# DESIGN OF A VARIABLE COMPLIANCE LEG USING SHAPE DEPOSITION MANUFACTURING

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## ABSTRACT

Biological studies have demonstrated that variable compliance legs in running animals respond to changes in terrain, running speed, and weight. Due to complexity and size limitations, no robot platform to date has been able to successfully integrate this capability. This paper describes the design and fabrication of variable compliance legs for the Edubot platform. The key design features of the major components are presented, followed by a discussion of the layered prototyping technique employed to fabricate the legs. Finally, some observations from initial leg prototypes are presented which demonstrate the design's advantages and limitations.

**TABLE OF CONTENTS**

## 1. INTRODUCTION

Biomimetics, the abstraction of good design from nature, is a prevalent research method in the field of robotics. Roboticists have found inspiration from biological systems in areas relating to artificial intelligence, controls theory, and locomotion. The motivation behind this method has been the observation that nature has addressed a number of the challenges that roboticists face. One challenge in particular, and the focus of the paper, is dynamic legged locomotion. By dynamic we refer to a running gait that has two phases: an aerial and a ground contact phase. Several studies of legged animals ranging from cockroaches to kangaroos have provided some insight into the mechanisms behind dynamic running in nature.

One conclusion made from these studies has been the importance of incorporating a spring element in the legs for storing and returning energy to the system. In [1], Alexander presents three ways in which natural systems have incorporated the use of springs in legged locomotion. The first of these is the storage of external kinetic energy as strain energy in legs to reduce energy lost to the environment. The second is the use of return springs to reverse the direction of leg swing, and the third is the prevention of excessive impact forces and chatter by using elastic foot pads. In an effort to understand the underlying mechanisms, Blickhan [2] demonstrated that despite variations in the number, length, shape, and positioning of legs, a wide range of animals could be accurately modeled as simple bouncing monopods. This model, also referred to as the spring loaded inverted pendulum (SLIP) model, has since been applied to many running robots. In SLIP, the body is modeled as a point mass attached to a linear spring element which behaves much like a pogo stick.

Further studies on the role of compliant legs have shown that in certain conditions animals can make use of variable stiffness to accommodate changes in speed, stride frequency, and terrain. This has been demonstrated in humans [4] and animals including dogs, goats, horses and kangaroos [3]. Drawing from these observations, several groups have developed variable compliance legs and actuators. These include the Pleated Pneumatic Artificial Muscle (PPAM) and Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA) at the Vrije Universiteit Brussel [5][6], the Biologically Inspired Joint Stiffness Control at Georgia Institute of Technology [7], the Variable Stiffness Actuator (VIA) at the University of Pisa [8], and the Actuator with Mechanically Adjustable Series Compliance (AMASC) and the Biped with Mechanically Adjustable Series Compliance (BiMASC) at Carnegie Mellon University [9][10].

Despite such a diverse collection of variable compliance actuators, none of these have demonstrated effective dynamic running. Furthermore, due to their complex designs, implementation on small running robots would be difficult due to size and weight considerations. To overcome this challenge, Galloway [11] at the University of Pennsylvania has developed a simple and robust method for varying the stiffness of the c-shaped legs used on the Edubot robot. The design uses a simple slider to structurally adjust leg stiffness. The current drawback of this design is that it requires manual adjustment via set screws to change the slider position.

Edubot, the platform referred to in this paper, and its predecessor RHex have demonstrated remarkably fast and robust dynamic running over a variety of terrains and speeds [12]. This is due in large part to the passive compliant c-shape leg design and the availability of a number of gaits which can be used to perform specialized tasks. In this paper, we present a method to incorporate sensors and mechanical actuation into the slider design to make a variable stiffness leg for dynamic locomotion. It should be noted that the idea of incorporating leg sensing has already been used successfully on robotic platforms for a number of tasks such as stride period adaptation [13], body pose estimation [14], gait transition [15], and gait regulation [16]. The distinguishing feature of this work stems from the fact that few groups have tried to incorporate leg sensing and variable stiffness capabilities into their locomotion platform, and to our knowledge no one has been able to physically demonstrate variable stiffness legs on a dynamic locomotion system.

Edubot is a 3 kg, shoe box-sized, hexapedal robotic platform. The mere size and weight of the robot pose a significant leg design and fabrication challenge. In addition, compliant mechanisms require materials with a wide range of properties and the ability to fabricate arbitrary shapes. To address these challenges we used a layered prototyping technique known as Shape Deposition Manufacturing (SDM) [17] [18] [19], which is a cyclic process of material deposition and removal. Three advantages of using SDM over other prototyping methods are the ability to make complex parts, the ease with which components can be embedded, and the possibility of using multiple materials within the same part. A detailed explanation of the process can be found in [20]. This paper presents the SDM design methodology taken to make the "smart" variable compliant leg for the Edubot platform.

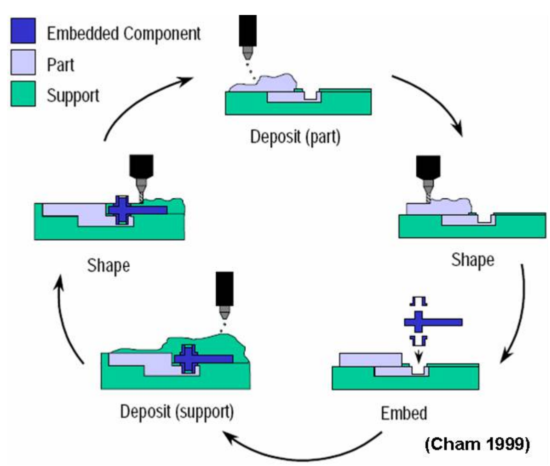
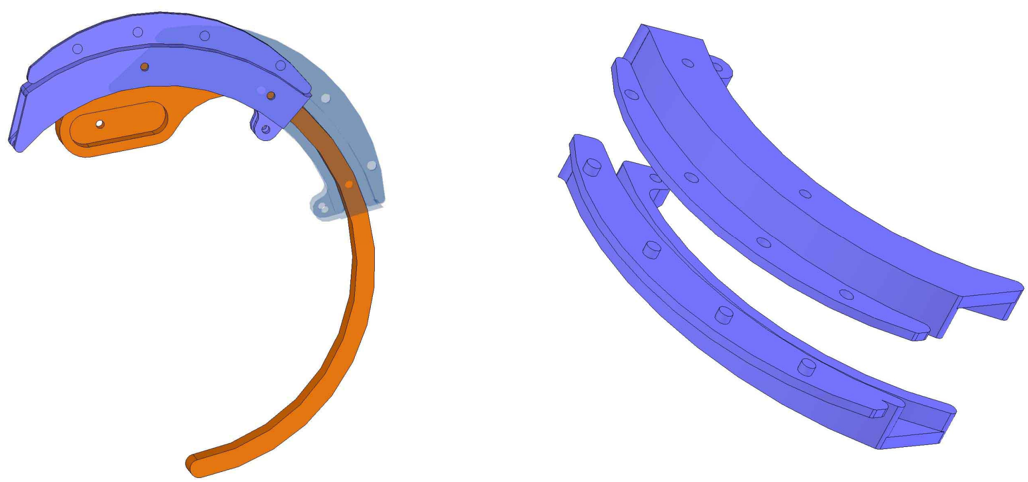



Figure 1: Steps in Shape Deposition Manufacturing.

## 2. MECHANICAL DESIGN

### 2.1 Design Motivation

Legged locomotion studies have shown that animals change their stiffness in response to speed, weight, and terrain changes. In order to close the performance gap between animals and robots, it is desirable for robots to be able to change their leg stiffness. A simple and readily manufacturable slider design was developed for Edubot by Kevin Galloway. As illustrated in Figure 2, the slider works on the principle of a cantilevered beam where the hip is modeled as a fixed end with the c-leg acting as an initially curved beam. As the slider is rotated down the length of the leg, the effective cantilevered portion of the c-leg is reduced; resulting in a stiffer leg. This design has been physically tested on the robot and has proven to be an effective method of easily changing leg stiffness.



(a) (b)

Figure 2: Initial slider design assembly (a) and two piece snap fit design (b).

The main drawback of the present design is that the leg stiffness must be manually adjusted. This is done by loosening the setscrews and repositioning the slider for each of the six legs. While they have been able to demonstrate the effectiveness of the design, these sliders do not significantly extended the capabilities of the robot since the same change in stiffness could be accomplished by adjusting leg thickness. The real motivation for variable compliance is to have legs which can adjust their stiffness to adapt to environment or behavior changes in real time.

### 2.2 Design Challenges

To make the leg ‘smart’ and capable of changing its stiffness, some additional components were needed including mechanical actuation to change the slider position and sensors to detect the slider position and the deflection state of the leg. A microcontroller and additional circuitry was also needed to take inputs from the sensors and to control the slider position. A source of power was required for the sensors, actuator, and circuitry. Communication with the robot body was also crucial to provide a form of high level control. Finally, since the leg is continuously rotating while in use, a direct wired connection cannot be used for power or communication. This required that all the components be housed on the leg.

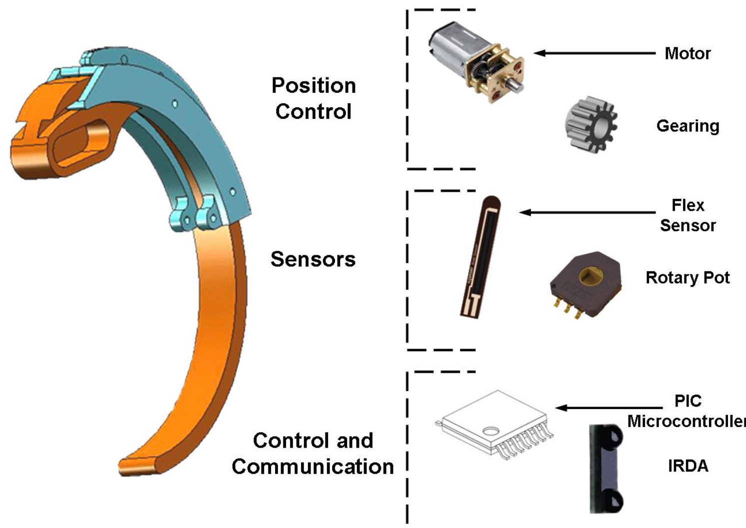



Figure 3: Additional components needed to make an intelligent variable compliance leg.

To incorporate these components, some important considerations were made. Manufacturability was a key concern for every feature of the design. The majority of the features in the final design were fabricated using either a 3mm or 6mm end mill with the only deviations being a 1mm end mill for the gears and a 1.5 mm drill for 4 holes. Weight and size are always important constraints in a robot of this size, especially when it is rotating mass. Much effort was taken to minimize the weight and rotational inertia of the leg by packaging everything close together around the axis of rotation (i.e. the hip).

### 2.3 Embedded Leg Design

The final leg design with all of the embedded components can be seen in Figure 4. As the leg deflects during stance, a flex sensor embedded in the c-leg indicates the degree of deflection by a change in its resistance. A microcontroller-based circuit located behind the shaft clamp pocket processes the sensor input and transmits data to the robot body wirelessly. Wireless communication with the body is achieved via IrDA transceivers on the leg and robot body which exchange information and commands each time they pass within range of one another. To maximize communication time, the transceivers are positioned to line up during stance and are located as close to the center of rotation as possible. While the leg transceiver is transferring data, it is also receiving commands from the robot body. A miniature gearhead motor is used for actuation and is positioned as close to the shaft clamp pocket as possible to minimize the leg's rotational inertia. The slider is geared to mate with the motor gear for mechanical actuation of slider position. A rotary potentiometer is positioned opposite the slider and attenuated by the motor via a gear. As the motor moves the slider down the leg, it also rotates the rotary potentiometer which indicates slider position by changing its resistance state. This basic functionality is performed continuously while the leg is in use to change leg stiffness in real time.

## 2.4 Design Features

The following sections will present the main design features for each of the major components in the variable compliance leg design.

