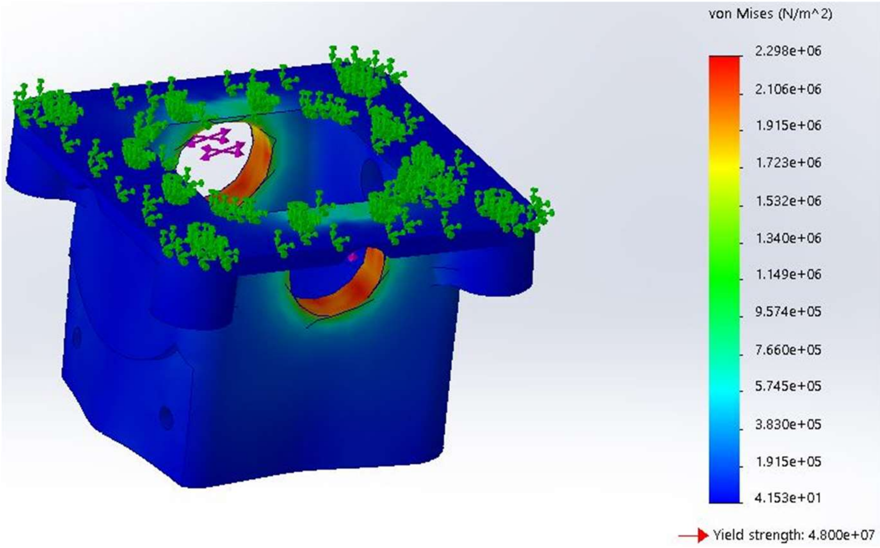


Figure 8.10: Base FEA

C-section:

The c-section allows the movement of the handle in one direction with the handle and its controller passes through it. The maximum axial load of 30 kg acts on the top surface and on the side wall. The safety factor is 2.

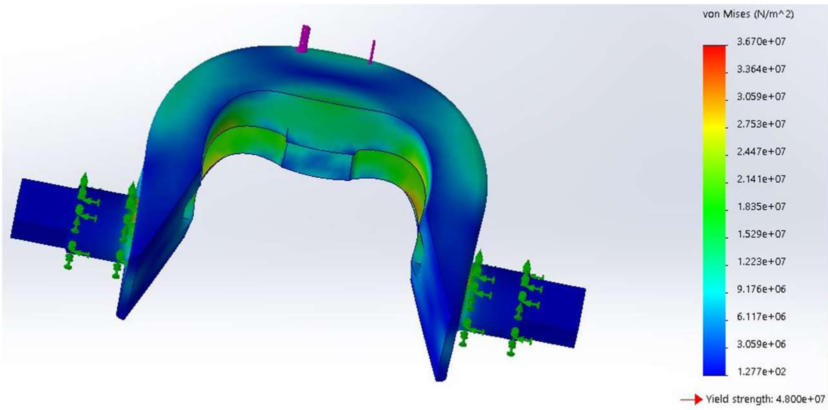


Figure 8.11: C-section FEA

Rectangular section:

The rectangular section is similar to the previous component in terms of function and its end are supported by ball bearings for load transfer. The two loads of 30 kg acts on the top surface and side wall. The safety factor is 2.4.

