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Executive Summary:

The robotic foot is designed for a bipedal robot to enable it to propel itself forward while walking, and recover from a push while standing on both feet. To accomplish these tasks, the foot needs a hinged toe-section, a method of sensing the center of pressure on the bottom of the foot, and a means of measuring the deflection of the toe. The design had three major constraints. First, the total weight of the foot and its components had to be less than 2.5 lbs. Second, the distance from the bottom of the ankle adapter to the bottom of the foot had to be less than 3.5." Finally, the entire foot had to fit within a men's size 12 shoe. The final design uses four compression-only load cells with a pre-load of 100 lbs placed at each corner of the bottom of the foot. The voltage output of each load cell is amplified by a strain gage amplifier and resolved to find the center of pressure at the bottom of the foot. The deflection angle of the toe is determined with a rotary encoder. A pulley-timing belt system connects the shaft at the hinge of the toe section to the shaft of the rotary incremental encoder. The final design meets all design constraints. The foot enables the robot to sense balance on its foot and walk by propelling itself forward with the spring force on the toe.

Design Evolution:

Over the course of the spring 2009 semester our design has changed significantly from what was initially proposed in December of 2008, Figure 1. There were several key changes that were made to the first design. The most noticeable and largest change was the use of load cells instead of a 3-axis, force/torque sensor, Figure 2. A two plate design was created rather than using a single plate so that the load cells would be protected. The main body section of the foot contained 4 pre-loaded donut load cells in the new design, strategically placed at the four corners to accurately obtain the location of the center of pressure on the foot. The toe section was also redesigned to contain three load cells placed in a triangular formation to detect the location of the center of pressure on the toe. However, only load cells for the main body section of the foot were purchased due to the high cost of each load cell. “Dummy” load cells were machined from aluminum to hold the place of the load cells in the toe section. This gives the customer (Jerry Pratt of IHMC) the ability to add load cells to the toe section at a later date or to leave them out and reduce the cost of each foot. The two plate design also allows for a lower center of gravity of the robot so that it is more stable. The ankle distal joint sits at about one inch off of the ground with the new load cell design, whereas the previous design has the ankle distal at over 3 inches off of the ground. Another advantage to using the two plate design was that the existing ankle distal joint on the robot could be used rather than having to fabricate a new joint to fit atop the 3-axis sensor. By using a two plate design the limit stop at the hinge had to be changed to fit the new design, make the hinge section stronger, and to allow for easier machining. The rounded edges of the hinge closest to the body section of the foot were made to be square instead of rounded so that all machining could be done by hand.

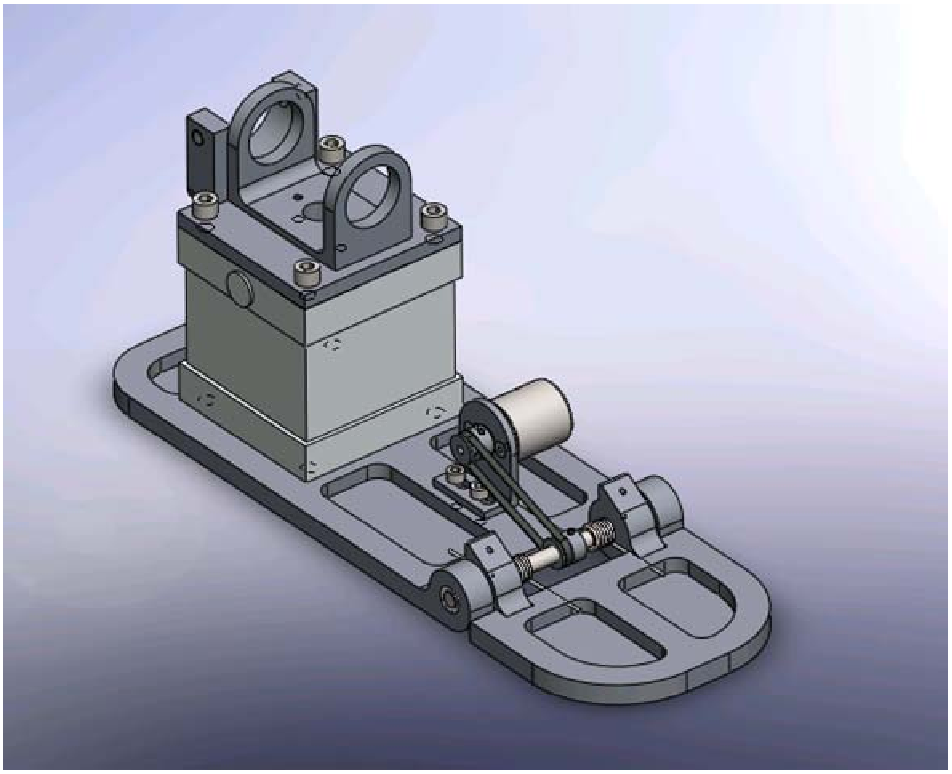


Figure 1 - Initial design of foot using 3-axis force/torque sensor and single plate

