# Design of a Hip Optical Encoder Assembly

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# ABSTRACT

*This paper details the design of a housing assembly for an optical encoder that will be installed on the Cornell Ranger. The encoder is used to detect the displacement angle of the inner hip relative to the outer hip. The housing assembly had to hold all parts of the encoder and not interact with the current motors and electrical systems already installed on the robot. Conceptual designs were suggested to meet the needs of the problem and the detailed design is a more thorough and finalized version of the selected conceptual idea. Fabrication was carried out and the hip encoder was installed on the robot. The system was then tested for hysteresis. The final design was evaluated against the specifications and suggestions for improvements are given.*

# 1. INTRODUCTION

The Cornell Ranger, a 4-legged biped robot was built in fall 2006. The objective of the robot was to break the record for the longest distance walked. The target distance set then was 10km. However, after two semesters, the Ranger had only managed to walk 1km and was having difficulty walk over slight bumps in the Barton Hall track. Thus, greater understanding of the robot had to be achieved. This would allow us to have better control of the overall walking dynamics.

To understand why the Ranger was not able to continue walking when the ground was uneven, various sensors had to be installed onto the robot. These sensors included the hip optical encoder, which would tell us the location of one hip relative to the other. Such information was important for us to know the state the robot was in, just before it fell over, which in turn would allow us to deduce why it was unable to maintain balance.

It had been decided that an Angular Magnetic Encoder manufactured by Rotary and Linear Motion Sensors (RLS) was the most inexpensive and effective method of determining the angular displacement of one hip relative to the other. This optical encoder consists of a rotating magnet and an Integrated Circuit on a Printed Circuit Board. Figure 1.1 below shows the IC on the PCB and the magnet. When the magnet is rotated, the IC outputs a signal based on the strength of the magnet field and its polarities. Thus it was necessary to design a housing that would hold the magnet and PCB in different hip boxes and yet allow them to function accurately.

This paper documents the design of this hip encoder assembly to hold the sensor in its proper position. The conceptual designs, needs and specifications of the design are mentioned in Section 2. The final detailed design is described in Section 3. Section 4 discusses the modeling, material acquisition, fabrication and drawbacks of the design. Section 5 summarizes the re-design of the housing assembly and Section 6 mentions the assembly of the system. Section 7 explains the tests performed and Section 8 evaluates the design. Further suggestions and discussions are given in Section 9.

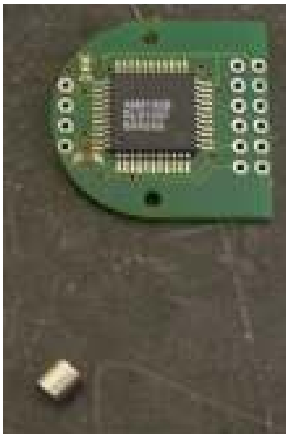

Figure 1.1: Photograph of Hip Magnetic Encoder PCB and Magnet

# 2. DESIGN SPECIFICATIONS

## 2.1 Problem Statement

To design a housing assembly that would hold the magnetic encoder and output the displacement angle of one hip relative to the other. This would allow for greater understanding of the various parts of the robot (one hip relative to the other) as it moves.

## 2.2 Objectives and Needs

The housing assembly has to meet the following needs:

- Must hold the magnet in one hip box and the PCB in the other to measure the relative displacement angle between the two hips.

- Must hold the magnet 2mm in front of the IC in order for the latter to sense the magnetic field.[1]

- Must be small enough to fit in the limited space of the hip boxes without interfering with the motors or current electronics.

- Must be made of non ferro-magnetic materials so it will not interfere with the magnetic field of the encoder's magnet.

- Must have limited friction as this would introduce hysteresis.

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[1] (RLS)

- Must be light, as any significant weight would affect the mass distribution and balance of the robot.
- Must be reliable and robust.
- Must be inexpensive and relatively quick to fabricate.
- Must be easily removed and reassembled.

## 2.3 Evaluation Criteria

A set of specifications can be worked out based on the qualitative needs stated above. This set of specifications given in Table 1 below, can then be used to evaluate the various designs and to select the design that best meets the needs of the problem.

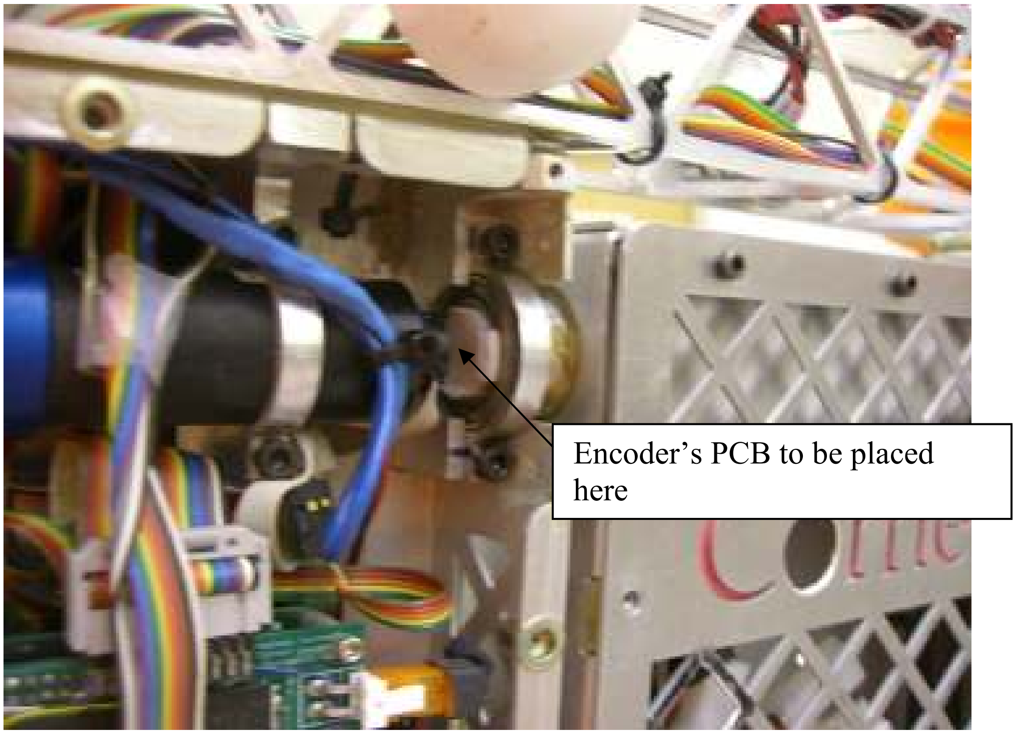
| Specification | Target Value |
|---|---|
| Mass | <50g |
| Dimensions | <16mm x 40mm x 40mm |
| Cost | < $100 |
| Fabrication Time | < 3 weeks |
| Distance between magnet and IC | 2mm ±0.5mm |
| Material | Not iron, nickel or magnetite |

Table 1: Specifications

## 2.4 Concept Generation

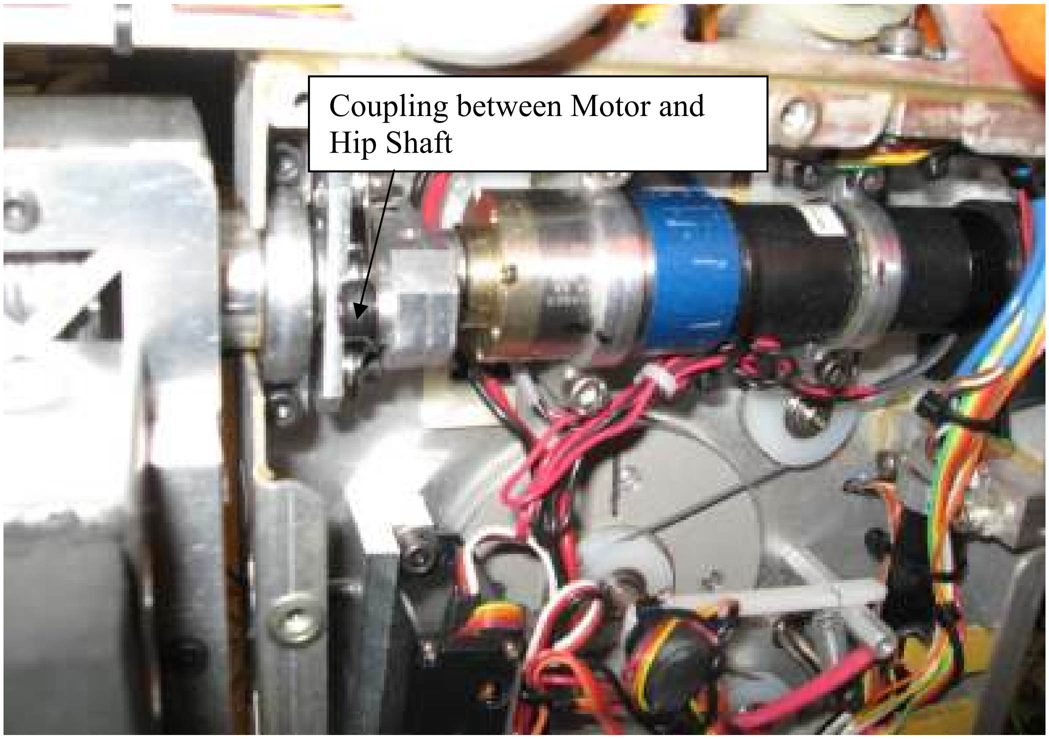
To accurately detect the displacement angle between the two hips, the magnet would have to be placed directly at the axis of rotation, i.e. in the hip shaft. Since there is only one hip shaft (that which controls the center box) in the Ranger, the magnet had to be placed in the center of this shaft. The PCB would then have to be affixed to either the left hip box which held the main microcontroller or to the right hip box which contained the steering system. See Figure 2.4.1 below for a photograph of the left hip box and Figure 2.4.2 for a photograph of the right hip box.

The coupling between the motor in the right hip box and the hip shaft eliminated the possibility of placing the PCB in the right hip box as there was no space next to the hip shaft in the right hip box. Thus the PCB had to be fixed to the left hip box in the space between the hip shaft and motor.



Encoder's PCB to be placed here

Figure 2.4.1: Photograph of Left Hip Box with Main Microcontroller Showing Location where Encoder will have to be Placed



Coupling between Motor and Hip Shaft

Figure 2.4.2: Photograph of Right Hip Box with Steering System

The two main functions of the housing assembly were:

1. To prevent the magnet from falling out of the hip shaft.
2. To ensure the distance between the magnet and the IC remained at ±2mm.

Two main designs were suggested and looked into. Both these designs allowed for the encoder system to be removed easily and complied with the needs of the problem statement. The suggested designs can be classified into two main categories:

- Compression Spring
- Leaf Spring

## 2.4.1 Compression Spring

In this design, a compression spring is used to hold the entire encoder assembly up against the hip shaft. By compressing the spring prior to being placed in the Ranger, the tension force generated will push the encoder's PCB against the hip shaft. However, in order for the compression spring to indirectly hold the magnet within the hip shaft, a front connecting device that attaches itself to the PCB on one end and the magnet on the other, will have to be made. (See below)

To attach the spring to the PCB, a back plate will have to be made. The spring will be coiled around a protruding knob in the center of the plate and the other end will be attached to the motor via a hook. Since there are pre-existing holes in the PCB, pins can be fitted through these holes to connect the back plate. Figure 2.4.3 shows a CAD diagram of this back plate, spring and motor.