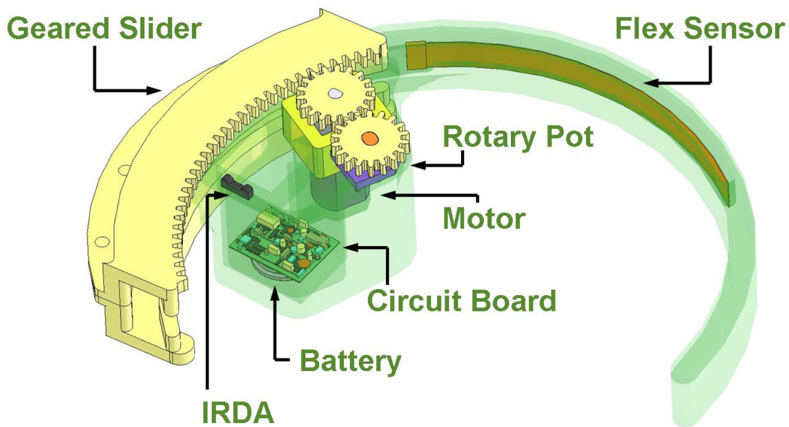
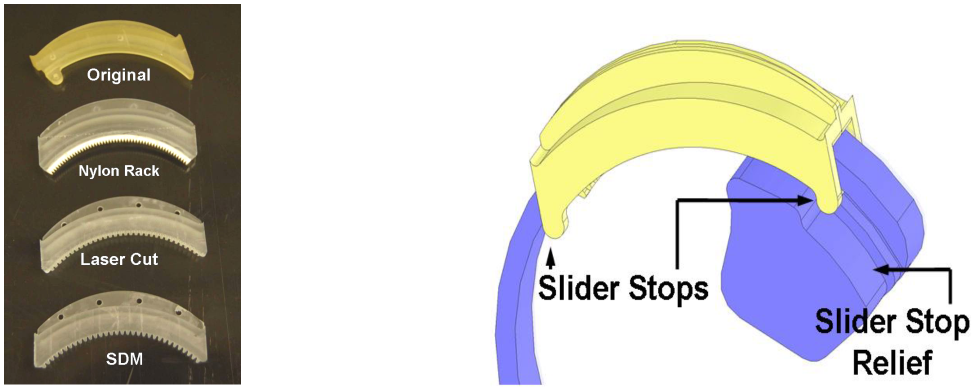



Figure 4: Final embedded leg design.

### 2.4.1 Slider

The main modification to the slider design was the addition of gearing to facilitate actuation. Three methods of adding gearing to the slider were explored. The first method was gluing a nylon rack purchased from Robot Objects to the bottom of the slider. This arrangement worked well but limited design flexibility because it relied on standard and available gear sizes. The next method used an X-660 Universal Laser System to cut the tooth profile into the slider. The accompanying motor gear was also cut using the laser. This arrangement also proved to be satisfactory but was not as dimensionally accurate as purchased gears due to the laser's wide and tapered cut. The advantage of using the laser cutter was the ability to make any size gear needed which provided great design flexibility See Appendix C for more notes on the laser cutting process. The final gearing method allows design flexibility while also providing dimensional accuracy by using a CNC mill to machine a mold for a slider with built in gearing. This is done as a step in the SDM process used to fabricate the sliders and is discussed in more detail in Section 3.7.

Another design feature of the slider is symmetry. Because of this feature, the same slider design can be used for both left and right legs. To make this possible, the back of the leg has a slider stop relief to give the slider full travel while preserving a positive stop at either extreme of slider travel. Finally, the overall change in stiffness that the slider provides from stop to stop can be easily controlled by varying the slider length.

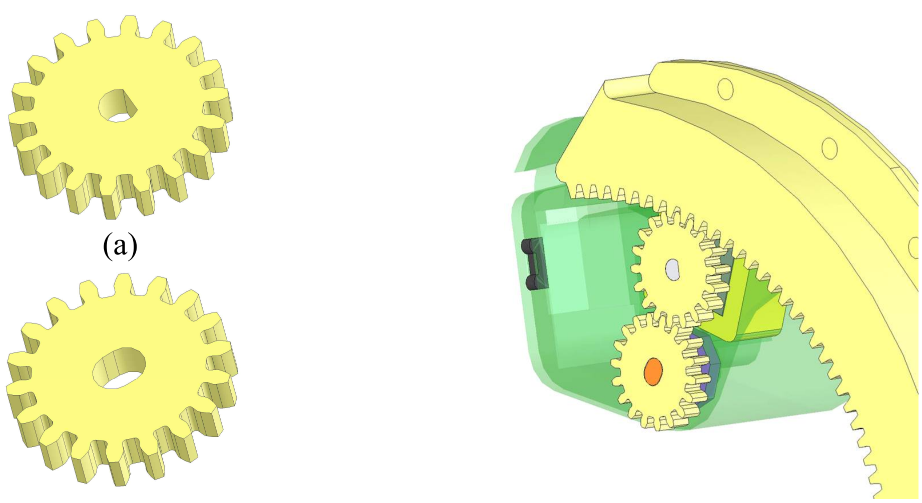



(a) (b)

Figure 5: Slider gearing iterations (a) and symmetric stops (b).

### 2.4.2 Motor and Pot Gearing

The initial motor gearing design used a worm gear to drive the slider. Due to the worm's large size and low speeds, this arrangement was quickly rejected. The second arrangement used a 48 pitch, 12 tooth spur gear. Unfortunately, no gears were available that could be directly mated with the motor so it was determined that the gears would have to be custom made. To make fabricating the gears easier, the design was changed to 32 pitch, 18 tooth gears which have significantly larger teeth. This change also resulted in a faster gearing ratio which reduced the time to actuate the slider from stop to stop. Figure 6 shows the custom gears made using the SDM process described in Section 3. Note how the thru hole allows for direct mating with the motor shaft and pot shaft.



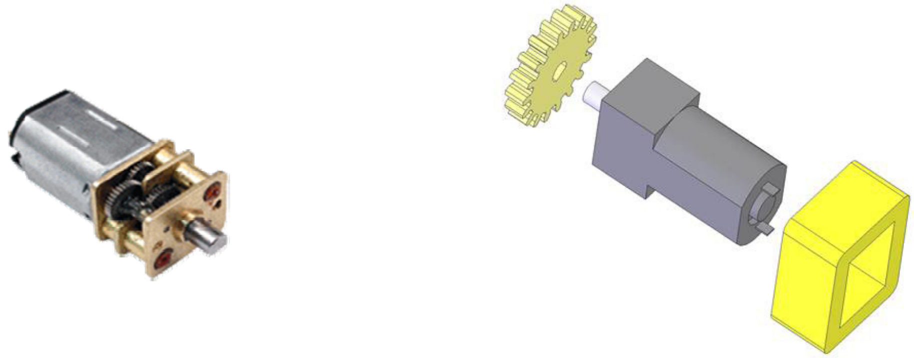
(a)

(b) (c)

Figure 6: SDM gears for the motor (a), rotary pot (b), and the final gearing assembly (c).

### 2.4.3 Motor Insert

A miniature 56:1 gearhead motor was embedded in the leg to provide actuation. To prevent the exposed gears from being encased during embedding, an insert was made which fit tightly around the gearhead. The insert served as a way to seal the gearhead as well as providing a means to position the motor in the leg during the embedding step.



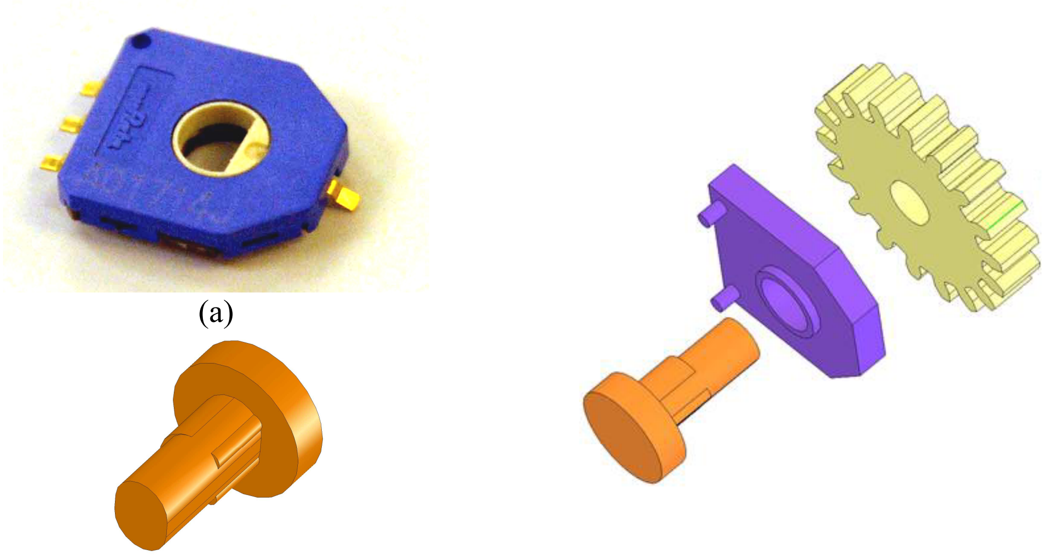
(a) (b)

Figure 7: Miniature gearhead motor (a) and the motor/insert/gear subassembly (b).

### 2.4.4 Slider Position

Before the microcontroller can send any actuation commands to the motor, it needs to know the current slider position. For this task, several sensors were considered. The most convenient solution would have been a motor with a built in encoder, but none could be found that were small enough. Another sensing method considered was a series of infrared LEDs positioned along the slider with a detector on the leg to determine slider position. This system, however, was rejected due to low resolution and to avoid having to embed numerous LEDs into each slider. The most promising option was to embed a magnet in the slider and use a Hall Effect sensor to detect displacement. However, as the slider moves down the c-leg, the magnet would have moved outside the range of the sensor.

The Murata rotary potentiometer was finally chosen for slider position detection for its high resolution and thin 2mm profile. Additionally, the D thru hole design made mating a gear to the pot possible. A custom shaft was made using SDM since no off-the-shelf alternative was found. The shaft needed to be a minimum of 9mm in height to reach thru the potentiometer and mate to a gear, so the smallest available end mill that could be used was 3mm. This resulted in a shaft that was too large in diameter for the thru hole. This problem was resolved by filing one side of the shaft until it fit in the thru hole. The resulting assembly can be seen in Figure 8.

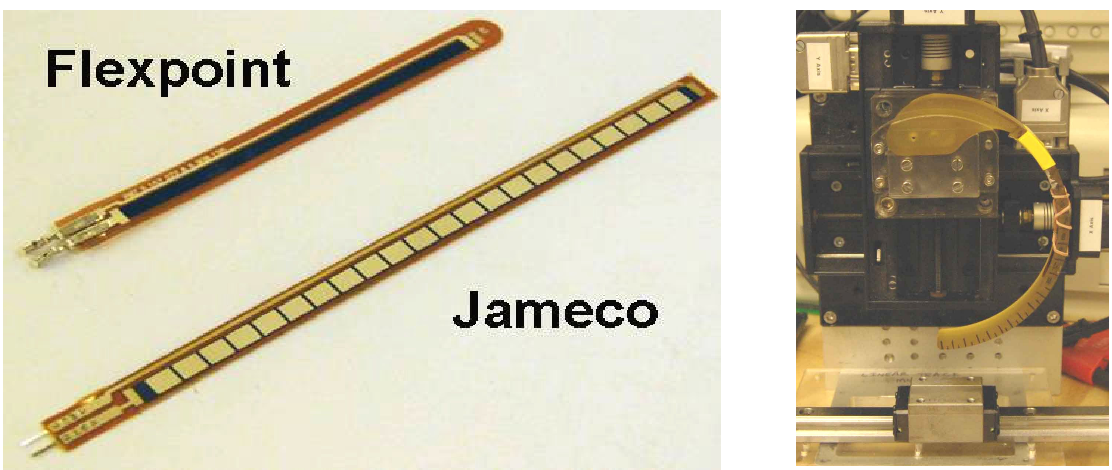


(a) (b) (c)

Figure 8: Murata rotary potentiometer (a), pot shaft (b), and pot gearing assembly (c).

### 2.4.5 Flex Sensor

A flex sensor is composed of a carbon/polymer ink which is printed on a thin flexible polyimide substrate. When deformed, the ink forms micro cracks which open and close according to how much the sensor is bent. This opening and closing causes a change in resistance of the sensor. By monitoring the resistance of the sensor, the microcontroller can determine the deflection state of the leg at any point in its rotation cycle.



