M A R M A R A U N I V E R SI T Y

FA C U LT Y O F E N G I N E E R I N G

DESIGNING A KINEMATIC RESISTIVE PROBE

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GRADUATION PROJECT REPORT

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DESIGNING A KINEMATIC RESISTIVE PROBE

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ABSTRACT

Measurement is a highly important concept in engineering. Engineers almost always do measurements and work with objects they measure. One cannot overlook the importance of measurement. With this undeniable need, the engineering world created tools that can measure and check the accuracy of a production line or parts that are still in process. The absence of reliable measurement tools in a production line will eventually lead to the delivery of faulty parts to service. Semi or fully-automated measurement systems, therefore, are a highly crucial component for any production. Visual process monitoring is one of them. In this paper's case; a measurement device that is based on measurements of the distance between reference and triggering points in various directions called touch-trigger probes. The probing technology has become the most vital and fundamental element of CNN's and CMM machines. The main purpose of this thesis is to design a kinematic resistive probe used that is used manually and can adapt to CNC machines. Designs are made in the SOLİDWORKS program and calculations are done with the help of MATLAB and EXCEL.

Keywords: Measurement, CNC, Engineer, Probe, Touch Trigger Probe, CMM, Kinematic Resistive Probe, Manuel

SYMBOLS

V : Battery volt

S_1 : Toggle switch

R_1 : Internal resistance of the LED

R_{ball} : Internal resistance of sphere ball

R_{ping} : Internal resistance of sphere ball

i : Support ball positions according to; $i = \{A, B, C\}$

F_{Li} : Support force of the right support ball to the probe positioning pin at the point i

F_{Ri} : Support force of the right support ball to the probe positioning pin at the point i

α : Included angle of F_{LA} and the connection line of the two supporting ball centers at point A

β : Included angle of F_{RA} and the connection line of the two supporting ball centers at point A

K : Sum of the spring pre-pressure force on the probe and the probe gravity

t : Distance between the force center of the mass of the probe

δ_1 : Angle between the line $\overline{OH}$ from the gravity point O of the probe to the point H of the force K and the positive direction of the $X-$axis

m : Distance between point A and the center of the probe

g : Distance between point B and the center of the probe

s : Distance between point C and the center of the probe

L : Distance between the center of the probe and the center of the probe ball

F_T : Measuring force when the probe contacts the tested part to generate the trigger signal

δ : Angle between the force F_T and the positive direction of the $Z-$axis

θ : Angle between the projection line of the force F_T on the XY plane and the positive direction of the X-axis

τ : Rotation distance of a point of the point A, point B, and point C; around the rotation axis comprised of two other points under the action of force F_T

L_a : Equivalent length from the point of τ to the rotation axis

L_c : Rigid displacement from the idle state of the probe to the trigger moment

L_p : Deflection displacement of the probe from the idle state of the probe to the trigger moment

L_k : Elastic compression displacement of the contact between the probe and the tested part when the force is F_T

n_δ : Contact coefficient

μ_1 : Poisson's ratio of the support ball

μ_2 : Poisson's ratio of the positioning pin

E_1 : Modulus of elasticity of the support ball

E_2 : Modulus of elasticity of the positioning pin

r_1 : Radius of the support ball

r_2 : Radius of the positioning pin

L : Length of the probe rod;

E : Elasticity of the probe rod;

x : Length from the root point H of the probe rod to the calculated point toward the direction of the probe ball tip

I : Moment of inertia of the probe rod cross-section face to the center axis.

d_r : Diameter of the probe rod

μ_3 : Poisson's ratio of the probe ball tip

μ_4 : Poisson's ratio of the tested part

E_3 : Modulus of elasticity of the probe ball tip

E_4 : Modulus of elasticity of the tested part

r_t : Radius of the probe ball tip

R : Internal Resistance

L_{con} : Length of the Conductor

A_{con} : Cross-sectional Area of the Conductor

ρ_{con} : Resistivity of the Conductor

ABBREVIATIONS

AKA : As Known As

ASIC : Application Specific Integrated Circuit

CAD : Computer-Aided Design

CAS : Continuous Analog Scanning

CNC : Computer Numerical Control

CMM : Coordinate Measuring Machine

LED : Light Emitting Diode

PTV : Pre Travel Variation

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CHAPTER 1: INTRODUCTION

1. INTRODUCTION

Human beings have begun to measure things since the creation of the world. Measurement is one of the main things in human life throughout history. Humans used different objects to measure. As time passed the importance of measurement is never decreased and on the contrary, it increased.

Measurement is also one of the most fundamental concepts in science. Without the ability to measure, it would be difficult for scientists to conduct experiments. Measurement is not only important in science, it is also essential in farming, engineering, construction, manufacturing, and numerous other occupations and activities. [1]

For manufacturers looking to reduce setup times, increase machine usage time and improve the dimensional accuracy of the finished workpieces. They started to search for different techniques to achieve that but the techniques used to achieve these tasks are often manual, laborious, and error-prone. With the invention of touch probes, the errors decreased drastically. Touch probes are a device to reduce production mistakes.[2]

Touch probes help reduce setup times, increase machine usage time, and improve the dimensional accuracy of the finished workpieces. Setup, measuring, and monitoring functions can be performed manually or—in conjunction with most CNC controls—can be controlled by a program. [3]

With the contributions to the manufacturing world, probes are at the center of this operation in CNC machining, with the probes, we gain so much time that people will lose and materials that are saved from going to the scrapyard.

Probes are mostly used in CMM machines. Coordinate Measuring Machine (CMM) accurately measures the geometry of an object along X, Y, and Z axes using a touch-trigger, scanning, or vision probe to take a series of precise points on the surface of an object. The probe's position can be manually controlled or, automatically (CNC) through the use of a computer. The position is defined using a reference sphere in the X-Y-Z coordinate system. CMMs also allows the probe angle to be controlled to enable the measurement of complex surfaces that may otherwise be unreachable. [4],[5]

1.1 PROBING

In recent years, the possibility of an on-machine measurement with a touch-trigger probe of an object directly on a CNC machine tool became widespread. This eliminates the necessity to transport an object to a CMM and of a repeated positioning of the object on the CNC machine tool to correct the detected defects. Inspection probes are mounted in the working center spindle or the CNC lathe's revolver head and they are used to set the object cutting and its initial dimension control.

As for now, all the models developed to apply only to probes used in CMMs. Those existing probe working models take under account the value of force operating on the tip of the stylus necessary to trigger the probe, depending on its operation direction. This way, elastic deflection of the stylus in the moment of triggering of the probe, depending on the operation direction, is determined. [6]

1.2. PROBING PROCESS

This project is about designing a manual probe that can be adapted to a CNC machine. For a CMM probe the work one needs to follow the measurement processes that can be classified into four successive tasks; positioning, probing, measuring, and evaluating.

Positioning is to bring the workpiece into the measuring range of the probing system. Actually, during this task, the probe system is moved to determine the safe zone to avoid the crash of the workpiece and the probe [7], [8].

Probing is to make the physical contact between the touching element (i.e.: stylus tip) and the surface of the workpiece.

Measuring is to compare the measured dimensions to pre-selected reference points by the measurement standards.

The evaluation process covers the transformation of the probing system's position vector (directed from probe coordinate system to the center of the stylus ball) into probed point's position vector (directed from machine coordinate system to the contact point established between the workpiece and the stylus tip) [7].

2. PROBE TYPES

Probes fall into two general categories: contact, or tactile, probes and non-contact probes. As the name suggests, a contact probe gathers data by physically touching the workpiece. Contact probes are classified as hard, or fixed, probes, touch-trigger probes, and analog scanning probes, which maintain contact with the workpiece surface during data collection.

2.1. HARD PROBES

CMM operator uses the hard probe manually that brings the probe into contact with the workpiece, allows the machine to settle, and manually signals the CMM to record the probe's position. The CMM's software automatically adjusts the readings to compensate for the diameter of the probe tip. For instance, when reading a bore diameter, the software compensates for the diameter of the CMM probe tip so that the actual diameter of the bore is shown. Although it compensates for the diameter of the probe tip, it cannot compensate for the bending of the probe.

While touch-trigger probes cause the CMM to report the position whenever the probe comes in contact with the part, a hard probe does not behave this way. Instead, a hard probe registers a hit whenever you press a button on the machine or arm, in the case of scanning, when certain conditions are met (such as crossing a predefined zone, elapsed time, elapsed distance, and so forth).

Hard probes are available in a variety of configurations and continue to have a broad application in coordinate metrology when used in conjunction with manual CMMs. They are most frequently used to measure curved surfaces, distances between workpiece features, angles, and the diameter and centerline location of bores in applications that require low to medium accuracy. Hard probes are simple to use and rugged, but their repeatability depends upon operator touch. Because every operator has a different touch when moving and bringing the probe into contact with the workpiece, inconsistencies in measurement results can occur from one operator to the next. With automated CMM machines, touch-trigger probes are used to eliminate the influence of operator.

2.2. TOUCH TRIGGER PROBES

The touch trigger probe is the most common type of probe used on CMMs today. Touch trigger probes are precision-built, touch-sensitive devices that generate an electronic signal each time the probe contacts a point on the workpiece. Contact with the part is usually indicated by an LED and an audible "beep." The probe head itself is mounted at the end of one of the CMM's moving axes. It can be rotated manually or automatically and can accommodate many different stylus tips and attachments. These features make the trigger probe a versatile and flexible data-gathering device.

Touch trigger probes eliminate the influence of operator touch on measuring results and can be fitted on direct computer control and manual CMMs.

An improvement on the basic touch-trigger probe design incorporates piezo-based sensors. These sensors translate the deflection of the probe into a constant digital acoustic signal that is recorded by the CMM. This design improves the accuracy of touch trigger probe measurement results because it eliminates the effect of stylus bending (caused by force variations when the touch-trigger probe contacts the workpiece) and inaccuracies caused by the probe's internal electromechanical parts.

A further improvement is the use of strain gauge technology. This principle of operation effectively triggers the probe at a constant force no matter what the probe's contact angle with the workpiece. The design eliminates direction sensitivity common to other touch-trigger probes. Submicron accuracy is possible, even with long stylus combinations.[4]

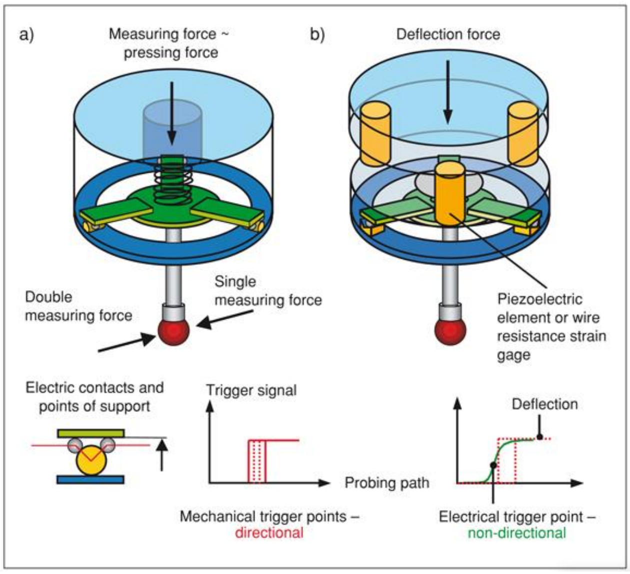


Figure 1. 1: Principles of Touch Trigger [15]

2.2.1. KINEMATIC RESISTIVE PROBE

In a kinematic resistive probe, the stylus is located such that all degrees of freedom are constrained by six points of contact between a set of spheres and cylinders.

A spring holds the stylus carrier against a ball plate that is fitted to the probe housing. The ultra-hard contacts ensure that there is little deformation of the surfaces under the retaining spring force. An electrical circuit runs through the six contacts and the electrical resistance is monitored.

When the probe stylus contacts the surface, this force acts against the retaining spring and causes one or two pairs of the contacts to move apart. As the force between the kinematic contacts reduces, the contact patch between the elements gets smaller. As a result, the electrical resistance around the circuit increases. It is this change that is sensed by the probe electronics.

The elegance of the kinematic resistive sensor is that it combines a mechanically repeatable location and electrical sensing in a simple mechanism. Kinematic trigger probes can be very compact, whilst their robust design makes them suitable for most measurement applications.

The arrangement of contacts means that the force required to trigger the probe in the XY plane varies depending on the direction of contact. This varying force causes the stylus to deflect by a different amount when the trigger occurs. This characteristic - called ‘lobbing’ or pre-travel variation (PTV) - can be easily compensated through probe calibration.[9]

In this project, we choose to follow this type of probe to design. The kinematic resistive probe follows the main simple steps to build and it is very effective for the measurement. A basic model is shown in (Figure 1.2.)

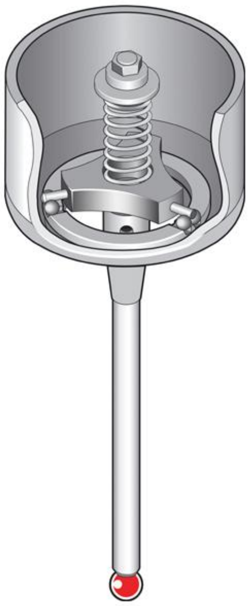


Figure 1. 2: Kinematic Resistive Model

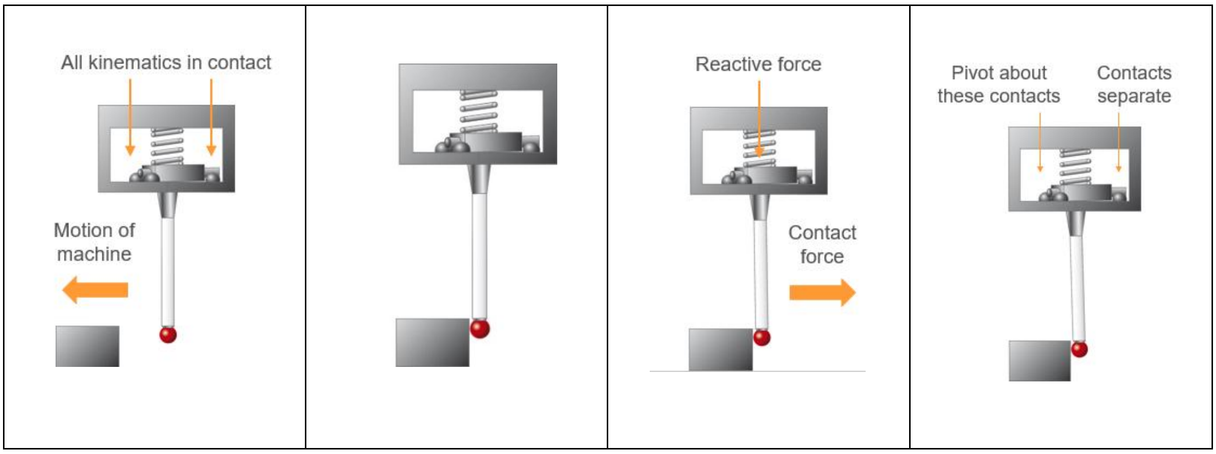


Figure 1. 3: Steps of Kinematic Resistance Probe

- Probe in a seated position
- The stylus makes contact with the component
- Contact force resisted by reactive force in probe mechanism resulting in bending of the stylus.
- Stylus assembly pivots about kinematic contacts, resulting in one or two contacts moving apart
- Trigger generated before contacts separate
- Machine backs off surface and probe reseat [9],[11]