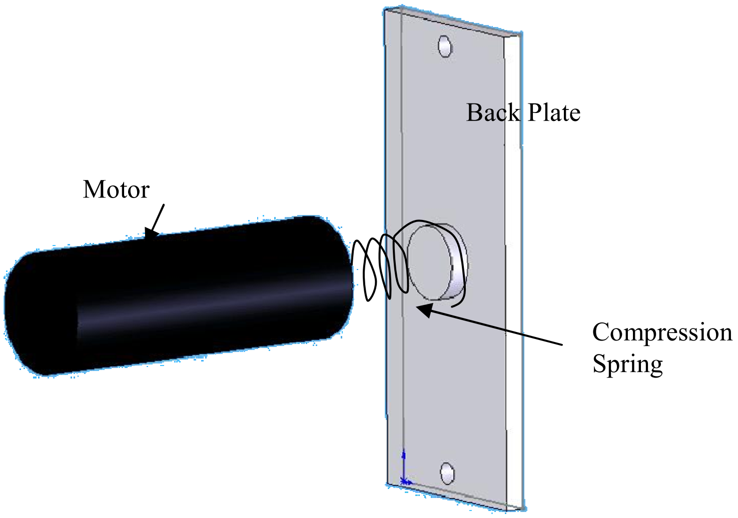


Figure 2.4.3: CAD Diagram of Back Plate, Spring and Motor

However, there are drawbacks to using a compression spring. Firstly, the distance between the hip shaft and the motor in the left hip box is only 10mm wide. Thus after inserting the encoder's PCB and back plate, there will be approximately only 2mm of space for the compression spring. This means that an uncommonly small spring will have to be used.

Furthermore, the compression spring poses a danger. Since it has been pre-compressed, the spring will want to extend and move out of its allocated space. Hence, there is a risk that the spring will "pop" out and injure somebody.

Lastly, removing the encoder will require a lot of force. Once the spring has been set in its position, it will have to be compressed even further to remove it. From the spring equation:

$$F = kx,$$

where k is the spring constant and x is the displacement, we see that to compress the spring further will require a greater force. Since there is minimal amount of room between the motor and hip shaft, applying a large force will be difficult and inconvenient.

### 2.4.3 Leaf Spring

A leaf spring performs the same function as a compression spring. When bent or compressed, it will tend to extend out to its original shape. Thus, depending on the shape and type of leaf spring used, if it was bent or compressed prior to being placed in the Ranger, it will exert a tensile force on the motor and PCB, pushing it away from the motor and towards the hip shaft.

As with the compression spring, this leaf spring will be attached to the encoder's PCB via pins and the pair of pre-existing holes on the PCB. The leaf spring will have to be made of a springy brass, copper or aluminum material in order for it not to affect the magnetic field from the encoder's magnet.

However, most leaf springs in the market are too large to fit in the 10mm space between the motor and hip shaft. Thus, a custom leaf spring will have to be designed and made. The pre-compressed height of this leaf spring will have to be larger than the allowed gap between the PCB and motor. Hence when compressed, one end will contact the motor while the other will be attached to the PCB. See Figure 2.4.4 below for a CAD diagram of this leaf spring.

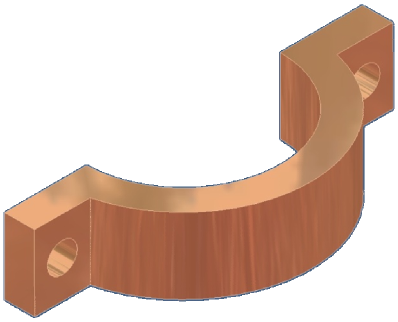


Figure 2.4.4: CAD Diagram of Leaf Spring

# 3. DETAILED DESIGN

After the two initial concepts were laid out, detailed CAD drawings were created for all parts of the housing assembly. However after the first round of parts were machined, it was discovered that there was one degree of motion which had not been constrained. Thus, modifications to the design had to be made and the parts re-machined (See Section 5 for more details).

## 3.1 Functionality Overview

Due to the various drawbacks posed by the compression spring, the leaf spring concept was chosen. The leaf spring was safe to use, easy to manufacture and assemble in the robot.

As first mentioned in Section 2.2, the magnet had to rotate at a height of 2mm above the IC. Since the poles of the magnet are located on its curved surface, as the magnet rotates, it produces a varying magnetic field. See Figure 3.1.1 for a schematic of the magnet and the IC. The IC senses the changes in this magnetic field and outputs a corresponding signal which is fed back to the microcontroller. From the values of this signal and an appropriate calibration, we are able to calculate the displacement angle between the inner and outer hips.

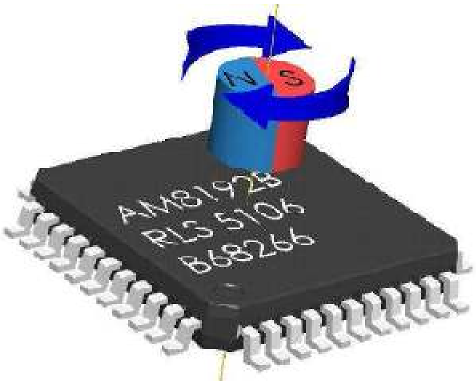


Figure 3.1.1: Schematic of Magnet and IC

A ribbon cable will also have to be connected to the PCB and satellite board of the Ranger in order for the output to be sent to the computer.

For the encoder to work, there has to be relative motion between the magnet and PCB. Hence, the magnet and PCB will have to be positioned on different hips of the Ranger. Furthermore, for the results to be as accurate as possible, the magnet will have to be inserted in the center of the rotating axis – the center hip shaft. Also, the coupling between the right motor and hip shaft limits the location of the PCB to the left hip box.

## 3.2 Design Overview

The housing assembly consists of various parts. Firstly, to ensure that the magnet is always centered in the hip shaft and on the IC, an insert will have to be made. This insert will rotate with the hip shaft and have a hole for the magnet.

The second part in the assembly consists of the front connecting device. This device has a hole for the insert, thereby ensuring that the magnet is always centered above the IC. It also ensures that the distance between magnet and IC is 2mm.

The third piece is the leaf spring which pushes up against the PCB, preventing it from falling backwards toward the motor. This ensures that the entire assembly is pushed up against the hip shaft at all times, allowing the distance between the magnet and PCB to be kept constant. A pair of pins holds the leaf spring, PCB and front connecting device together.

### Hip Shaft Insert

This insert will be made of aluminum. One end of it will be threaded and screwed into the hip shaft, ensuring that the insert turns with the shaft. However, such a design necessitates the drilling and tapping of a hole in the hip shaft. Since the shaft cannot be removed from the Ranger's center hip box, the entire box and legs will have to be clamped in the mill while the hole is drilled. (See Section 4.4 for details on machining the hip shaft) The other end of the insert will have a hole for the magnet. This will have to be a tight fit since the magnet is merely being pressed into the hole. Silicone adhesive will hold the magnet in the right position in the insert and allow it to rotate together with the insert.

Since the top of the insert will be flushed with the hip shaft, the only way to remove it will be to create a slot on its exposed surface – the end with the magnet. A customized screw driver that fits into this slot without scraping the magnet will then have to be made. See Figure 3.2.1 for a CAD diagram of this insert and Figure 3.2.2 for a photograph of the insert. Figure 3.2.3 shows this customized screw driver.

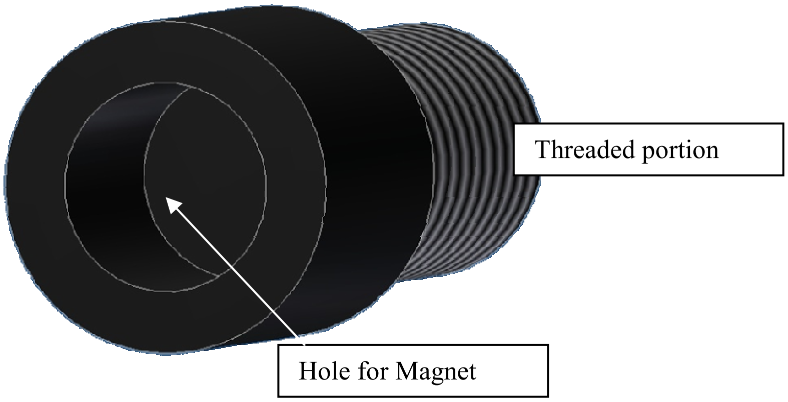


Figure 3.2.1: CAD Diagram of Insert

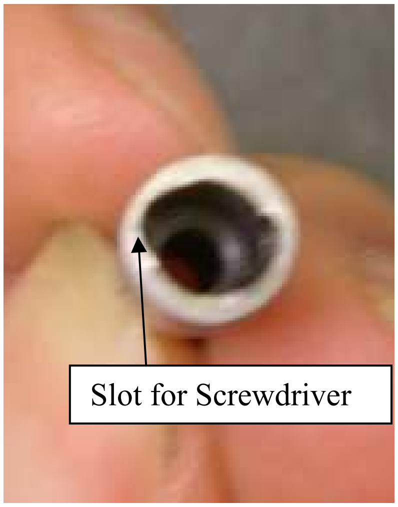


Figure 3.2.2: Photograph of Insert Showing Slot for Screwdriver

Figure 3.2.3: Photograph of Customized ScrewDriver

## Front Connecting Device

The front connecting device that holds the PCB to the magnet will also have to serve as a centering tool ensuring the latter is always located at the center of the IC. Furthermore, the thickness of this tool also determines the distance between the IC and magnet. Thus, the ability of the encoder to output an accurate signal will depend on the precision of this centering device.

Using pins and the pre-existing holes on the PCB, the front connecting device can be attached to the PCB. Furthermore, since the holes are already aligned with the center of the IC, the magnet will just have to be placed on the center of the vertical line joining these holes, at a height of 2mm above the IC. Thus, we only have to ensure that the thickness of this front connecting device is 2mm.

Approximately 1mm of the insert will fit into the sleeve of the front connecting device while this protruding sleeve will fit into a hole on the hip shaft. This allows us to ensure the magnet is always positioned directly above the center of the IC. However, since the front connecting device is held stationary against the PCB, it will not rotate with the insert nor with the hip shaft. Hence there will be considerable friction both on the inside and outside surfaces of this sleeve. This friction might produce a hysteresis and distort the output signal. Thus, the front connecting device will be made of delrin, a plastic with a low coefficient of friction.

Figure 3.2.4 below shows a picture of this centering tool.

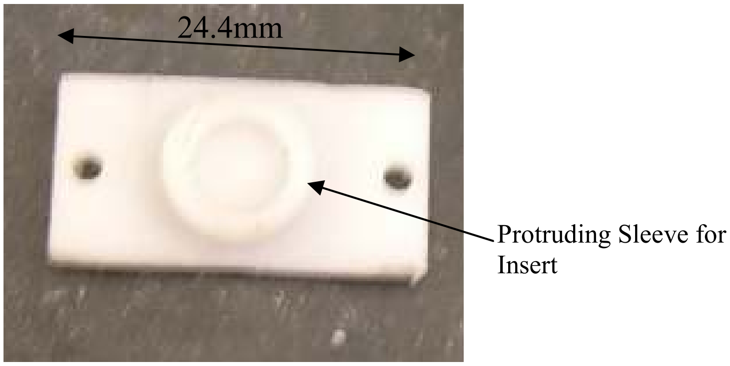


Figure 3.2.4: Photograph of Front Connecting Device

## Leaf Spring

Instead of creating an arced leaf spring shown in Figure 2.4.4, a simplified leaf spring will be designed instead. This simplified leaf spring will be a right angled piece of aluminum sheet metal. One surface of the sheet metal will be screwed to the back of the left hip box while the other surface will rest against the back of the PCB. Since the sheet metal was originally unbent, it will tend to return to its former shape and increase the angle between the two surfaces (return to a flat sheet). Thus, it provides a pushing force against the PCB, preventing it from moving backwards where the front connecting device will no longer be contacting the insert. Figure 3.2.5 below shows a CAD diagram of the leaf spring pushing up against the PCB.