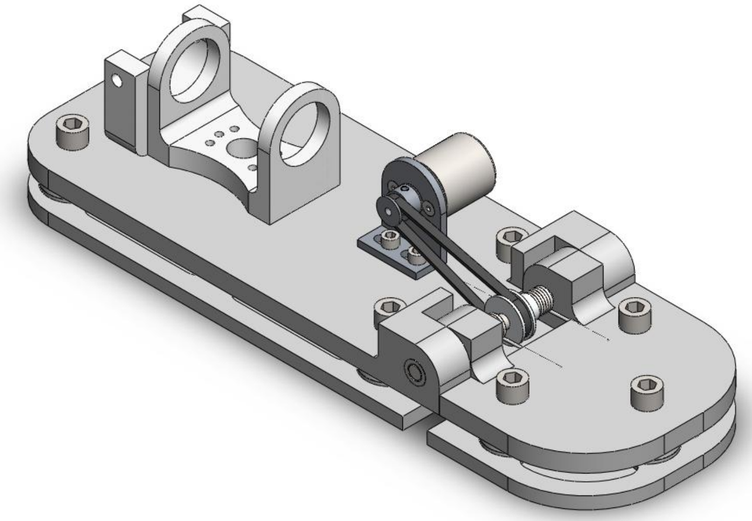


Figure 2 - Final design of foot using load cells and two plates

At the beginning of the spring 2009 semester the engineering specification for the weight changed from 3.5 lbs or less to 2.5 lbs or less. Therefore, weight needed to be removed from the foot while maintaining the strength. This was accomplished by changing the thicknesses of both plates and the pockets cut out of the plates based on finite element analysis. Material was also added at the hinge section to increase the strength and durability of the foot because this is the portion of the foot that will experience the highest dynamic loads. Also, a larger pulley had to be purchased to fit around the shaft at the hinge. The previous pulley required too much material to be bored out in order to fit around the axle. This changed the gear ratio from 1:1 to 2:1 for the measurements taken from the rotary encoder.

Manufacturing:

The foot consists of a total of six non-standard parts that had to be machined out of aluminum stock. The sandwich design that holds the load cells necessitated at least two separate parts, and the moving toe section doubled the number of parts. To attach the encoder to the foot for deflection angle measurement, a simple bracket was created that didn't need to be structural, just enough to hold the encoder in the right position. The connection to the leg of the robot required an ankle distal part, and to conserve time and materials our foot design reused the distal currently on the foot, reducing the number of parts that had to be machined by the team.

The main four plates of the foot were specified at the beginning of the design process to be the same material as the rest of the robot (6061-T6 aluminum), and it was found that the department already had this alloy in stock. The parts were designed with the knowledge that the team would need to machine them, so many cosmetic curves and other difficult to mill features were not included in the final versions. Because the parts didn't need to be very complex and because each was to be made only one or two times, the CNC mills were not used, which had the added benefit of allowing other design groups to use the machines.

To make machining as simple as possible, all interior radii in the webbing areas were set to 0.25" so that entire step could be completed with a single ½" end mill. In the hinge area, as many corners as possible were left straight so special cutters would not be needed, the exceptions being the top corner that slides past the other plate and where the back of the hinge hits the foot. The former was left at ½" radius, and the latter was cut with a ball-end mill as large as was available, both for strength and clearance reasons. Another way machining was simplified was relaxing tolerances on the external shape, since the bolt pattern and the hinge geometry are the only critical components. The rounds on the front and back corners were roughed out with a band saw and sanded to shape.

All of the four main plates were cut out of a single piece of stock measuring 1"x5"x14" (length ±0.5"), which was the smallest that could be used due to the part shapes and what was available. The foot itself is only 4" wide at any point, which unfortunately meant that 1/5 of the stock was wasted immediately, but the 5" stock was what was available. The total volume of the finished parts is 21 in^3; meaning 49 in^3 was wasted in machining, though if the chips were saved they could easily be recycled.

For testing purposes a set of 7 dummy load cells were made which are the same size as the actual load cells. These were turned on a lathe from 1” diameter aluminum stock, cut to length and drilled in the center. All of the dummy load cells (spacers) were made from aluminum scrap stock lying around in the shop, and could be made out of any metal if desired.

Safety:

The robotic foot has minimal safety concerns. The majority of safety hazards are related to installation of the foot to the leg. There are pinch points at the hinge and at the axle that could lead to injury. Unfortunately, in the interest of having a secure limit stop for the toe, the pinch points are a necessary inherent part of the design. Sharp edges were minimized by sanding, but that does not imply that it is impossible to cut oneself on the foot.

The initial foot design didn’t have an issue with pinch points because it was a single plate foot with a tri-axis load cell at the center. This would leave no parts for fingers to get caught, but it doesn’t satisfy the design requirements of height or weight of the foot. The next design was a two plate foot, leaving the bottom plates flush against each other when closed. This is far more dangerous than the current design because the springs would clamp down on the finger. The current design has a half-inch clearance between the two plates when the foot is flat on the ground, thus minimizing the possibility of clamping an operators’ finger.

The main safety concern to both the operator and the robot is if the bolts connecting the ankle distal to the foot fail. This would cause the robot to crash to the ground, possibly injuring the operator, and definitely injuring the robot. To prevent damage to the robot or operator, the robot is attached to the ceiling by a harness. Additionally, the screws were over-specified to make sure that they would be strong enough.

Sustainability:

A sustainable design is one that minimally impacts the environment, either by using the minimum amount of newly manufactured parts, or containing recycled parts that can be reused for future products. The goal of this project is to make a prototype for a robotic foot that allows for the maximum amount of modification for future generations. This goal has been achieved by using load cells and an encoder that can be reused on future generations of the foot, and machined aluminum that can be recycled.