2.1.2. ELECTRICAL SWITCHING

An electrical circuit is built through the kinematic contacts. The ball plate is isolated from the tungsten carbide spheres, while the cylinders and the stylus carrier are also insulated from one another (Figure 1.4). Wires in the ball plate carry the current between the contact patches. Due to the load of the spring, the contact elements experience elastic deformation (Figure 1.4), creating small contact areas through which the current can move along. The resistance across each contact patch is inversely related to the area of the contact patch ($R = \rho/A$). Due to the nature of this mechanism, whilst the force between the stylus and the component is forming, the reactive moment that is generated in the probe mechanism causes the forces between some contact elements to increase, whilst the force between others will decrease. This behavior is due to the kinematical constraints. As the force between two contact elements reduces, the contact patch area gets smaller, thus increasing the resistance between those contact elements. With all six contact patches wired in series, the contacts with the lowest force between them greatly affect the overall resistance in the probe circuit. When the resistance reaches a threshold level that is defined, the probe's output is set to trigger (Figure 1.4). Furthermore, the balls and rods are still in contact when the trigger signal is generated, so in other words, the stylus is in a defined position, providing repeatable measurement task [9], [10], [11],

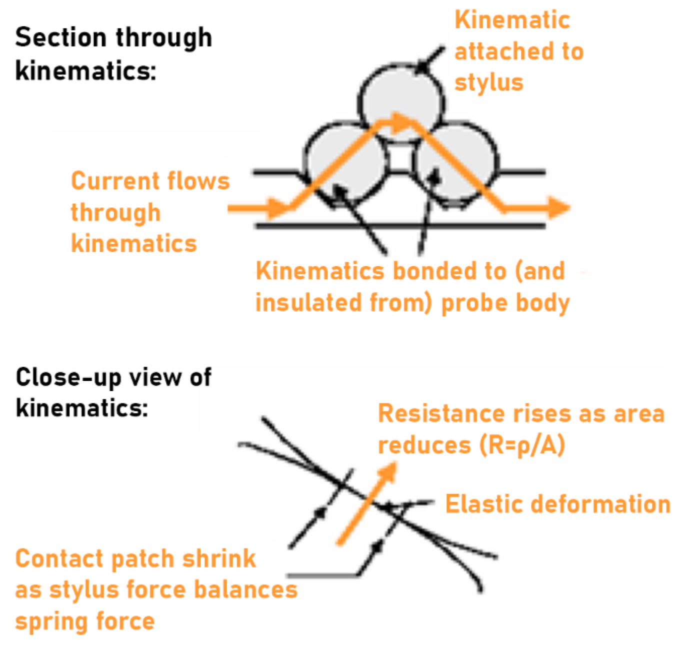


Figure 1. 4: Electrical circuit through kinematics and the close-up view of the contact patch[11]

2.2. STRAIN GAUGE PROBE TECHNOLOGY

Since the invention of the touch-trigger probe by Sir David McMurtry in 1972, probing has become a vital component of automated production processes on machine tools. This simple mechanism, employing a kinematic location to retain a stylus in a highly repeatable manner, has formed the basis of many probes for over 30 years**.**

When looking for a technology to produce a high-accuracy probe that could interface easily to a machine, the target is a lower pre-travel and hence lower PTV. Renishaw developed a new form of sensing technology that addressed the 3D measuring limitations of the kinematic resistive touch probe mechanism: silicon strain gauges. This has been made possible by ultra-compact application-specific integrated circuit (ASIC) electronics and solid-state sensing technology. Although strain gauge touch probes still use a kinematic mechanism to retain the stylus, they do not use the resistance through the contact elements as the means to sense a trigger. Instead, a set of strain gauges is positioned on carefully designed webs in the probe structure beyond the kinematics. These gauges measure the contact force applied to the stylus and generate a trigger once the strain exceeds a threshold value in any direction. This provides a low trigger force, low pre-travel, and low PTV. The MP700 touch probe, introduced in 1995, was the first Renishaw machine tool probe to use strain gauges. It has brought to users all the benefits expected of the technology – improved repeatability, reduced pre-travel, and practical elimination of PTV. Such benefits manifest themselves in more accurate measurement, especially on 3D surfaces where many sensing directions are used, or in set-up, when approach vectors to the workpiece are not known.[14]

Figure 1.5 and Figure 1.6 below show schematics of a strain gauge touch probe. At low contact forces, the kinematics remain seated and the force is transmitted through them to the probe structure. The strain gauges are mounted on precision-manufactured webs designed to maximize the sensitivity of the probe, without compromising its robustness. They detect forces in the structure and their outputs are processed through electronics so that, once a force threshold is breached in any direction, a trigger signal is generated. This threshold force is typically a few grams – much lower than the trigger force on an equivalent mechanical probe.

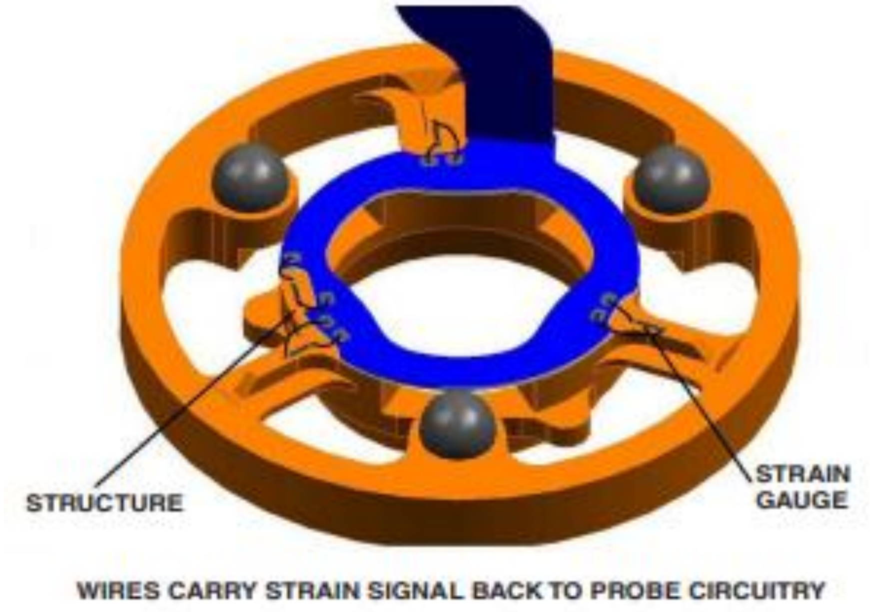


Figure 1. 5: Schematics of a Strain Gauge Touch Probe

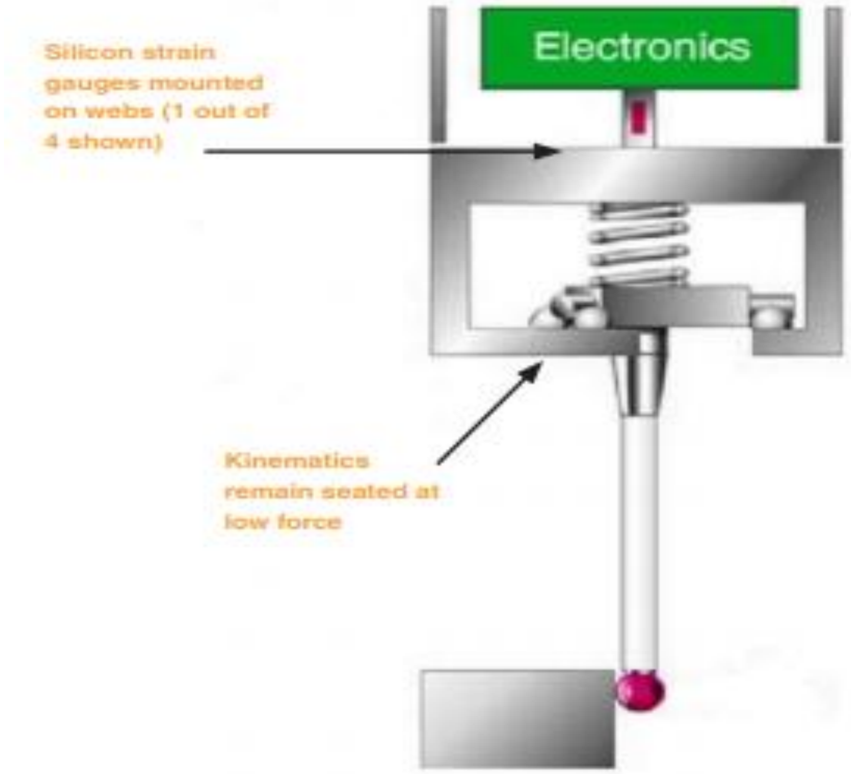


Figure 1. 6: Schematics of a Strain Gauge Touch Probe

Figure 1. 7: The OMP400 touch probe by Renishaw

	Kinematic Resistive Probe	Strain Gauge Probe
Pros	- Simple mechanism, - Low mass (so low inertia at the triggering instant), - Cost-effective, - Easy to retrofit to all types of CMM.	- Improved repeatability, - Low and almost uniform pre-travel variations in all directions, - More accurate measurement, - Low bending deflection (leading to low hysteresis), - Low trigger force (few gm.), - Support much longer stylus,
Cons	- Directional dependent pretravel variation, - Micro-degradation of contact surfaces, - Exhibit re-seat failures over time, - Limiting the length of a stylus, - Resistance through the contact elements as the means to sense trigger.	- Extra mass (filtering circuitry), - Expensive

Table 1: Comparison of the Kinematic Resistive and Strain Gauge Probes

In Table 1 kinematic resistive and strain gauge probe technologies are compared. While kinematic probes are simpler and more cost-effective its measurement abilities are less advanced than the strain gauge probes.

2.3. ANALOG SCANNING PROBES

Analog scanning probes are a type of contact probe used to measure contoured surfaces such as sheet metal assemblies. The analog scanning probe remains in contact with the workpiece surface as it moves and produces analog readings rather than digital measurements.

Figure 1. 8: Analog Scanning Probe by Renishaw

Continuous analog scanning is a relatively new technology. It adds versatility to CMMs by offering dramatically increased levels of data acquisition, which speeds and improves the accuracy of measurement and inspection operations.

CAS technology is based on continuous rather than the point-to-point acquisition of data with specialized probes and software. It is particularly useful for gaging and surface-mapping complex, contoured shapes, including crankshafts and cams, turbine engine blades, and prosthetic devices. It is also suitable for inspecting the form of large sheet metal assemblies, such as automobile bodies.

Continuous analog scanning systems can acquire 10 to 50 times more data than traditional touch-trigger probes in a given amount of time. The added data provides users with more confidence in the measuring and inspection process. More confidence may be needed if there are large gaps between data points using point-to-point probing techniques.

CAS allows users to scan irregular shapes. This is particularly valuable for measuring workpiece features that change continuously, such as the arc on a turbine blade. The ability to acquire data in this manner also allows CAS systems to be used in reverse engineering applications where a new part has to be built to match or fit an existing part.

Figure 1. 9: SP25M modules and stylus holders

Form and shape measurement requires a different approach than prismatic parts measurement. CMMs used in form measurement applications must be capable of collecting large amounts of data quickly, and measurement software must be capable of processing this data accurately. Because of this, special scanning routines not found in other CMM software packages are required.

For example, scanning software must have a filtering ability to distinguish between subtle changes in the surface direction and variability in the workpiece surface finish, such as the rough area on a turbine blade. Filters can also eliminate the effects of vibration caused when the probe tip moves along the workpiece surface.

Non-scanning CMMs use probe center coordinates for measurement in that the data generated by the machine is the location of the ball's center point. In scanning applications, the data must be shifted by the radius of the probe, using the parallel curve function, to represent the real surface of the workpiece. During analysis, spline functions are used to remove the mismatch between the scanned points and the nominal points. This way, deviations from the nominal to the actual can be calculated.

Two types of CAS systems are used in measuring and inspection applications: closed-loop and open-loop.

In a closed-loop system, the probe automatically detects changes in the surface direction of the part and adjusts itself to maintain contact with the part surface. Closed-loop scanning is particularly useful for digitizing unknown complex shapes. In the past, closed-loop scanning was performed at a relatively low speed, although improvements in controller technology have helped increase closed-loop scanning speeds markedly in the last five years. Five years ago, closed-loop scanning could be performed at only 10 mm/sec. New systems can perform closed-loop scanning at 50 mm/sec., with extremely high accuracy.

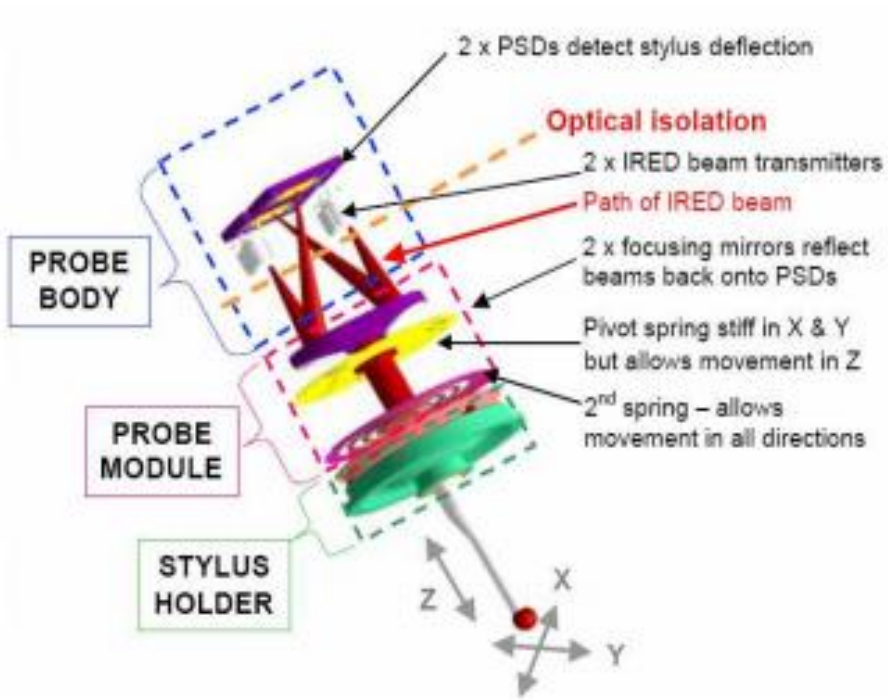


Figure 1. 10: Renishaw's SP600Q Compact Analog Scanning Probe for Small CMMs

Open-loop scanning is a high-speed data-gathering technique used with continuous analog probes on parts whose geometry is well defined by surface points and vectors, or CAD data. The CMM drives the probe along a path using dimensional information from a data file. An example would be a sheet metal assembly such as an automobile hood. The probe head is driven along a vector perpendicular to the nominal surface and records the magnitude of the error between the actual surface and the nominal. CMMs now available can perform open-loop scanning at up to 150 mm/sec.[4]

Figure 1. 11: Renishaw SP25M probe

2.4. LASER PROBES

Non-contact trigger probes are used in the same manner as touch-trigger probes. However, with non-contact probes, a beam of light operating as an optical switch contact the workpiece. The non-contact probe is permanently set to a specific stand-off distance at which the light beam is triggered and measurements are taken. Because the probe never comes into contact with the workpiece surface, the damage is eliminated, and measurement speed is greatly improved.

Laser probes project a laser beam onto the surface of the part, the position of which is then read by triangulation through a lens in the probe receptor. The technique is much like that used by surveyors to find a position or location with bearings from two fixed points that are a known distance apart. Laser probe triangulation provides the actual position of the feature on the workpiece being measured.[4]

Figure 1. 12: CMM Laser scanning probe by Laser Design Inc.

CHAPTER 2: PROBE DESIGN

1 INTRODUCTION

The scope of this thesis is to design mechanical and electrical modeling of a kinematic resistive probe. Through the design process, four consecutive models were considered. Design improvements mainly arouse due to production and proper embedding of the electric circuits.

One of the important things in design is that it should be adaptable to production. A bad design can't be produced in a factory. In this project; the probe is designed as it can be produced in a factory.

2. MAJOR DESIGNS

Before starting our design, we have some priorities that we need to focus on. These are;

1- Easy to Produce
2- Its size needs to be small
3- Electric circuit place should be well placed.
4- Material cost should not be high.