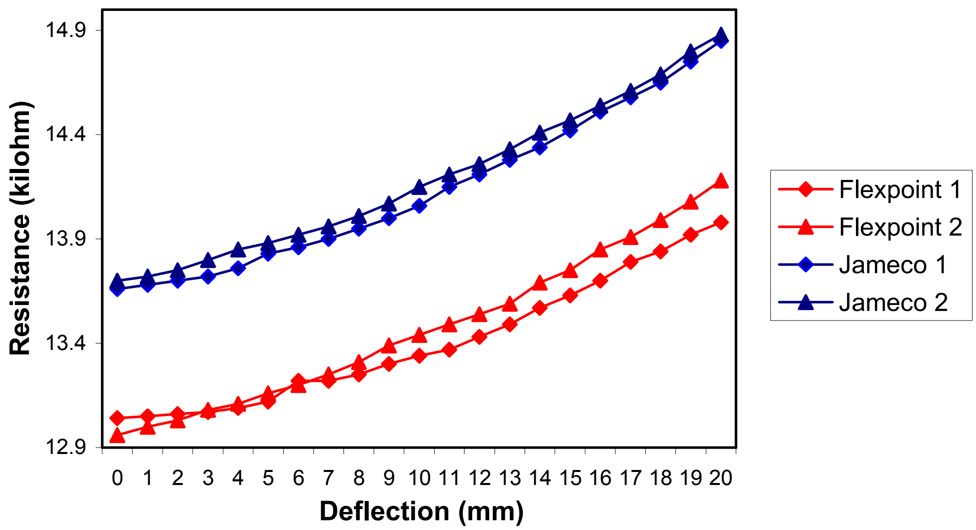

(a) (b)

Figure 9: Flexpoint and Jameco flex sensors (a) and linear stage setup used in testing (b).

Flexpoint Sensor Systems and Jameco are two suppliers that have flex sensors readily available. The Flexpoint sensors are significantly thinner and more flexible than the Jameco sensors. They are available at a variety of lengths, although the longest that was available at the time was 3 inches. Flexpoint is capable of manufacturing custom sensors at any combination of length, width, or laminate material to achieve desired resistance characteristics. The Jameco sensor comes at a single length of 4 inches. This is the only configuration which is available. Both sensors are 0.25 inches in width.

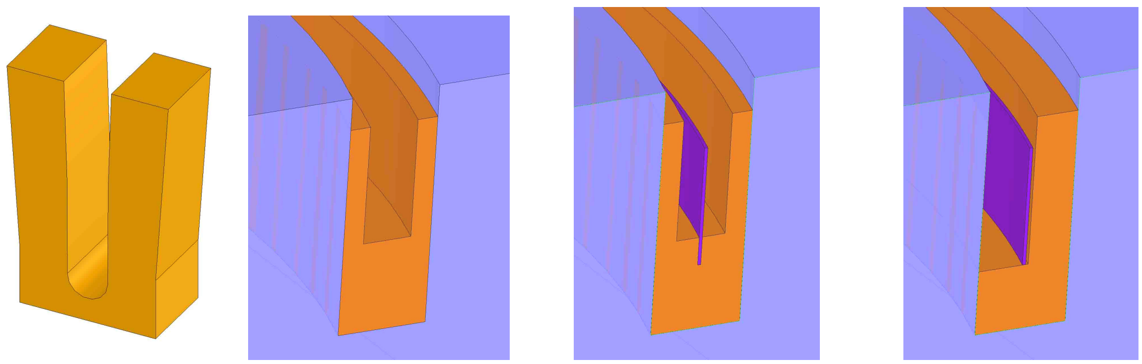
To compare performance characteristics, the flex sensors were attached to a leg which was positioned in a vertical linear stage as shown in Figure 9. The leg was deflected a total of 20mm in the vertical direction to simulate typical deflections that may be encountered under normal operation. The change in resistance as a function of deflection for 2 trials of each sensor is shown in Table 1. The overall change in resistance of the Jameco sensor was 1.19 kilohm compared to a change of 1.08 kilohm in the Flexpoint sensor. The Jameco sensor was selected because of this larger overall change in resistance and because it was longer. The extra length gives it a better range of detection as the slider is moved down the leg. Nevertheless, it is suggested that the possibility of custom sensors from Flexpoint be explored. A 6 inch flex sensor with custom tailored resistance properties could potentially be superior to any currently available sensor for our application. See Appendix C for a more detailed discussion of the Flexpoint sensors.

Table 1: Flex Sensor Resistance vs. Deflection




Embedding flexible components is inherently challenging. To prevent shear forces from affecting deflection readings, the sensor was required to be positioned exactly in the middle of the leg along the neutral axis. Three possible fixturing solutions are illustrated in Figure 10. All three are based on the principle of machining a pocket into the leg once it has been poured, inserting the sensor, and then pouring a second layer of polymer. The inserts shown in (a) would be made of the same TP-4004 polymer used in the leg to preserve consistent material properties. When pressed into the slot, the insert clamps onto the sensor and positions it along the neutral axis. Option (b) uses a slot in the middle of the leg. A laser cutter is then used to cut a thin slit along the neutral axis. The sensor is then slipped into this slit for fixturing. Option (c) uses a slot along the face of the c-leg instead of the middle. This allows the sensor to be glued directly to the inside of the leg before pouring the second layer of polymer.

Since option (a) relies on custom fabricated inserts and option (b) requires an extra step for the laser slit, option (c) appears to be the best solution in terms of simplicity. For the initial leg prototypes, option (a) could not be tested due to time constraints. Nevertheless, between options (b) and (c), gluing the sensor directly to the inside face was the easiest way to fixture the sensor. It should be noted, however, that from a structural perspective option (c) is more prone to delaminating. For this reason, it is suggested that (a) or (b) be used if delamination becomes a problem.



(a) (b) (c)

Figure 10: Flex sensor embedding options: Insert and Insert Slot(a), Middle Slot with laser slit and flex sensor (b), and Face Slot with flex sensor(c).

One possible alternative to flex sensors that was explored was a thin piezoelectric sensor from Advanced Cerametrics. Since piezoelectric sensors output a voltage proportional to force, these could be used to detect leg touchdown and liftoff but would not be able to indicate the degree of leg deflection. However, flex sensors were selected because they can be used to detect not only touchdown and liftoff, but also deflection.

### 2.4.6 Electronics

At the time of this writing, the electronics side of the leg design has not been completed. A lot of progress has been made on wireless IrDA communication but microcontroller cannot yet read sensory input or control slider position. Therefore, the prototype legs that will be discussed in Section 3 have no electronics or battery embedded. Nevertheless, a pocket meant to accommodate the necessary circuitry is built into the design under the shaft clamp pocket. To allow for changes in design, the solid model is easily reconfigurable to accommodate any reasonable size circuit board.

The eventual choice in battery could have a significant impact on the leg design. If a coin battery is used, it could easily be positioned with the circuitry under the shaft clamp pocket. If instead a cylindrical battery is chosen, the battery could be embedded under the rotary potentiometer. These design decisions will need to be made once the power requirements of the electronic components are determined.

### 2.5 Design Outcomes

With the leg design described in the preceding sections, it is possible to have an intelligent leg which can react to its environment by changing its stiffness in real time. The flex sensor can used to detect leg deflection, time of contact, time of liftoff, and overall stance time. Using degree of deflection, the robot could adjust leg stiffness to compensate for changes in speed, terrain, and even weight. The timing of touchdown and stance time could be useful in climbing stairs or adjusting for a change in slope as discussed in [13]. How much of this potential is taken advantage of is mostly dependant on microcontroller processing power and information throughput between the leg and robot.

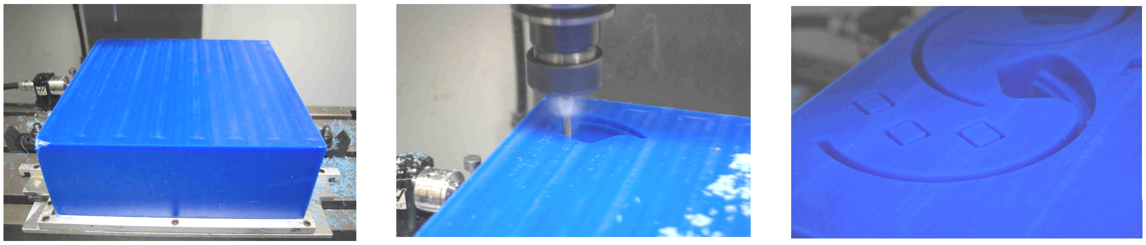
Decision making hierarchy is one of the yet to be answered questions. By hierarchy, we mean how much of the sensory information should be passed to the robot body for high level decisions and how much should be used for low level control. For instance, each leg could, in theory, alter its own stiffness based on deflection without any input from the robot. Alternatively, each leg could communicate its deflection state to the robot which would then use all 6 leg deflections to make more informed decisions. The answers to these questions will become clearer as the electronic design progresses. Regardless of the exact application that is eventually implemented, the mechanical aspect of the design will stay constant.

## 3. SHAPE DEPOSITION MANUFACTURING

As mentioned in the introduction, Shape Deposition Manufacturing offers a number of advantages over other prototyping techniques. Of particular interest for robotics is the ability to construct complex geometries without resorting to unconventional machining, the possibility of using multiple materials in the same part, and most importantly, the ability to embed components. As implemented in the current leg design, material removal consists of machining operations using either a HAAS CNC MiniMill or a Laser Cutter. The material used for the leg and other components is a two component thermoset polyurethane from Innovative Polymers. A number of formulations are available providing a wide range of material properties. The leg and motor insert use TP-4004 material while the slider, gears, and pot shaft use VA-273.

### 3.1 Machining Step 1

Every SDM part starts as a solid block of machinable blue wax available from a number of suppliers. The wax is easy to machine, self lubricating, and requires no release agents. The first step of the process is to CNC a cavity to the outside dimensions of the leg. The cavity has raised features (islands) that form features on the back side of the leg including the slider stop and slider slot. Since this is the deepest machining step, it is important to keep in mind the depth limitations of the end mills that are available. The leg was design so that either a 3mm or 6mm end mill could machine the features. Since a 3mm end mill can only machine to a depth of 25, and a 6mm end mill can only machine to a depth of 40 mm, it is important that the features at the respective depths can be machined using those diameters.



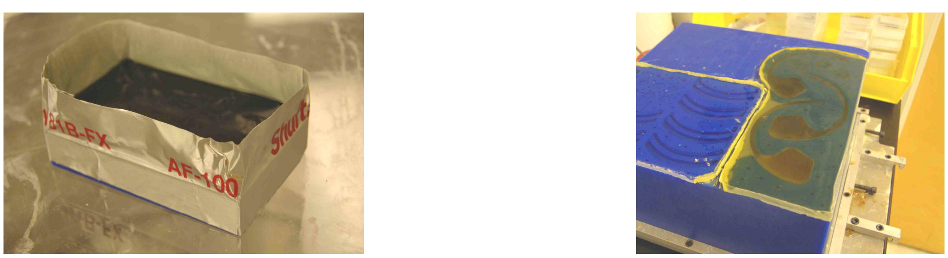
(a) (b) (c)

Figure 11: Machining Step 1 pictures: Wax block (a), Machining the cavity (b), Wax mold (c).

### 3.2 Pour 1

Once the cavity is machined, the next step is to deposit material. To prevent overflowing, the wax block is lined with aluminum tape along its parameter. If it is undesirable to flood the entire wax block with polymer, additional barriers can be constructed using modeling clay and the same aluminum tape. The resin and hardener are carefully measured out to the appropriate ratio using an electric scale. The less viscous liquid is poured into the more viscous liquid and vigorously mixed. The mixture is poured into the cavity with plenty of extra material to make sure that any imperfections at the surface are not included in the part. This extra material will be planed in the subsequent machining operation.

The material is degassed using a vacuum chamber to get rid of any air bubbles created during mixing and to make sure that all of the mold cavities are completely filled. When placed under a vacuum, the polymer mixture 'boils' and expands, sometimes as much as 4 times its original volume. For this reason it is important that the aluminum tape overflow barrier be high enough to contain this expansion. After a few minutes, the chamber is returned to atmospheric pressure and the polymer is allowed to cure.

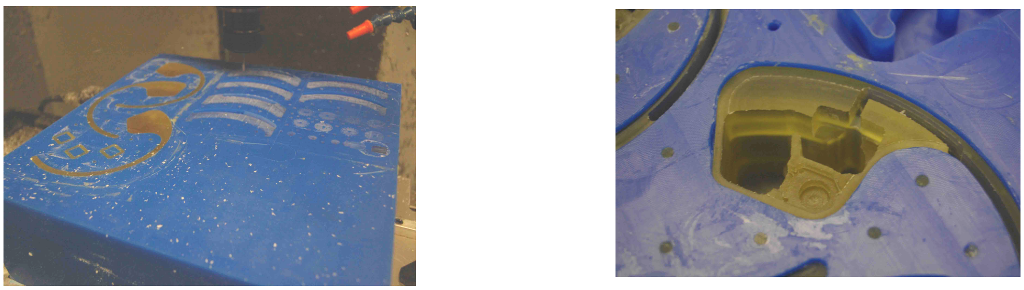



(a) (b)

Figure 12: Pour 1 pictures: Example of aluminum tape lining (a), After curing (b). Note the left over yellow modeling clay where a barrier was placed between the two materials.