Parts inventory and sustainability:

All manufactured parts were made from aluminum stock found in the PDL. The strength constraints of the foot could be easily attained through recycled aluminum, thus minimizing the environmental impact. The weight of the raw stock was 4 lbs, to end up with 2.5 lbs of finished products. The aluminum scrap could have been recycled, but the PDL chooses to throw away the scrap metal. This practice of the PDL is unsustainable, and cost constraints should not come in the way of recycling the aluminum.

The purchased parts, namely the encoder and the load cells can be taken off of the foot and used in later research projects. The individual components of the load cell, like the strain gauge bridge, likely could be removed and reused. The other components might be harmful to the environment and might have to be disposed of by other means. It is unknown how environmentally damaging it is to manufacture the encoder and the load cell, so that aspect of sustainability can’t be fully analyzed.

End of Use Plan:

A solvent will be used to dissolve the glue from the rubber. The rubber can be recycled as well as the aluminum used to construct the foot. The purchased parts can be reused for later models of the foot. The fasteners can be used for other projects. The pulley can be recycled along with the rubber. The timing belts were modified to custom fit the foot, so they must be recycled instead of reused for another iteration of the foot.

Design Changes:

The design was altered to use glue to attach the foot instead of recyclable metal fasteners. This makes the design less sustainable, but the glue is a more viable way to attach the rubber to the foot than fasteners. Aluminum was used in the design instead of steel because it is easier to recycle and lighter. It is also lower cost and easier to machine.

Ethics:

There are few ethical concerns in the design of the robot. The amount of non-recyclable materials in the encoder and load cells are unknown. This renders the team unable to fully understand the impact of the purchase of the load cells on the environment. It would be more environmentally responsible if the load cell and encoder manufacturers had an end of use plan for their products, but that is not the case.

There could be ethical concerns about the defense applications of the final robot. The robot will not, however, be used in active combat. It will be used to for reconnaissance in areas where it is too dangerous for a soldier. The ethics of war are an issue outside the scope of this project, but the robot will contribute to more saved lives in dangerous regions and thus should be considered an ethical design.

Materials and their Disposal:

All manufactured parts were made from 6061 T6 aluminum stock found in the PDL (Project Development Lab at Bucknell University). The strength constraints of the foot could be easily attained through recycled aluminum, thus minimizing the environmental impact. The weight of the raw stock was 4 lbs, to end up with 2.5 lbs of finished products. The only other materials used on the foot were steel and rubber. Steel was used for the rod at the hinge, the load cells, and rotary encoder. Rubber was used for traction on the bottom of the foot. The rubber had to be attached with adhesive, but all other parts were attached via set screws, bolts, or press fitting.

The aluminum used to machine the foot may be recycled; however the individual components of the load cell, like the strain gauge bridge, could likely be removed and reused. A solvent will be used to dissolve the glue from the rubber. The rubber can be recycled as well as all parts made from aluminum. The purchased parts can be reused for later models of the foot. The fasteners can be used for other projects. The timing belts were modified to custom fit the foot, so they must be recycled instead of reused.

Electrical System:

The foot has four 500 lb load cells on the four corners of the foot, and has space to add three load cells in the toe section of the foot. The FUTEK 500 lb load cells function as a Wheatstone bridge and have four outputs each (RED= E+, BLACK=E-, GREEN=S+, WHITE=S-).

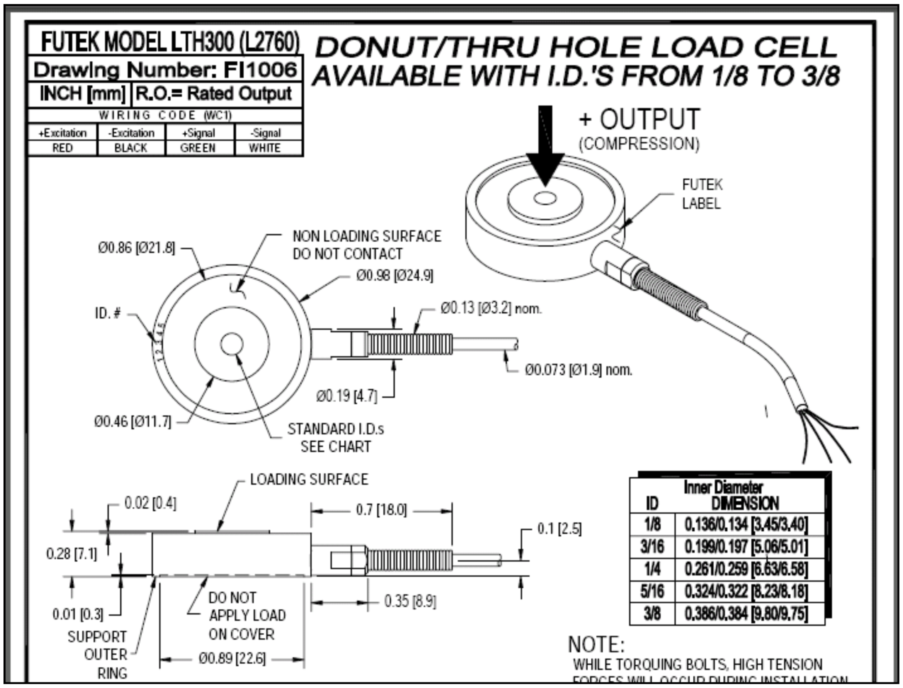


Figure 3- Dimensions of donut load cells used in final design

FUTEK MODEL LTH300 500 lb Load Cell
<http://www.futek.com/files/pdf/Product%20Drawings/lth300.pdf>