2.1. DESIGN 1

In the first design, we wanted to see what could be done and how the would model look like. A circular body is chosen for the main part (Figure 2.1). The upper part is decided as circular so that can adapt to the CNC machine (Figure 2.2). And for the lower part; a tip is a stylus that will eventually contact the material (Figure 2.3).

After deciding on the basics, we started to draw our design with the SOLIDWORKS program. Firstly, start with the inner main part which can be described as the model's skeleton (Figure 1.4). After drawing that transmission pins are added to the design. Then the base part is designed which will be the home of the electric circuit. A place for carbide balls is opened that is going to transmit electricity. Six carbide balls and 3 pins (Figure 2.4) are chosen for transmission. This part is very important with the model because their places should be all well placed. Balls are placed 120 degrees apart from each other, so they all will make a 360 degrees perfect circle. After that, a path is opened for electric wires and a place for the battery is made (Figure 2.5). This concludes the inner parts. Next are the upper parts. Upperparts consist of oil impermeability part; oring that will not let oil drop which comes from CNC machining. The stylus part is drawn. The stylus part is actually can be bought and we also consider buying it because it is a sensitive part that will be one of the main sections. But it is showed in our design models to observe (Figure 2.6).

One of the problems that have come to the surface during the first design, what exactly the model will look like, one needs to imagine it before starting to draw it. To overcome this problem, literature and some of the company's products are examined. With the examination, a basic design idea presented itself. Another mistake we came to realize was after finishing our model. We draw all the parts of our design as one big part. We couldn't change our design easily. Because of this main problem and can see each part easily. After that, we started to draw our second design from scratch but with the knowledge, we experienced from our first design.

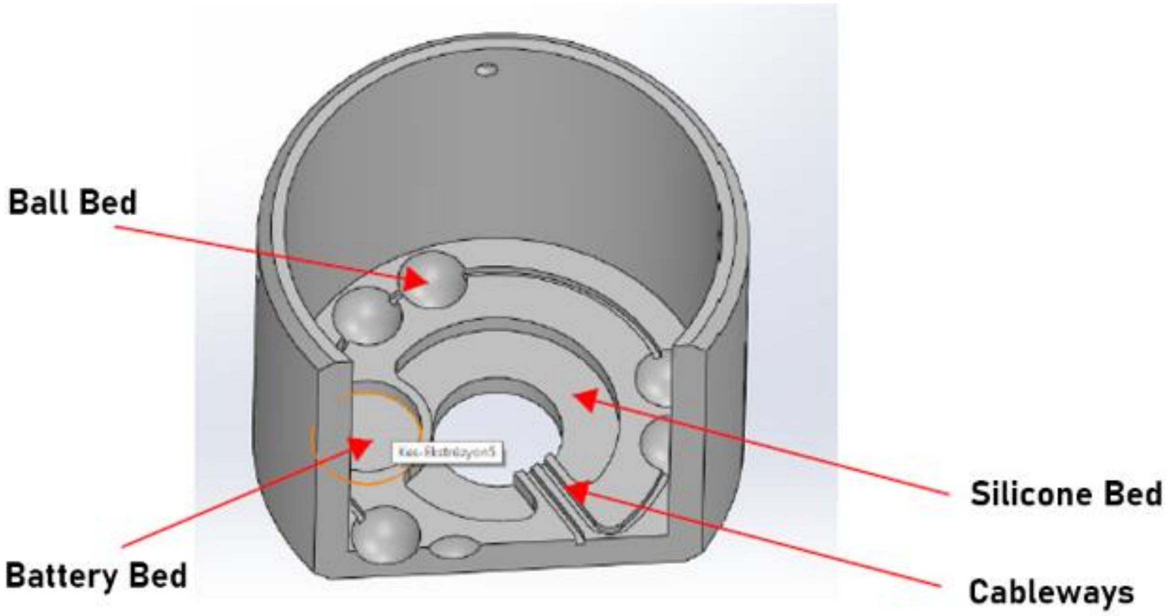


Figure 2. 1: Main Part of the Design 1

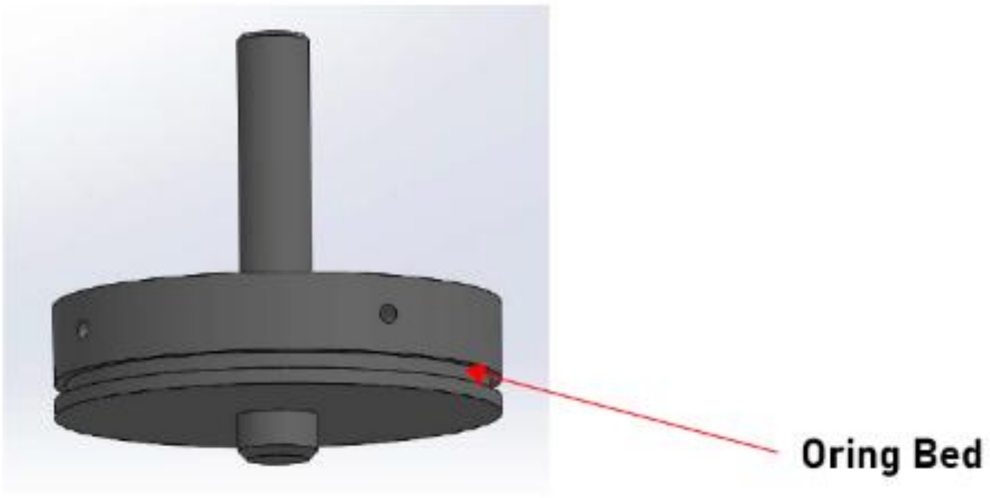


Figure 2. 2: Upper Part of the Design 1 (aka Connector)

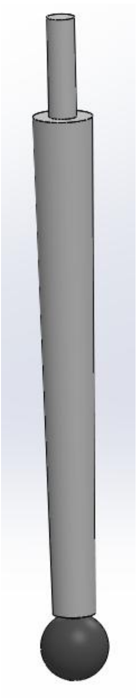


Figure 2. 3: Lower Part of the Design 1 (aka Stylus)

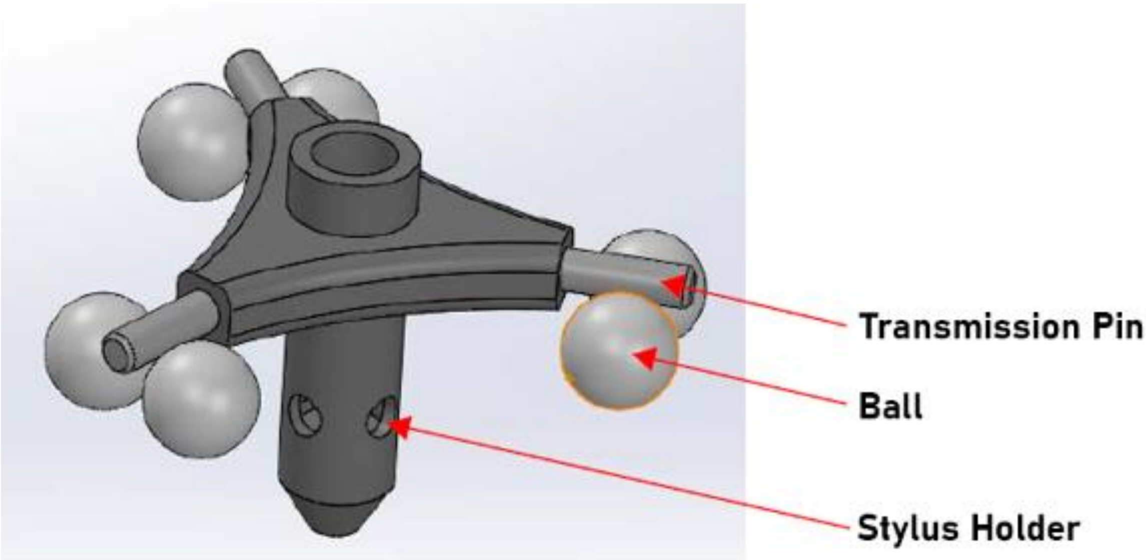


Figure 2. 4: Skeleton of the Design 1 (Stylus Holder, Transmission Pins & Balls)

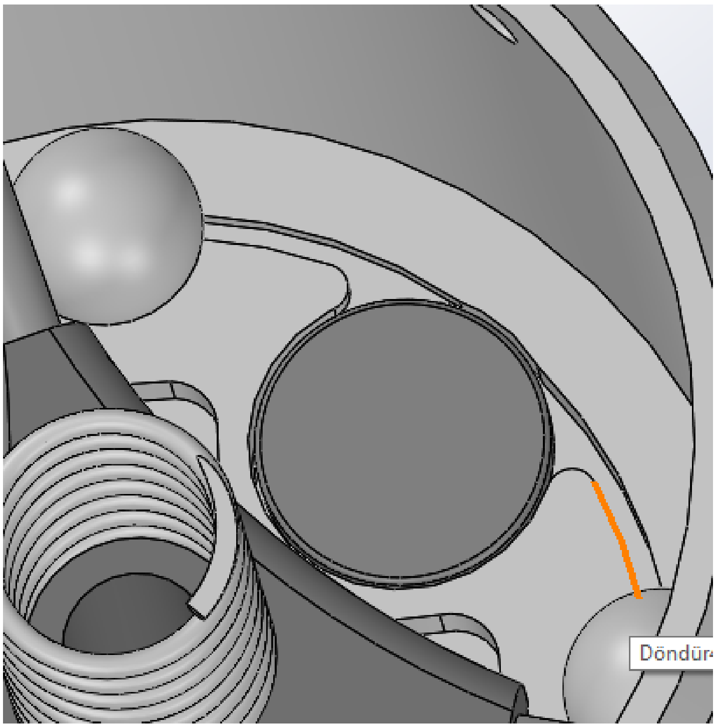
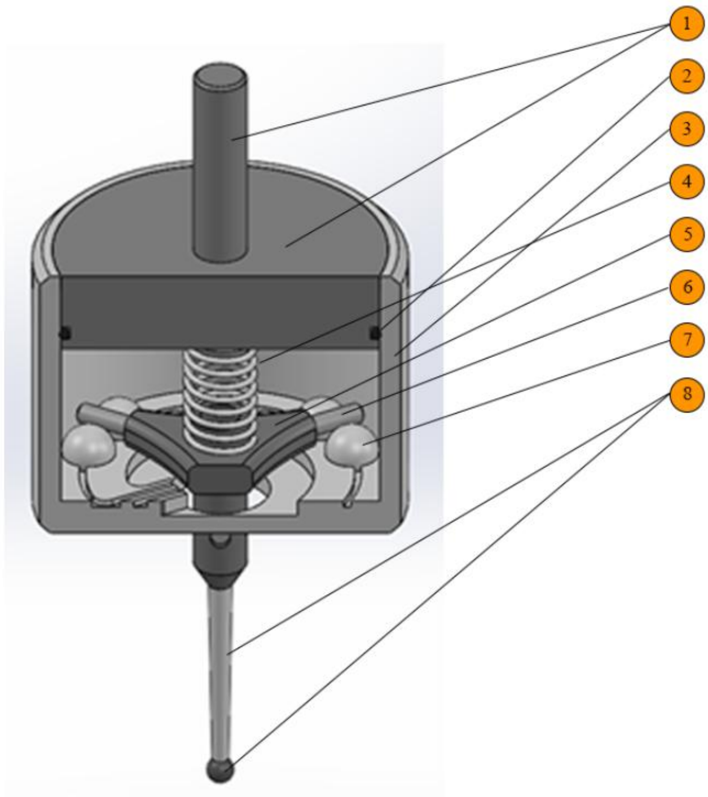


Figure 2. 5: Battery Bed of Design 1



1) Connector
2) Oring
3) Housing
4) Spring
5) Stylus Holder
6) Transmission Pin
7) Ball
8) Stylus

Figure 2. 6: Whole Body of First Design

2.2. DESING 2

As for the second design, dimensions were not included. With this design, all parts drawn differently than assembled. With this design, drawings are improved. A silicone funnel is added to the base part that will help the stylus' base part to be more stable (Figure 2.7). A cage designed to hold the carbine balls from the housing (Figure 2.8) to prevent a possible scatter of balls. But despite all the improvements to the design, a place for the battery is not considered.

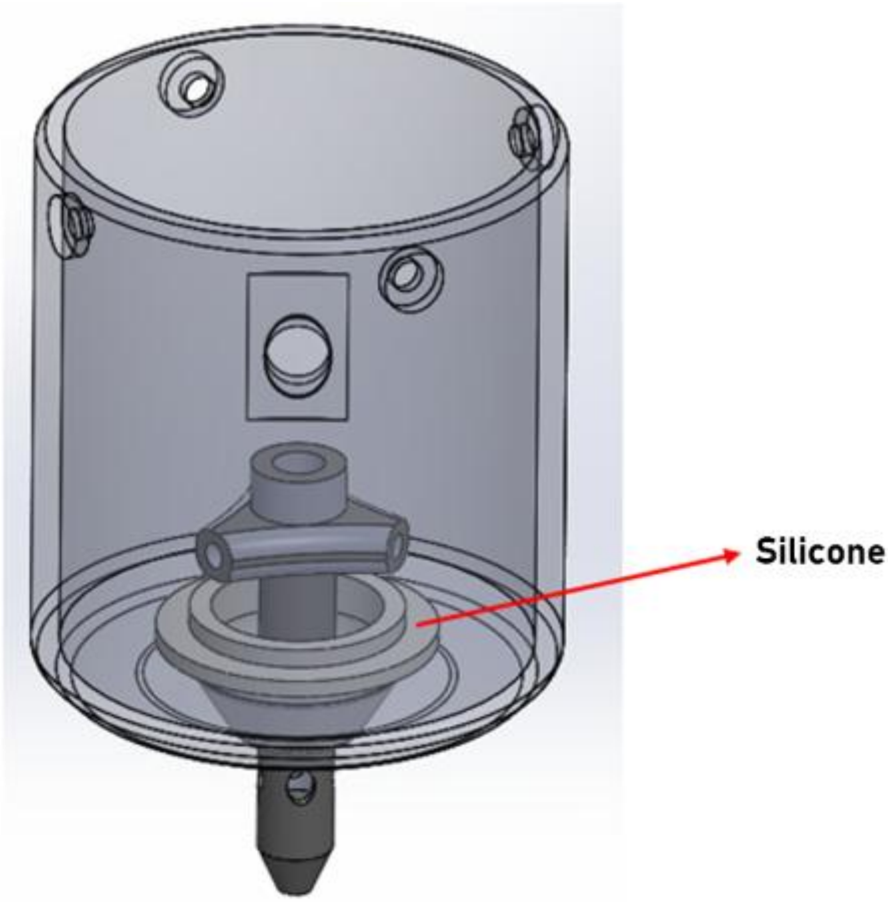


Figure 2. 7: Silicone Funnel Shown in Assembly

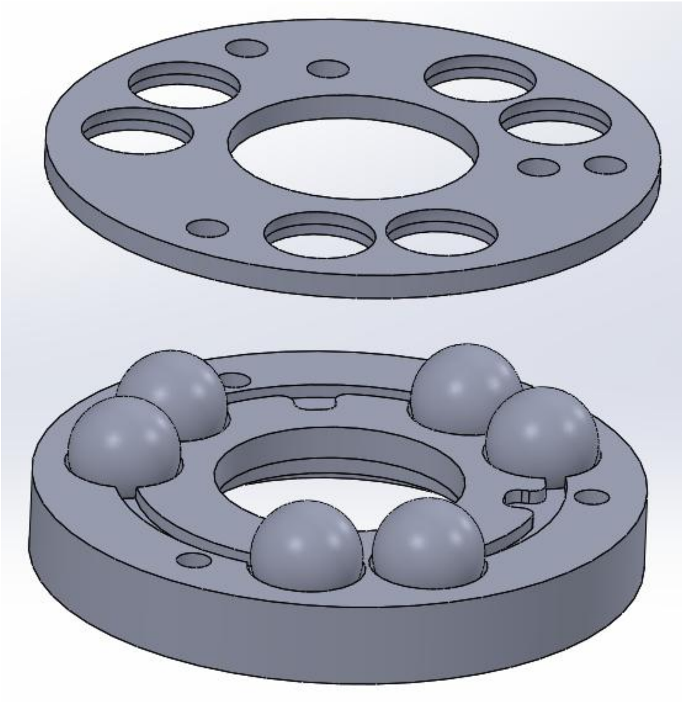


Figure 2. 8: Cage System

2.3. DESIGN 3

Before starting the third design, what is missing is known so this design is mostly focused on these things.