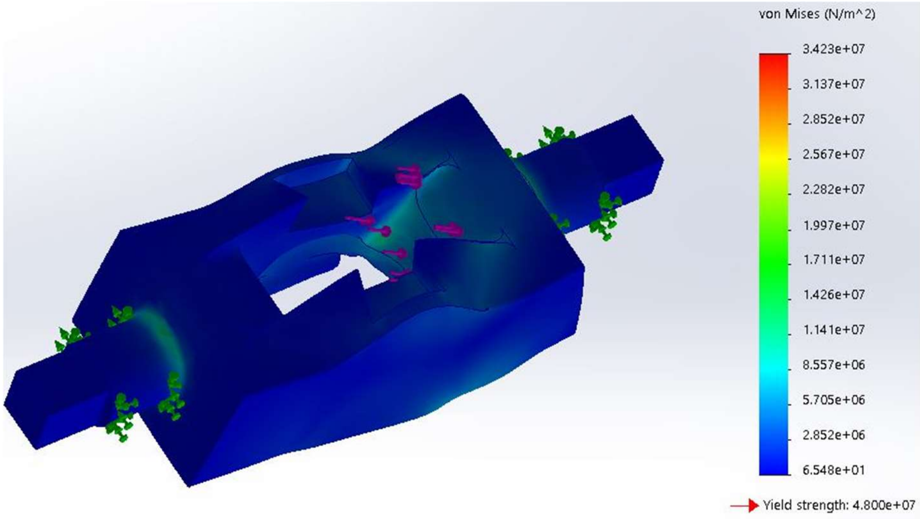


Figure 8.12: Rectangular section FEA

Ball handle:

The ball handle is placed in the rectangular section during printing and it allows the handle to rotate in various requirements. The maximum load of 30 kg acts on the side wall and threaded section. The safety factor is 3.4 and this is considered as one of the critical components as the load acts directly on it.

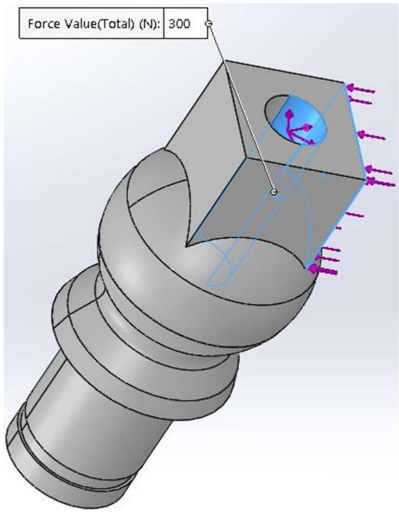


Figure 8.13: Ball handle load

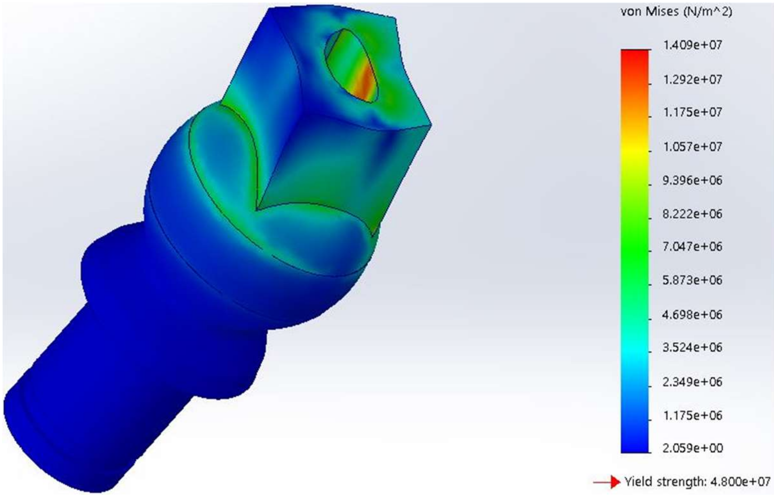


Figure 8.14: Ball handle FEA

Metal handle:

The metal handle is introduced in the concept to ensure the infinite life of the joystick. The load of 30 kg is applied radially on the side wall and the safety factor is 14.

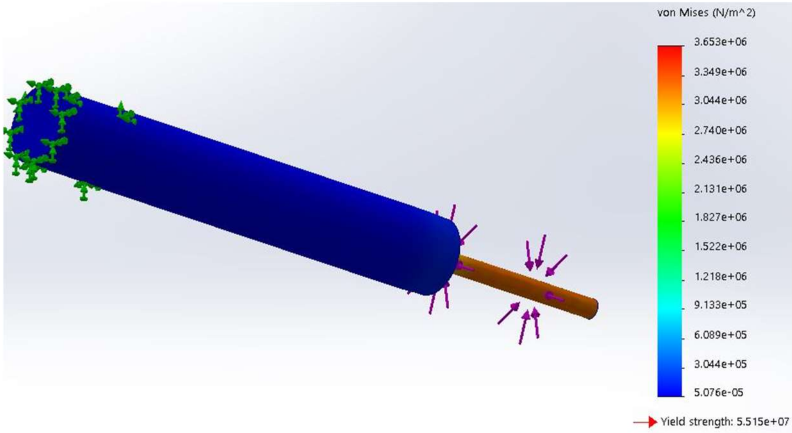


Figure 8.15: Metal handle FEA

Handle Controller:

The handle controller's function is similar to the previous concept with some changes in the geometry. The load of 30 kg is applied axially on the surface and the safety factor is 1.8

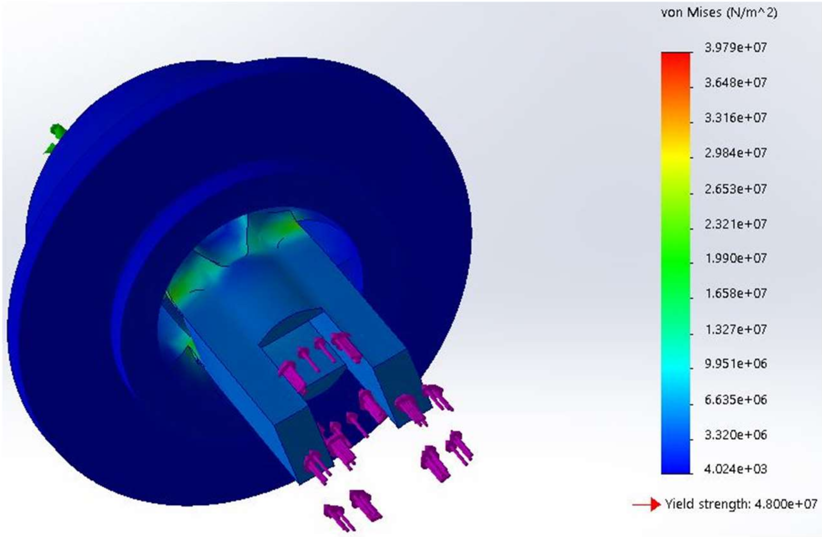


Figure 8.16: Handle controller FEA

Top Support:

The top support is fixed on the top of the handle controller using threaded connection. The load of 30kg is applied radially and the safety factor is 6.4.

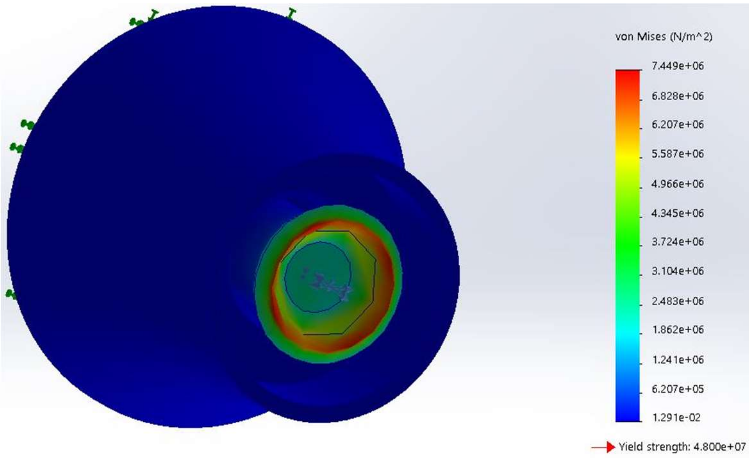


Figure 8.17: Top support FEA

8.2 Fatigue assessment

There are three main philosophies of fatigue design.

1. Safe life approach: The structure is designed to sustain the loads for the whole system life (defined during the design phase). The component/structure is replaced at the end of the mechanical system life. The features of this approach are high thickness, lower stress, structural integrity. The stress-based approach belongs to high cycle fatigue and strain-based approach belongs to low cycle fatigue.

2. Fail-safe approach: Fail safe components assure the structural integrity incase of partial failures (redundancy concept). This condition could be guaranteed by means of multiple load paths or advanced materials with particular characteristics (crack arrester,etc). The features are lower safety factors, alternative load paths, maintenance scheduling.
3. Damage tolerance approach: The methodology allows the presence of minor damages or cracks within the structure with resulting drop in strength and resistance. According to this concept, the component/structure is not replaced until the minimal strength is satisfied accounting for proper safety factors and strict maintenance schedules.