The output is 2mV/V nom so an amplifier was needed to get an output greater than the noise. FUTEK, the load cell manufacturer, does make strain gage amplifiers (model # QSH00602) to go with the load cells. Unfortunately, the QSH00602 is both prohibitively expensive at $375 each and takes up to much space on the foot. The four amplifiers would cost $1500 and weigh 5.6 ounces, which is unreasonable for a project so constrained by weight. Instead, the AMP 04 strain gage was specified for the project. It is only $69 and weighs less than the QSH00602. Unfortunately, after wiring the AMP 04 to the load cells, there was too much internal noise in the circuit for a reading. At the lowest gain the noise was greater than any signal, and increasing the gain only increases noise. The electrical expert at Bucknell, Tom Thul made a circuit on a breadboard for testing of the load cells. The circuit worked at a gain of 1000 with high repeatability at weights at the given error for the load cell (2.5 lbs) and even below. The circuit diagram is included on the next page. All parts of the circuit are necessary. The bottom portion of the circuit serves to reduce noise within the circuit. Without it, at a gain of 1000 it would be too noisy to get useful data.

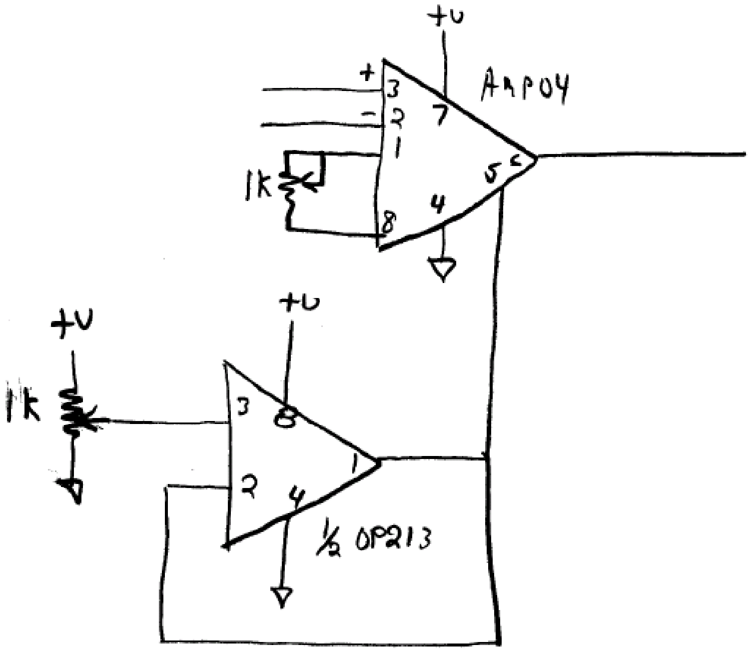


Figure 4: Load Cell Amplifier Circuit Diagram

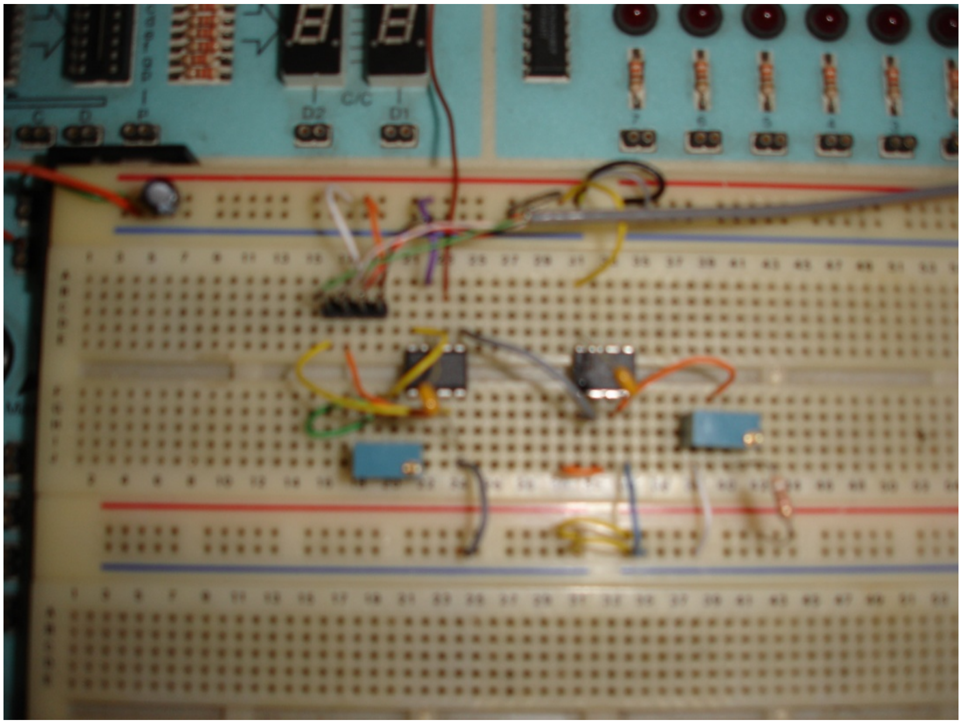


Figure 5: Load cell circuit on breadboard

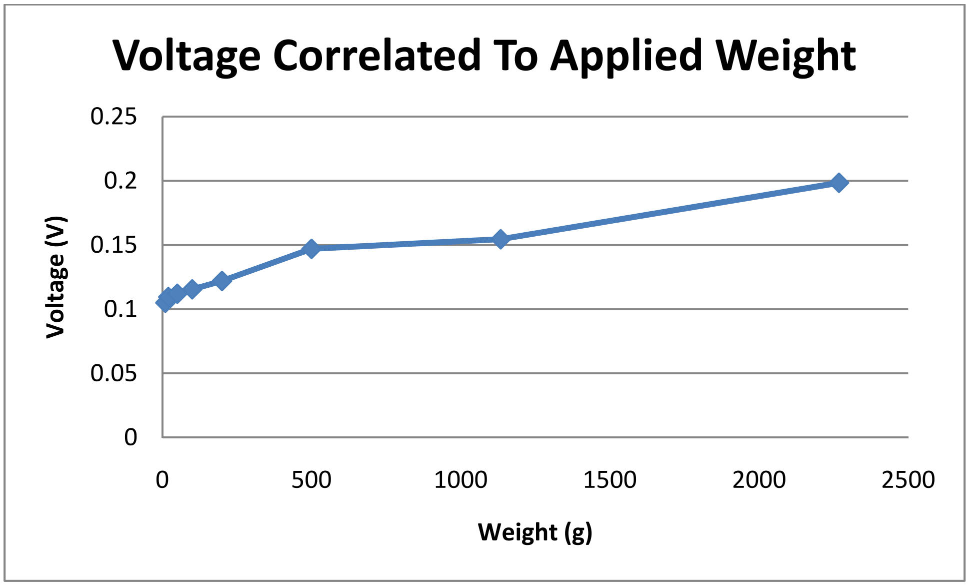


Figure 6: Voltage output from load cell under varying loading conditions

Table 1: Voltage output from load cells for two trials with averages

Vo	0.105 DVM		
Weight (g)	Reading 1 (V)	Reading 2 (V)	Average
10	0.105	0.105	0.105
20	0.11	0.109	0.1095
50	0.111	0.113	0.112
100	0.115	0.116	0.1155
200	0.123	0.121	0.122
500	0.147	0.147	0.147
1134	0.154	0.155	0.1545
2268	0.2	0.197	0.1985

The encoder was tested and it does give off pulses. The encoder selected was the OMRON E6A2 CW5C 200 P/R 0.5M rotary encoder. This is the lightest weight rotary encoder on the market and reasonably priced at less than $200. A test apparatus for the encoder was not set up at Bucknell because it would be overly time consuming and there is already an encoder reader and A/D boards on the robot. The current iteration of the foot assumes that the wires will extend out through the hinge of the foot and connect to the leg from there, as no hole has been drilled through the top plate. This is to allow for placement of the strain gage amplifier circuit to be placed at any point on the top of the foot. Following placement of the circuits a hole can be drilled for the wires.

Final Design Description:

The objectives for our robotic foot design are as follows:

1. Push recovery compatible
2. Propels itself forward while walking
3. Hinged toe section
4. Center of pressure detection
5. Toe deflection measurement

The technical requirements of the foot were originally as follows:

1. Weight less than 3.5 lbs
2. Distance from bottom of ankle adapter to bottom of foot less than 3.5”
3. Fits in men’s size 13 shoe

At this point, the weight must be less than 2.5 lbs and the foot does not need to fit inside a shoe.

The features of the robotic foot that accomplish the objectives are as follows:

1. Hinged toe section
2. Four compression-only load cells
    a. 100 lb preload
    b. Stain gauge amplifier to amplify voltage output