To provide a certain amount of leeway least the PCB should rotate, a slot was cut into the leaf spring. This slot allows the pin, which holds the front connecting device to the PCB, to slide when the PCB rotates. Furthermore, this slot allows for easy installation of the entire assembly.

The pin mentioned above will be made of brass instead of aluminum, since aluminum tends to bind with each other over time. It will have a conical shape on one end, with the tapered end pointing towards the motor, away from the PCB. The diameter of the slot will however be wide enough to fit the mid-point of this cone. This allows the PCB and front connecting device to move nearer to the hip shaft, but not towards the motor where the distance between the IC and magnet will be larger than the specified amount. The IC is able to sense the magnetic field even if the distance between itself and the magnet is less than 1.5mm but not larger than 2.5mm. Figure 3.2.6 shows a CAD diagram of how this pin fits into the slot in the leaf spring.

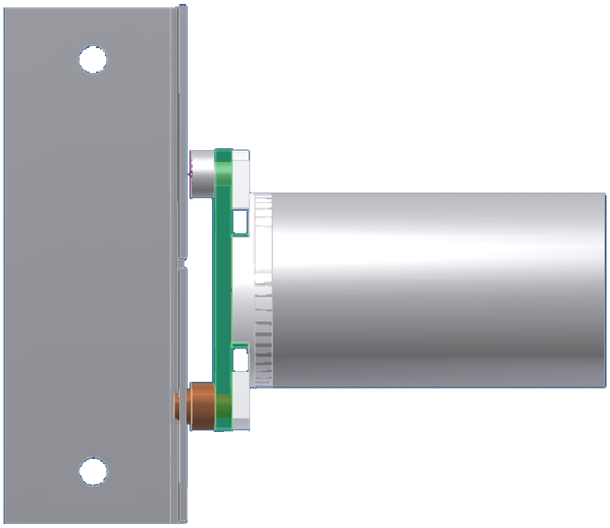


Figure 3.2.5: CAD Diagram of Leaf Spring Pushing against PCB

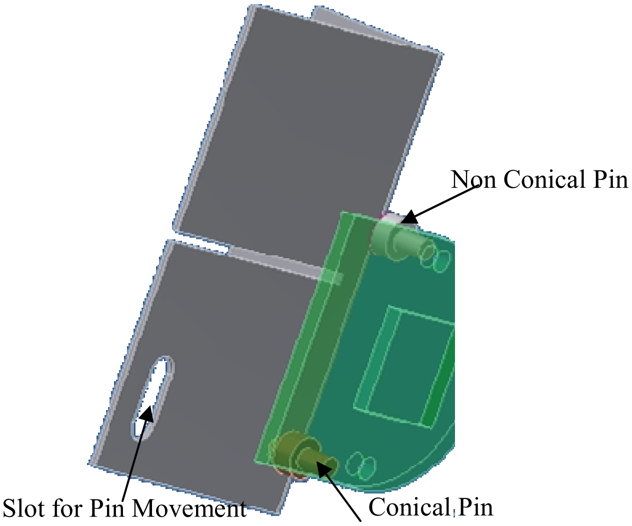


Figure 3.2.6: CAD Diagram of Leaf Spring Showing Slot for Movement and PCB

The second pin on the PCB will not need to fit through the leaf spring. It merely contacts it and hence can be made of aluminum. The lack of a hole allows for the PCB to rotate a little, which causes the pin to shift position. Also, this pin need not be conical and only has to be offset from the back of the PCB by the height of the components on the back (prevents the leaf spring from contacting these components).

Figure 3.2.7 shows a side view of the entire assembly with the leaf spring and motor.

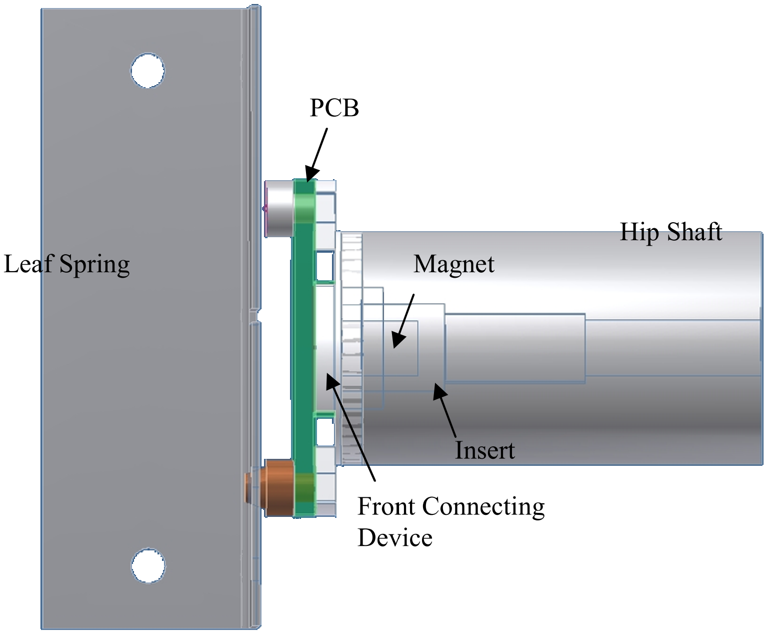


Figure 3.2.7: Side View of Encoder Assembly with Motor

## 3.3 Analysis

Tests were carried out on the magnet and IC to locate the zero position of the former. From previous testing carried out on the encoder, it was discovered that the range of values output to the computer was 3000 to 9000 for a 360° rotation of the magnet. Thus it was suggested that the appropriate output when there was zero displacement between the two hips would be between 4000-5000. This would result in a smooth increase and decrease of values as the Ranger swung its inner legs forward and backward, preventing a jump in the output value from 9000 down to 3000 as the upper limit of the output is crossed.

A ribbon cable was first soldered to the encoder's PCB and connected to a microcontroller. The PCB was held in the same orientation as when fixed in the ranger, with its two parallel ends at the top and bottom. Secondly, a mark was drawn on the magnet. See Figure 3.3.1 below for a schematic. Next, the magnet was held approximately 2mm in front of the IC and rotated clockwise until a value of approximately 4500 was output on the computer. The relative position of the mark to the PCB was noted. The magnet will then be installed on the Ranger with the mark at the same relative position while the two hips were aligned together.

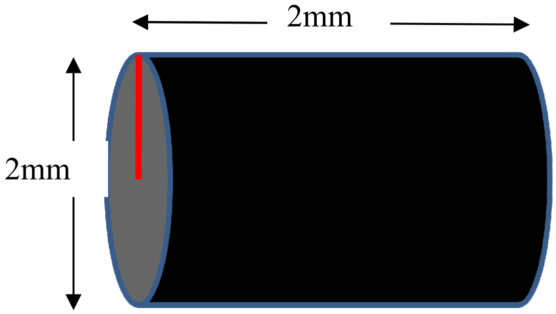


Figure 3.3.1: Mark on Magnet

# 4. FABRICATION

## 4.1 Drawings

Once the leaf spring design, including the dimensions of each part, was finalized, CAD drawings were created. Critical dimensions were labeled along with notes regarding thread sizes and hole diameters. Tolerances were not included in the drawings as caution taken during machining was deemed sufficient for a successful design. Since the hip encoder was needed urgently to increase our understanding of why the robot fell, severe time-constraint was faced. Thus, adhering to strict tolerances would severely increase the time needed to complete the product. The machining drawings are included in Appendix A.

## 4.2 Parts

None of the parts in the housing assembly were ordered. All parts were machined using the equipment available in the laboratory.

## 4.3 Materials

All the raw materials required for the housing assembly were taken from the machine shop. To prevent any interaction with the magnetic field from the encoder's magnet, all parts were made of non-ferromagnetic material. For parts where friction had to be minimized, delrin was used as it has a low coefficient of friction. Since the only sheet metal in the shop was made of aluminum, it was decided that aluminum would be used for the leaf spring. Stainless steel and brass were used for other parts where binding with aluminum was to be prevented.

The stock was chosen based on the desired dimensions of the part that was being machined. To ease machining and reduce machining time, the stock used had dimensions as close to the desired dimensions as possible.

## 4.4 Machining

All parts were machined using the conventional mill and lathes found in the Kimball Hall Machine Shop. Since all the parts to be machined were small, the machining steps had to be planned beforehand to account for the additional material that would be gripped in both the mill vise and lathe chuck.

Parts that were machined on the mill only required a standard vice to grip the parts. No rotary table was needed. A regular boring bar was used to cut the protruding sleeve on the front connecting device. However, the bar was turned around and the mill rotated counter-clockwise. This allowed the boring bar to cut around the outside diameter.

The hip shaft on the robot had to be drilled and tapped. Since the shaft could not be removed from the inner hip box and removing the legs would be unnecessarily tedious, the entire inner hip box and legs were gripped in the vise using a pair of customized "clips". Figure 4.4.1 shows a photograph of these clips. The clips would fit onto the bottom of the box while the shaft pointed upwards. Special precautions were taken to locate the center of the hip shaft by measuring the diameter of the shaft in two different directions. Figure 4.4.2 shows a schematic of how the robot was gripped in the mill.

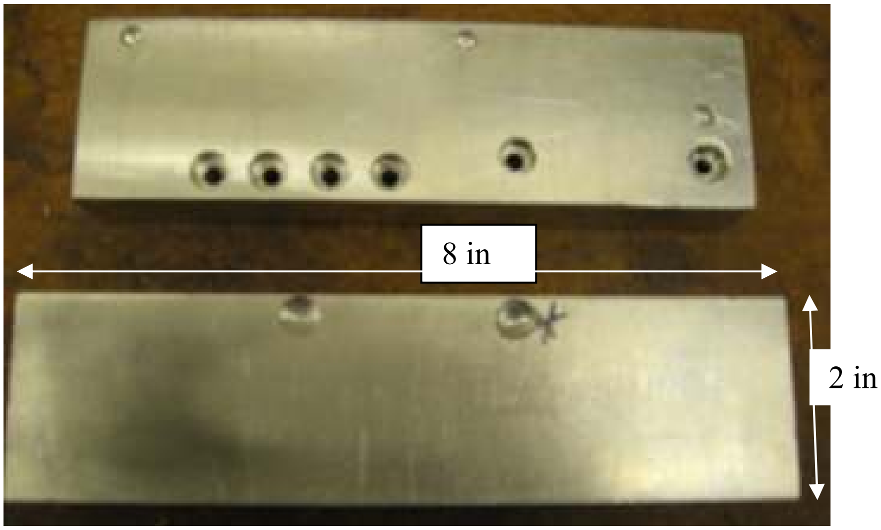


Figure 4.4.1: Photograph of Clips Used to Hold Robot while Milling

Since the parts to be machined on the lathe were too small to fit in a regular jaw chuck, a special American long-nose Taper Type L spindle nose chuck was used. Other operations included horizontal linear cutting on the horizontal band saw and shear, external threading using a die set and internal threading using a tap. The size of the body drills and tap drills for each specific threaded hole size was obtained from a tap and die chart. The sheet metal was bent by gripping it in a vice and bending it down manually using a mallet.