As first thing carbide balls are changed to the aluminum cylinder (Figure 2.9). The reason behind this change is that aluminum cylinders are cheaper and also they will be more useful for an electric circuit. After that, a place for the battery is needed and it should stay stable inside the model. When CNC is operated, the battery could move from its original place and this can affect the electric system. (Figure 2.10). Again, in this design dimensions are not given to the parts. The electric circuit is placed on the mainboard section.

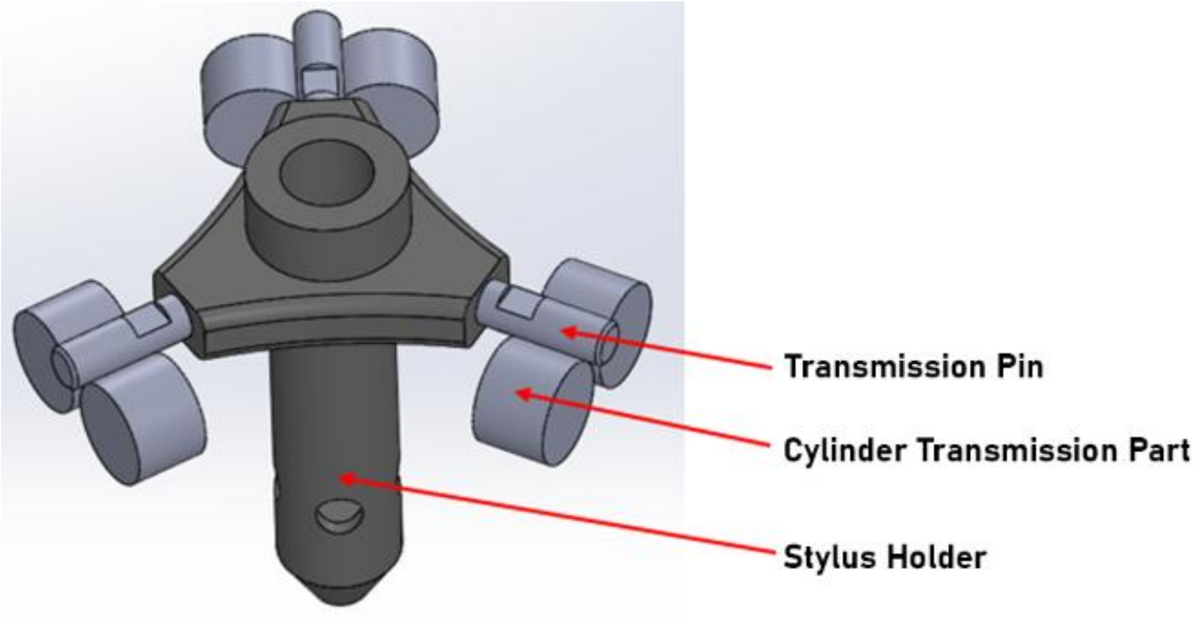


Figure 2. 9: Stylus Holder, Transmission Pin, and New Cylinder Transmission Part

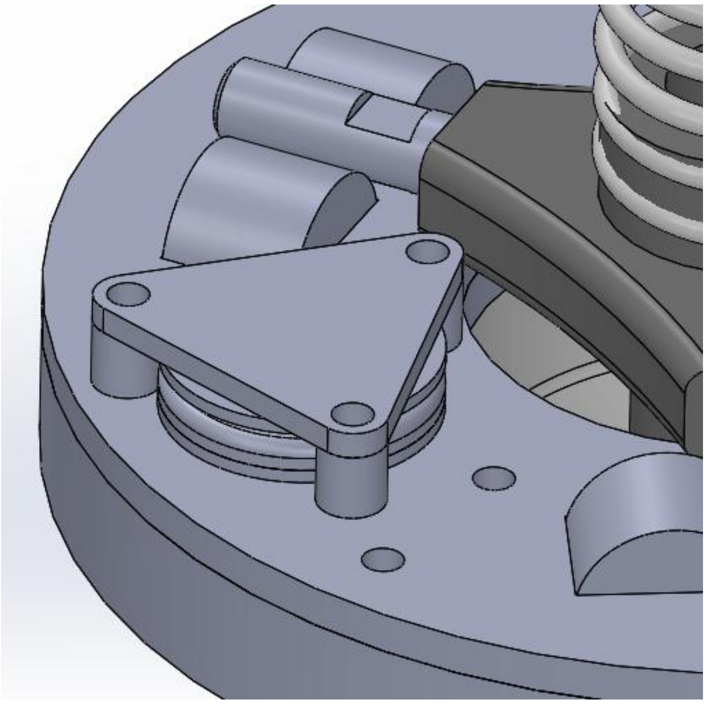


Figure 2. 10: Battery Bed Design

2.4. FINAL DESIGN

With the final design, many things changed that will be helpful with the model. With this final design, dimensions are given to the parts and drawn according to them. The model is designed as small as it can be.

- At first, the housing part and roof part are combined as one body housing. With this move, imperviousness is reduced by enclosing the inner mechanism in a fully sealed assembly. (Figure 2.11)
- To hold the spring, a holder is placed in the shape of a disc to the design. (Figure 2.12)
- The aluminum cylinder is changed to carbide balls again. The reason behind this change is a cylinder contact with the pins as a line but this situation is unacceptable. A single merge point is needed and this is ensured with sphere balls. For this reason, the model is designed according to carbide balls.
- The battery is placed in the battery housing as shown in the figure (Figure 2.13). Battery housing could be removed from its place to charging the battery with the new one.
- A place for the switch is designed. (Figure 2.13)
- Screw places are opened on the surface of housing thoroughly to combine inner mechanism with housing with the help of screws.
- In the end, the final version of the probe is reached. (Figure 2.14)

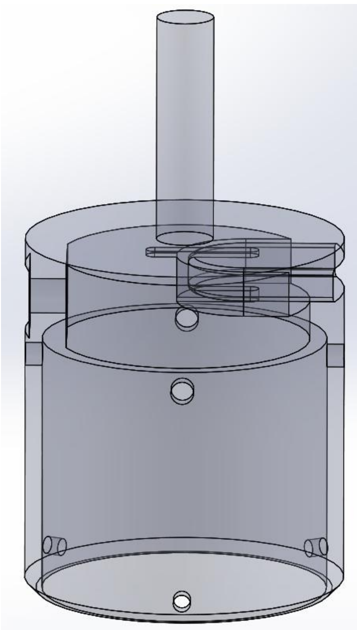


Figure 2. 11: Housing of the Final Design

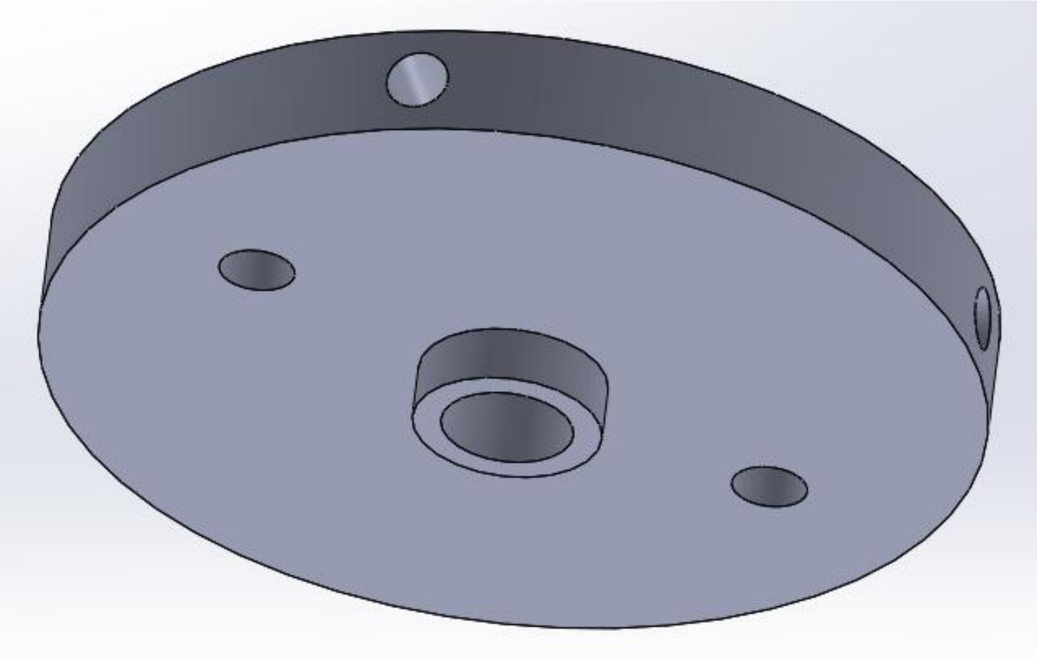


Figure 2. 12: The Holder that holds the spring in the Final Design

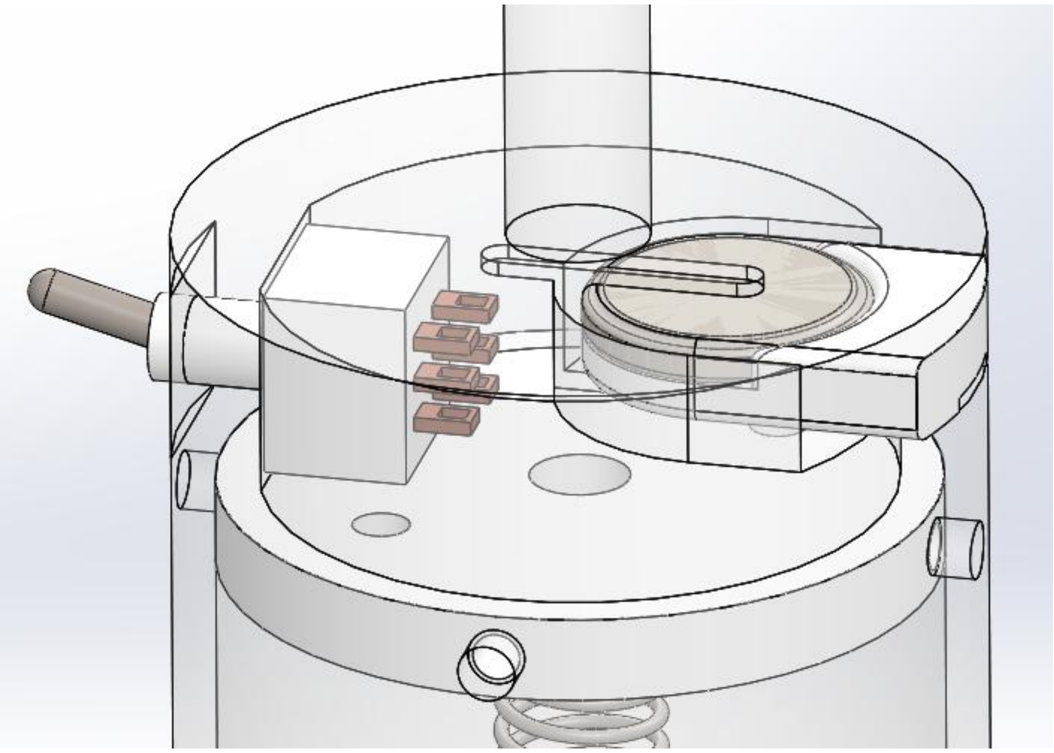
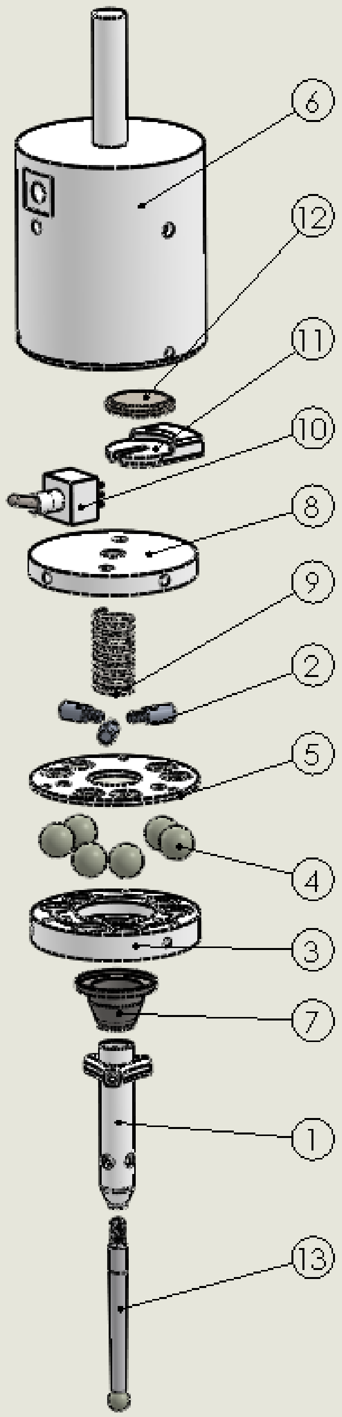


Figure 2. 13: Battery and Switch placements at Roof in the Final Design

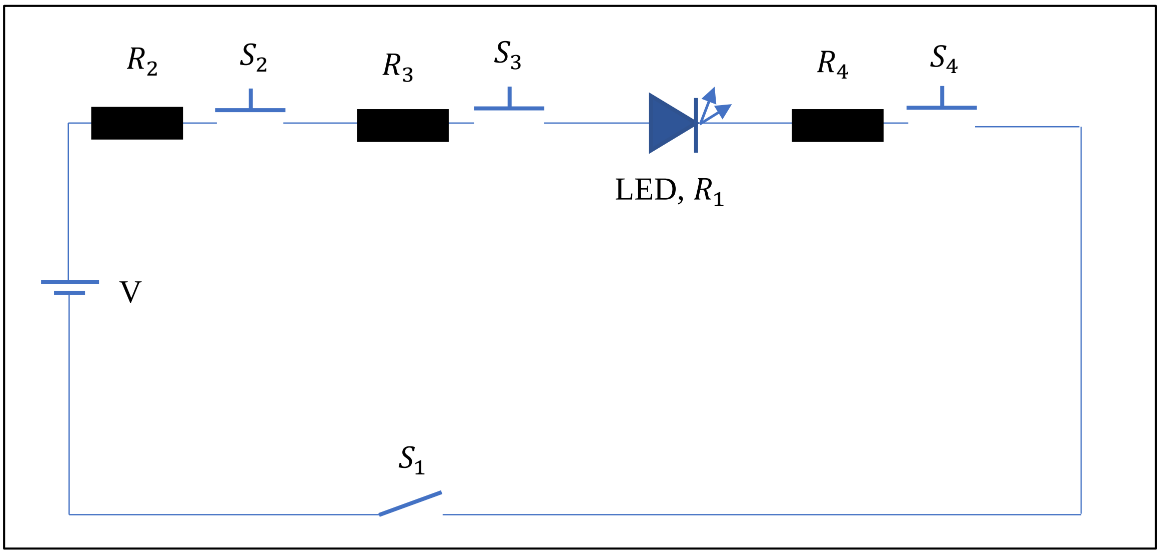


NO.	PART NAME	MATERIAL	#
1	stylus_holder	ABS	1
2	transmission_pin	Alu 6061	3
3	lower_cage	ABS	1
4	ball	Tungsten	6
5	upper_cage	ABS	1
6	housing	ABS	1
7	silicone_funnel	Silicone	1
8	disc	ABS	1
9	spring	CR-1600	1
10	switch	Ni & ABS & Cu	1
11	battery_housing	ABS	1
12	battery	Ni	1
13	stylus	Tungsten & Ceramic	1

Figure 2. 14: Part List for the Final Design

3. ELECTRICAL CIRCUIT

Firstly, wanted to keep the circuit simple. Therefore the whole circuit is connected in series.



where,

V: Battery Volt

S_1: Toggle Switch

R_1: Led internal resistance

S_2, S_3, and S_4: Balls and Pin connections act like button switches.