    c. Center of pressure calculated
3. Rotary encoder
    a. Pulley-timing belt to translate rotation of hinge axle into encoder rotation
    b. Sends pulses that are counted to determine the angle of deflection
4. Torsion springs on hinge axle that compress as the robot shifts weight to a foot and release and it shifts weight off

The specifications of the robotic foot are as follows:

1. 2.45 lb
2. 1” from bottom of ankle adapter to bottom of foot
3. Constraint to fit inside size 13 shoe removed

The robotic foot is essentially comprised of a body section and a toe section connected by a hinge. The ankle of the robot connects through a universal joint to a distal plate which connects to the top of the body section. At its most basic level, the robotic foot is a simple foot with a bending toe section, much like a human foot. As the robot will move its legs, the robotic feet (assuming a second is fabricated and implemented along with the first) will act like human feet. The feet will land flat and as the weight shifts forward, the back foot will bend its body section up, rotating about the hinge, and as the foot steps off, the toe section will snap back into place. Torsional springs, (or a single torsional spring if this option is pursued) located along the hinge between the body and toe sections, will compress as the toe section moves up, storing energy. As this foot steps off, this energy will be released, providing a “toe-off” aiding in propelling the robot forward.

Another component located on this axle is a pulley connected by a set screw. As the toe section deflects, the axle and pulley rotate at the same rate. A timing belt connects this pulley to another pulley, attached to the incremental rotary encoder. The encoder is screwed to a fabricated L-bracket, which is screwed to the top of the base plate. As the second pulley rotates the shaft of the encoder, the encoder will send a pulse signal with a frequency proportional to the rotation to a reader on the robot. The encoder is powered from the robot, along the same wiring as the signal being sent out. The encoder measures to within 1.8 degrees of accuracy. The deflection of the toe section will thus be measured and recorded.

The forces on the foot are measured through four compression-only load cells sandwiched in between the top and bottom plates of the body section. The load cells are given a preload of 100 pounds, so that some tension forces can be measured in addition to compression forces. The load cells must be protected from side loading in order to prevent failure, so a bolt goes through them and the plates on either side, so that side loads will be absorbed by the bolt rather than the load cell. The load cells are powered through wiring that connects them to the robot. This same wiring will send the signals from the load cells to the readers on the robot. Each load cell is located in a corner of the base plate. By compiling the readings from all four load cells, the robot’s software can determine where on the base plate the center of pressure is located. The toe section does not use load cells, but it has the capacity for them in the future if it is desired. The load cells have slight accuracy errors, so, factoring the maximum error into the center of pressure calculation, the most the center of pressure could be off by is 0.3889 inches along the length and 0.1667 inches along the width.