Fatigue properties of materials are often described using the fatigue limit or the S-N curve (Wöhler curve). The materials show no damage in tests below a certain threshold value of the stress amplitude (s_{ai}), even for very high numbers of load cycles (n_i > 1000000). This amplitude value is often simply called fatigue strength or endurance strength. If the largest occurring stress amplitude remains below the fatigue strength, then the proof is fulfilled for the complete spectrum.

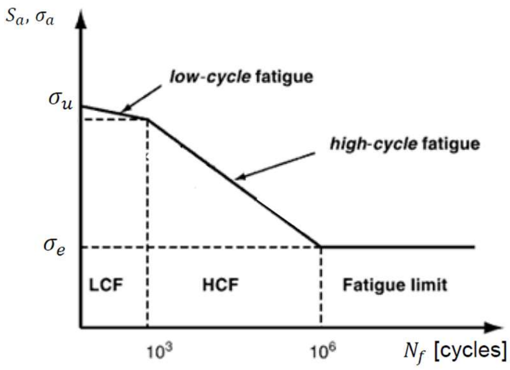


Figure 8.18: S-N curve

The number of load cycles, which is considered “infinite” varies between approximately 1 to 100 million cycles, depending on material, joining technology and stress state as well as the specific code used for assessment.

The assessment of infinite life fatigue strength is commonly used for structures or machinery components experiencing very large numbers of load cycles or a long service life with often more than 30 years of service time.

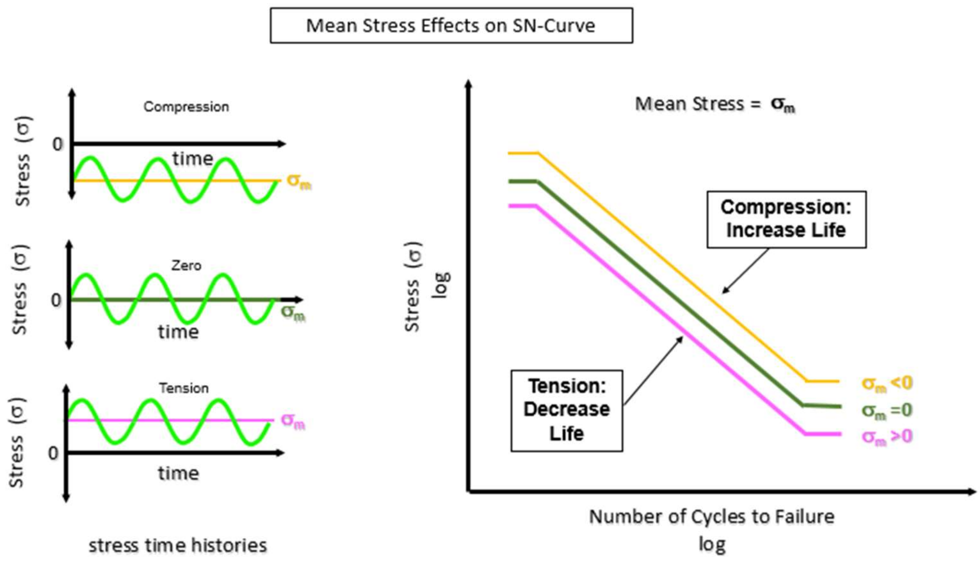


Figure 8.19: S-N curve

8.2.1 Lever force

The concept C requires an effort force of 1 kg using second class lever mechanism and concept D requires approximately 2 kg of effort force using first class lever mechanism.

8.2.2 Fatigue life

The product is required to satisfy the infinite life (>10^8 million cycles). The selection of proper concept using contactless magnet working ensures zero wear and the material selection should also satisfy the uninterrupted working of the joystick. The fatigue life is calculated for the critical parts considering the average and maximum load during the entire operation. The critical components are ball handle and metal handle, since the load acts directly on these components and the safety factor is low.