R_2, R_3, and R_4: Balls and Pin's internal equivalent resistance.

We used the 5V button cell as the power source. We used the MT-2 model switch at S_1.

We can represent the internal equivalent resistance of balls and pin as "R"

$$R = R_2 = R_3 = R_4$$

where

$$R = 2R_{ball} + R_{pin}$$

CHAPTER 3: THEORETICAL BACKGROUND AND CALCULATIONS

1. CALCULATION OF PRE-TRAVEL OF THE PROBE

When the stylus is in contact with the surface, a balance of forces is established. Before the trigger threshold is reached, these growing forces cause the stylus to bend. Since the machine is still moving, the amount of bending in the stylus that occurs before the probe triggers affects the latched position of the machine when the trigger is recorded. This stylus bending before the trigger is known as pre-travel.

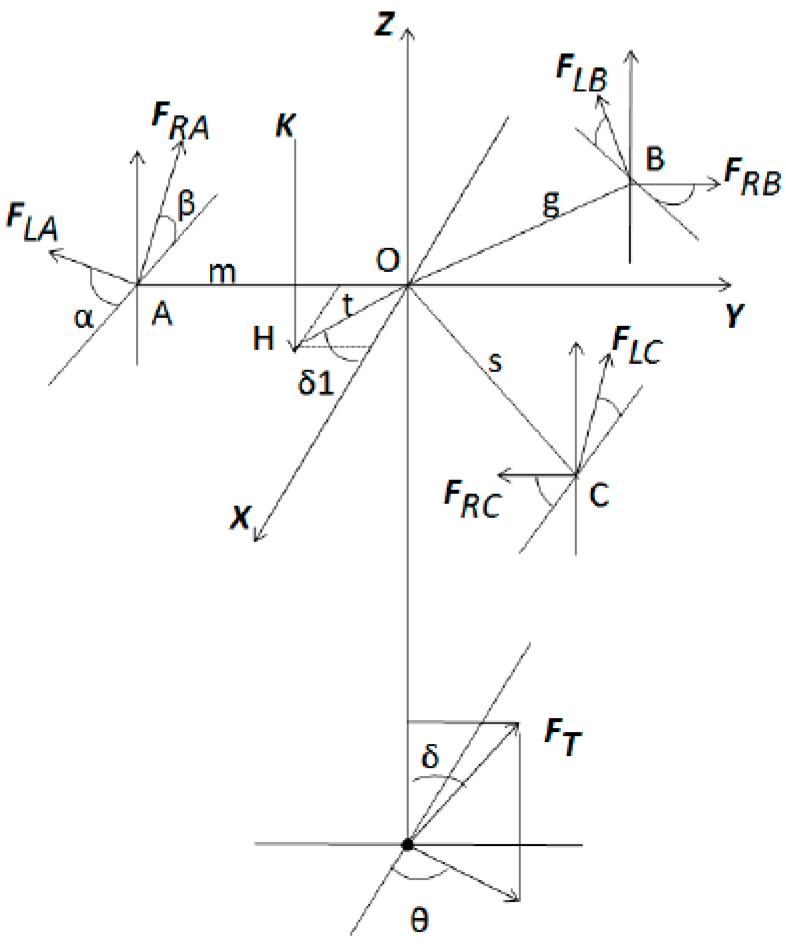


Figure 3. 1: Force analysis in the process of probe triggering

where;

"F_{Li}" (i = A, B, C) is the support force of the right support ball to the probe positioning pin at the point i;

“F_{Ri}” (i = A, B, C) is the support force of the right support ball to the probe positioning pin at the point i;

“α” is the included angle of F_{LA} and the connection line of the two supporting ball centers at point A;

“β” is the included angle of F_{RA} and the connection line of the two supporting ball centers at point A. The included angles at point B and point C, are the same as those at point A.

“K” is the sum of the spring pre-pressure force on the probe and the probe gravity.

“t” is the distance between the force center of the mass of the probe, that is, the eccentricity.

“δ_1” is the angle between the line $\overline{OH}$ from the gravity point O of the probe to the point H of the force K and the positive direction of the $X-axis$.

“m” is the distance between point A and the center of the probe;

“g” is the distance between point B and the center of the probe;

“s” is the distance between point C and the center of the probe;

“L” is the distance between the center of the probe and the center of the probe ball;

“F_T” is the measuring force when the probe contacts the tested part to generate the trigger signal;

“δ” is the angle between the force F_T and the positive direction of the $Z-axis$;

“θ” is the angle between the projection line of the force F_T on the $XY\ plane$ and the positive direction of the X-axis.

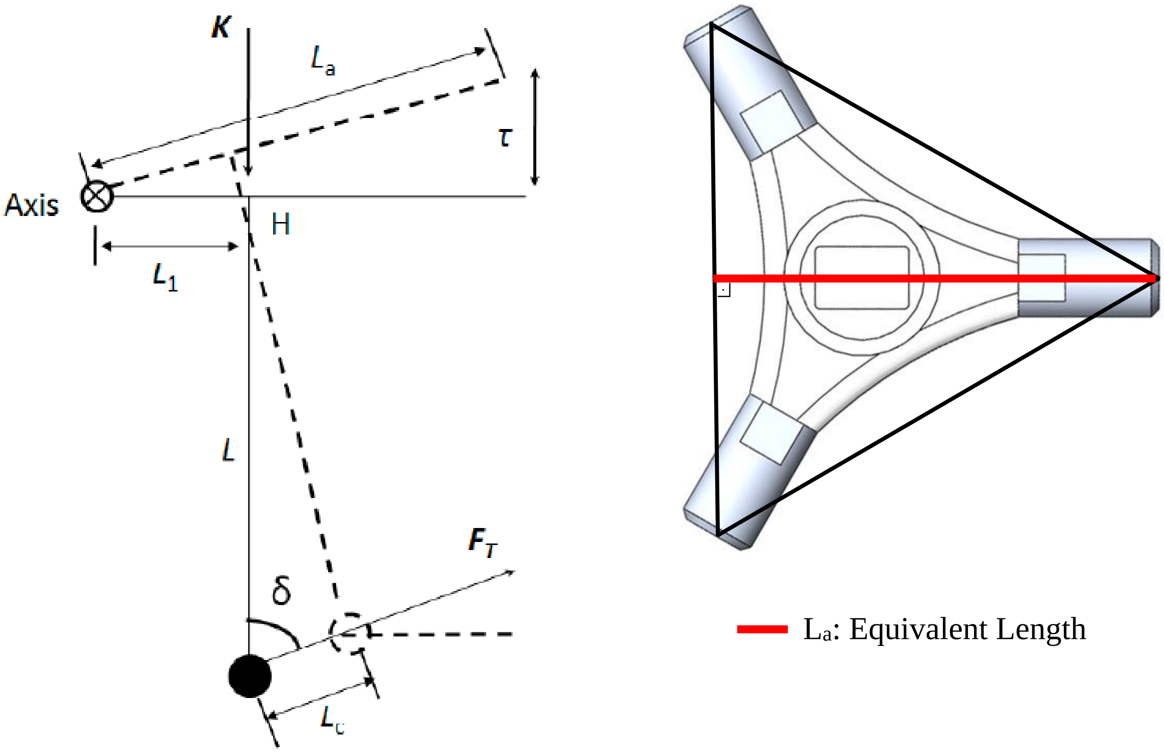


Figure 3. 2: Equivalent diagram of force and rigid displacement change of the probe in the process of probe triggering

where;

"τ" is the rotation distance of a point of the point A, point B, and point C; around the rotation axis comprised of two other points under the action of force F_T,

"L_a" is the equivalent length from the point of τ to the rotation axis.

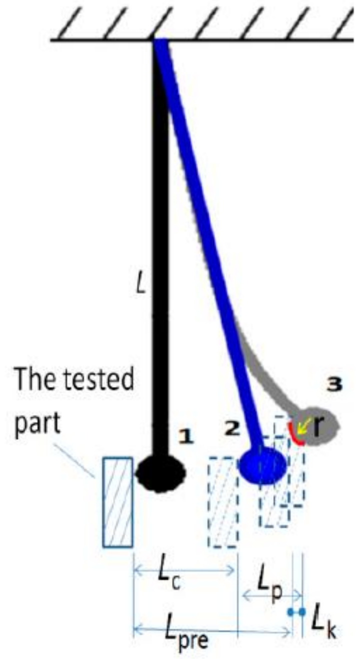


Figure 3. 3: Displacement change of each stage in the process of probe triggering

where

"L_c" is the rigid displacement from the idle state of the probe to the trigger moment;

"L_p" is the deflection displacement of the probe from the idle state of the probe to the trigger moment;

"L_k" is the elastic compression displacement of the contact between the probe and the tested part when the force is F_T.

According to Figure 3.3, the pre-travel (L_{pre}) of the probe can be calculated according to;

$$L_{pre} = L_c + L_p - L_k \tag{1}$$

1.1. RIGID DISPLACEMENT, L_c

Considering the probe as a rigid body, when the probe reaches the force balance state at the trigger moment, according to the static balance concept, the combined external force and the combined external moment are zero, as shown in Figure 3.1.

When the probe is triggered, the force of a certain point of the probe will change from F_{Li} or F_{Ri} (i = A, B, C) to zero in Figure 3.2.

According to the elastic mechanic theory, the distance (τ) can be calculated according to;

$$\tau = 0.665 * n_\delta * \sqrt[3]{\left(\frac{1-(\mu_1)^2}{E_1} + \frac{1-(\mu_2)^2}{E_2}\right)^2 * \left(\frac{2r_2 + r_1}{r_2 r_1}\right) * (F_T)^2} \quad (2)$$

where;

"n_δ" is the contact coefficient;

"μ_1" and "μ_2" are the Poisson's ratio of the support ball and the positioning pin, respectively;

"E_1" and "E_2" are the modulus of elasticity of the support ball and the positioning pin, respectively;

"r_1" and "r_2" are the radius of the support ball and the positioning pin, respectively.

When the displacement of a certain point of point A, point B, and point C is the elastic deformation (τ), the displacement change of the probe ball tip can be calculated according to;

$$L_c = \frac{\tau}{L_a} * L \quad (3)$$

Substituting τ into Equation 3;

$$L_c = \frac{L}{L_a} * 0.665 * n_\delta * \sqrt[3]{\left(\frac{1-(\mu_1)^2}{E_1} + \frac{1-(\mu_2)^2}{E_2}\right)^2 * \left(\frac{2r_2 + r_1}{r_2 r_1}\right) * (F_T)^2} \quad (4)$$

EXPLANATION		ITEM	MATERIALS	VALUES	
μ_1	Poisson Ratio	Support Ball	Tungsten	0,28	
E_1	Modulus of Elasticity	Support Ball	Tungsten	124000	N/mm^2
r_1	Radius	Support Ball	Tungsten	10	mm
μ_2	Poisson Ratio	Transmission Pin	Aluminum	0,33	
E_2	Modulus of Elasticity	Transmission Pin	Aluminum	69000	N/mm^2
r_2	Radius	Transmission Pin	Aluminum	5	mm
L	Length	Probe Rod	Ceramic	87,5	mm
L_a	Equivalent Length			27,75	mm

Table 2: Parameters from Final Design to find Rigid Displacement (L_c)

$$n_\delta = \cos(94{,}33) = 0{,}9966 \quad (5)$$

So the Equation 4 becomes

$$L_c = \frac{87{,}5}{27{,}75} * 0.665 * 0{,}9966 * \sqrt[3]{\left(\frac{1-(0{,}28)^2}{124000} + \frac{1-(0{,}33)^2}{69000}\right)^2 * \left(\frac{2*5+10}{5*10}\right) * (F_T)^2} \tag{6}$$

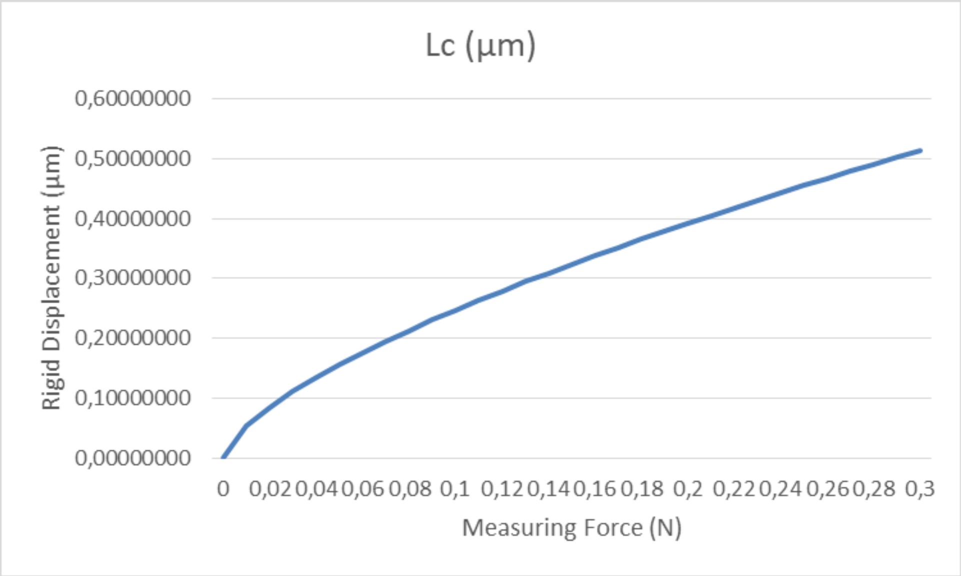


Figure 3. 4: Rigid Displacement change with the change of Measuring Force

Assuming the measuring force; $F_T = 0{,}1$ N, Rigid displacement is;

$$L_c = 0{,}2472\ \mu m \tag{7}$$

1.2. DEFLECTION DISPLACEMENT, L_p

According to material mechanics, the deflection of the cantilever beam is as follows:

$$L_p = \frac{F_T * x^2}{6EI} * (3L - x) \tag{8}$$

where;

L is the length of the probe rod;

E is the modulus of elasticity of the probe rod;

x is the length from the root point H of the probe rod to the calculated point toward the direction of the probe ball tip (e.g., x equals L when the calculated point is the center of the probe ball tip);

L_p is the deflection of the probe rod;

I is the moment of inertia of the probe rod cross-section face to the center axis.