Along the bottom surface area of the robotic foot is a 1/16” thick layer of Butyl rubber. According to friction tests performed on the rubber, it has an average friction coefficient of .93 on concrete, the only surface that the coefficient needed to be known for. The highest possible friction on concrete was called for from the customer, and although other rubbers were rated for higher frictions on the same surface, other factors were considered as well. Butyl rubber is the only rubber of those tested that not only had a high enough friction coefficient, but also was rated for abrasion resistance, tear resistance, weather resistance, and electrical resistance. Because of these factors, the butyl rubber should not only provide enough traction, but stay in good shape for a long time as the feet are being used on the robot.

Finite Element Analysis:

In order to model the supposed linear deformation of the aluminum foot, the SolidWorks model was analyzed with the FEA analysis of CosmoWorks. The worst case scenario for loading on the foot was determined to be restraining the back end over the screw holes for the distal plate and loading at the edge of the base plate, ignoring the toe section. This loading condition was modeled in CosmoWorks by restraining the inner surface area of each screw hole and placing a 500 pound load (the maximum required) onto the inner surface area of the hinge holes. An approximation that ignored the load cells had to be made so that the model could fully mesh. Additionally, the bolts that go through the load cells had to have two heads on either end so that CosmoWorks could restrain them to the top and bottom plates. The results are below.

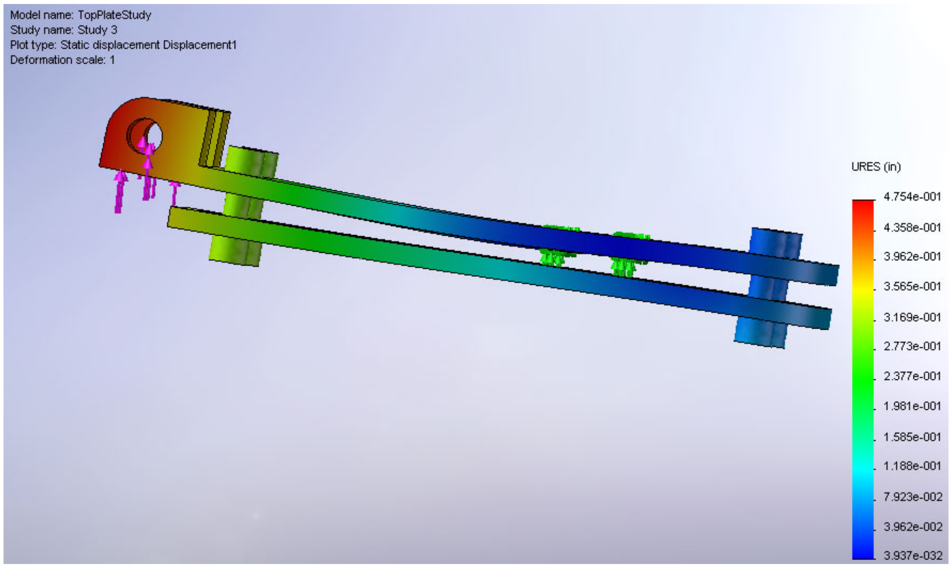


Figure 7: Deflection of hinge area in FEA analysis

These results show that the simulation (which ignores load cells, a component that makes the design stiffer) does not plastically deform. The maximum load of 500 pounds, applied in a feasible location to maximize the possible moment on the foot, yields a deformation of 0.475 inches. If an extrapolation of the results of a similar test yield similar results, the validity of this FEA analysis is much more likely, and it can be assumed that the robotic foot could be loaded with 500 pounds under similar conditions.

Discussion of Results:

Physical testing was performed on the base section of the foot under similar constraints as the FEA analysis. Weights of 25, 50, 75, 100 pounds were hung from to the edge of the base plate. Elastic deformations and a linear trend were observed. An extrapolation of this relationship yields a deflection of 0.493 inches under 500 pounds of loading. The CosmoWorks FEA analysis yielded 0.475 inches under 500 pounds of loading. These two deflection results are very similar, and so our results for physical deflection are more trustworthy and repeatable. According to CosmoWorks, the foot does not reach the yield strength under 500 pounds of loading, so the physical foot should be able to reproduce these results linearly under maximum loading conditions in this worst case scenario.