8.2.2.1 Concept C

The two cases are considered for each concept. The first case is the average load of 2 kg to move the handle. This load is derived from the effort force of 1 kg to move the handle and a safety load of 2 kg to overcome the effort force. The fatigue life is calculated using sines method. The ball handle is a solid circular section with a diameter of 6 mm and inserted into the ball through press fit. The material is 6082 Aluminium alloy with ultimate tensile strength of 200 MPa. The endurance strength of the material is given by,

$$\sigma_e'(mech\ component) = \frac{\sigma_e m_s m_d}{K_f}$$

where,

σ_e = 0.5 * UTS ;

m_s and m_d derived from graph ;

K_f = 1+q(K_t-1)

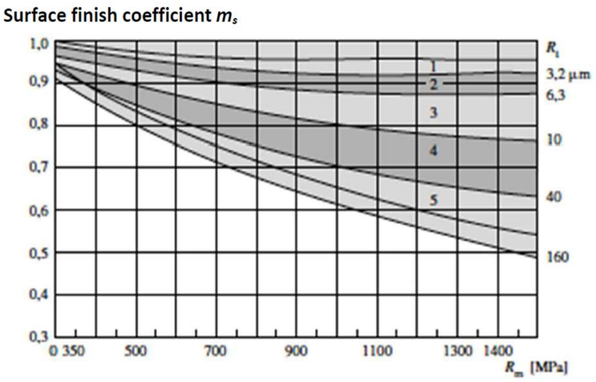


Figure 8.20: Surface finish coefficent(m_s)

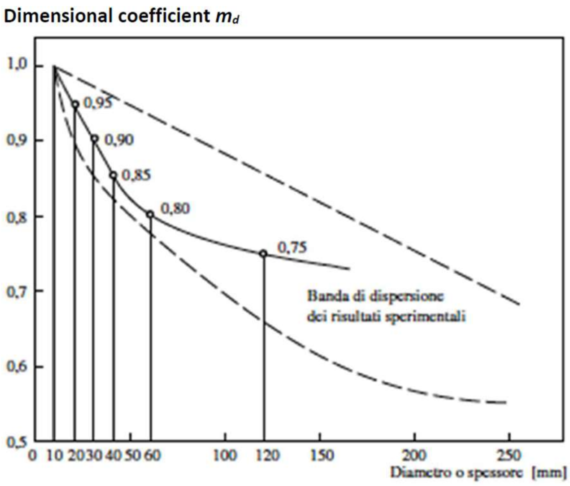


Figure 8.21: Dimensional coefficent

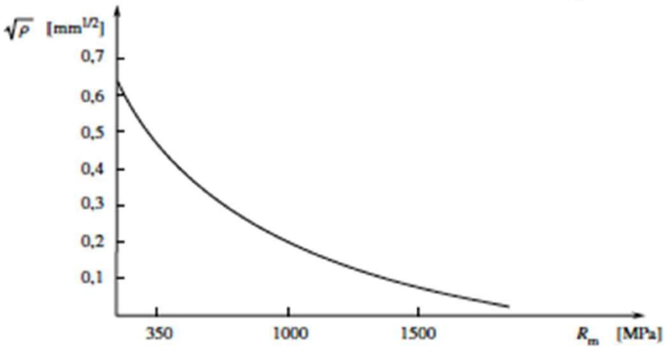


Figure 8.22: Constant

$$\sigma_e = 0.5 * 200 = 100 \text{ MPa}$$

m_s = 0.96 (for roughness of 3.2 μm and UTS of 200 MPa)

m_d = 1 (for diameter of 6mm)

$\sqrt{\rho} = 0.52$ and r = 3

$$q = \frac{1}{1 + \sqrt{\frac{\rho}{r}}}$$

q = 1/(1+0.52/1.732) = 0.769

K_f = 1+ 0.769 (2-1) = 1.769

Therefore,

$$\sigma_e' = 100 * 0.96 * 1/1.769 = 54.27$$

The endurance strength is 54 Mpa which indicates that if the stress acting on the material is less than the endurance strength, the infinite life is ensured according to Wöhler curve. For the average load of 2 kg, the stress acting on the material is,