For a circular probe rod, the value of I can be calculated according to;

$$I = \frac{\pi {d_r}^4}{64} \tag{9}$$

where d_r is the diameter of the probe rod

Then, the deflection value at the position of the probe ball tip can be calculated according to;

$$L_p = \frac{F_T L^3}{3EI} = \frac{64}{3} \frac{F_T L^3}{E\pi {d_r}^4} \tag{10}$$

EXPLANATION		ITEM	MATERIALS	VALUES	
L	Length	Probe Rod	Ceramic	87,5	mm
E	Modulus of Elasticity	Probe Rod	Ceramic	220590	N/mm^2
d_r	Diameter	Probe Rod	Ceramic	5,3	mm

Table 3: Parameters from Final Design to find Deflection Displacement (L_p)

So Equation 10 becomes;

$$L_p = \frac{64}{3} \frac{(87{,}5)^3}{220590 * \pi * (5{,}3)^4} F_T \tag{11}$$

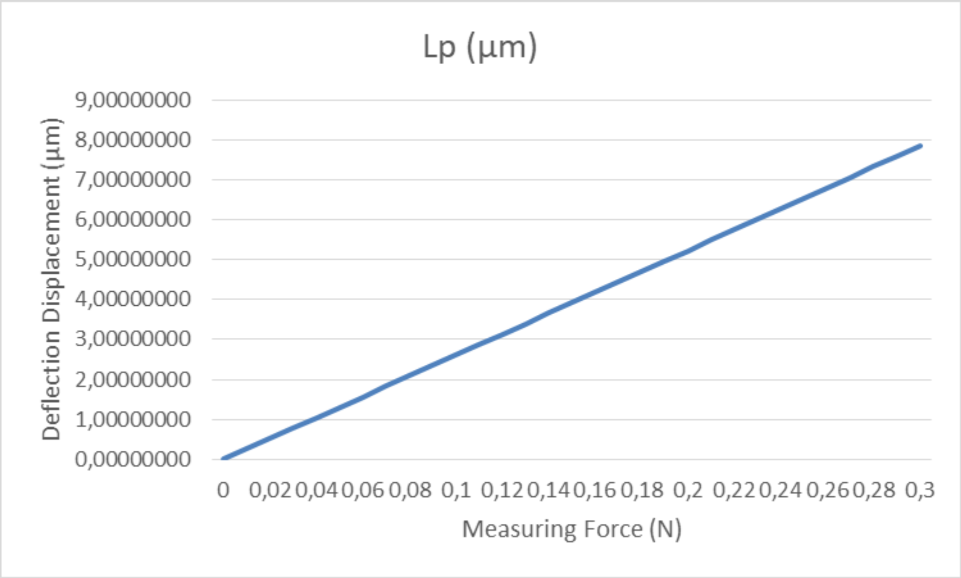


Figure 3. 5: Deflection Displacement change with the change of Measuring Force

Assuming the measuring force; $F_T = 0{,}1$ N, Deflection displacement is;

$$L_p = 2{,}6136\ \mu m \tag{12}$$

1.3. ELASTIC COMPRESSION DISPLACEMENT, L_k

Since the contact between the probe and the tested part belongs to the contact type of the ball tip and the plane, the contact deformation L_k can be calculated according to;

$$L_k = 0.8255 * \sqrt[3]{\left(\frac{1-(\mu_3)^2}{E_3} + \frac{1-(\mu_4)^2}{E_4}\right)^2 * \frac{(F_T)^2}{r_t}} \tag{13}$$

where;

"μ_3" and "μ_4" are the Poisson's ratio of the probe ball tip and the tested part, respectively;

"E_3" and "E_4" are the modulus of elasticity of the probe ball tip and the tested part, respectively;

"r_t" is the diameter of the probe ball tip.

EXPLANATION		ITEM	MATERIALS	VALUES	
μ_3	Poisson Ratio	Probe ball tip	Tungsten	0,28	
E_3	Modulus of Elasticity	Probe ball tip	Tungsten	124000	N/mm^2
r_t	Radius	Probe ball tip	Tungsten	3	mm
μ_4	Poisson Ratio	Tested Part	Aluminum	0,33	
E_4	Modulus of Elasticity	Tested Part	Aluminum	69000	N/mm^2

Table 4: Parameters from Final Design to find Compression Displacement (L_k)

So Equation 13 becomes;

$$L_k = 0.8255 * \sqrt[3]{\left(\frac{1-(0{,}28)^2}{124000} + \frac{1-(0{,}33)^2}{69000}\right)^2 * \frac{(F_T)^2}{r_t}} \tag{14}$$

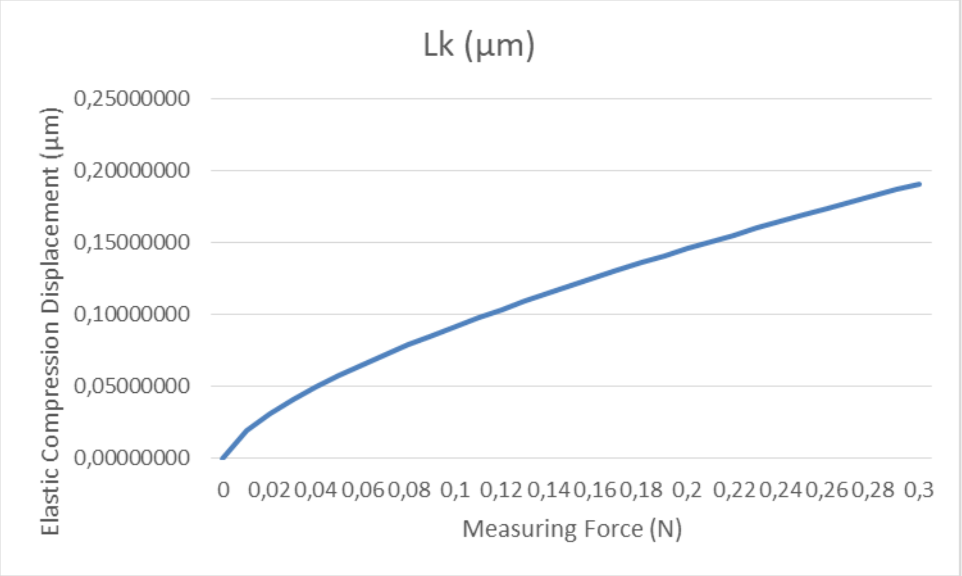


Figure 3. 6: Elastic Compression Displacement change with the change of Measuring Force

Assuming the measuring force; $F_T = 0{,}1$ N, Elastic compression displacement is;

$$L_k = 0{,}0919\ \mu m \tag{15}$$

1.4. THE PRE-TRAVEL OF THE PROBE, L_{pre}

Under the action of force, F_T, the displacement change at the position of the probe is computed according to;

$$L_{pre} = L_c + L_p - L_k$$

$$= \left[\frac{L}{L_a} * 0.665 * n_\delta * \sqrt[3]{\left(\frac{1-(\mu_1)^2}{E_1} + \frac{1-(\mu_2)^2}{E_2}\right)^2 * \left(\frac{2R_2 + R_1}{R_2 R_1}\right) * (F_T)^2}\right] + \left[\frac{64}{3}\frac{F_T L^3}{E\pi {d_r}^4}\right] - \left[0.8255 * \sqrt[3]{\left(\frac{1-(\mu_3)^2}{E_3} + \frac{1-(\mu_4)^2}{E_4}\right)^2 * \frac{(F_T)^2}{r_t}}\right] \quad (16)$$

It can be seen from "Equation 16" that the pre-travel is inversely proportional to the elastic modulus E of the material of the probe and the tested part, directly proportional to the trigger force F_T and the length L of the probe rod, and less affected by the Poisson's ratio μ of the material. It is also related to the contact radius r_1, r_2, and r_t.

In our design we found displacements as;

Rigid Displacement, L_c	$0{,}2472\ \mu m$
Deflection Displacement, $\boldsymbol{L_p}$	$2{,}6136\ \mu m$
Elastic Compression Displacement, $\boldsymbol{L_k}$	$0{,}0919\ \mu m$

Table 5: Parameters from to find Pre-Travel Displacement

So, Pre-travel displacement is;

$$L_{pre} = L_c + L_p - L_k = 0{,}2472 + 2{,}6136 - 0{,}0919 = 2{,}7689\ \mu m \quad (17)$$

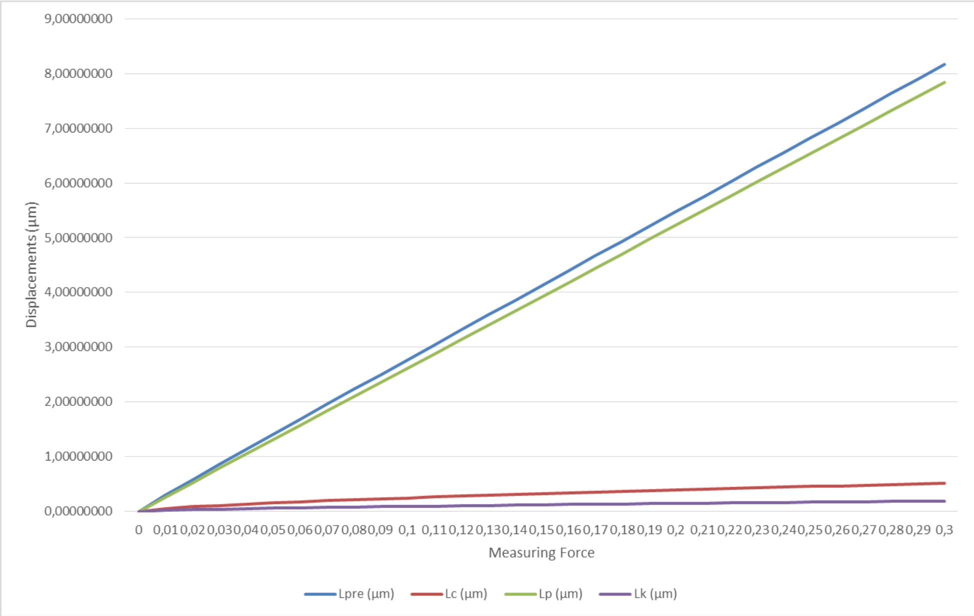


Figure 3. 7: Displacements change with the change of Measuring Force

In Figure 3.7; how pre-travel changes with the contact force are shown. Contact forces can vary with each CNC machine and how the operator uses it.

2. CALCULATION OF THE ELECTRICAL CIRCUIT

At calculations, we need to find the internal resistance of the ball and transmission pin. We can use the following formula:

$$R = \frac{\rho_{con} * L_{con}}{A_{con}} \tag{18}$$

where;

R: Internal Resistance

L_{con}: Length of the Conductor

A_{con}: Cross-sectional Area of the Conductor

ρ_{con}: Resistivity of the Conductor

We take conductor resistivities from Table 2;

Materials	Resistivity (ρ) (Ω•mm)
Tungsten	$5{,}60 * 10^{-5}$
Aluminum	$2{,}82 * 10^{-5}$

Table 6: Resistivity of Selected Materials

So we can find internal resistance of ball which made of tungsten;

$$R_{ball} = \frac{\rho_{tungsten} * L}{A} = \frac{\rho_{tungsten} * 2r}{4\pi\, r^2} = \frac{\rho_{tungsten}}{2\pi r} = \frac{5{,}60 * 10^{-5}}{2\pi * 5} = 1{,}78 * 10^{-6}\Omega \quad (19)$$

and we can find internal resistance of transmission pin which made of aluminum;

$$R_{pin} = \frac{\rho_{aluminum} * L}{A} = \frac{\rho_{aluminum} * L}{4\pi\, r^2} = \frac{(2{,}82 * 10^{-5}) * 9}{4\pi\, (2{,}5)^2} = 3{,}23 * 10^{-6}\Omega \quad (20)$$

By using the serial circuit principle; we can reach equivalent resistance of balls and pin;

$$R = 2R_{ball} + R_{pin} = 6{,}79 * 10^{-6}\Omega \quad (21)$$

The value of the resistance is found $6{,}79 * 10^{-6}\Omega$ which is a very small value. That is to say, it will be neglected in the calculations.

RESULT AND REVIEW

Through this thesis authors designed a kinematic resistive probe. The kinematic resistive probes that are designed use a simple electric circuit with an accurate design that can be produced further in the production stage.

One of the main problems in the writing of this thesis is the design of the kinematic resistive probe. The authors reached the final design on the fourth try. Lengths of the design are chosen as small as they can be so it won't be an obstacle when it is adopted to the CNC machine. Tungsten Carbide is chosen for balls and Aluminum is chosen for transmission pins to raise conductivity. A small led is used to alarm the touch of the probe, so the user of the CNC can be notified.

The probe's length is 87,5 cm. Probe length is the main perimeter for the sensitivity of the touch probe. It should not be too small to adapt the CNC or it can't be too long to avoid more error. A special probe tip will be used in the real kinematic resistive probe.

To find the error or to say the pre-travel distance of the probe, authors need to choose to measure force as 0.1 N. Former studies suggest that measuring force can change with the operator of CNC. The test part is assumed as aluminum as it is the most used material in the industry. Contact coefficient is also assumed in this study with the help of previous studies suggested. With the calculation of resistance of the circuit is found very small value, it is neglected in this study.

The pre-travel distance of the probe or the error margin in this study is $2{,}7689\ \mu m$ with the values shown in the calculation part. This error is very small with these parameters. As the length of the probe tip grows or contact force increases, the error will be much higher as shown in Figure 3.7.

CONCLUSION

With the importance of touch probes to the engineering world, in this thesis authors designed a kinematic resistive touch probe. Touch probe technology is already used widely in the world and it reached an advanced stage. The designed kinematic resistive probe in this thesis is outrun itself with every step to be more adaptable to the production. To write this work, previous studies followed and searched through the works of many precious writers' documents.

Through the design process, four main designs have been tried to reach the most convenient one. The size of the design is the one that matters most as well as the length of the stylus and diameter of the tip. These values will highly affect the pre-travel distance that can be interpreted as the error of resistive kinematic probe. The final design is reached in the fourth design. With each step, enhancements have been made to the design. A design is as good as its producibility. The authors paid attention to the producibility of the touch probes design while keeping in mind how the real-life problems affect the design in the process of production.

In this thesis, the electric circuit is built serial. Carbide balls, aluminum transmission pins, battery, and light source are all connected in serial connection. With the design of this probe; when the stylus tip is pushed by the material, one of the transmission pins or pins is going to lift and thus electric circuit will be open that will alarm the user.

As this design cannot be produced, real-life experiments couldn't occur to observe the results and reliability. Instead of test results, this thesis is mostly consisting of theoretical results. And these theoretical results have shown that this designed kinematic resistive probes pre-travel value is very satisfying when it is compared to real produced touch probes.

Design is open to further advancements with the improving technology and with the possible enhancements the error margin surely will drop drastically.

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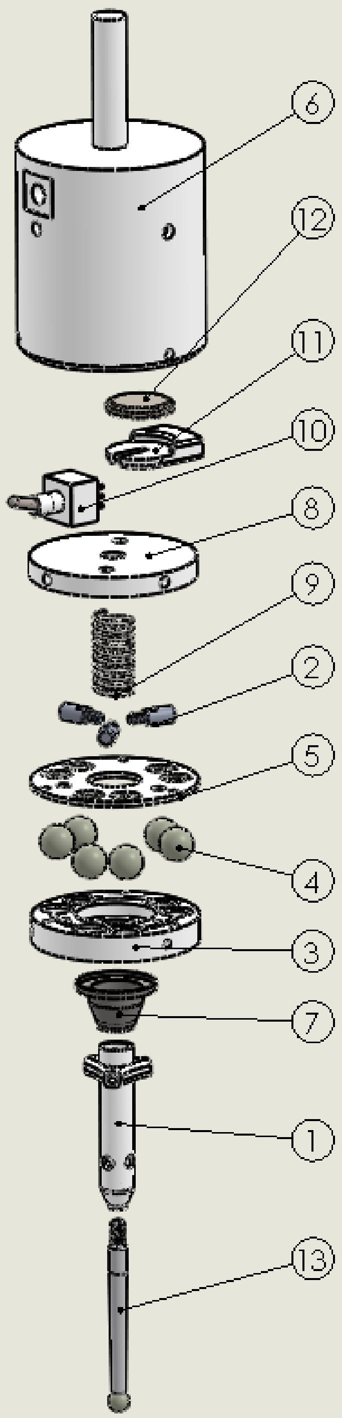
APPENDICES

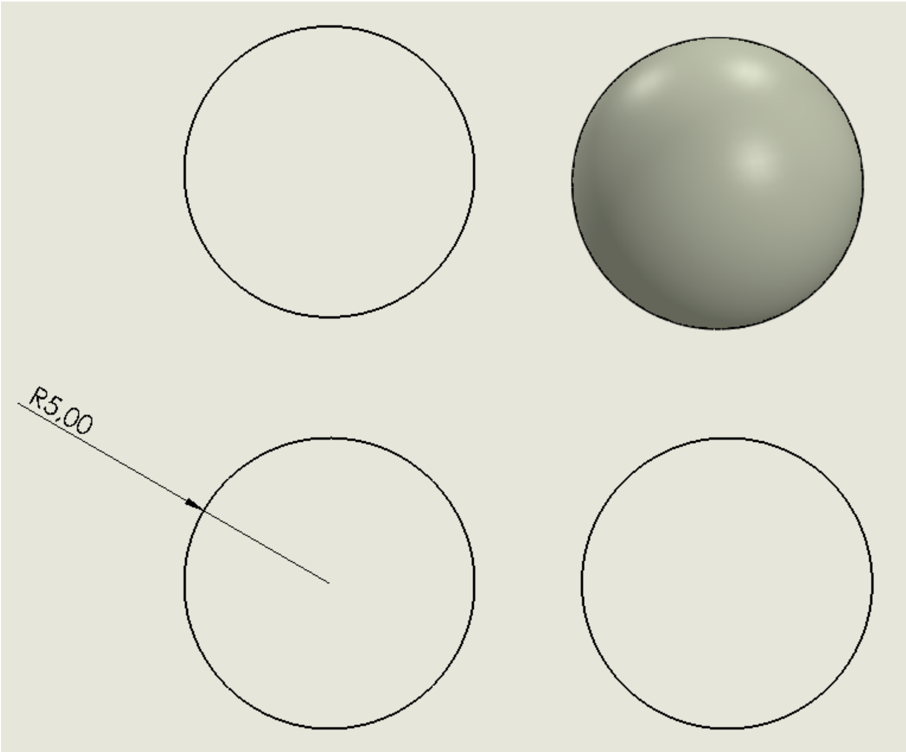
APPENDIX A: Technical Drawings of Final Design

(All dimensions are millimeters.)