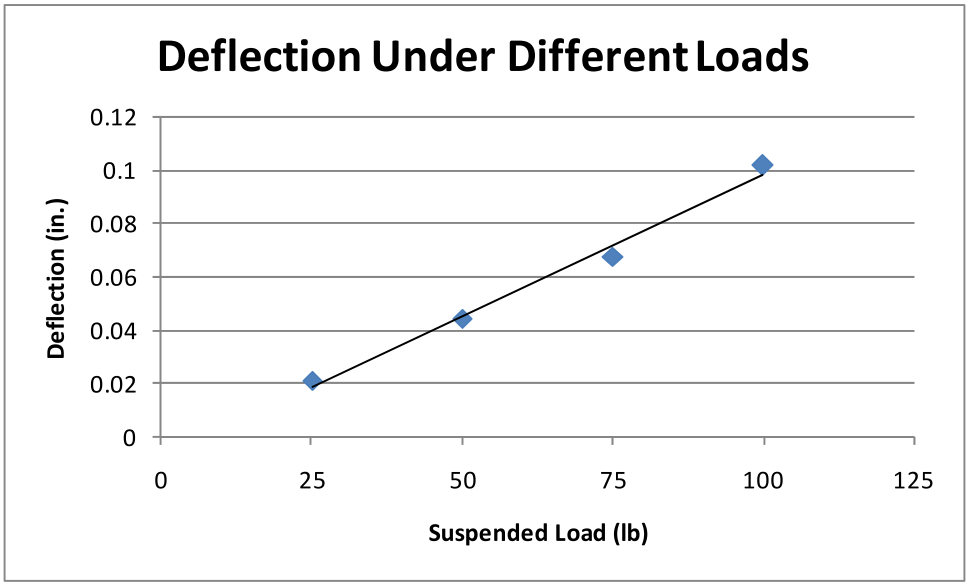


Figure 8: The deflection of the base plates was strongly linear with varying load conditions

Testing was also performed on a load cell to determine the linearity of the voltage response varying compression loads. Repeatability was important because all load cells will need to be tested before they can be used in either foot. The graph below shows a linear correlation between compression load and voltage output.

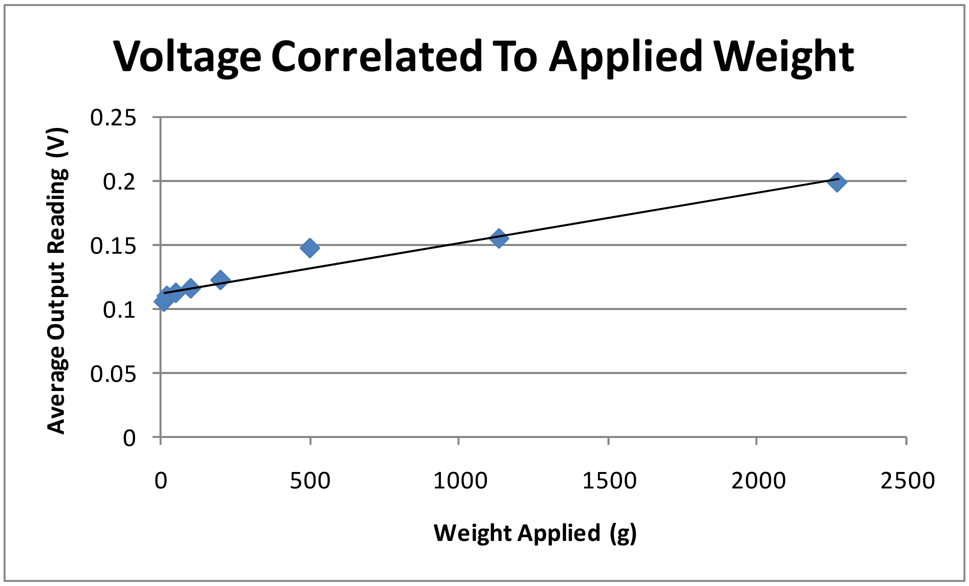


Figure 9: The voltage output from the load cells was linearly proportional to the weight applied

The testing on the encoder did not verify the ability to convert output to a rotational measurement. Without an A/D board or encoder reader this was impossible. It was verified through an oscilloscope connected to the encoder that rotation altered the signal frequency. Further testing can be conducted at IHMC, where the appropriate equipment is available.

Testing was performed on 14 rubber sample squares to see which had the most friction. Additionally, McMaster-Carr data provided for the samples described resistance to abrasion, tear, and weather. Professor Brungraber, retired professor of Bucknell's Civil Engineering department used his friction testing machine to test the samples on a concrete block. A table of frictions is shown below. Butyl was chosen because of its high friction, and excellent wear properties.

Rubber Sample	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Average
Viton	0.66	0.65	0.63	0.64	0.63	0.64	0.64
ECH	0.81	0.81	0.81	0.81	0.81	0.81	0.81
Silicone	0.66	0.67	0.66	0.66	0.68	0.68	0.67
Hypalon	0.67	0.67	0.67	0.66	0.67	0.66	0.67
Neoprene	0.95	0.92	0.93	0.93	0.93	0.93	0.93
Santoprene	0.96	0.92	0.98	0.94	0.96	0.98	0.96
Butyl	0.93	0.94	0.93	0.93	0.94	0.93	0.93
Polyurethane	0.86	0.87	0.85	0.91	0.95	0.95	0.90
Latex	1	1.05	1.03	0.98	0.97	0.99	1.00
EPDM	0.86	0.84	0.83	0.84	0.83	0.83	0.84
Buna-N-Rubber	0.96	0.94	0.96	0.98	0.98	0.97	0.97
Natural Gum Rubber			off	scale			>1.08
Oil Resistant Vinyl	0.63	0.63	0.63	0.65	0.66	0.66	0.64
SBR	0.71	0.74	0.76	0.76	0.76	0.76	0.75

Table 2: Friction results for rubber selector pack

Conclusions:

Possible improvements for the next generation design will help to make the foot readout more accurate, as well as the foot more structurally sound. More accurate load cells can be purchased to allow for a more accurate center of pressure calculation. Additionally, load cells can replace the spacers in the toe section so that a center of pressure can be obtained in this area of the foot. Stronger springs may be designed and fabricated, so that the proper amount of force is delivered on to the toe. A better encoder could also be purchased to allow for more accurate measurements of the toe section deflection. Finally, the incremental rotary encoder could be shielded in order to protect it from potential harm.