### 3.3 Machining Step 2

The next step is the second machining operation. The extra material from the first pour is planed down to the wax surface using a 1inch end mill. Care needs to be taken during this step to make sure that the legs do not lift out of the mold. Channels for wiring and pockets for the motor insert, rotary pot, flex sensor, and electronics are machined. Again, it is important to keep in mind the depth of cut limitations of available end mills. Once the pockets and channels are machined, all of the components to be embedded can be inserted. This machining step is also used to make a set of wax caps for the motor and pot shafts. For more on the wax caps, see Appendix C.

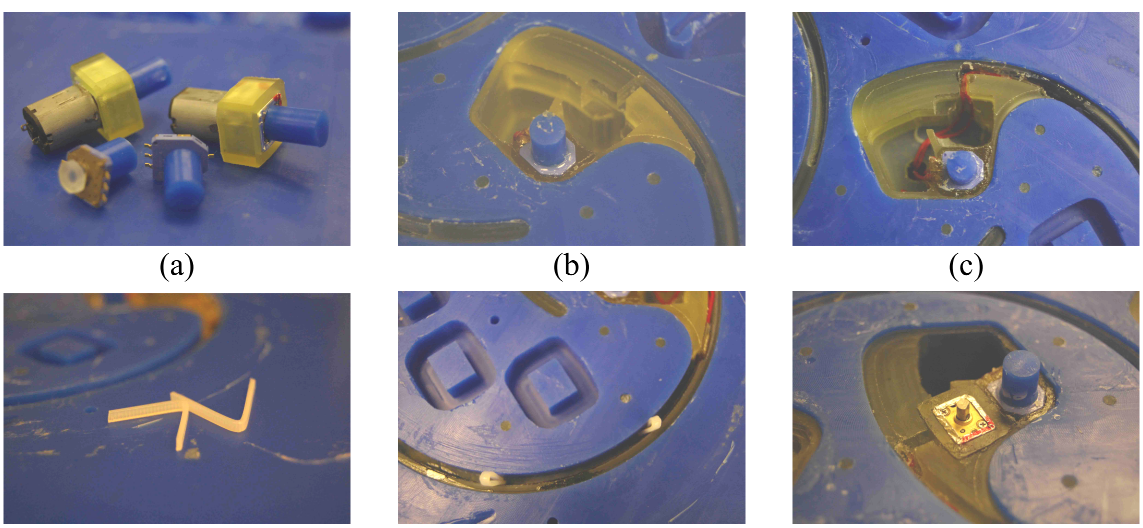


(a) (b)

Figure 13: Machining Step 2 pictures. Planed Mold (a), Machined Cavity (b).

### 3.4 Embedding

The flex sensor is positioned into place using one of the three methods described in Section 2.4.5. Next, the potentiometer assembly described in Section 2.4.4 is inserted. To allow the pot shaft to freely rotate after embedding, a relief has been machined under the pot which is sealed off to prevent any polymer from entering. The motor/insert/cap assembly shown in Figure 14a is then inserted into the motor insert pocket. Using the outside dimensions of the insert as the inside dimensions of the pocket resulted in a nice tight press fit between the insert and pocket.



(a) (b) (c)

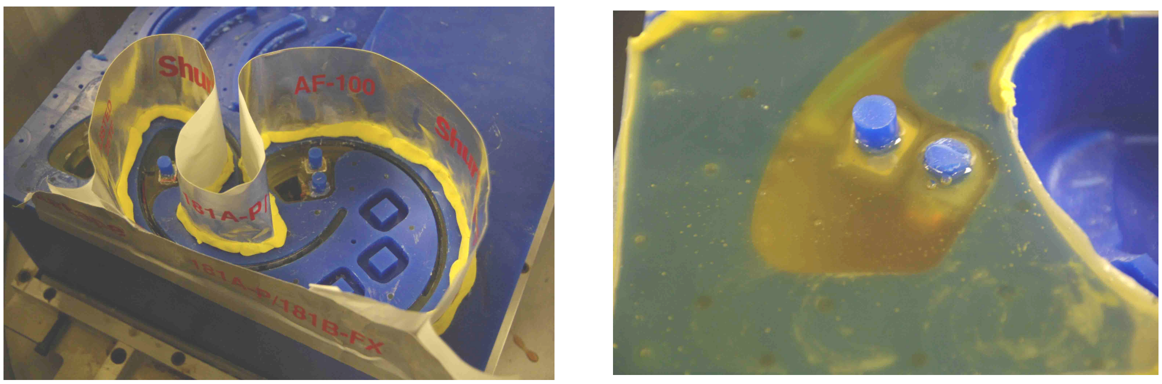
(d) (e) (f)

Figure 14: Embedding: Motor/insert/cap assembly (a), Embedded Pot (b), Flex Sensor Wiring (c), Zip Tie Holders (d), Holding the Flex Sensor in place (e), Motor Inserted (f).

In the final leg design, all of the components would be soldered to a circuit board and inserted during this step. In our case, since the circuitry was not ready yet, all of the wires were pushed into a hole drilled through the back of the leg and filled with modeling clay. The wires were later used to test each of the components.

### 3.5 Final Pour

Once the components to be embedded were inserted, a second pour of polymer is deposited on top of the components. This time, however, the mixture iss first degassed in the mixing cups and then poured into the mold. This iss done to prevent and polymer from being forced into any of the sealed components. Again, it is important to pour plenty of extra material to make sure that any bubbles or other imperfections on the surface do not extend into the part.




(a) (b)

Figure 15: Final Pour pictures: Aluminum Tape Barrier (a), After Curing (b).

### 3.6 Machining Step 3

At this time, the final machining operation is performed. As before, the extra material is planed down to the surface of the wax. It is important not to cut into the protruding motor or pot shafts. To aid in this, the wax caps are used as a buffer between the end mill and shafts. Once the surface is planed, the final features (shaft clamp pocket, slider slot) on the front of the leg can be machined. As before, care needs to be taken to make sure that the leg does not get lifted out of the mold. It is also important to slow down the cutting feed rate to prevent the first pour and the second pour from delaminating. The final machining step is to machine the wax around the leg to aid in leg removal. The leg can then be removed from the wax.

### 3.7 Slider

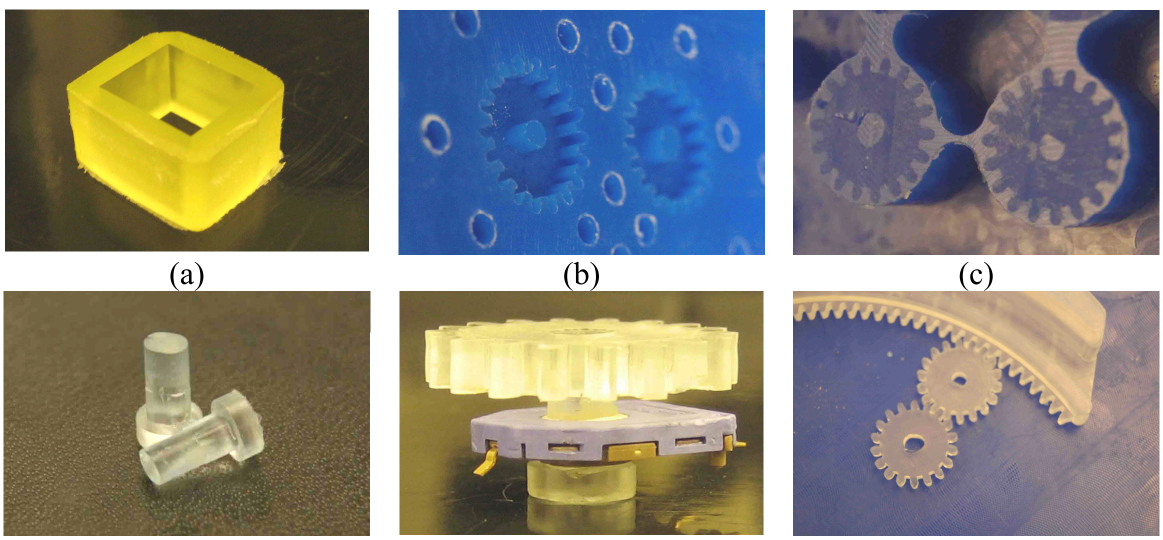
The slider is fabricated using a similar, albeit simpler, SDM process. Since there are no embedded components, the intermediate machining and embedding steps can be skipped. The slider's 2 piece snap fit design dramatically simplifies the manufacturing process compared to what would be necessary to achieve a one piece design. Just like the leg, the slider starts with a solid block of machinable blue wax. A cavity is machined with the appropriate profile and with islands to define all of the features on the back of the slider. Note that the cavity includes the gear teeth for the geared side of the slider. Once the mold is machined, VA-273 polymer is mixed and poured into the mold before being degassed. The final machining step thins the flange and removes the wax surrounding the slider halves for easy removal.

(a) (b) (c)

Figure 16: Slider Cavity (a), After 2$^{nd}$ Machining Step (b), Close Up of Gears (c).

**3.8 Insert/Pot Shaft/Gears**

The insert, pot shaft, and gears are made using an even simpler SDM process. For these components, a cavity defines all of the necessary features in the first step. Once the material has cured, the wax around the components is machined away and each piece is removed.



(a) (b) (c)

(d) (e) (f)

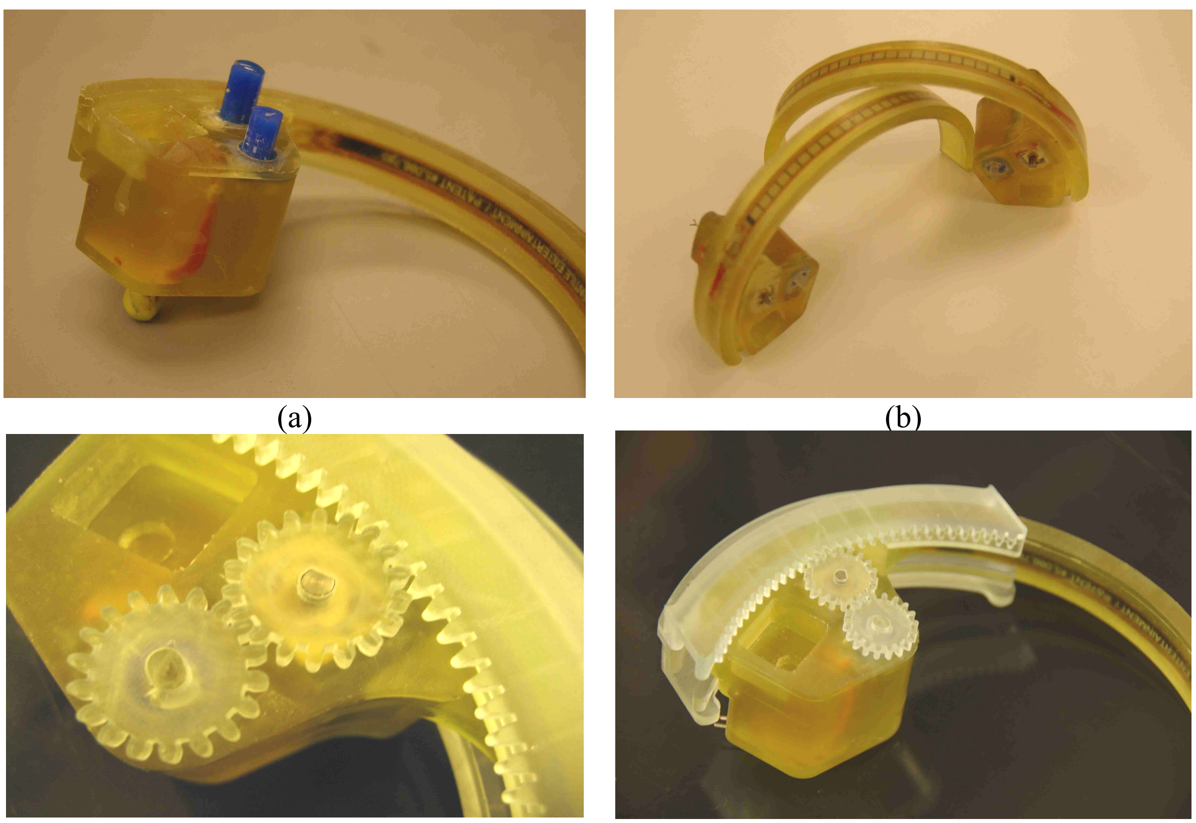
Figure 17: Motor Insert (a), Gear Pockets (b), Planed Gears (c), Pot Shaft (d), Pot/Shaft/Gear Assembly (e), Motor Pot and Slider Gears (f).