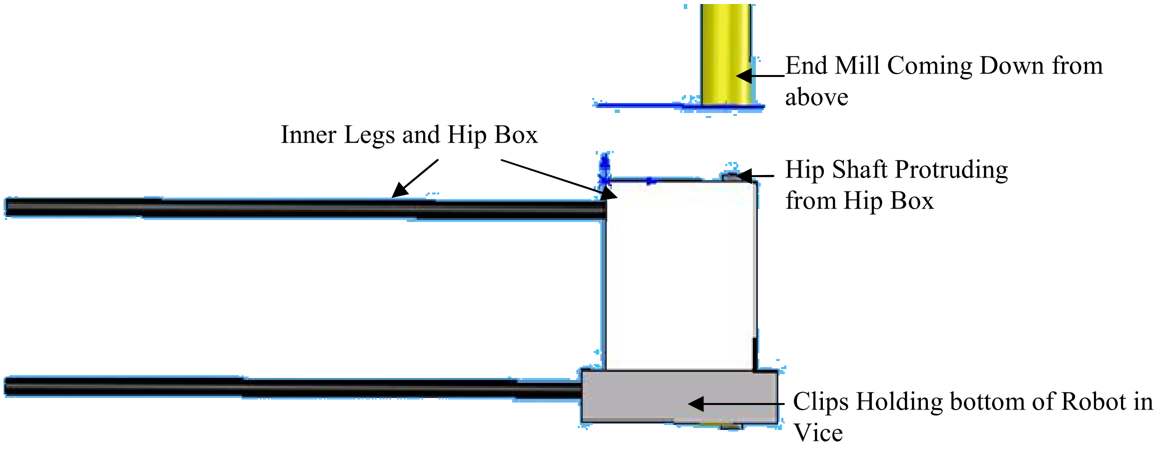


Figure 4.4.2: Schematic of how the Robot was Gripped in the Vise

## 4.5 Flaws

Once all the parts had been manufactured, they were put together on the robot. However assembly was not as easy as expected and flaws in the design were discovered.

Firstly, the entire length of the insert could not fit into the hip shaft. As a result, the surface was not flushed with the end of the shaft. It was discovered that in the process of machining, the insert had become bent and the threaded portion was no longer aligned with the rest of the insert. This resulted in the unthreaded portion coming into contact with the edges of the hole in the hip shaft. A second insert was made but the same problem occurred. However, care was taken to ensure that this insert was straight and hence the problem was attributed to the pre-existing hole in the hip shaft. A 6-32 threaded hole had been drilled in the hip shaft when it was first machined. This hole was not centered and as a result was not aligned with the larger holes for the unthreaded portion of the insert. To solve this problem, the outer diameter of the unthreaded portion of the insert was sandpapered down. However, the resulting suitable diameter was too small for the hole and would result in the magnet no longer being centered. Figure 4.5.1 below shows a photograph of this sandpapered insert. A third insert was made and a larger hole was drilled through part of the threaded hole. This created enough room for the insert to fit into the shaft.

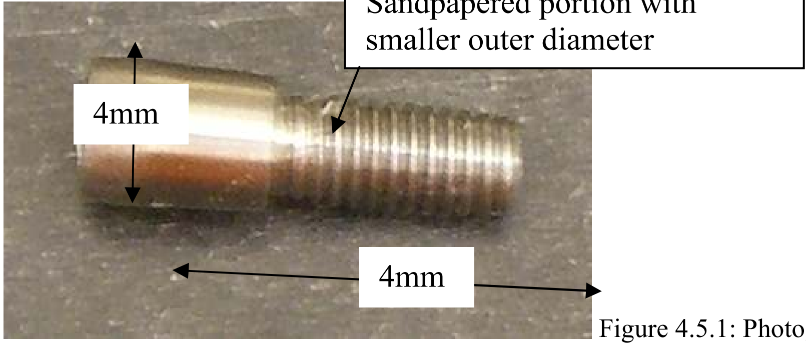


Figure 4.5.1: Photograph of Sandpapered Insert

Secondly, it was discovered that the front connecting device did not constrain rotation about one axis. This device was supposed to be held stationary while the insert and magnet rotated in its sleeve. The design did mange to prevent rotation about the hip shaft's axis. However, it could rotate about the axis normal to the back of the hip box (axis pointing from back of robot to front of robot). This was undesirable as it meant the distance between the magnet and IC would not be held constant. Thus a review of the design had to be conducted.

# 5. RE-DESIGN

A new front connecting device was designed. This device minimized the areas that were not used to hold the insert, minimizing any movement or rotation in the device. It also made use of a pre-existing bearing that was mounted on the hip shaft to hold the device. This bearing had been mounted such that it protruded above the surface of the hip shaft and had a inner diameter that was slightly larger than the diameter of the shaft. Hence by having a device whose diameter was as large as the shaft, the bearing could be used to prevent the device from any translational movement. Furthermore, the area of the front connecting device that was not sunk into the hip shaft would have the same cross-sectional area as the shaft. This would prevent rotation about the axis that the previous design could not. Figure 5.1 shows a CAD diagram of this new front connecting device.

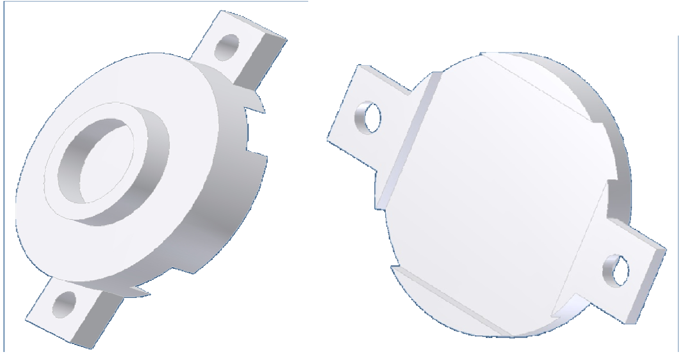


Figure 5.1: CAD Diagram of New Front Connecting Device Showing Isometric View and Back View

As with the previous design, friction on the outer and inner surfaces of the protruding sleeve had to be minimized. Hence delrin was used once again.

Unlike the old design, this new design had a circular base area along with irregularly shaped tabs. These would be impossible to machine on a regular mill and hence required the use of a Computer Numeric Control (CNC) machine. The CNC machine in the Kimball Machine Shop was programmed with G-codes. Specific coordinates for where the end mill cut had to be calculated and input into the code. A plotting program, NC plot, was used to give a preview of the final product. Once the resulting 2-d preview was deemed acceptable, the code was input into the CNC and a "dry-run" was done, where the end mill ran through its motions in the air without cutting any material. Errors in the program were detected and corrected. As with the previous design, the piece was too small to be gripped in the vise. Furthermore, it was irregularly shaped. Hence special cuts had to be carried out to remove this excess material as a final step in the machining. See Appendix B for the G-code used.

# 6. ASSEMBLY

Once the front connecting device was completed, the entire assembly was fixed in the Ranger. The insert was first screwed into the shaft and silicone was used to glue the magnet in its hole. Care was taken to ensure that the magnet was positioned in the same relative position as per the initial analysis (See Section 3.3).

The PCB was positioned in front of the magnet and the output value was read. The magnet had to be removed and repositioned several times until the desired output value at zero displacement angle was achieved. This had to be done before the silicone dried and hardened.

The front connecting device was slotted onto the shaft and rotated until the tabs were in the correct location. The pins were glued into their holes on the PCB using 3M strong general adhesive glue and the PCB was fixed onto the front connecting device. Lastly, the leaf spring was slotted into place and screwed down to the back of the left hip box.

# 7. TESTING

Testing was carried out on the installed encoder to determine if the housing assembly managed to minimize friction successfully and hold the various components in the right position. The main objective of the test was to check for hysteresis. Any large jumps in the output value would mean that the indicated displacement angle did not correspond to the actual displacement angle and that friction had resulted in a “time lag” between the magnet’s change in position and the change in magnetic field sensed by the IC. To find out the amount of hysteresis in the values obtained, a graph of output values vs. actual displacement angles was desired.

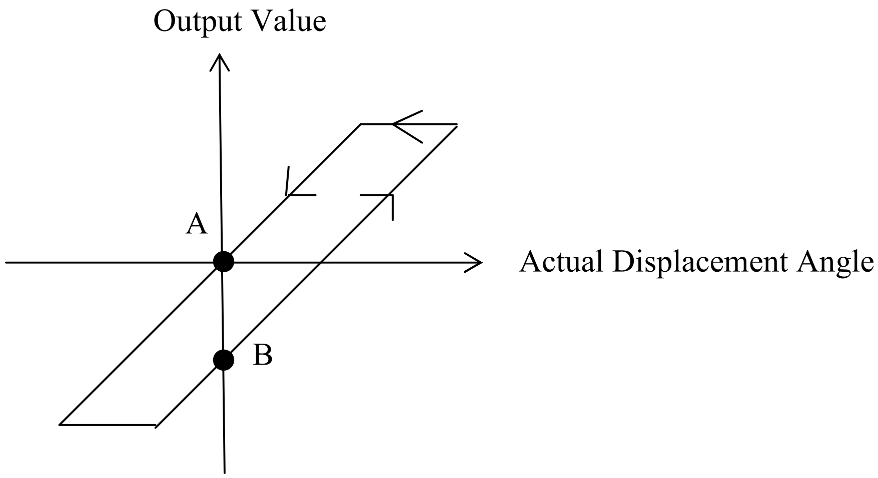


Figure 7.1: Graph of Output Values vs. Actual Displacement Angles Showing Hysteresis

The output values at points A and B were found. These points corresponded to zero displacement angle between the outer and inner hips. Point A corresponds to the output value at zero displacement angle as the inner leg is swinging from backward. Point B corresponds to the output value at zero displacement angle as the inner leg is swinging forward. A large difference between the two values indicates an undesirable hysteresis.

A steel pipe was slotted across all the robot's legs. This ensured that all the legs were aligned and there was no displacement angle between the outer and inner hips. The inner legs were then forced back behind the pipe and brought forward to the pipe again before the output value was found. This corresponded to point B. To find the value at point A, the outer legs were swung backward and brought to rest against the pipe before the value was read.

The resulting output value at A was 0.007675 and that at B was 0.0000004768. This corresponds to a difference of 0.03rad, which is negligible. Hence, it can be concluded that there is no significant hysteresis in the output values and that friction was minimal. The housing assembly was successful at holding the magnet and PCB in their correct positions.

# 8. EVALUATION

The housing assembly can be compared to the specifications to see how well it meets the needs. Other aspects such as safety and aesthetics can also be compared.

## 8.1 Meeting Specifications

| Specification | Target Value | Actual Value |
|---|---|---|
| Mass | <50g | < 30g |
| Dimensions | <16mm x 40mm x 40mm | 16mm x 40mm x 40mm |
| Cost | < $100 | $0 |
| Fabrication Time | < 3 weeks | 1 month |
| Distance between magnet and IC | 2mm ±0.5mm | 1.5mm |
| Material | Not iron, nickel or magnetite | Delrin, Stainless Steel, Aluminum, Brass |

Table 8.1.1: Target values and actual values of the specifications

As seen from the Table 8.1.1, the actual values have met the target value except the fabrication time. This was not surprising since the design that best fits the specifications was chosen. The fabrication time exceeded its target value due to the problems encountered with the insert and pre-existing hole in the shaft, as well as the re-design of the front connecting device which required learning the G-code and operating the CNC machine.