Moment, M = 20 x 43.2 = 864 Nmm

$$\sigma_{max.} = 32 M / \pi d^3$$

$$\sigma_{max.} = (32*864)/(\pi*6^3) = 40.76 \text{ MPa}$$

$$\sigma_m = \sigma_a = 40.76/2 = 20.38 \text{ MPa}$$

$$\sigma_{sines} = \sigma_a / (1 - \sigma_a / UTS)$$

$$\sigma_{sines} = 20.38 / (1 - (20.38 / 200)) = 22.68 \text{ MPa}$$

Since, $\sigma_{sines} < \sigma_e'$, the life of material is higher than 5 million cycles (Infinite life). The safety factor(η) with respect to infinite life is

$$\eta = \sigma_e' / \sigma_{sines}$$

$$\eta = 54.27/22.68 = 2.4$$

The number of cycles to fail the material is calculated. To find the fitting constants A & B,

$$\sigma_a = A \cdot N_f^B$$

Two cases of UTS (200 MPa) with N_f = 10^3 cycles and σ_e(54.27 MPa) with N_f = 5x10^6 cycles are considered. Taking log on both sides,

log 200 = log A + b log (1000)

log 54.27 = log A + b log (5000000)

we find that fitting constants, b = -0.1531 and A = 576.03

Now,

$N_f = (\sigma_{sines}/A)$^(1/b)

N_f = (22.68/576.03)^(1/-0.1531)

N_f = 1516581025 cycles ≈ 1517 million cycles

8.2.2.2 Concept D

In this concept, the two components ball handle and metal handle are considered as critical. The two cases are considered. The first case is the average load of 3 kg to move the handle. This load is derived from the effort force of 2 kg to move the handle and a safety load of 3 kg to overcome the effort force. The fatigue life is calculated using sines method. The ball handle is a hollow circular section with external diameter of 6mm and internal diameter of 3mm. The material is PA12 with ultimate tensile strength of 48 MPa. The metal handle material is 6082 Aluminium alloy with ultimate tensile strength of 200 MPa.

At first, the PA12 material with average load of 3 kg and maximum load of 30 kg is subjected to analysis. The endurance strength of the material is given by,

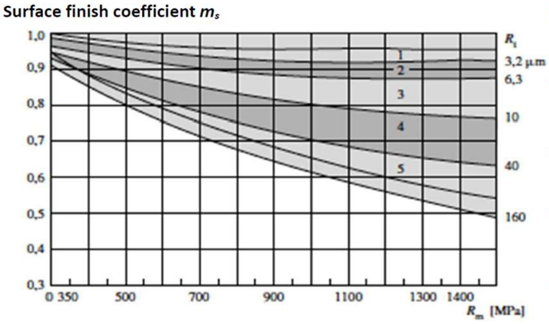
$$\sigma_e'(mech\ component) = \frac{\sigma_e m_s m_d}{K_f}$$

where,

σ_e = 0.5 * UTS ;

m_s and m_d derived from graph ;

$K_f = 1+q(K_t-1)$



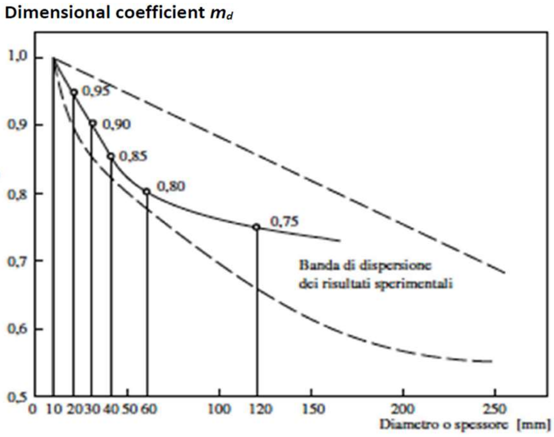


Figure 8.23: Surface finish coefficient   Figure 8.24: Dimensional coefficient

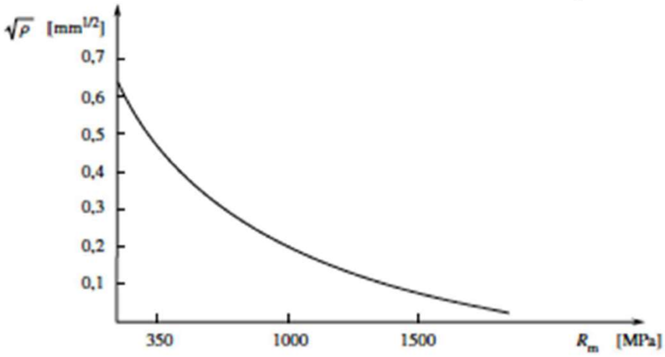


Figure 8.25: Constant

σ_e = 0.5 * 48 = 24 MPa

m_s = 0.96 (for roughness of 3.2 μm and UTS of 48 MPa)

m_d = 1 (for diameter of 6mm)