## 4. RESULTS

### 4.1 First Prototypes

Initially, two legs were made using the steps discussed in Section 3. For these prototypes, only the motor, rotary potentiometer, and flex sensor were embedded since the other components were not available. The wiring from the embedded components was passed thru a hole drilled in the back of the hip as seen in Figure 18a. The only difference in technique between the legs was that one of the legs used a face slot to embed the flex sensor while the other used a middle slot.

The motor wires were connected to a power supply to test functionality. Unfortunately, neither leg had a working motor. This was most probably due to insufficient sealing of the insert to withstand the vacuum pressures. The flex sensors were also tested revealing that the middle slot flex sensor worked as expected while the face slot flex sensor failed to change resistance under bending. No immediately identifiable explanation for this was found unless the sensor was faulty even before embedding. One of the pots worked as planned while the other did not rotate at all. It is believed that excess superglue got into the pot during sealing.



(a) (b) (c) (d)

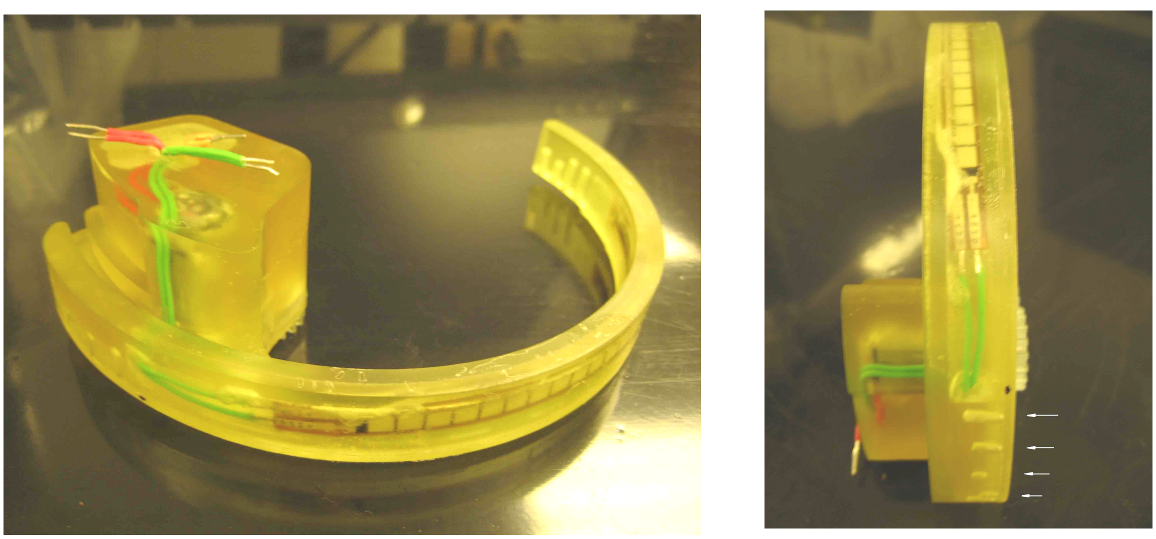
Figure 18: Pictures of the first prototype legs.

Another observation was delamination between the first and second pours of polymer. It was most evident where flat horizontal surfaced were found. Due to scheduling conflicts on the CNC machine, the second pour was deposited over one week after the first pour had cured. It is suggested that the second pour be deposited as soon as possible to promote better adhesion between layers. It would also be helpful to include anchoring holes where large horizontal surfaces are found to provide more surface area for bonding.

### 4.2 Final Prototype

A third leg was fabricated to address the problems found in the first prototypes. Much more care was taken to carefully seal each the motor and potentiometer. The polymer was also degassed before being poured into the mold to avoid putting the sealed insert under vacuum. Finally, some holes were drilled in large horizontal surfaces in the hope of preventing delamination.

The third leg had a fully functioning motor thanks to the more careful sealing. The flex sensor worked as expected and changed its resistance as the leg was bent. The pot worked mechanically, but one of the wires had a poor electrical connection due to rough handling during embedding. Unfortunately, the holes drilled in an effort to improve bonding were too small in diameter to get air bubbles out as seen in Figure 19b. It is suggested in the future to use channels instead of holes to prevent air pockets.



(a) (b)

Figure 19: Leg prototype 3. Note the white arrows in (b) marking the air pockets where holes were drilled to improve bonding.

## 5. CONCLUSION

Biological studies have shown that running animals change their leg stiffness to adjust to changes in terrain, speed, stride frequency and weight. In an effort to extend Edubot's already impressive capabilities, a variable compliance leg has been designed. Working on the principle of a cantilevered beam, the slider design is both simple and effective. However, the leg also needed mechanical actuation, deflection sensing, slider position detection, microcontroller control, and wireless communication to change its stiffness in real time.

The inconvenience of a continuously rotating leg combined with weight and size constraints led to a significant design challenge. A layered prototyping technique known as Shape Deposition Manufacturing was chosen for its ability to embed components and fabricate arbitrary shapes. The key to the SDM process is decomposing a complex 3-D design into a series of simple 2.5-D steps that can be performed using conventional machinery. Thanks to the top-down design methodology and parametric modeling environment described in Appendix A, the leg design is easily editable. This is of particular importance since the electronic components were not yet available at the time of this writing.

Using the SDM prototyping method as outlined, three prototypes were made. The results demonstrated a number of challenges inherent to the process. Most important of which is the need to completely seal vulnerable components from polymer. Despite some problems, the final prototype demonstrated that the design was feasible and readily manufacturable. The eventual goal of this project is to give Edubot legs which by sensing their leg deflection can adjust their own stiffness to accommodate changes in terrain, speed, or weight while also communication wirelessly with the robot for higher level decision making.

## 6. ACKNOWLEDGMENTS

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# Appendices

**Appendix A**
SolidWorks Walkthrough

**Appendix B**
FeatureCAM/SolidWorks/AutoCAD Interface

**Appendix C**
Assorted Remarks

**Appendix D**
List of Materials and Suppliers

**Appendix E**
List of Important Files

## Appendix A
## SolidWorks Walkthrough

SolidWorks is a robust parametric 3D design and modeling software package. The solid models typically start as 2D sketches which get extruded into 3D parts. Subsequent operations can then add or remove material via extrusions or holes. In parametric modeling, the part or assembly is defined with constraints and dimensions to impart the design intent desired. A constraint is a relation used to drive the behavior of a sketch entity or set of entities. Common constraints are parallel, perpendicular, vertical, horizontal, concentric, tangent, and coincident. Dimensions in a parametric model can also be used to impart design intent. Many parametric modeling software programs including SolidWorks allow mathematical equations within the dimensions which allows for interdependent dimensions. If one of the dimensions is changed, the part or assembly automatically updates based on the parametric constraints and relations.

For more information on parametric modeling, constraints, and equation driven dimensions, see the ***SolidWorks Fundamentals*** and ***Sketching*** articles in the SolidWorks ***Help Topics*** found in the ***Help*** dropdown menu. This help file has additional information and tutorials which can be referenced for more information on any of the topics to be discussed in the following sections.

### Bottom-Up vs. Top-Down

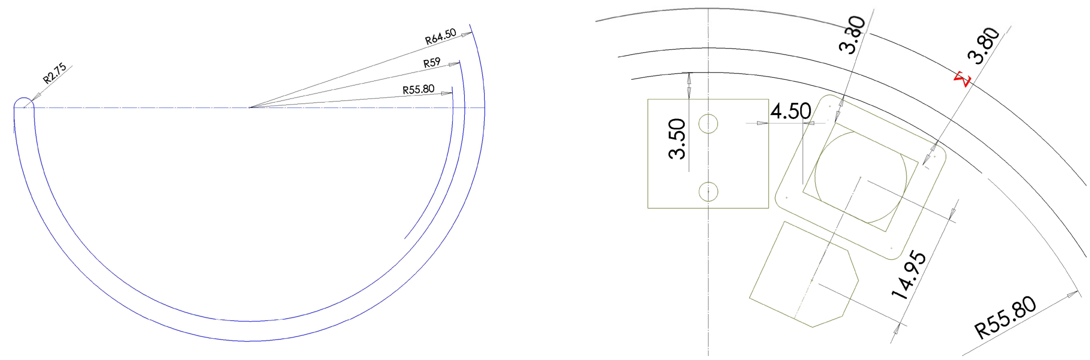
The traditional design methodology is often termed bottom-up design. In this method, parts are created separately and then inserted into an assembly where various mates define their relations to other parts. This method is very convenient when using off-the-shelf parts. For designs where parts have interrelated dimensions and features, however, this method can prove to be difficult and inefficient. For instance, in bottom-up design a change in dimension on one part may require manual adjustment of several other parts to maintain design intent. To avoid having to essentially redesign the leg every time a small change is needed, a top-down design methodology was used. In this method, design starts in an assembly with each component designed in context to other components. The geometry of one part can be used to define other parts.

***Note: the following discussion is a walkthrough of the design implemented in the assembly file Motor Embed Rev 4. It is suggested that the reader have access to this file for reference.***

### Layout Sketch

Using top-down design methodology, the composite SDM leg assembly starts with a layout sketch. This feature is crucial to an easily editable design. The layout sketch defines where each component is positioned relative to every other component. Before anything is designed, the components that have to remain constant need to be sketched.

For this design, the leg radius, leg thickness, slider slot radius, and hip clamp position were fixed, so these components were drawn up first as seen in Figure 20.

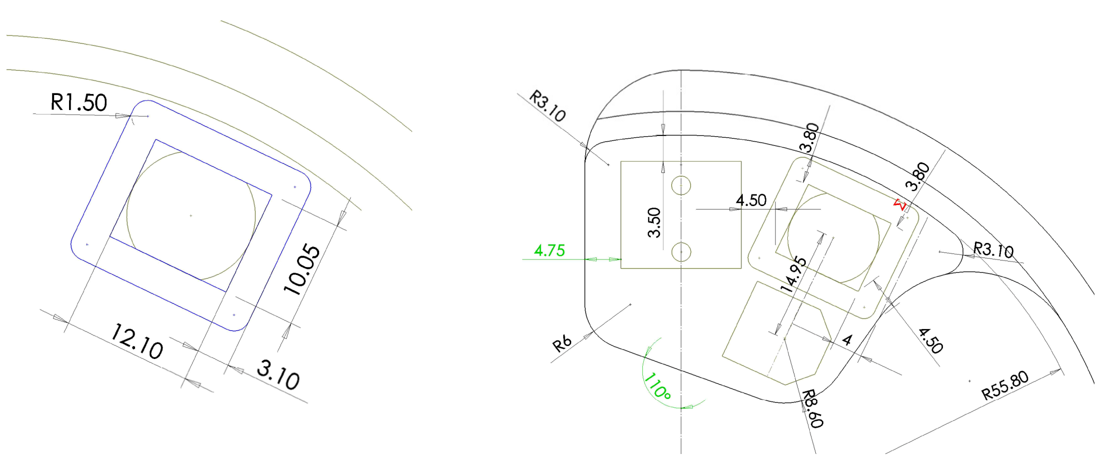



(a) (b)

Figure 20: Layout Sketch Steps: Defining the leg and slider slot (a), and positioning the embedded components (b).

**Blocks**

Since the outside dimensions of the motor, insert, rotary pot, and shaft clamp pocket are constant, the perimeters of these two components are sketched next. To help keep the layout sketch uncluttered, blocks were used. A block acts as a sketch within a sketch and is very useful for defining the outside parameters of the motor and pot. To form a block in SolidWorks, go to ***Blocks*** in the ***Tools*** pull down menu and select ***Make***. Select the relevant sketch entities and click ok. From now on, to edit any of the entities within the block, right-click the block in the feature tree and chose edit. You can also break up the entities by choosing explode block. Note that once a block is formed, the dimensions that were used to define the entities are hidden when not editing the block. This cleans up the sketch from unnecessary dimensions. Additional blocks for the motor insert and shaft clamp were also made. The motor insert in this case is simply a 3.1mm ring around the motor with 1.5mm rounded outside edges. This allows for the insert to be machined using only a 3mm end mill.