## 8.2 Safety

There is little danger associated with this housing assembly. The insert and magnet are sunk into the hip shaft while the front connecting device, PCB, leaf spring and pins are completely enclosed in the left hip box. The leaf spring concept does not pose a risk to the user, unlike the compression spring.

## 8.3 Aesthetics

The individual wires of the ribbon cable soldered onto the PCB were trimmed to their appropriate lengths to increase the appearance of the system. The white colored front connecting device also helped to beautify the system by covering the holes in the hip shaft and providing a nice contrast to the surrounding grey metal. The aesthetics could be improved by using fillets on the leaf spring. This also aids assembly, preventing the user from being cut by the sharp corners. However, since attractiveness was not a major need of the housing assembly, the design was not chosen based on its aesthetics and any major attempt to increase its aesthetics would have been a waste of resources and time.

## 8.4 Reliability

One drawback of the housing assembly is its reliability in the long run. Each time the encoder is removed or installed, the leaf spring will have to be bent backwards. After doing this a certain number of times, the aluminum might start to yield and no longer retain its elasticity. Thus, it will not be able to hold the PCB up against the hip shaft.

Another point of concern is the silicone holding the magnet in the insert. The silicone might have hardened during the process of repeated removable and re-insertion of the magnet while trying to locate the correct zero displacement angle position. To remove any doubts about the adhesiveness, a new coat of silicone should be applied to the magnet and insert. The magnet should then be installed and left in the insert without any further removal.

# 9. DISSCUSSION

The housing assembly met most of the objectives listed in Section 2.2. It is able to hold the encoder's PCB and magnet in their respective positions and allow the PCB to output a value that corresponds to the displacement angle between the outer and inner hips. However the real success of the housing assembly can only be judged in the long run, after the Ranger has walked long distances. This will allow us to determine the reliability of the assembly. More improvements could certainly be made to the assembly and are listed below.

## 9.1 Conceptual Design

The decision to go with the leaf spring has been proven wise as it has managed to keep the encoder in the right position. A more durable leaf spring could be used, such as those available in the markets, where there is no risk of surpassing the yielding point.

## 9.2 Detailed Design

The use of silicone as an adhesive between the magnet and insert raises much cause for concern. A design which involves securing the magnet to the insert with the use of mechanical components such as clips, could potentially provide a more reliable way of ensuring the magnet remains in the right position.

Secondly, removal of the insert requires that the inner leg be removed from the entire robot. This is a rather tedious process and requires at least 2 people. Thus, a more convenient design could be made where the removal of the insert and magnet did not require the robot to be taken apart. This may involve the insert and front connecting device be made of one single part as the front connecting device could potentially perform the functions of the insert.

## 9.3 Fabrication

The pieces that were machined with the lathe were too long and narrow and often broke at critical joints during the machining process. The use of a smaller lathe could save time, since the cutting tools would be smaller and hence result in a smaller lateral pushing force. Also, the “dry-run” of the CNC machine took considerable amount of time. A 3-d preview program could be used to view the actual finished product prior to machining and eliminate the need for a “dry-run”. Lastly, the need to calculate the coordinates for the end-mill to move to could be eliminated by the use of commercial programs, where the user would only have to draw the outline of the product and the program would output the required G-code.

## 9.4 Testing

The testing mentioned in Section 7 did yield satisfactory results. However, these tests were rudimentary. More detailed testing could be carried out where the actual displacement angle was measured using a protractor and the values read. The process would be repeated for several readings and the graph shown in Figure 7.1 could be plotted to observe the behavior of the encoder.

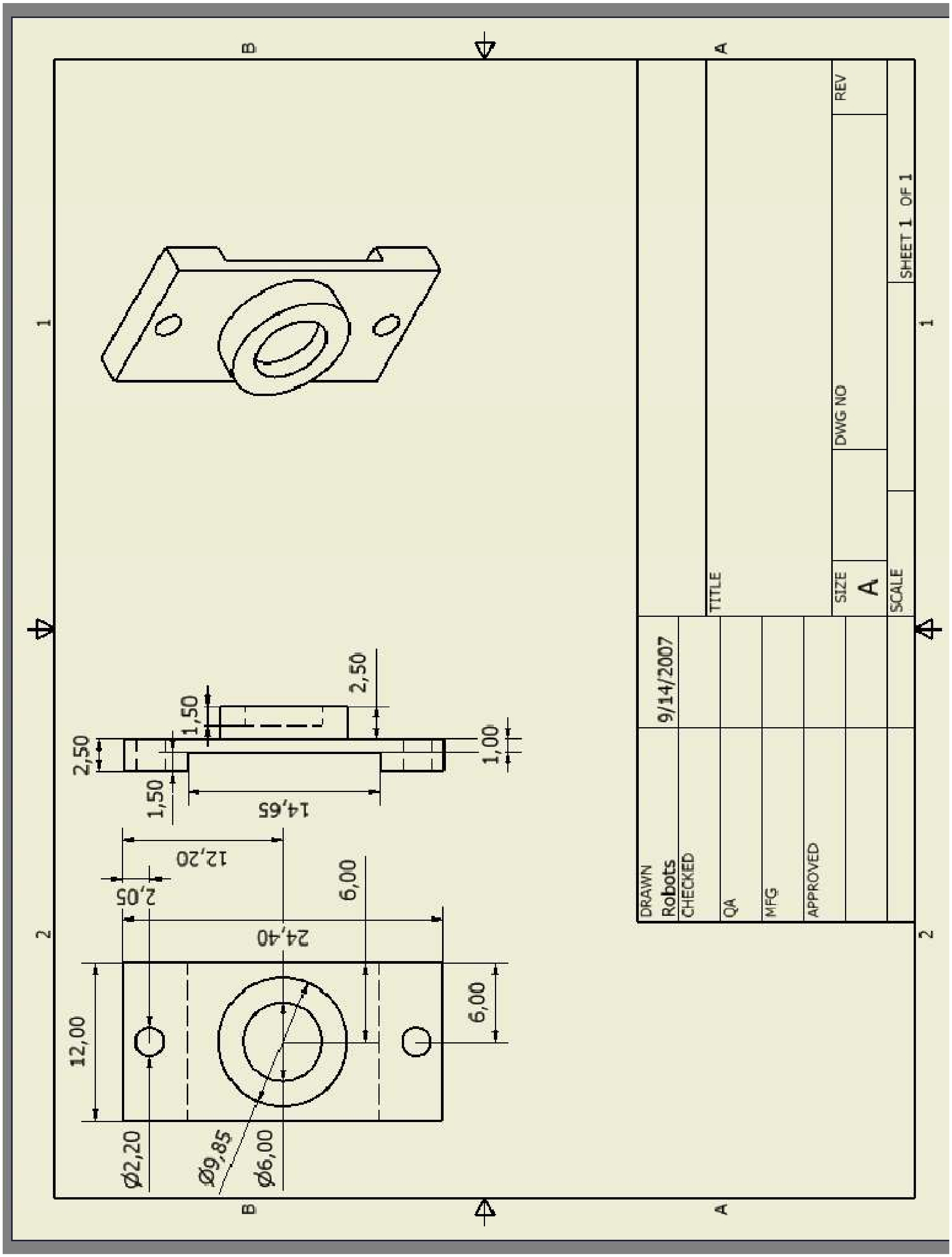
# 10. CONCLUSION

The housing assembly for the hip encoder has provided a fairly reliable way to hold the encoder’s PCB and magnet in their correct locations. This allows us to determine the displacement angle between the robot’s inner and outer hips, which improves our understanding of the walking dynamics behind the Cornell Ranger. It will also help us to determine why the robot loses its balance and apply the right gains in the various control systems of the robot. Several suggestions have been made above which if implemented on the assembly, can increase the reliability and performance of the hip encoder.

# Bibliography

RLS. (2007, June 29). *RLS.* Retrieved September 2007, from AM8192B - 13 bit angular magnetic sensor chip: http://www.rls.si/default.asp?prod=am8192B

# APPENDIX A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APPROVED
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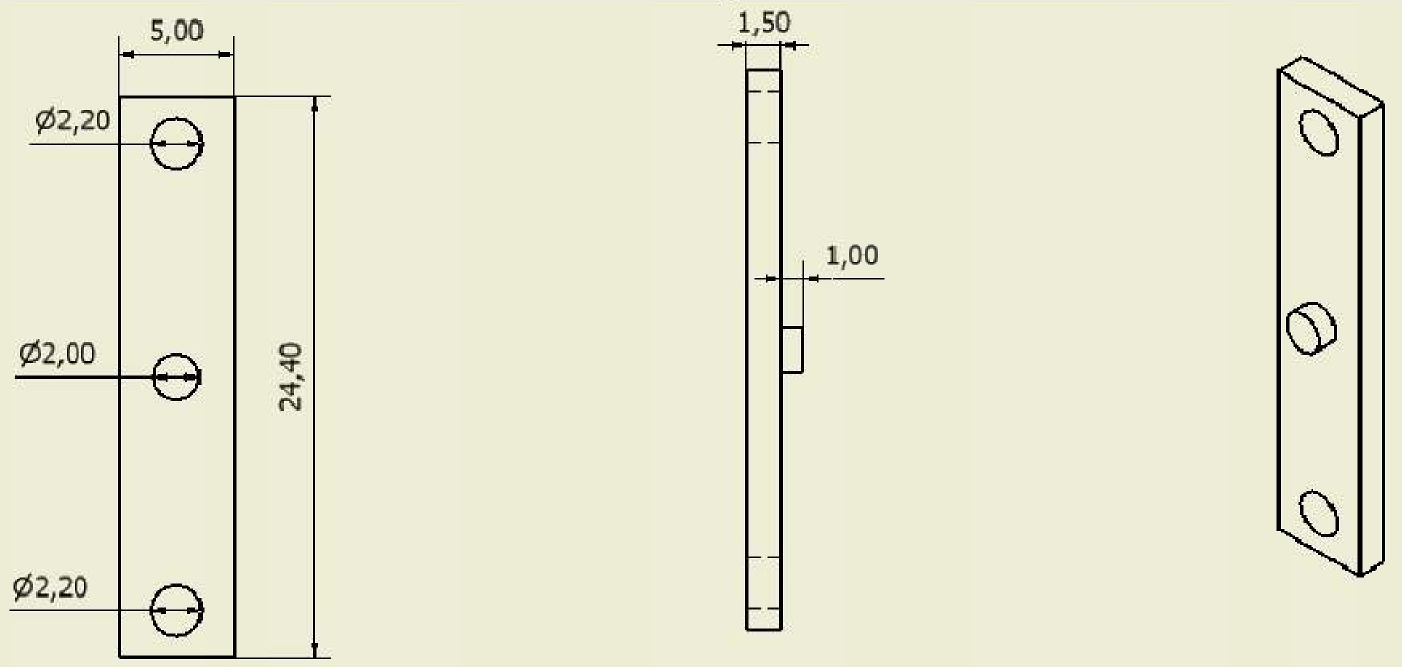
REV
SHEET 1 OF 1