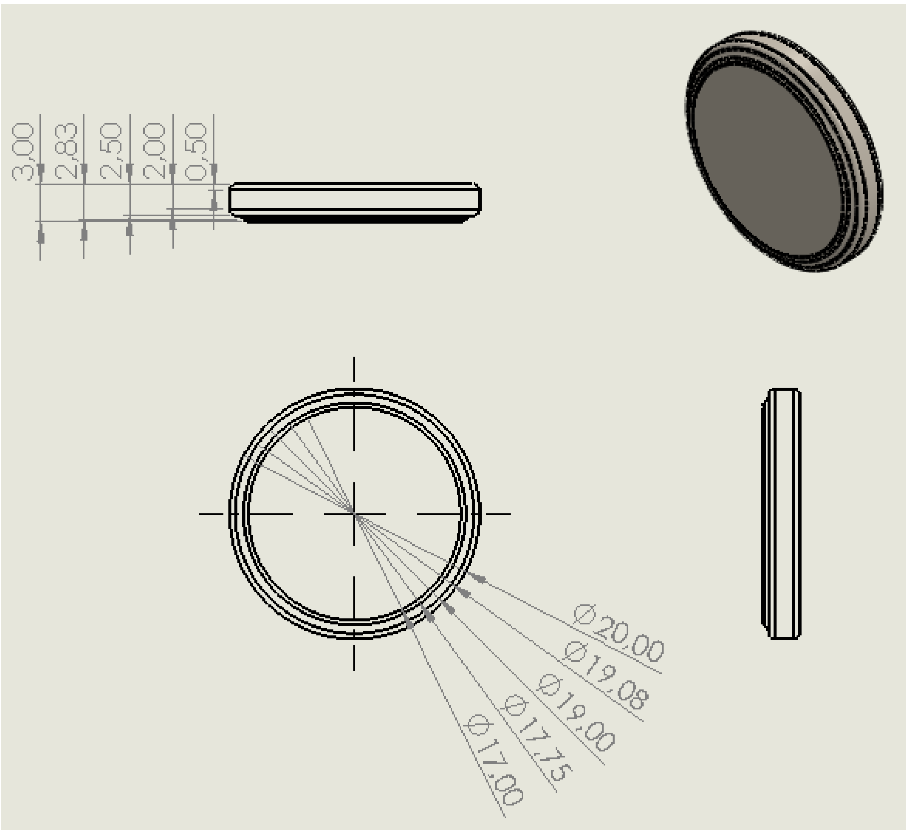


NO.	PART NAME	MATERIAL	#
1	stylus_holder	ABS	1
2	transmission_pin	Alu 6061	3
3	lower_cage	ABS	1
4	ball	Tungsten	6
5	upper_cage	ABS	1
6	housing	ABS	1
7	silicone_funnel	Silicone	1
8	disc	ABS	1
9	spring	CR-1600	1
10	switch	Ni & ABS & Cu	1
11	battery_housing	ABS	1
12	battery	Ni	1
13	stylus	Tungsten & Ceramic	1