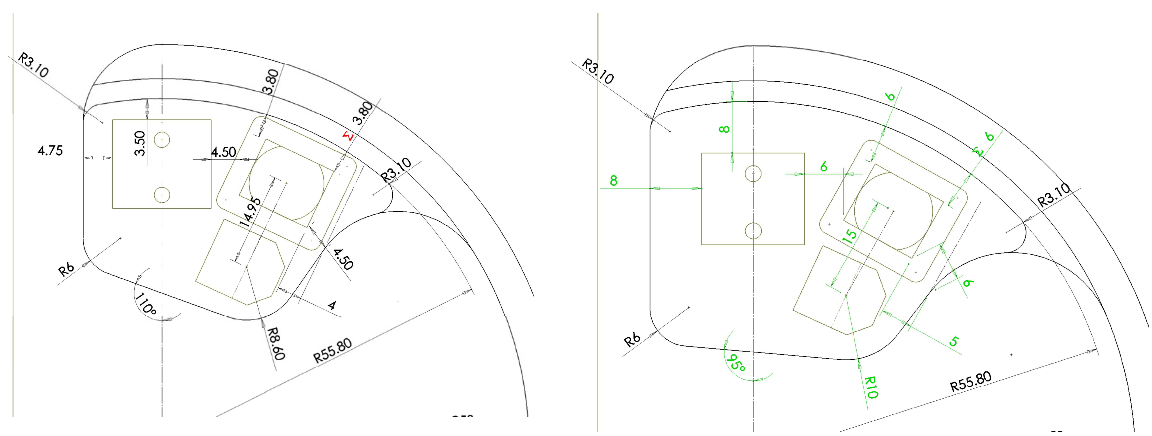

(a) (b)

Figure 21: SolidWorks Blocks: Editing the Insert Block (a), and final hip design (b).

Once the blocks are formed, they can be dragged and rotated as a single entity. At this point, the motor can be positioned as close as possible to the shaft clamp as mentioned earlier. It was decided that a minimum of 1.5mm should be left between the various components so the motor was defined as being a total of 4.5 mm away from the shaft clamp. The other dimensions used to place the motor and pot are driven by the pitch diameters of the gearing and are explained in detail later in this section. Note the use of an equation driven dimension to position the motor perpendicular to the slider slot arc. Also note the orientation if the pot. The lone pin on the front of the pot in Figure 8 is not required for normal operation. To make wiring to the circuit board easier, the pot was oriented such that the necessary pins face where the circuit pocket will be machined.

### Hip Design

At this point, a design for the hip shape can be developed. In addition to housing components, the hip also needed to be aesthetically pleasing. And as mentioned earlier, it had to be easily editable to accommodate the yet to be completed circuitry. To this end, the hip was designed using continuous curves and defined using parametric dimensions. A 1.5mm minimum offset was maintained around each component for structural integrity. Since the hip was the deepest feature in the leg, all of the radiuses were at least 3mm to make sure that they could be machined using a 6mm end mill. The 8.6mm radius at the potentiometer made sure that the hip profile contained the pot gear having a radius of 8.13mm.




(a) (b)

Figure 22: Demonstration of parametric design capabilities: Before any changes (a), and after adjustments (b). All of the dimensions in green have been changed drastically. Note how the overall design intent is maintained.

To achieve the clean continuous curvature of the hip, careful attention was paid to how each arc and line was constrained to achieve a design that would be able to accommodate perturbations. For instance, if it were decided that the motor should be further away from the shaft clamp, the curves should be able to automatically reconfigure to maintain the design intent. This concept is something that is not easily described on paper. To best appreciate the flexibility offered by parametric modeling, the reader should change some of the dimensions to see first hand how the sketch adjusts to changes. Figure 22 shows an example of how the design intent is maintained despite dramatic changes in dimension values. One interesting result of this design is that even with significant changes in the hip size, the length of the c-leg remains essentially unchanged.

Note that the layout sketch does not contain all of the features that will eventually be included in the design. There are two reasons for this sketch. The first reason is to figure out how each of the embedded components will be arranged relative to each other. The second reason is to define the outside perimeter of the leg. Since the remaining features and components have no influence on the leg perimeter, they can be left out of this sketch and defined in a later sketch. The motivation behind this is to keep the sketches as uncluttered as possible so the design intent behind the constraints and dimensions is easily identifiable. The only other components that may need to be included in the layout sketch are the circuit board and IrDA when the electronics development is complete. If so, only the outside parameter of each component should be made into a block and used to redefine the sketch. For now, the distance and angle in green in Figure 22 can be changed to accommodate any reasonably sized circuit board.

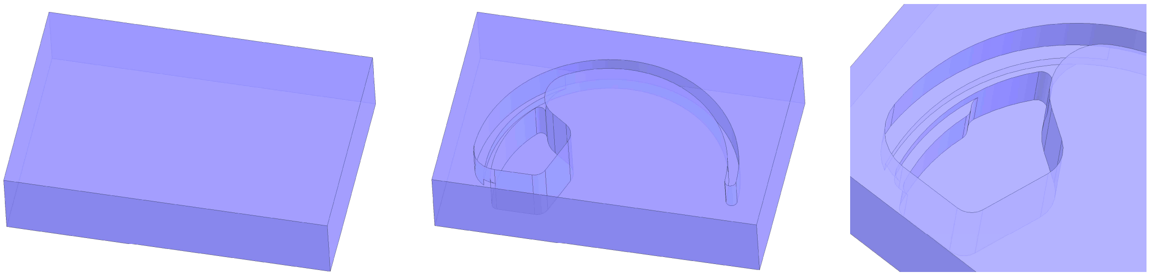
The final entity to be created in the layout sketch is the wax block perimeter. For now, the dimensions are arbitrary but could eventually be used to define the raw material dimensions being used. The resulting layout sketch can now be used to define the remainder of the features and components in this assembly.

**Side Note: SolidWorks for SDM**

Being a layered prototyping technique, SDM presents a number of challenges for the designer. The design process has to be thought of in terms of each layer and its manufacturability. A careless design could be difficult or even impossible to make. The top-down methodology is a useful tool to combat this problem because it allows for easy adjustment of dimensions and components as problems in the design are realized. Another technique used in the leg design was to develop the design using the same alternating steps of depositing and removing material used in SDM. In other words, the eventual 3D solid model is built up using the same 2.5D steps taken during fabrication. This approach allows the designer to easily identify potential manufacturability issues; ensuring that the part can be made using SDM.

**Wax**

The assembly begins just as the SDM process does with a solid wax block. For this, we need to insert a new part by going to ***Insert>Component>New part***. In this new part, make a new sketch called Leg Mold. Make the Layout Sketch visible by right clicking on it in the feature tree and select ***Show***. The outside perimeters of the leg and slider slot are selected by holding down ***Ctrl*** and clicking on all of the edges. Now click ***Convert*** in the sketch menu. The Layout Sketch can now be hidden. Convert has projected the selected edges in the Layout Sketch onto the current sketch. This new sketch will be updated automatically when any changes in the layout are made. The next step is to machine the cavity for the leg mold. Using the same convert function, the edges defining the leg can be transferred to a new sketch. This sketch is then used to 'machine' the leg mold using an extruded cut feature.



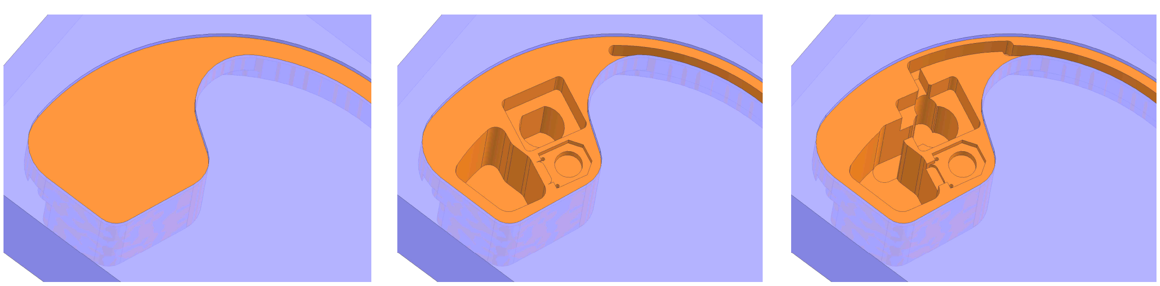
(a) (b) (c)

Figure 23: Wax block (a), Leg Mold (b), and slider stop relief extrusion (c).

To add the slider stop relief, we start another new sketch. Hiding the wax block and making the Layout Sketch visible will let us again convert the edges we want from the layout. This time, we only need the bottom edge of the slider slot and the left edge of the hip. Make sure to hide the Layout Sketch to avoid confusion. The converted edges are now used as references to design the slider stop as desired. This resulting profile is then used to extrude a boss up from the bottom of the hip pocket. Make sure to check the merge result box in the feature options. The cavity, representing the first machining step is now complete. At this point, it is important to make sure that this step is feasible in terms of manufacturability. For example, any radius below 25mm needs to be a minimum of 3mm.

**Pour 1**

The next step is to insert another new part to represent the first pour of polymer called Pour 1. The outside perimeter of the leg is converted to a new sketch and extruded using the ***Down To Body*** option. Now the pockets and wiring channels can be 'machined'. Again, any relevant edges are converted from the Layout Sketch and used to define the new features. Note that each pocket or channel is defined in a new feature using its own sketch. Decoupling the features in this manner is crucial to making the part easily editable.



(a) (b) (c)

Figure 24: Pour 1 (a), with machined pockets (b), and with wiring channels (c).

It is important to note here that it is helpful to make the sketch plane for all sketches the top plane of the assembly to prevent any confusion when the depth of any features needs to be changed. It is also usually simpler to define depths with respect to the top plane of the assembly.

It is also important to note that Pour 1 has two configurations. The configurations define the features necessary for embedding the flex sensor using either a face slot or middle slot as discussed in Section 2.4.5. To change the configuration, open the part, and click on the configuration tab in the feature tree. Double clicking on the configuration will change the configuration for the part and assembly automatically. The middle slot configuration will automatically suppress the face slot pocket and set the middle slot to resolved whole the face slot configuration does the opposite.

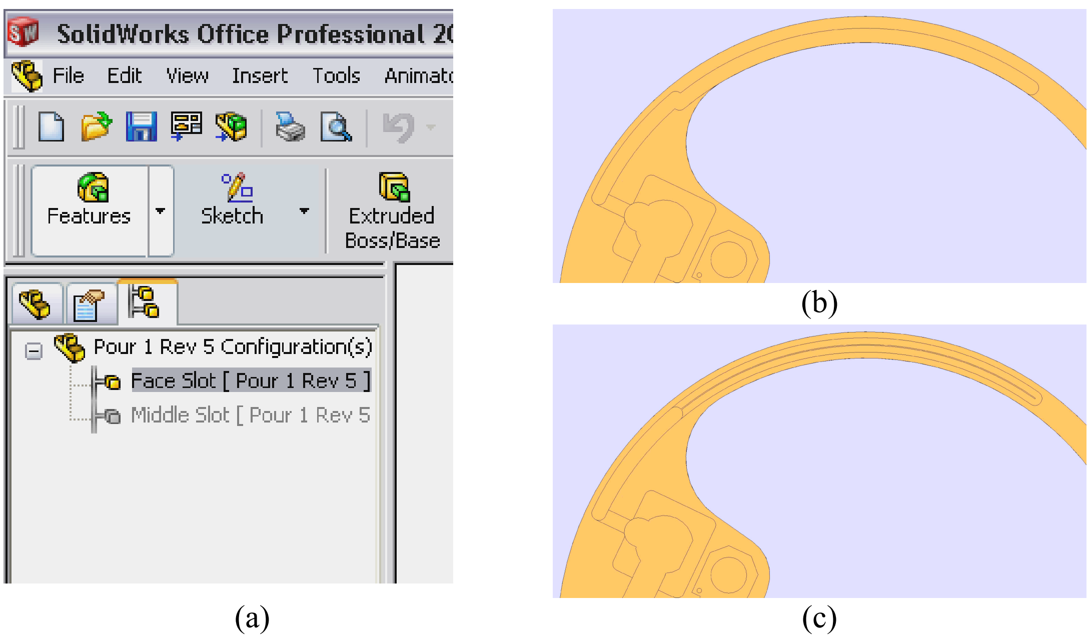
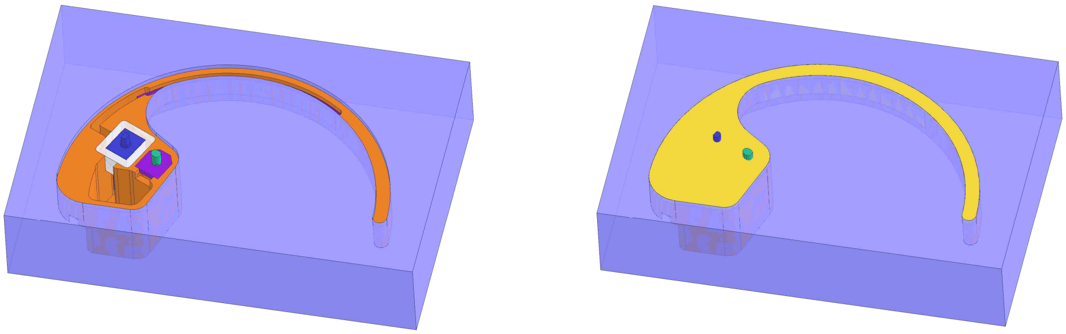


Figure 25: SolidWorks Configurations: Location of configurations tab (a), Face Slot Configuration (b), and Middle Slot Configuration (c).