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| APPROVED | | | | |
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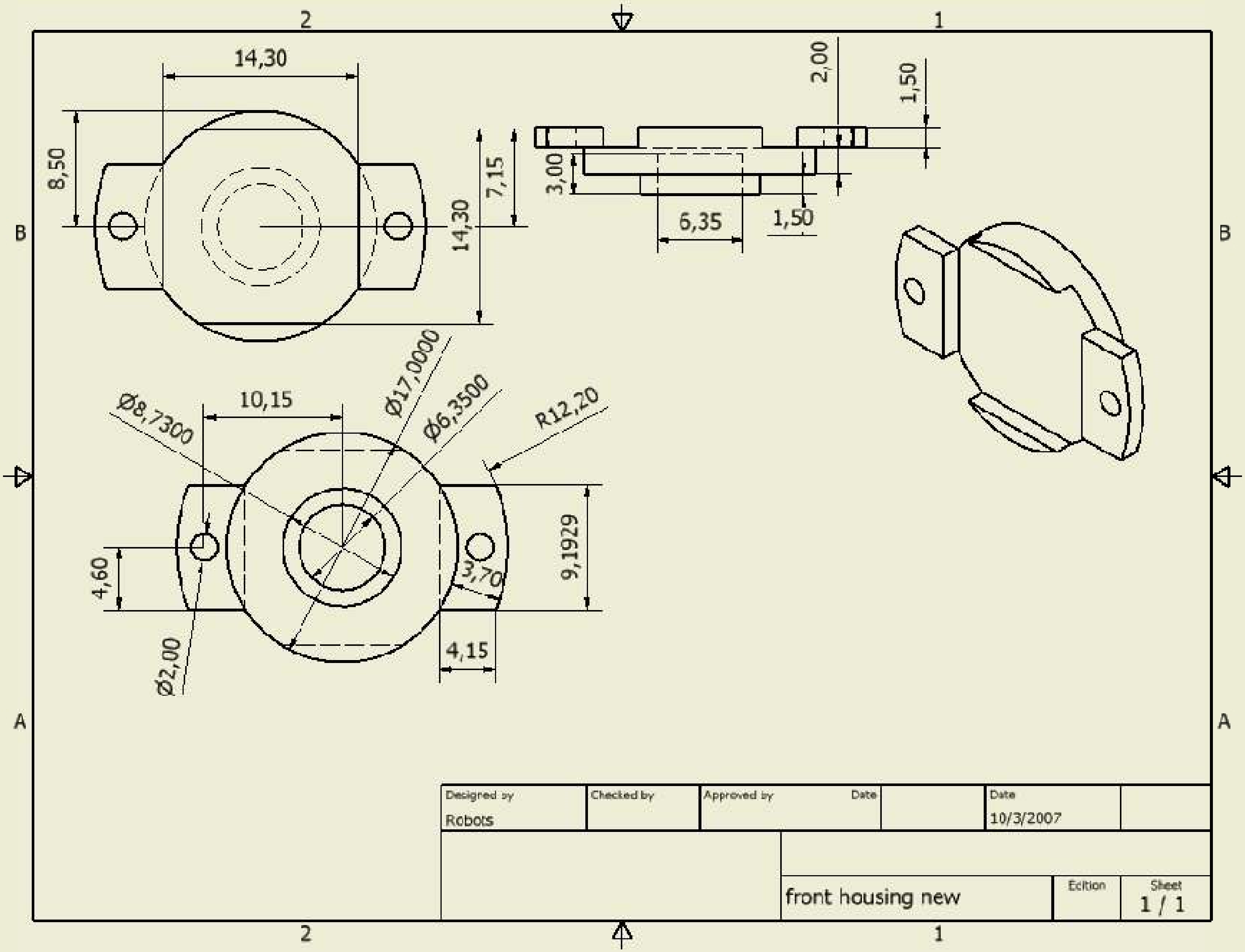

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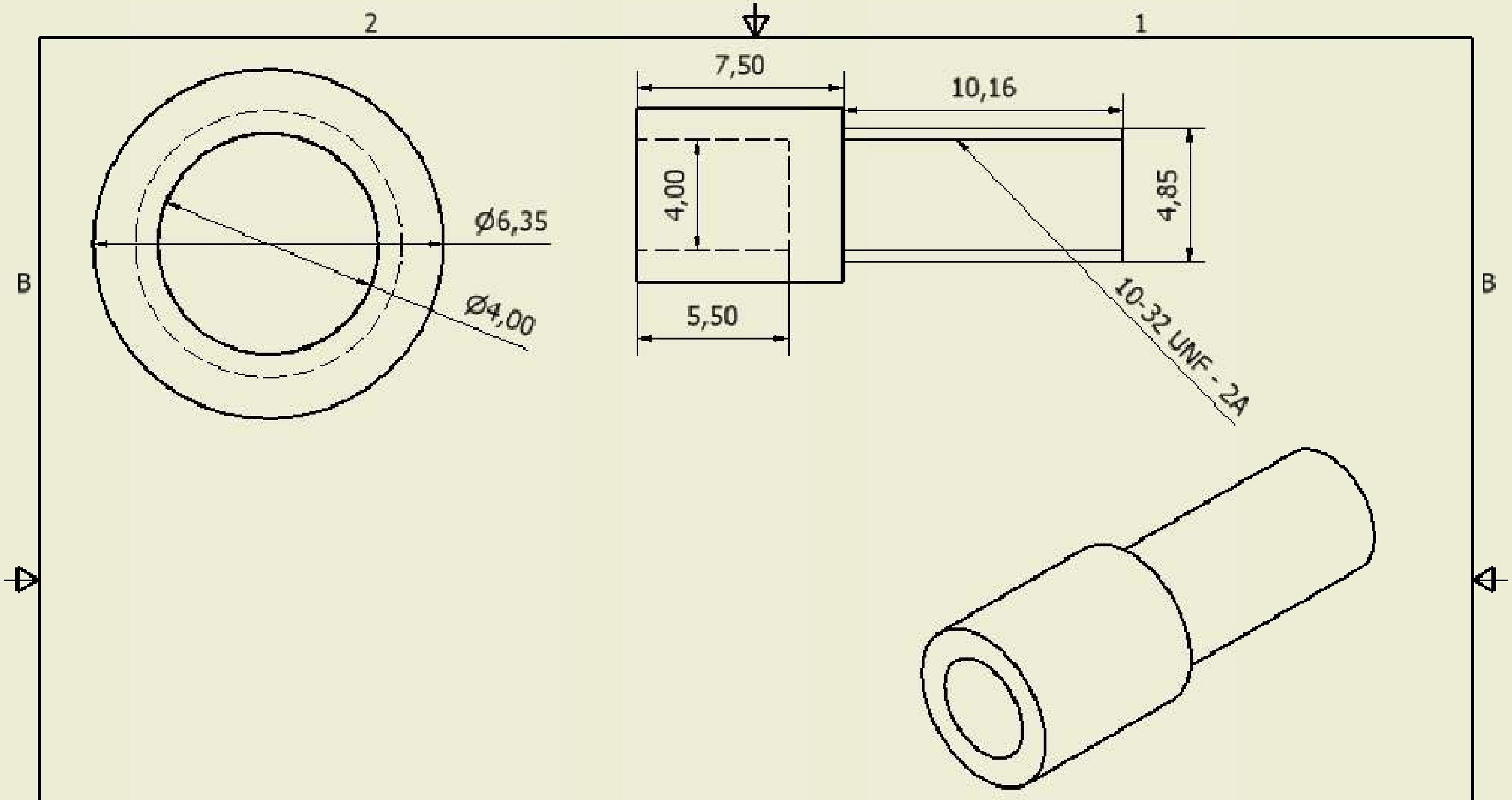
| Robots | | | | 10/3/2007 |

front housing new

Edition

Sheet 1 / 1



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| | Edition | Sheet |
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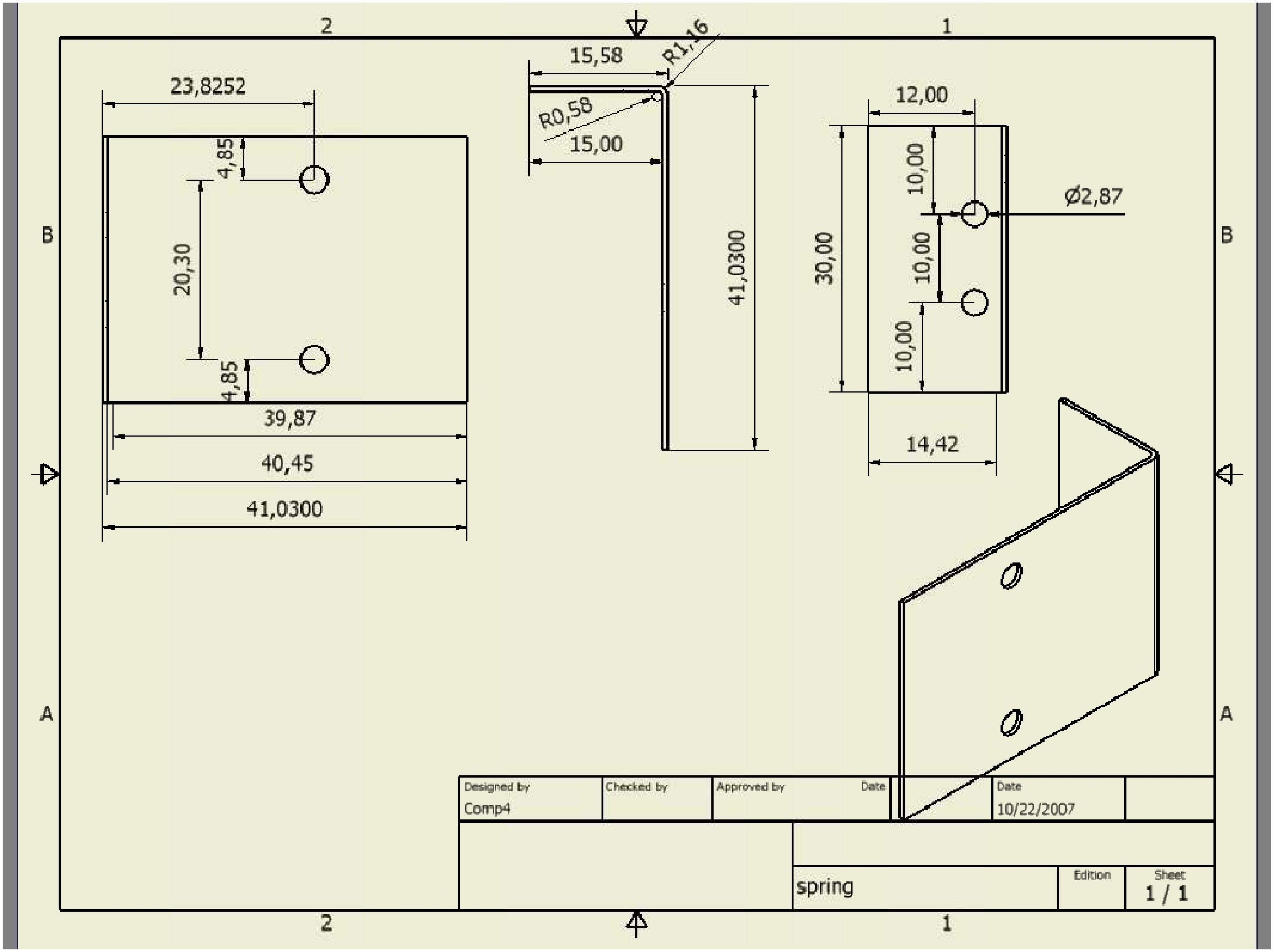