$\sqrt{\rho}$ = 0.62 and r = 1.5

$$q = \frac{1}{1 + \sqrt{\frac{\rho}{r}}}$$

q = 1/(1+0.62/1.224) = 0.6086

K_f = 1+ 0.6086 (2-1) = 1.6086

Therefore,

σ_e' = 24 * 0.96 *1/1.6086 = 13.893 MPa

The endurance strength is 13.89 Mpa which indicates that if the stress acting on the material is less than the endurance strength, the infinite life is ensured according to Wöhler curve. For the average load of 3 kg, the stress acting on the material is,

Moment, M = 30 x 12 = 360 Nmm

$$\sigma_{max.} = 32\ M*D\ /\ \pi*(D^4-d^4)$$

$$\sigma_{max.} = (32*360*6)/(\pi*6^4-3^4) = 18.12\ MPa$$

$$\sigma_m = \sigma_a = 18.12/2 = 9.06\ MPa$$

$$\sigma_{sines} = \sigma_a\ /\ (1 - \sigma_a\ /\ UTS)$$

$$\sigma_{sines} = 9.06\ /\ (1 - (9.06\ /\ 48)) = 11.17\ MPa$$

Since, $\sigma_{sines} < \sigma_e'$, the life of material is higher than 5 million cycles. The safety factor(η) with respect to infinite life is

$$\eta = \sigma_e'\ /\ \sigma_{sines}$$

$$\eta = 13.89/11.17 = 1.24$$

The number of cycles to fail the material is calculated. To find the fitting constants A & B,

$$\sigma_a = A \cdot N_f^B$$

Two cases of 0.9*UTS (43.2 MPa) with N_f = 10^3 cycles and σ_e(13.89 MPa) with N_f = 5x10^6 cycles are considered. Taking log on both sides,

$$\log 43.2 = \log A + b \log (1000)$$

$$\log 13.89 = \log A + b \log (5000000)$$

we find that constants, b = -0.1331 and A = 108.413

Now,

$$N_f = (\sigma_{sines}/A)^{(1/b)}$$

$$N_f = (11.17/108.413)^{(1/-0.1331)}$$

$$N_f = 26094797 \text{ cycles} \approx 26 \text{ million cycles}$$

Now, the maximum load of 30 kg is subjected to analysis.

Moment, M = 750 Nmm

$$\sigma_{max.} = 32\, M*D / \pi*(D^4-d^4)$$

$$\sigma_{max.} = (32*750*6)/(\pi*6^4-3^4) = 37.74 \text{ MPa}$$

$$\sigma_m = \sigma_a = 37.74/2 = 18.87 \text{ MPa}$$

$$\sigma_{sines} = \sigma_a / (1 - \sigma_a / UTS)$$

$$\sigma_{sines} = 18.87 / (1 - (18.87 / 48)) = 31.096 \text{ MPa}$$

Since, $\sigma_{sines} > \sigma_e'$, the life of material is lower than 5 million cycles. The number of cycles to fail the material is calculated. To find the fitting constants A & B,

$$\sigma_a = A \cdot N_f^B$$

Two cases of 0.9*UTS (43.2 MPa) with N_f = 10^3 cycles and σ_e(13.89 MPa) with N_f = 5x10^6 cycles are considered. Taking log on both sides,

$$\log 43.2 = \log A + b \log (1000)$$

$$\log 13.89 = \log A + b \log (5000000)$$

we find that constants, b = -0.1331 and A = 108.413

Now,

$$N_f = (\sigma_{sines}/A)^{(1/b)}$$

$$N_f = (31.096/108.413)^{(1/-0.1331)} = (0.2868)^{(-7.5075)}$$

$$N_f = 11809 \text{ cycles}$$

The 6082 Aluminium alloy with ultimate tensile strength of 200 MPa is analysed for average load of 3 kg and maximum load of 30 kg. For the average load of 3 kg, the stress acting on the material is,