**Insert/Motor/Pot/Pot Shat/Flex Sensor**

Since these components can be modeled without referencing the layout sketch, there is no need to model them in the context of the assembly. Therefore, they are modeled separately and inserted into the assembly by going to ***Insert>Component>Existing Part***. They are then positioned by defining mates between the part and other parts in the assembly. For more information on mates within assemblies, see the ***Assembly Mates*** help file.



(a) (b)

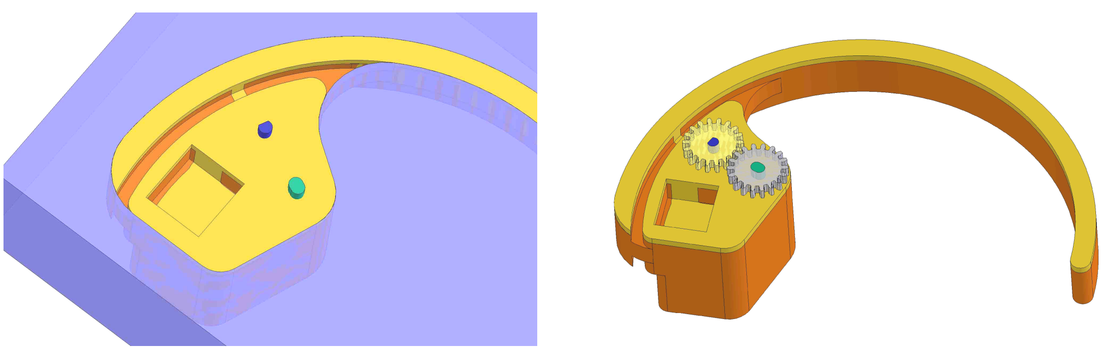
Figure 26: Mated components to be embedded (a), and the final pour of polymer (b).

**Final Pour**

The next step is to 'pour' the second layer of polymer. Again, the necessary edges are converted from the Layout Sketch. The leg profile is then extruded down. For this operation, select ***Up To Body*** in the ***Direction 1*** pull down menu. Then select Pour 1 from the feature tree. This 'fills' in the cavity up to the first pour in a manner synonymous to the actual SDM step. One interesting advantage of doing this is the ability to calculate the volume of polymer required for each individual step. It is also helpful in visualizing what is happening in the SDM process.

**Clamp Pocket/Slider Slot**

Note that the Clamp Pocket and Slider Slot extruded cuts are defined in terms of the assembly instead of within a part. This is an advantage of the top-down design methodology. Since these two cuts extend through both Final Pour and Pour 1, they can be defined within the assembly and set to cut through both parts. This is accomplished by selecting ***All Components*** in the ***Feature Scope*** section of the ***Edit Feature*** window. After this step, the wax block can be hidden and the motor and pot gears can be added to finish the leg design.



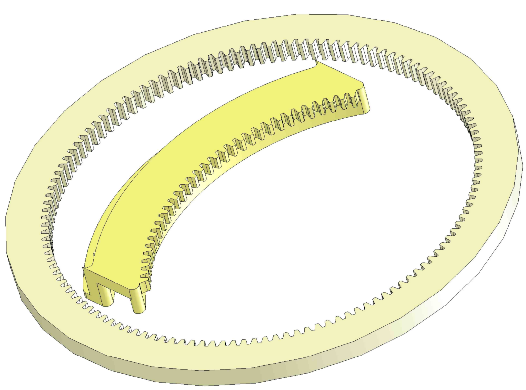
(a) (b)

Figure 27: Hip clamp pocket and slider slot pocket (a), wax removed and gears added (b).

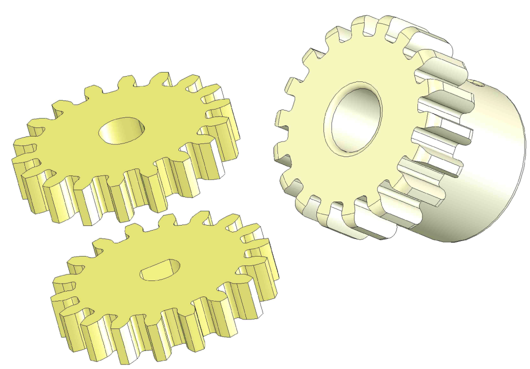
## Gearing

The challenge to design the gears for the slider, motor, and pot was an interesting one. No off-the-shelf gears were available at the desired size/pitch combination. It soon became apparent that we would have to make our own gears. However, the task of designing a gear profile is not an easy one. To make things worse, no gear design software package was available. To overcome these challenges, we took advantage of an online resource. Boston Gears is a gear supplier that has solid models of all their gears available online. See the list of suppliers for a link to their website. Since no gear was available at the desired size, the next closest gears in size were chosen and downloaded. These gears happened to be the 32 pitch 18 tooth spur gears. Unfortunately, the models that are available are not editable so we needed to somehow transfer the tooth profile from the uneditable part to our own solid model. In a new sketch, the tooth profile was selected and converted to the sketch. This sketch was then copy and pasted into a new part. These profiles were then made into blocks and used to extrude our own custom gears. For the slider, we found a solid model of an internal gear from the same website that was as close as possible in radius to the slider radius. This happened to be the 32 pitch 192 tooth internal gear. The same steps were taken to convert the tooth profile into a new part file.

These profiles however were still not the right sizes. To address this, the gear profiles were scaled by a factor of 1.025. This factor gave us the internal gear radius we needed for the slider. Because of these changes, the pitch diameters, or spacing between gear centers, were also scaled by the same factor to determine the distances between slider, motor, and potentiometer.



(a)



(b)

Figure 28: Boston Gears internal gear and the derived slider gearing (a), Boston Gears spur gear and the derived motor and pot gears (b).

### Left vs. Right Leg

Another convenient aspect of using SolidWorks is the ability to mirror parts easily. Since the leg is designed to be a right leg, we just mirror the design when we need to fabricate left legs. Note that due to its symmetry, the slider does not require mirroring.

### SolidWorks Animator

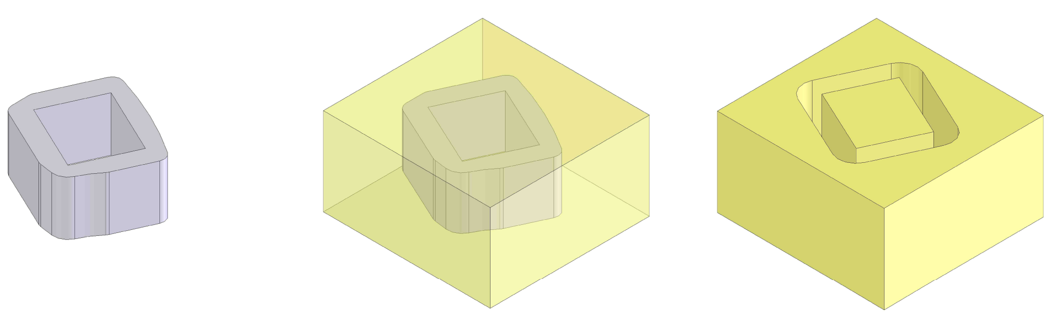
The animations used in presentations were made using the SolidWorks Animator. Once an assembly is made, it is very easy to make animations using its user friendly timeline interface. It is suggested to save a copy of the assembly and accompanying parts into a separate directory to use exclusively for the animation to avoid inadvertent changes. For more information on how to use the Animator, see the Animator help topic in SolidWorks Help.

## Appendix B
## FeatureCAM/SolidWorks/AutoCAD Interface

FeatureCAM is a Computer Aided Manufacturing (CAM) software used to write G-code for CNC machines. A part file or set of curves is imported and based on either geometry or user input, the software generates a set of instructions for the CNC machine to follow. A number of methods can be used with FeatureCAM to generate the desired CNC code. The best method to use depends on the part's geometry and the CAD program that was used to design it. For our purposes, we either imported a 2-D DWG file from AutoCAD, or a 3-D part file from SolidWorks.

Importing a 3-D model is useful for generating complicated geometries because it allows the user to take advantage of FeatureCAM's built in ***Automatic Feature Recognition***. This feature automatically finds surfaces and generates the necessary tool paths and commands. It was found that this method worked really well for steps that already defined features in terms of extruded cuts. For example, when the part Wax Block was imported, FeatureCAM was able to automatically generate the tool paths without any difficulty.

For other parts like the motor insert, gears, pot shaft and sliders, it is necessary to include an extra step. Since these 3-D parts are made by machining a mold for them, we need to import a mold, not the part, into FeatureCAM. To make a mold, we use the ***Combine*** feature in SolidWorks. Save a new copy of the desired part in a separate directory. Create a new sketch of a rectangle that surrounds the entire part. Now, extrude the rectangle 5mm past the lowest point in the part. Before clicking ***OK***, make sure to uncheck the ***Merge Results*** box. This will form a new body in the part file instead of merging the extrusion with the existing part. Now go to ***Tools>Features>Combine***. In the options box, select ***Subtract*** and chose the block extrusion as the ***Main Body***. Chose the other part file for ***Bodies to Combine***. This subtracts the part from the block leaving a cavity with the desired features. Now this file can be imported directly into FeatureCAM to take advantage of Automatic Feature Recognition. An example of these steps can be seen in Figure 29.



(a) (b) (c)

Figure 29: Combine Feature: Insert Part (a), Insert and Block (b), After subtracting the insert from the block (c).

This method works well for simple parts that can be machined in one or two steps. For more complicated parts, a number of combine and subtract steps can be performed to generate the desired mold. For more information on combine and subtract features in SolidWorks, see the ***Combine Bodies*** help file.

For other features, it may be easier to define the part geometry within FeatureCAM using only a set of 2-D curves. In this method, the curves are imported as a DWG (AutoCAD) file and are used to define the perimeters of machined pockets. This is especially useful when a feature is defined in context of an assembly where it is not unique to a single part. Good examples of this are the Shaft Clamp Pocket and Slider Slot Pocket that make up the final machining step. These features are extruded thru both Pour 1 and Final Pour. For these features, it was easier to create a 2-D drawing from the 3-D part file and save it as a DWG. AutoCAD was then used to create polylines using the pedit command. The polyline curves are recognized by FeatureCAM and are used to define pockets or islands by specifying depths.

In some cases, it may be desirable to export the FeatureCAM model geometry into a format that could be recognized by either SolidWorks or AutoCAD. This is particularly important if the Laser Cutter is ever to be used to cut features since it only works with AutoCAD. Unfortunately, there is no direct way to export directly from FeatureCAM into AutoCAD. Because of this, everything has to go through SolidWorks. FeatureCAM exports files in a number of different file formats, but only parasolids worked when imported into SolidWorks. Once the parasolid geometry is in SolidWorks, it can be turned into a 2-D drawing to be recognized by AutoCAD.

# Appendix C
# Assorted Remarks

## CNC Machine

During the second machining step while the motor pocket was being machined, one of the legs lifted out of the wax mold. To address this issue, the leg was glued back into place using super glue. Another possible solution could be making anchor holes that would secure the leg which could later be cut or ground off. It was noticed that the parts using the VA-273 material did not have a problem with lifting due to their low shrinkage percentage.

## SDM

An important step in the SDM process is to seal any components to be embedded. This proved to be more difficult that it may seem at first. It is suggested to use the Loctite SuperBonder 409 Gel because it has the ability to fill in large gaps and does not require mixing like the 5 minute epoxy. A hot glue gun was also useful to quickly secure wiring.