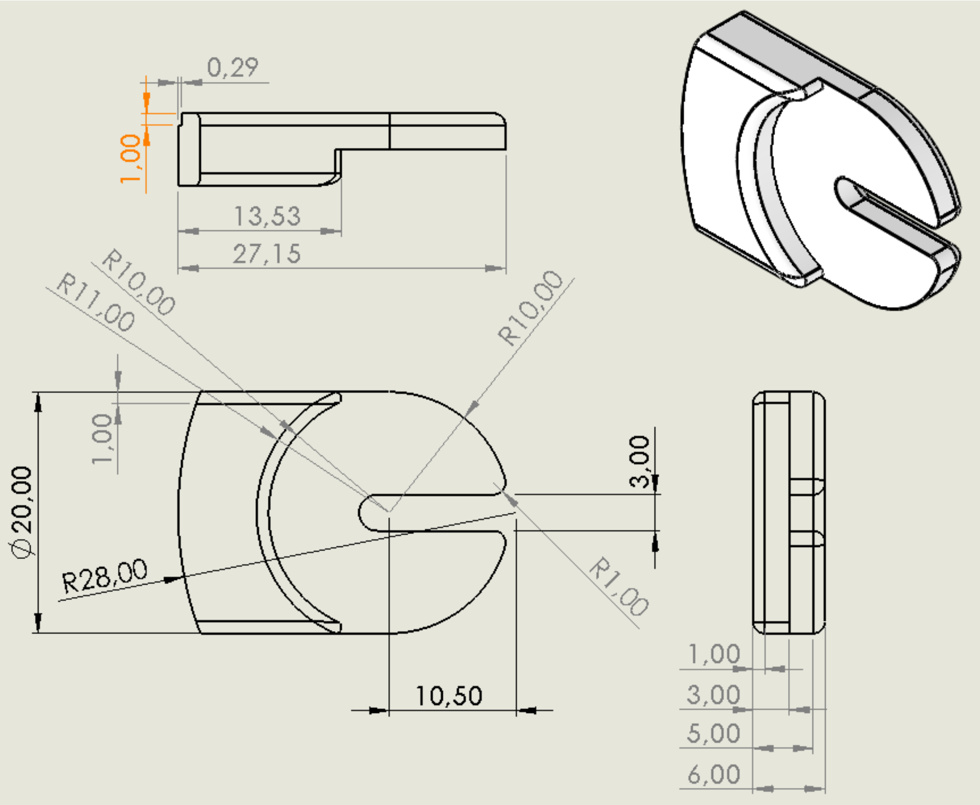
Part List of the Final Design



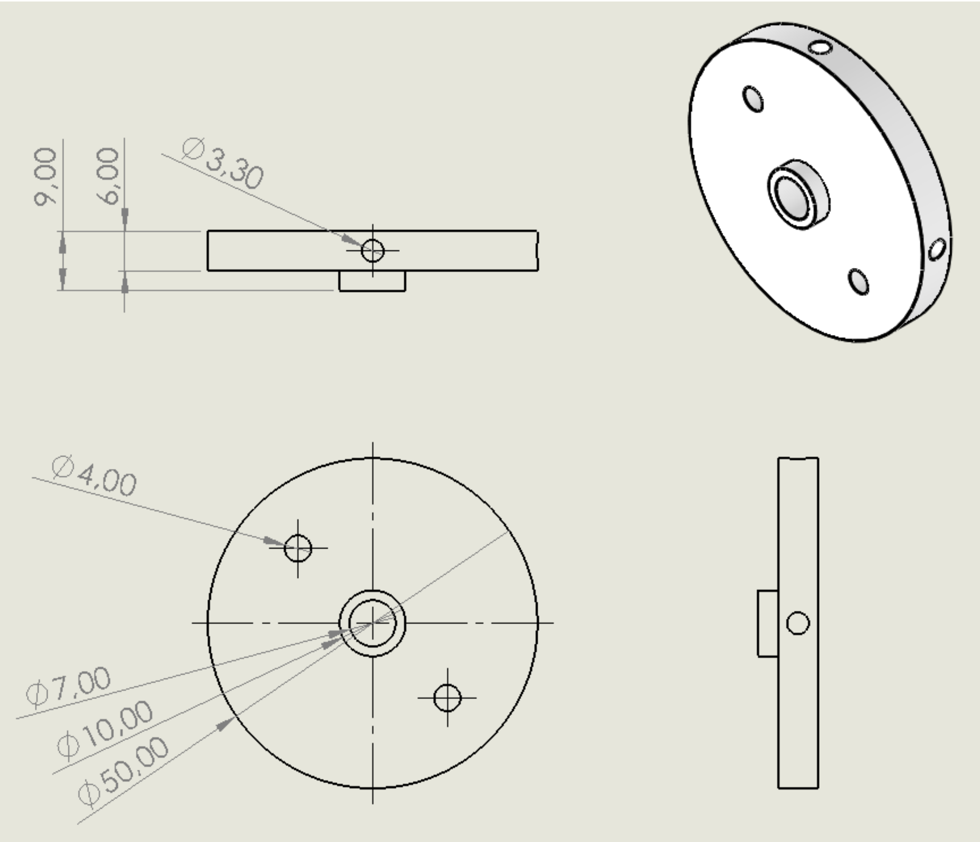
Ball



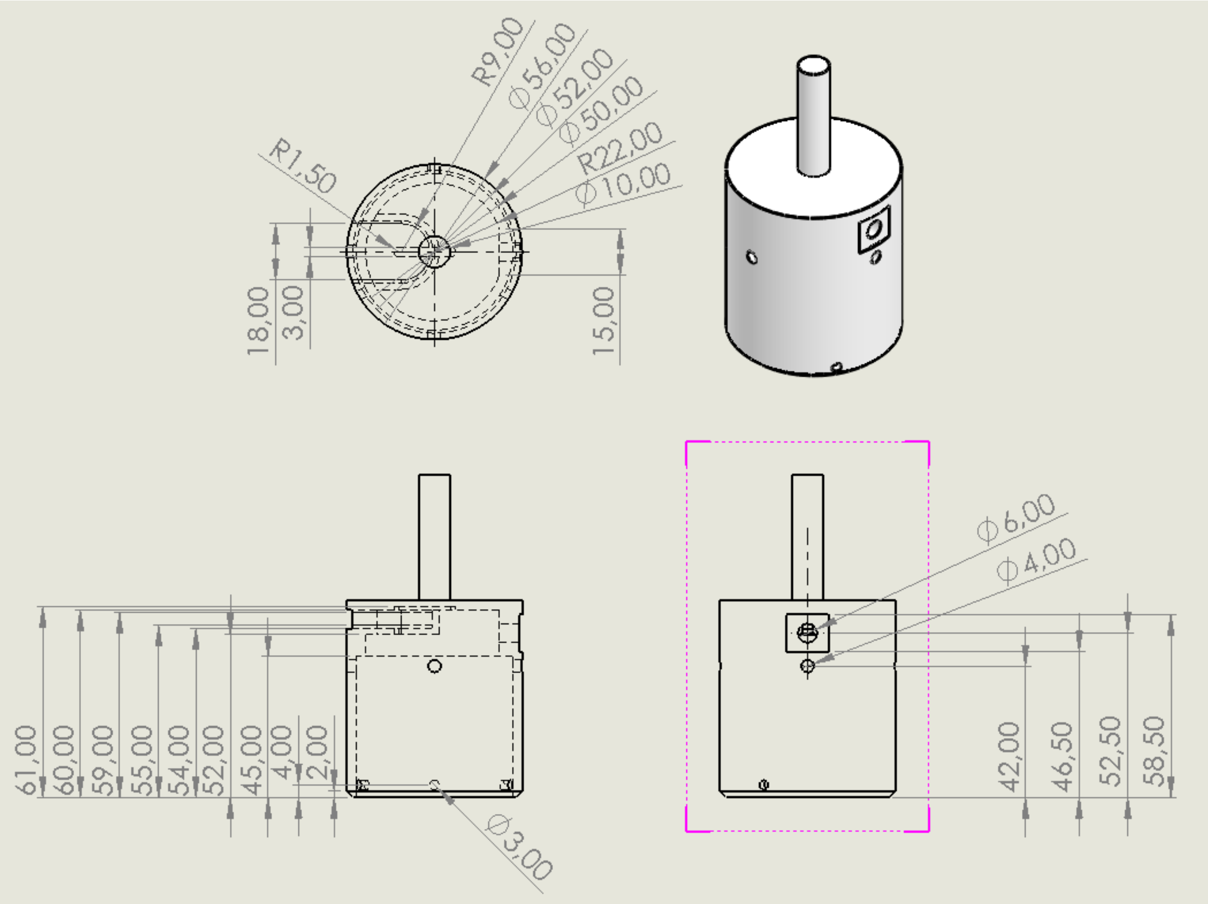
Battery



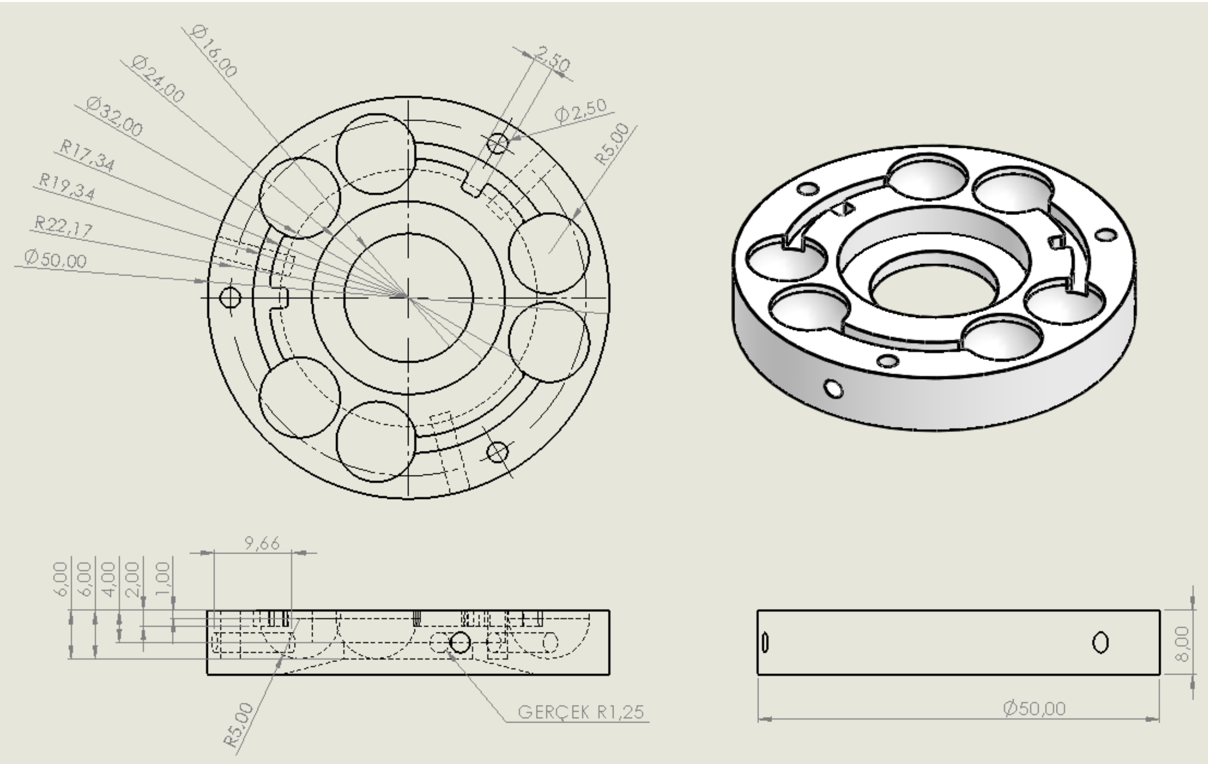
Battery Housing



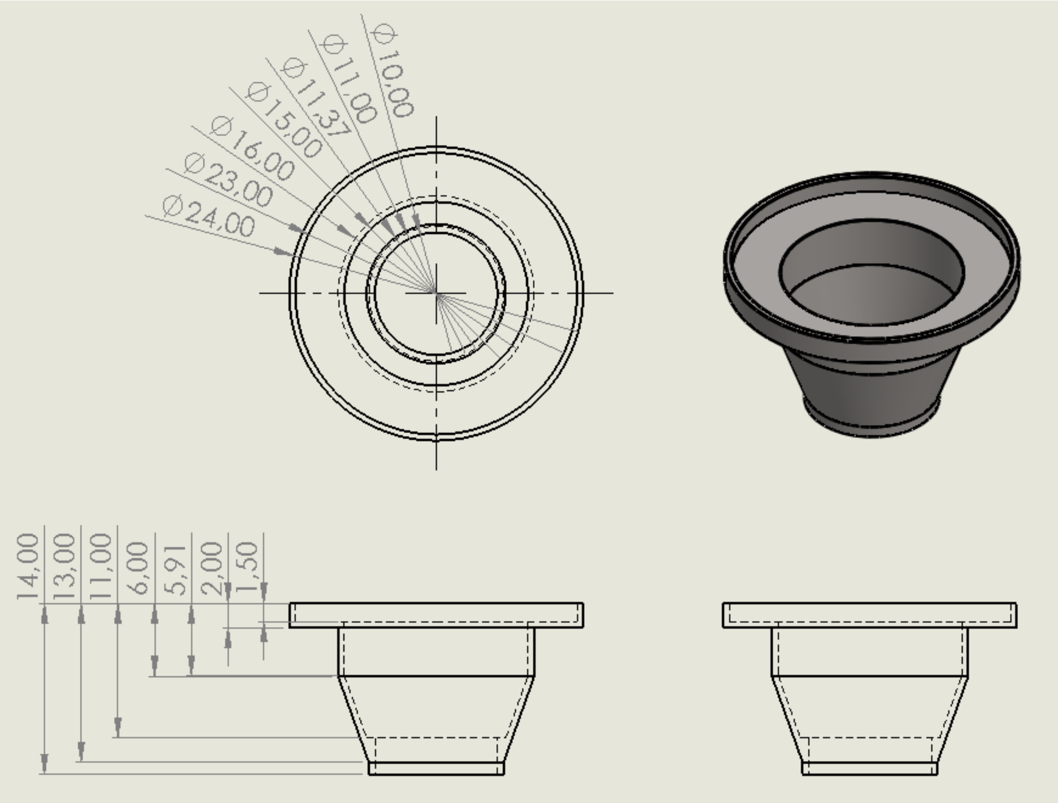
Disc (Spring Holder)



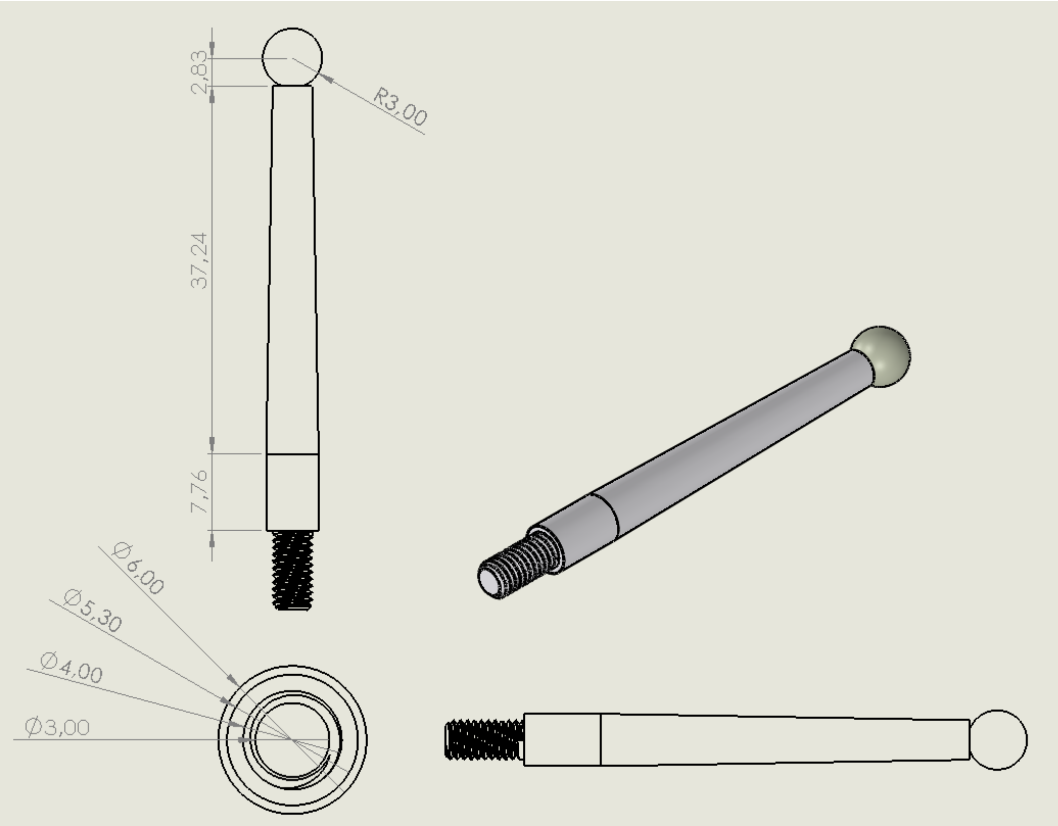
Housing



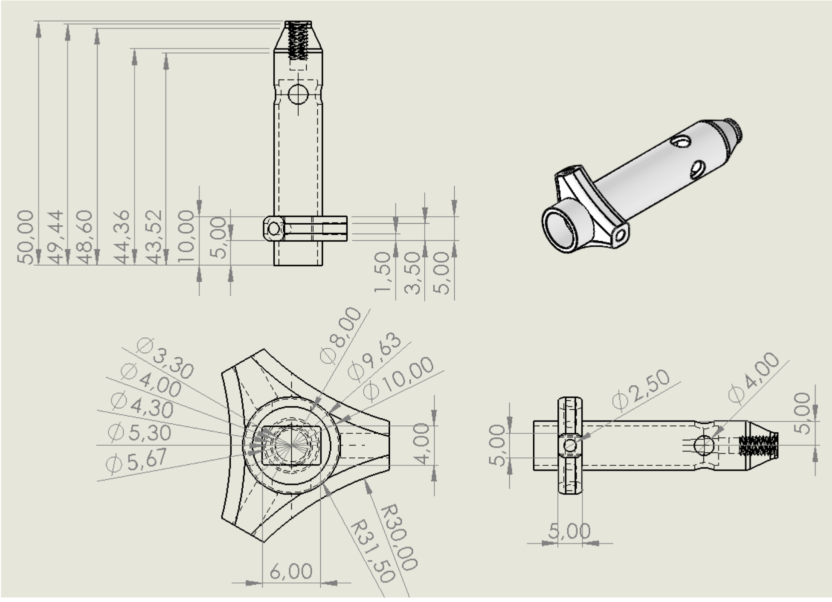
Lower Cage



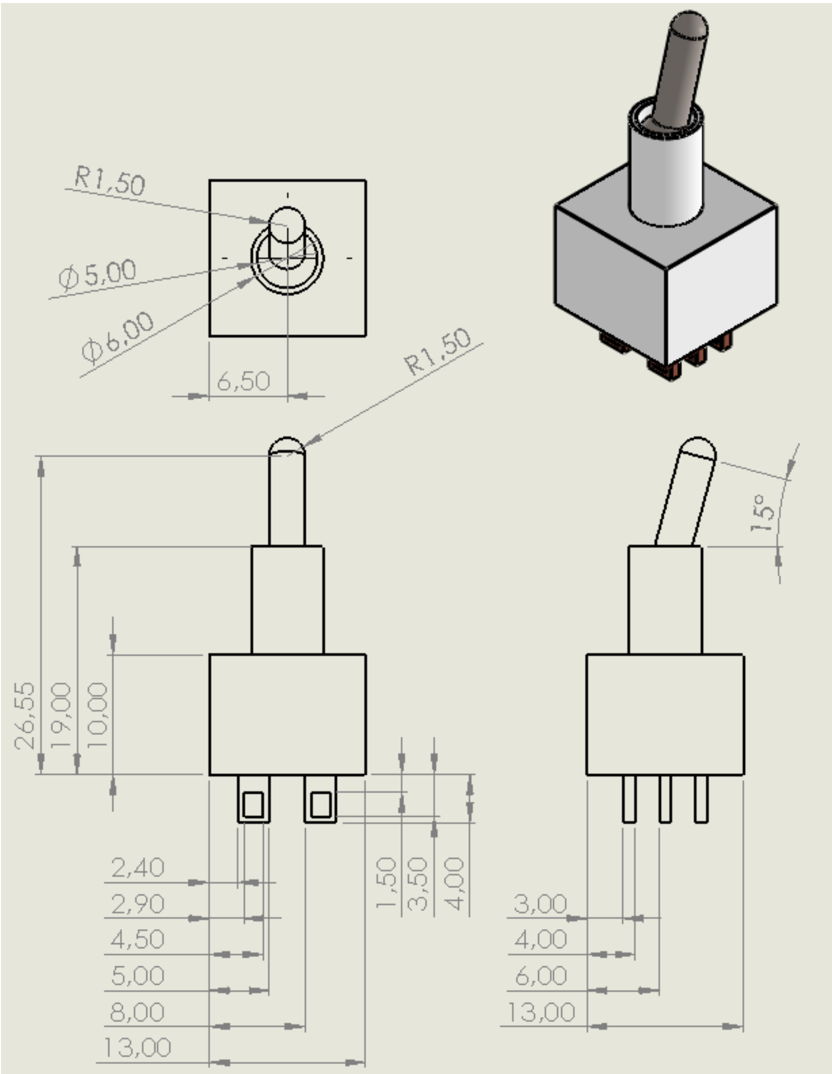
Silicone Funnel



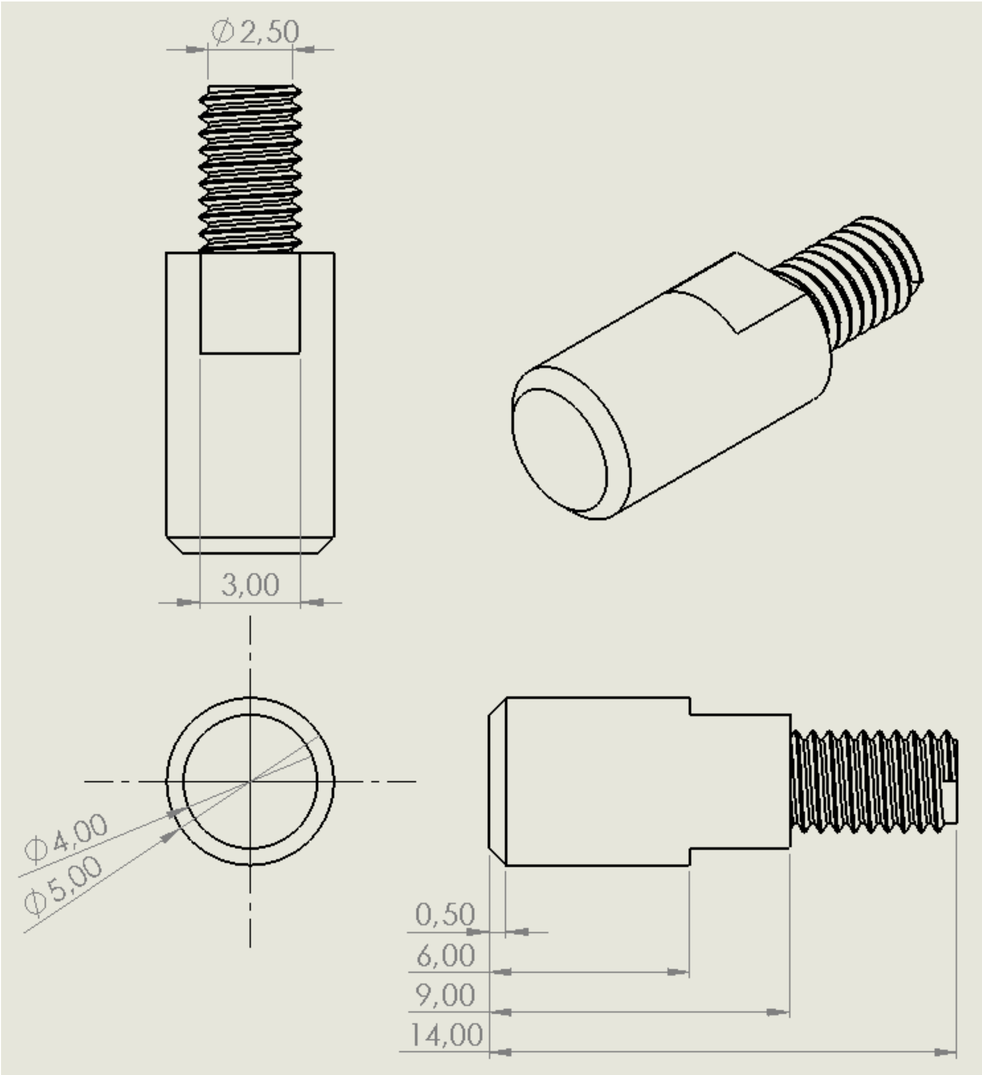
Stylus



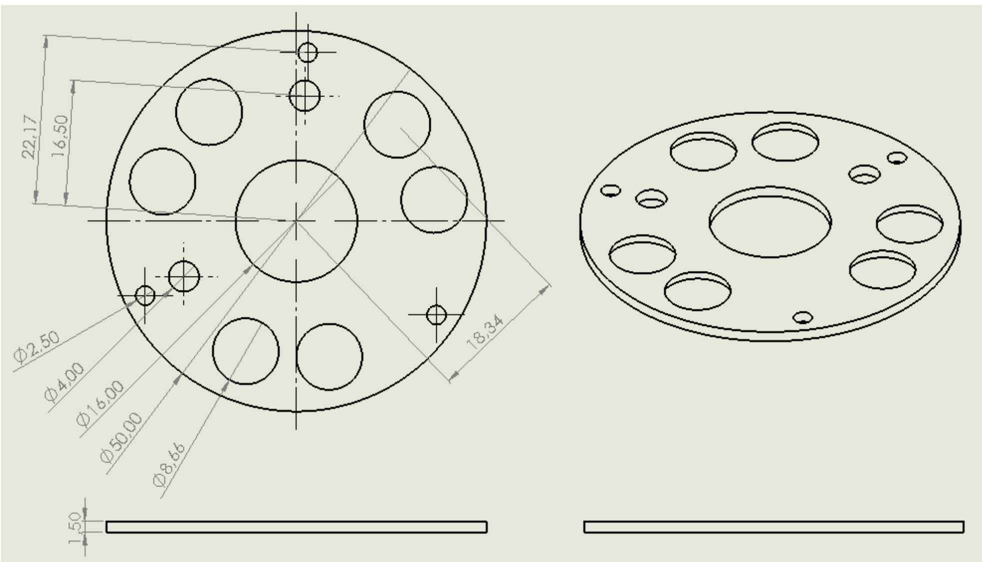
Stylus Holder



Switch



Transmission Pin



Upper Cage