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| Comp4 | | | | 10/22/2007 |

spring

| Edition | Sheet |
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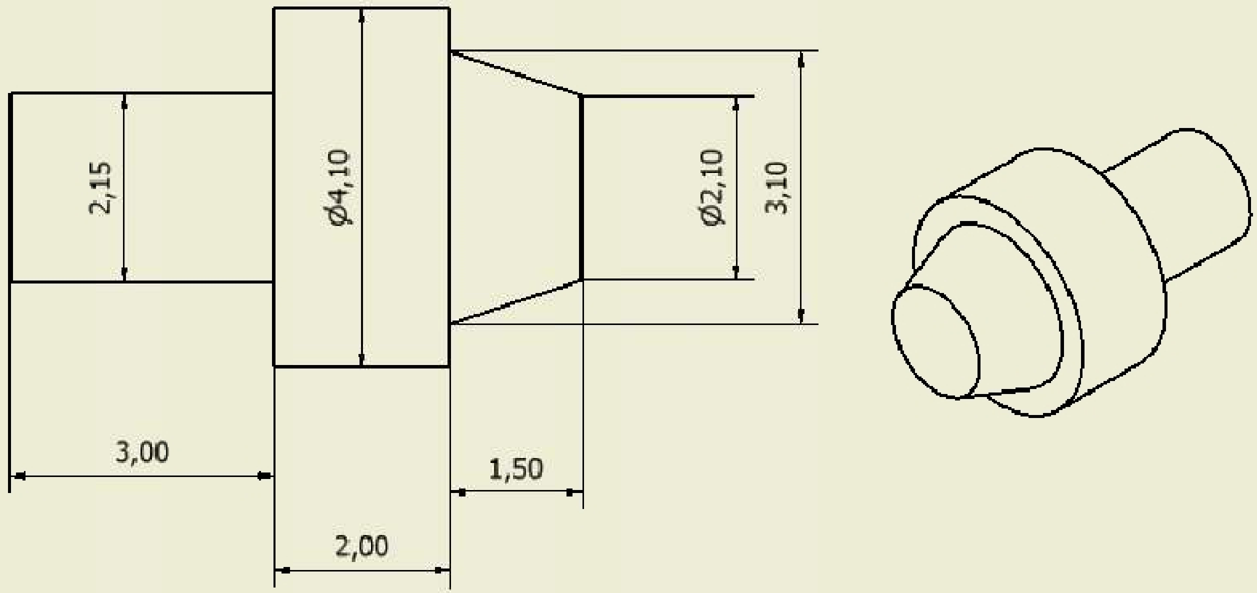
| | 1 / 1 |



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| | | Edition | Sheet |
|---|---|---|---|
| | pin | | 1 / 1 |