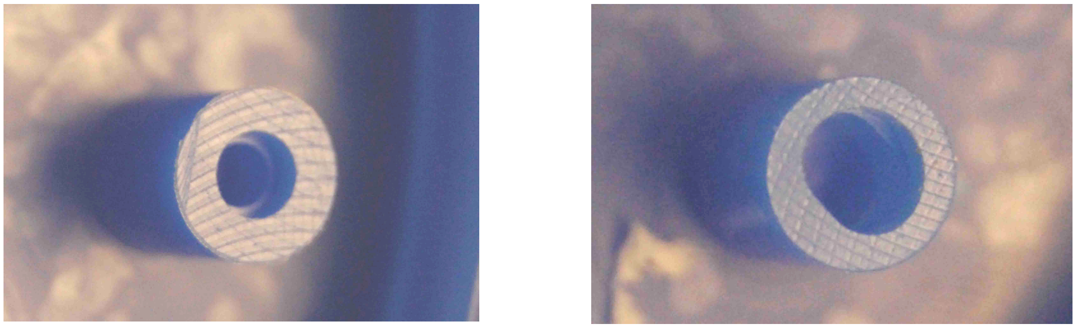
Despite the effort taken to seal off components, if they are placed under vacuum, it is possible for the polymer to still seep through small holes and into the component. For this reason, it is suggested that the polymer is degassed first and then poured for any steps where components are being embedded.

Positioning the flex sensor using both the middle slot and face slot proved challenging. The laser slit was not deep enough to firmly secure the sensor. This problem has been addressed by decreasing the depth of the slot and increasing the depth of the slit in the final revision included with this report. The flex sensor at first proved to be very difficult to position in the face slot. To aid in the process, a couple of inserts were fashioned out of a cut zip tie as seen in Figure 14. These were used to hold the sensor against the inside face so that it could be super glued in a couple of spots to secure it for embedding.

It was also observed that the polymer could be easily cut during a short interval of time just before it starts to completely harden. This could be useful to decrease machining time if there is a lot of excess material.

The use of sacrificial material such as soap or low melting temperature wax should be explored. This could be useful for embedding circuitry or batteries.

As mentioned in Section 3.3, the set of wax caps is machined in the second machining operation. During embedding, the wax caps are used to keep polymer out of the shafts. They also serve a purpose in the later machining steps because they provide a buffer between the end mills and shafts. After the leg is taken out of the mold, the wax is easily scraped out.



(a) (b)

Figure 30: Motor Wax Cap (a), and Pot Shaft Wax Cap (b).

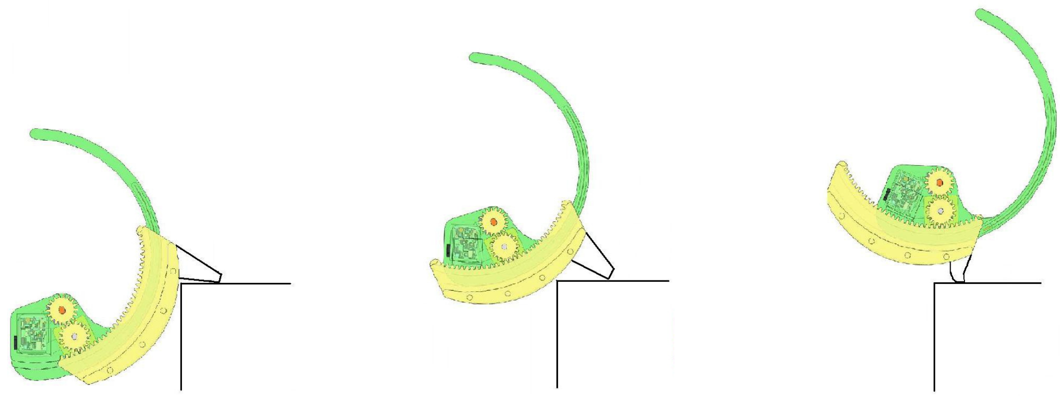
**Laser Cutter**

The laser cutter could be potentially useful when fine features need to be cut in the polymer. Three possible uses are for positioning the flex sensor, positioning wires, and cutting gear profiles. The two biggest problems when using the laser cutter are the laser cutting width of .0035 inches and the tapered cut that results from the Gaussian laser intensity distribution. To account for the laser thickness, the cutting profiles were offset by half the cutting thickness. Using different colored layers, the parts were cut using many successive low powered cuts instead of one at high power. This allowed for good control of cutting depth as well as keeping the polymer from heating up too much. It was observed that when the material gets too hot, it will just try to melt instead of being cut. Using many low power cuts instead of one high powered cut also allowed higher resolution by allowing the laser head to go slower during cutting while maintaining its 1000 pulses per inch maximum. This factor was of particular importance when cutting the gear profiles.

A speed setting of 10 and power at 4% worked well for acrylic and took 20 cuts to make it through ¼ inch of acrylic. For ABS plastic, the settings used were 10 for speed and power at 6%. A speed of 8 and power at 30 worked well for cutting the VA-273 material used in the slider and gears. It was noticed that for each successive cut, the laser removed less and less material. This can be explained by the sloping sides of the cut. The deeper the cut, the gentler the slope on the sidewalls are which means that instead of cutting material, the laser is mostly just heating up the sidewalls of the cut. The fact that the laser loses focus also affects the cut's penetration. This lack of focus was observed when cutting the flex sensor slit. The long distance between the laser head and cutting surface caused a wider than desirable cut and required more iterations to cut to the desired depth.

**Slider for Obstacles**

One possible use of the slider is helping the leg in climbing obstacles. One example can be seen in Figure 31. In this series of images, a lip on the slider is used to help Edubot traverse steps. Notice that in these images, the slider is being actuated by the motor to help lift the leg onto the step. This would probably require a higher torque motor than is currently being used. Alternatively, the slider could be left stationary and just serve the purpose of added traction.



(a) (b) (c)

Figure 31: Slider with a lip being used to climb stairs.

**Flexpoint Sensors**

Tom Danielson (tom@flexpoint.com) of Flexpoint Flexible Sensor Systems was contacted on June 15, 2007. Flexpoint's phone numbers are (801) 568-5111 and (866) 766-3539. They are capable of printing their ink on a wide variety of substrates to cater the deflection properties of the sensor to any application. Some other parameters that can be configured are the sensor thickness, width, length, material, and even the radius or shape of the sensor. These changes are capable of producing sensors with a wide range of initial resistances as well as resistance changes as high as 500% of the initial resistance. They seemed very willing to work with customers to design custom sensors and seemed intrigued by our particular application.

**Piezoelectric Sensors**

In the course of investigation for leg deflection sensors, flexible piezoelectric fiber sensors were tested. The sensors are fabricated by Advanced Cerametrics and output a voltage proportional to the stress acting on them. As discussed in Section 2.4.5, these sensors could potentially be used to detect time of contact and liftoff but are not well suited to detect leg deflection. An intriguing potential use of these sensors is in the form of energy harvesting. The output voltage from the piezoelectric sensor could be stored for use by the leg's electronics.

## Appendix D
## List of Suppliers and Parts

| Supplier | Description |
|---|---|
| Advanced Cerametrics | Ceramic Piezoelectric Sensors |
| Boston Gears | Supplies 3D solid models of all available gears including part files for SolidWorks |
| Digi-Key | General supplier of electronic components |
| Express 3d | SolidWorks add-on for rapid prototyping quotes |
| Flexpoint | Flex Sensors, Variety of customizable lengths and substrates |
| Innovative Polymers | Range of industrial polyurethane, polyurethane systems, and silicone mold-making compound |
| Jameco | General supplier of electronic components |
| McMaster-Carr | General supplier of hardware |
| Robot Objects | Small robot kits and components including motors, gears, and electronics |
| Small Parts | General supplier of hardware |
| Solarbotics | Beam robotics supplier specializing in small low weight components |

| Supplier | Part Number | Description |
|---|---|---|
| Digi-Key | | |
| | 490-2400-ND | Rotary Potentiometer, Short Leads |
| | 490-3913-ND | Rotary Potentiometer, Long Leads |
| Innovative Polymers | | |
| | TP-4004 | Polyurethane Polymer: for leg and insert |
| | VA-273 | Polyurethane Polymer: for slider and gears |
| Jameco | | |
| | 150551 | Flex Sensor |
| McMaster-Carr | | |
| | 7592A31 | 5 minute epoxy gel: 2 Part |
| | 7608A57 | Loctite SuperBonder 409 Gel |
| | 7520A12 | Loctite SuperBonder 495 |
| | 8940A26 | 3mm End Mill |
| | 29605A44 | 6mm End Mill |
| Robot Objects | | |
| | WRMGR-48-20-3-16 | Worm Gear: 48 pitch, 20 teeth |
| | WRM-48-RH1L-A | Worm: 48 pitch |
| | GEAR-48-RACK-01 | Rack: 48 pitch, 1 foot |
| | GEAR-48-12-1-08-1 | Gear: 48 pitch, 12 teeth |
| | GEAR-48-16-1-08-1 | Gear: 48 pitch, 16 teeth |
| Solarbotics | | |
| | GM11a - 56:1 | Miniature motor: 56:1 Ratio |
| | GM18 - 30:1 | Miniature motor: 30:1 Ratio |

## Appendix E
## List of Important Files

**FeatureCAM**

**Leg Embed Rev 3**

**Embed Rev 3 Files**

Contains the intermediate files used to make the mold part files to be imported into FeatureCAM

**Motor Embed Rev 3 Take 1**

Contains the FeatureCAM files used to make the first two prototypes. All the files are divided into 3 folders representing the 3 machining steps it took.

**Motor Embed Rev 3 Take 2**

Contains the FeatureCAM files used to make the third prototype.

**Other**

Contains all other FeatureCAM files including those used to make Leg Rev 1 and Leg Rev 2

**SolidWorks**

**Assemblies**

**Assembly Rev 1**

First leg assembly made. Uses Leg Rev 1, a 48 pitch 12 tooth gear, and Slider Rev 1.

**Assembly Rev 2**

Uses Leg Rev 2, and a geared Slider Rev 1. This assembly was used to make the animation used in the Midterm Presentation.

**Laser Gearing Trial**

Contains the scaled gearing profiles used for initial laser cutting tests.

**Shaft Clamp v2**

Rectangular shaft clamp that Sam designed.

**Tunable Leg**

The assembly used to create the animation used in the Midterm Presentation.

**Animation**

The assembly used to create the animation used in the final presentation.

**Motor Embed Rev 1**

The first design iteration for embedding the motor using an insert. This design was used for Lab Presentation 2. Only the motor is embedded.

**Motor Embed Rev 2**

This design was used as a test bed for motor and pot positioning used in Motor Embed Rev 3.

**Motor Embed Rev 3**

This is the design which was used for the three prototypes made at the end of the program. This design includes a motor, pot, and flex sensor which are embedded. Has both middle slot and face slot configurations.

**Motor Embed Rev 4**

Final redesign meant to address several issues that came up when making the prototypes. Main changes from Rev 3 are:

-Changed how the hip shape is constrained and defined to allow easy adjustment for accommodating electronics

-Redesigned pot shaft relief to increase clearance and allow shaft to rotate easier

-Redesigned pot shaft to make it smaller and reduce the amount of filing needed to fit it thru the pot

-Adjusted pot gear thru hole to mate with the new pot shaft

-Removed the excess material behind the pot since it is just extra material. This area could potentially be used to store a battery, but for now it is superfluous

-Redesigned insert only requires one machining step. Also has a tighter fit with the motor

-Extended clearance for the flex sensor wires that pass beside the insert

-Reduced middle slot depth and increased laser slit depth to aid in flex sensor positioning

-Increased clearance around motor to aid embedding

-Added extra pockets to aid bonding between the two polymer layers

**Parts**

**Animation**

Contains part files used in the Animation Assembly

**Gears**

Includes the gear tooth profiles converted from the Boston Gears solid parts. Also has the original solid parts in an Archive folder.

**Legs**

**Leg Rev 1**

First leg design using a vertically aligned motor that was inserted into a pocket

**Leg Rev 2**

Second leg design using a horizontally aligned motor that was inserted into a pocket

**Leg Rev 3**

Same as Rev 2, but with a casing that fully enclosed the motor

**Leg Rev 4**

Same as Rev 2, but with more motor clearance and repositioned motor to accommodate a bigger gear

**Left/Right Slider Rev 1**

First redesign of the slider to incorporate a lip where a gear rack could be glued

**Left/Right Slider Rev 2**

Final slider design with gearing built into the SDM design

**Motor Embed Rev 1/2/3/4**

Each folder contains the part files used in the accompanying assembly