$$\text{Moment, } M = 30 \times 36 = 1080 \text{ Nmm}$$

$$\sigma_{max.} = (32 M / \pi^* D^3)$$

$$\sigma_{max.} = (32^*1080)/(\pi^* 6^3) = 50.95 \text{ MPa}$$

$$\sigma_m = \sigma_a = 50.95/2 = 25.475 \text{ MPa}$$

$$\sigma_{sines} = \sigma_a / (1 - \sigma_a / \text{UTS})$$

$$\sigma_{sines} = 25.475 / (1 - (25.475 / 200)) = 29.18 \text{ MPa}$$

Since, $\sigma_{sines} < \sigma_e'$, the life of material is higher than 5 million cycles. The safety factor(η) with respect to infinite life is

$$\eta = \sigma_e' / \sigma_{sines}$$

$$\eta = 54.27/29.18 = 1.86$$

The number of cycles to fail the material is calculated. To find the fitting constants A & B,

$$\sigma_a = A \cdot N_f^B$$

we know that b = -0.1531 and A = 576.03

Now,

$$N_f = (\sigma_{sines}/A)\text{^}(1/b)$$

$$N_f = (29.18/576.03)\text{^}(1/-0.1531)$$

$$N_f = 288663327 \text{ cycles} \approx 288 \text{ million cycles}$$

Now for the maximum load of 30 kg,

$$\text{Moment, } M = 3375 \text{ Nmm}$$

$$\sigma_{max.} = (32\ M / \pi * D^3)$$

$$\sigma_{max.} = (32*3375)/(\pi*6^3) = 159.24\ \text{MPa}\ (191.08)$$

$$\sigma_m = \sigma_a = 159.24/2 = 79.62\ \text{MPa}\ (95.54)$$

$$\sigma_{sines} = \sigma_a / (1 - \sigma_a / \text{UTS})$$

$$\sigma_{sines} = 79.62 / (1 - (79.62 / 200)) = 132.28\ \text{MPa}$$

Since, $\sigma_{sines} > \sigma_e'$, the life of material is lower than 5 million cycles.

The number of cycles to fail the material is calculated. To find the fitting constants A & B,

$$\sigma_a = A \cdot N_f^B$$

we know that b = -0.1531 and A = 576.03

Now,

$$N_f = (\sigma_{sines}/A)^{\wedge}(1/b)$$

$$N_f = (132.28/576.03)^{\wedge}(1/-0.1531)$$

$$N_f = 14911\ \text{cycles}$$

9 Conclusion

The purpose of this thesis was to design and develop a new smallest version of 3D proportional industrial joystick for TER Tecno Elettrica Ravasi. To achieve that, the requirements generated from the customer survey are taken as input. The projected started with a preliminary design passing through the concept generation using functional analysis, detailed design, DFMEA, FEM analysis, cost analysis, fatigue analysis.

Two concepts are selected as optimum and developed using 3D printing technology. One of the selected concepts is developed using a printer which generates a functional product rather creating multiple parts and assemble together externally. A new printer HP MJF580 with an investment of 150 k € (150.000 €) is purchased to realise the prdouct. A comparison with injection molding shows the advantage of buying a new 3D printer for low quantity production unless mass production with injection molding.

To achieve the infinite operational life (>5x10^6 cycles) of the product, a new method of control using contactless permanent magnets is introduced. Permanent magnets will likely to lose 1% of their flux density over 100 years. This is 10 times higher than operational life time of the joystick considering the electrical components and control boards. Standard axial ring magnets are chosen which results in cost saving.

The concept C is utilized for the non-proportional hall effect joystick and concept D is utilized for proportional joystick. The easily available material PA12 and 6082 Aluminium alloy is chosen and the static stress and fatigue stress on the material ensure the infinite life of the product without any structural issues.

Concluding, a new smallest version of 3D industrial joystick prototype for infinite life is developed and the testing in a laboratory will be conducted to compare with the theoretical fatigue life.

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