# APPENDIX B

```
ABS
G0Z0.03937                  MOVES UP TO Z=+1mm
G0X0.7087Y-0.5650             MOVES TO CENTER OF PIECE
G92X0Y0                       SETS NEW ORIGIN

G0X-0.5984Y0.45276             MOVES TO X=-15.2mm,Y=11.5mm

G1Z-0.03937F0.5               MOVES DOWN BY 1mm
G1X0.5984F2                   CUTS TO X=15.2mm
Y0.3937                      CUTS TO Y=10mm
X-0.5984                 CUTS TO X=-15.2mm
Y0.3346                      CUTS TO Y =8.5mm
X0.5984                      CUTS TO X=15.2mm
Y0.2756                      CUTS TO Y=7mm
X-0.5984                 cuts to x=-15.2mm
Y0.2165                      CUTS TO Y=5.5mm
X0.5984                      cuts to x=15.2mm
Y0.1575                      CUTS TO Y=4mm
X-0.5984                 cuts to x=-15.2mm
Y0.0984                      CUTS TO Y=2.5mm
X0.5984                      CUTS TO X=15.2mm
Y0.03937                  CUTS TO Y=1mm
X-0.5984                 cuts to x=-15.2mm
Y0                      CUTS TO Y=0mm
X0.5984                      CUTS TO X=15.2mm
Y-0.03937
X-0.5984
Y-0.0984
X0.5984
Y-0.1575
X-0.5984
Y-0.2165
X0.5984
Y-0.2756
X-0.5984
Y-0.3346
X0.5984
Y-0.3937
X-0.5984
Y-0.45276
X0.5984

G1Z-0.0787             MOVES DOWN TO 2mm
X-0.5984
Y-0.3937
X0.5984
Y-0.3346
X-0.5984
Y-0.2756
X0.5984
Y-0.2165
X-0.5984
Y-0.1575
X0.5984
Y-0.0984
X-0.5984
Y-0.03937
X0.5984
Y0
X-0.5984
Y0.03937
X0.5984
Y0.0984
X-0.5984
Y0.1575
X0.5984
```

```
Y0.2165
X-0.5984
Y0.2756
X0.5984
Y0.3346
X-0.5984
Y0.3937
X0.5984
Y0.45276
X-0.5984

G1Z-0.11811            MOVES DOWN TO Z=-3mm
X0.5197                MOVES TO X=13.2mm
Y0.3937
X-0.5197
Y0.3346
X0.5197
Y0.2756
X-0.5197
Y0.2165
X0.5197
Y0.1575
X-0.5197
Y0.0984
X0.5197
Y0.03937
X-0.5197
Y0
X0.5197
Y-0.03937
X-0.5197
Y-0.0984
X0.5197
Y-0.1575
X-0.5197
Y-0.2165
X0.5197
Y-0.2756
X-0.5197
Y-0.3346
X0.5197
Y-0.3937
X-0.5197
Y-0.45276
X0.5197

G1Z-0.1575            MOVES DOWN TO z=-4mm
X-0.5197
Y-0.3937
X0.5197
Y-0.3346
X-0.5197
Y-0.2756
X0.5197
Y-0.2165
X-0.5197
Y-0.1575
X0.5197
Y-0.0984
X-0.5197
Y-0.03937
X0.5197
Y0
X-0.5197
Y0.03937
X0.5197
Y0.0984
X-0.5197
Y0.1575
X0.5197
```

```
Y0.2165
X-0.5197
Y0.2756
X0.5197
Y0.3346
X-0.5197
Y0.3937
X0.5197
Y0.45276
X-0.5197

G1Z-0.1969          MOVES DOWN TO Z=-5mm
X0.5197
Y0.3937
X-0.5197
Y0.3346
X0.5197
Y0.2756
X-0.5197
Y0.2165
X0.5197
Y0.1575
X-0.5197
Y0.0984
X0.5197
Y0.03937
X-0.5197
Y0
X0.5197
Y-0.03937
X-0.5197
Y-0.0984
X0.5197
Y-0.1575
X-0.5197
Y-0.2165
X0.5197
Y-0.2756
X-0.5197
Y-0.3346
X0.5197
Y-0.3937
X-0.5197
Y-0.45276
X0.5197

G1Z-0.236           MOVES DOWN TO z=-6mm
X-0.5197
Y-0.3937
X0.5197
Y-0.3346
X-0.5197
Y-0.2756
X0.5197
Y-0.2165
X-0.5197
Y-0.1575
X0.5197
Y-0.0984
X-0.5197
Y-0.03937
X0.5197
Y0
X-0.5197
Y0.03937
X0.5197
Y0.0984
X-0.5197
Y0.1575
X0.5197
```

```
Y0.2165
X-0.5197
Y0.2756
X0.5197
Y0.3346
X-0.5197
Y0.3937
X0.5197
Y0.45276
X-0.5197

G1Z-0.2756              MOVES DOWN TO Z=-7mm
X0.5197
Y0.3937
X-0.5197
Y0.3346
X0.5197
Y0.2756
X-0.5197
Y0.2165
X0.5197
Y0.1575
X-0.5197
Y0.0984
X0.5197
Y0.03937
X-0.5197
Y0
X0.5197
Y-0.03937
X-0.5197
Y-0.0984
X0.5197
Y-0.1575
X-0.5197
Y-0.2165
X0.5197
Y-0.2756
X-0.5197
Y-0.3346
X0.5197
Y-0.3937
X-0.5197
Y-0.45276
X0.5197

G1Z-0.315               MOVES DOWN TO z=-8mm
X-0.5197
Y-0.3937
X0.5197
Y-0.3346
X-0.5197
Y-0.2756
X0.5197
Y-0.2165
X-0.5197
Y-0.1575
X0.5197
Y-0.0984
X-0.5197
Y-0.03937
X0.5197
Y0
X-0.5197
Y0.03937
X0.5197
Y0.0984
X-0.5197
Y0.1575
X0.5197
```

```
Y0.2165
X-0.5197
Y0.2756
X0.5197
Y0.3346
X-0.5197
Y0.3937
X0.5197
Y0.45276
X-0.5197

G1Z-0.3205              MOVES DOWN TO Z=-8.14mm
X0.5197
Y0.3937
X-0.5197
Y0.3346
X0.5197
Y0.2756
X-0.5197
Y0.2165
X0.5197
Y0.1575
X-0.5197
Y0.0984
X0.5197
Y0.03937
X-0.5197
Y0
X0.5197
Y-0.03937
X-0.5197
Y-0.0984
X0.5197
Y-0.1575
X-0.5197
Y-0.2165
X0.5197
Y-0.2756
X-0.5197
Y-0.3346
X0.5197
Y-0.3937
X-0.5197
Y-0.45276
X0.5197

G92X0.5197Y-0.45276Z0              SETS NEW Z=0 TO HEIGHT OF PIECE
----------------------------------------------------------------------------

G0Z0.03937                  MOVES UP TO Z=+1MM
X0Y0                       MOVES TO ORIGIN

G1Z-0.03937                  MOVES DOWN BY 1mm
X-0.05906                  MOVES TO X=-1.5mm
G2I0.05906                  CUTS CLOCKWISE 1 ROUND
G1X-0.08563                  MOVES TO X=-2.175mm
G2I0.08563                  CUTS CLOCKWISE 1 ROUND WITH DIAMETER = 6.35mm

G0Z0                       MOVES TO Z=0mm
G0X0Y0                       MOVES BACK TO ORIGIN
G1Z-0.07874                  MOVES DOWN TO 2mm
X-0.05906                  MOVES TO X=-1.5mm
G2I0.05906                  CUTS CLOCKWISE 1 ROUND
G1X-0.08563                  MOVES TO X=-2.175mm
G2I0.08563                  CUTS CLOCKWISE 1 ROUND WITH DIAMETER = 6.35mm

G0Z-0.03937                  MOVES TO Z= -1 mm
G0X0Y0                       MOVES BACK TO ORIGIN
G1Z-0.11811                  MOVES DOWN TO 3mm
X-0.05906                  MOVES TO X=-1.5mm
```

```
G2I0.05906                    CUTS CLOCKWISE
G1X-0.08563                     MOVES TO X=-2.175mm
G2I0.08563                    CUTS CLOCKWISE 1 ROUND WITH DIAMETER = 6.35mm

--------------------------------------------------------------------------------
G0Z0.03937                          MOVES BACK UP TO Z=+1 mm
X-0.21122                    MOVES TO X=-5.365mm
G1Z-0.03937                     MOVES DOWN BY 1mm
G2I0.21122                    CUTS CLOCKWISE 1 ROUND WITH OD=12.73mm, ID=8.73mm
G1X-0.27027                     MOVES TO X=-6.865mm
G2I0.27027                    CUTS CLOCKWISE 1 ROUND WITH OD=15.73mm, ID=11.73mm
G1X-0.29527                     moves to x=-7.5mm
G2I0.29527                    CUTS CLOCKWISE 1 ROUND WITH OD=17MM, ID=13MM

G0Z0.03937                     MOVES BACK UP TO Z= +1 mm
G0X-0.21122                     MOVES BACK TO X=-5.365mm
G1Z-0.059055                     MOVES DOWN TO 1.5mm
G2I0.21122                    CUTS CLOCKWISE 1 ROUND WITH OD=12.73mm, ID=8.73mm
G1X-0.27027                     MOVES TO X=-6.865mm
G2I0.27027                    CUTS CLOCKWISE 1 ROUND WITH OD=15.73mm, ID=11.73mm
G1X-0.29527                     moves to x=-7.5mm
G2I0.29527                    CUTS CLOCKWISE 1 ROUND WITH OD=17MM, ID=13MM

--------------------------------------------------------------------------------
G0Z0.03937                     MOVES TO Z = +1mm
X-0.374Y0                    MOVES TO X=-9.5mm
G1Z-0.03937                     MOVES DOWN TO 1mm
G2I0.3740                    CUTS CLOCKWISE 1 ROUND WITH 0D=21mm, ID=17mm
G1Z-0.07874                     MOVES DOWN TO 2mm
G2I0.3740                    CUTS CLOCKWISE 1 ROUND WITH OD=21mm, ID=17mm
G1Z-0.11811                     MOVES DOWN TO 3mm
G2I0.3740                    CUTS CLOCKWISE 1 ROUND WITH OD=21mm, ID=17mm
G1Z-0.1378                    MOVES DOWN TO 3.5mm
G2I0.3740                    CUTS CLOCKWISE 1 ROUND WITH OD=21mm, ID=17mm
G0Z-0.11811                     MOVES DOWN TO 3mm
X-0.3022Y0.22                     MOVES TO X=-7.677mm,Y=5.5965mm
G1Z-0.1772                    MOVES DOWN TO 4.5mm
G2X0.3022Y0.22I0.30220J-0.22        CUTS CLOCKWISE TOP PORTION OF CIRCLE WITH
OD=21mm,ID=17mm
G1Z-0.19685                     MOVES DOWN TO 5mm
G3X-0.3022Y0.22I-0.3022J-0.22       CUTS COUNTER-CLOCKWISE TOP HALF OF CIRCLE WITH
OD=21mm,ID=17mm

G0Z-0.11811                     MOVES DOWN TO 3mm
X-0.3022Y-0.22                     MOVES TO X=-7.677mm,Y=-5.5965mm
G1Z-0.1772                    MOVES DOWN TO 4.5mm
G3X0.3022Y-0.22I0.3022J0.22        CUTS COUNTER-CLOCKWISE BOTTOM HALF OF CIRCLE
WITHOD=21mm, ID=17mm
G1Z-0.19685                     MOVES DOWN TO 5mm
G2X-0.3022Y-0.22I-0.3022J0.22        CUTS CLOCKWISE BOTTOM HALF OF CIRCLE WITH
OD=21mm,ID=17mm

---------------------------------------------------------------------------------

G0Z0.03937                     MOVES TO Z=+1mm
X-0.4528Y0                     MOVES TO X=-11.5mm,Y=0mm
G1Z-0.03937                     MOVES DOWN TO 1mm
G2X-0.3955Y0.2203I0.4528           CUTS CLOCKWISE left flap WITH OD=25mm,ID=21mm
G0Z0
X-0.4528Y0                     MOVES BACK TO X=-11.5mm,Y=0mm
G1Z-0.03937                     MOVES DOWN TO Z=-1mm
G3X-0.3955Y-0.2203I0.4528        CUTS COUNTER-CLOCKWISE LEFT FLAP WITH
OD=25mm,ID=21mm
G0Z0                    MOVES BACK TO Z=0 mm
G1X-0.4707                     MOVES TO X=-11.955mm,Y=-5.5965mm
G1Z-0.03937                     MOVES DOWN TO Z=-1mm
G2X-0.4707Y0.2203I0.4707J0.22        CUTS CLOCKWISE LEFT FLAP WITH OD=28.4mm, ID=24.4mm

G1Z-0.07874                     MOVES DOWN TO z=-2mm
G3X-0.4707Y-0.22I0.4707J-0.22        CUTS COUNTER-CLOCKWISE LEFT FLAP WITH
```

```
OD=28.4mm,ID=24.4mm
G0Z-0.03937                      MOVES UP TO Z=-1mm
G1X-0.3955                      MOVES TO X=-10.0463mm,Y=-5.5965mm
G1Z-0.07874                      MOVES DOWN TO Z=-2mm
G2X-0.3955Y0.220I0.3955J0.22        CUTS CLOCKWISE LEFT FLAP WITH OD=25mm, ID=21mm

G1Z-0.11811                      MOVES DOWN TO 3mm
G3X-0.3955Y-0.220I0.3955J-0.22        CUTS COUNTER-CLOCKWISE left flap WITH
OD=25mm,ID=21mm
G0Z-0.07874                              MOVES UP TO Z=-2mm
G1X-0.4707                    MOVES TO X=-11.955mm,Y=-5.5965mm
G1Z-0.118111                              MOVES DOWN TO Z=-3mm
G2X-0.4707Y0.22I0.4707J0.22               CUTS CLOCKWISE WITH LEFT FLAP
OD=28.4mm,ID=24.4mm

G1Z-0.1378                      MOVES DOWN TO 3.5mm
G3X-0.3955Y-0.220I0.3955J-0.220       CUTS COUNTER-CLOCKWISE LEFT FLAP WITH
OD=25mm,ID=21mm
G0Z-0.07874                              MOVES UP TO Z=-2mm
G1X-0.4707                          MOVES TO X=-11.955mm,Y=-5.5965mm
G1Z-0.1378                            MOVES DOWN TO Z=-3.5mm
G2X-0.4707Y0.22I0.4707J0.22               CUTS CLOCKWISE LEFT FLAP WITH
OD=28.4mm,ID=24.4mm


G0Z0
X-0.3022Y0.22                       MOVES TO X=-7.677mm, Y=5.5965mm
z-0.11811                     MOVES DOWN TO z=-3mm
G1Z-0.15748                      MOVES DOWN TO z=-4mm
X-0.4707                      MOVES TO X=-11.955mm, Y=5.5965mm
G3X-0.4707Y-0.22I0.4707J-0.22        CUTS COUNTER-CLOCKWISE LEFT FLAP
G1X-0.3022                      MOVES TO X=-7.677mm, Y=-5.5965mm

G0Z-0.098425                   MOVES TO z=-2.5mm
X-0.3022Y0.22                       MOVES TO X=-7.677mm, Y=5.5965mm
G1Z-0.2165                     MOVES TO z=-5.5mm
G0Z-0.098425                     MOVES TO 2.5mm
X-0.4707                      MOVES TO X=-11.955mm,Y=5.5965mm
G1Z-0.2165                      MOVES TO z=-5.5mm
G3X-0.4707Y-0.22I0.4707J-0.22        CUTS COUNTER-CLOCKWISE LEFT FLAP
OD=14.2mm,ID=12.2 mm
G0Z-0.098425                      MOVES TO 2.5mm
X-0.3022                          MOVES TO X=-7.677mm
G1Z-0.2165                     MOVES TO z=-5.5mm

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G0Z0.03937                      MOVES TO Z=+1mm
X0.4528Y0                      MOVES TO X=11.5mm,Y=0mm
G1Z-0.03937                      MOVES DOWN TO 1mm
G3X0.3955Y0.220I-0.4528           CUTS counter-CLOCKWISE right flap WITH
OD=25mm,ID=21mm
G0Z0
X0.4528Y0                      MOVES BACK TO X=11.5mm,Y=0mm
G1Z-0.03937                      MOVES DOWN TO Z=-1mm
G2X0.3955Y-0.220I-0.4528        CUTS CLOCKWISE right FLAP WITH OD=25mm,ID=21mm
G0Z0                          MOVES BACK TO Z=0 mm
G1X0.4707                      MOVES TO X=11.955mm,Y=-5.5965mm
G1Z-0.03937                      MOVES DOWN TO Z=-1mm
G3X0.4707Y0.220I-0.4707J0.22        CUTS counter-CLOCKWISE right FLAP WITH
OD=28.4mm, ID=24.4mm

G1Z-0.07874                      MOVES DOWN TO z=-2mm
G2X0.4707Y-0.22I-0.4707J-0.22        CUTS CLOCKWISE right FLAP WITH OD=28.4mm,ID=24.4mm
G0Z-0.03937                      MOVES UP TO Z=-1mm
G1X0.3955                      MOVES TO X=10.0463mm,Y=-5.5965mm
G1Z-0.07874                      MOVES DOWN TO Z=-2mm
G3X0.3955Y0.220I-0.3955J0.22        CUTS counter-CLOCKWISE right FLAP WITH OD=25mm,
ID=21mm
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G1Z-0.11811               MOVES DOWN TO 3mm
G2X0.3955Y-0.220I-0.3955J-0.22        CUTS CLOCKWISE right flap WITH OD=25mm,ID=21mm
G0Z-0.07874                    MOVES UP TO Z=-2mm
G1X0.4707               MOVES TO X=11.955mm,Y=-5.5965mm
G1Z-0.118111                    MOVES DOWN TO Z=-3mm
G3X0.4707Y0.22I-0.4707J0.22               CUTS counter-CLOCKWISE right FLAP
OD=28.4mm,ID=24.4mm

G1Z-0.1378                MOVES DOWN TO 3.5mm
G2X0.3955Y-0.220I-0.3955J-0.220       CUTS CLOCKWISE right FLAP WITH OD=25mm,ID=21mm
G0Z-0.07874                    MOVES UP TO Z=-2mm
G1X0.4707                   MOVES TO X=11.955mm,Y=-5.5965mm
G1Z-0.1378                    MOVES DOWN TO Z=-3.5mm
G3X0.4707Y0.22I-0.4707J0.22               CUTS counter-CLOCKWISE right FLAP WITH
OD=28.4mm,ID=24.4mm


G0Z0
X0.3022Y0.22                MOVES TO X=7.677mm, Y=5.5965mm
z-0.11811               MOVES DOWN TO z=-3mm
G1Z-0.15748               MOVES DOWN TO z=-4mm
X0.4707               MOVES TO X=11.955mm, Y=5.5965mm
G2X0.4707Y-0.22I-0.4707J-0.22       CUTS CLOCKWISE right FLAP
G1X0.3022                MOVES TO X=7.677mm, Y=-5.5965mm

G0Z-0.098425              MOVES TO z=-2.5mm
X0.3022Y0.22                MOVES TO X=7.677mm, Y=5.5965mm
G1Z-0.2165               MOVES TO z=-5.5mm
G0Z-0.098425               MOVES TO Z=-2.5mm
X0.4707               MOVES TO X=11.955mm,Y=5.5965mm
G1Z-0.2165                MOVES TO z=-5.5mm
G2X0.4707Y-0.22I-0.4707J-0.22       CUTS CLOCKWISE RIGHT FLAP OD=14.2mm,ID=12.2 mm
G0Z-0.098425                MOVES UP TO Z=-2.5mm
X0.3022                   MOVES TO X=7.677mm
G1Z-0.2165               MOVES DOWN TO z=-5.5mm
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G0Z0                     MOVES BACK UP TO HEIGHT OF RING SECTION
X0.3996Y0                 MOVES TO X=10.15mm (position of right hole)
Z-0.11811                    MOVES DOWN 3mm
G1Z-0.20866                MOVES DOWN 5.3mm

G0Z0.03937                MOVES UP TO Z=+1mm
X-0.3996Y0                MOVES TO X=-10.15mm (position of left hole)
Z-0.11811                    MOVES DOWN 3mm
G1Z-0.20866                MOVES DOWN 5.3mm


G0Z1                 MOVES UP 1"

M30                     ENDS PROGRAM
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