Based on the above report and ensuing appendices, this robotic foot should be easily reproduced and upgraded if deemed necessary. This design can be used for the right or left foot because of foot symmetry. Due to the simplicity of the design, the foot is easy to assemble after all parts have been obtained. A parts list in Appendix 1 details component costs, ordering information, description, and quantity. The order in which parts are assembled is both logical and trivial, and a description for this process was not necessary. Testing procedures are outlined in the Test Plan in Appendix 3. The testing procedures are reproducible and important in ensuring that properly functioning components are used.

Several important aspects of the design and testing could not be completed. For instance, the foot is not currently using springs that will deliver the appropriate force at 90 degrees. General Wire Spring Company located in McKees Rocks, PA was contacted regarding a spring design, and will contact the team soon. Other custom spring companies have been contacted but have all declined to work on the design project due to the small quantity of springs asked for. Whether or not an appropriate spring can be designed and produced will nonetheless be determined. If this is not possible, the theoretical data that must be incorporated in order produce a spring in house are outlined in Appendix 2.

As mentioned in the Discussion of Results section, encoder testing is not complete. Instructions for this process are found in Appendix 3.

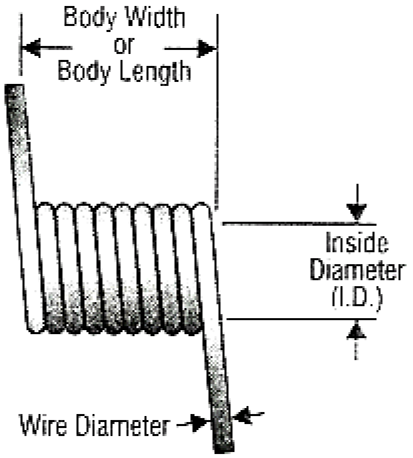
The functionality of the foot is in line with the requirements posed by the customer, Jerry Pratt, as detailed in the Final Design Description section, with the exception of the springs. The rotary encoder and load cells will be wired to the robot. The hardware and software for taking the readout from the encoder is included on the robot. However, an amplification device for the load cells is needed in order for the robot to be able to interpret this signal. Otherwise, the foot is ready to be attached to the rest of the robot.

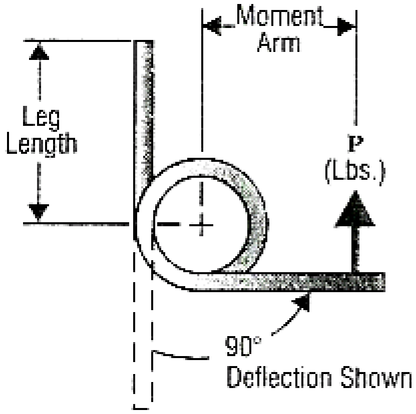
Appendix 1: Purchased Parts List

Part #	Quantity	Description	Ordering Information	Unit Price	Total Price
FSH00295	4	LTH300 - 500lb Donut Load Cell (5/16" Thru hole)	FUTEK 10 Thomas Irvine CA 92618 Phone: (800) 23-FUTEK (949) 465-0900 Fax: (949) 464-0905	$ 425.00	$ 1,700.00
MCP00988	4	XAC400 - Hardened top washer (5/16" thru hole)	(FUTEK see above)	$ 20.00	$ 80.00
MCP00989	4	XAC400 - Hardened bottom washer (5/16" thru hole)	(FUTEK see above)	$ 30.00	$ 120.00
1375K26	1	Pulley for timing belt	McMaster-Carr 200 New Canton Way Robbinsville, NJ 08691-2343 Tel. (609) 689-3000 Fax.(609) 259-3575	$ 9.07	$ 9.07
1375K13	2	Pulley for timing belt	(McMaster see above)	$ 8.53	$ 17.06
7887K16	1	Timing belt	(McMaster see above)	$ 2.00	$ 2.00
91251A383	1	Socket cap screws for top and bottom plate	(McMaster see above)	$ 5.68	$ 5.68
91294A126	1	Socket cap screws for mounting encoder bracket	(McMaster see avove)	$ 6.76	$ 6.76
9287K84	2	Torsion Springs (2.500 in*lbs)	(McMaster see above)	$ 5.68	$ 11.36
9287K79	2	Torsion Springs (1.000 in*lbs)	(McMaster see above)	$ 5.51	$ 11.02
8450K2	1	Rubber Selector pack (15 pieces)	(McMaster see above)	$ 43.48	$ 43.48
3009A127	1	Steel rod for hinge	(McMaster see above)	$ 3.78	$ 3.78
5905K61	2	Needle Roller Bearing	(McMaster see above)	$ 9.79	$ 19.58
9287K124	1	New Torsion Spring for foot	(McMaster see above)	$ 9.24	$ 9.24
8609K12	1	Butyl Rubber	(McMaster see above)	$ 10.32	$ 10.32
E6A2-CW5C 200 P/R 0.5M	1	Miniature optical encoder	Omron Electronics LLC Industrial Automation One Commerce Drive Schaumburg, IL 60173 (847)-285-7011	$ 159.76	$ 159.76
				Total	$ 2,209.11

Appendix 2: Torsion Spring Analysis

Analysis for Determination of Torsion Spring:





$$k = \frac{FM}{D} = \frac{(Force\ Exerted\ on\ Spring)(Moment\ Arm)}{Max\ Deflection\ in\ degrees}$$

Assumptions:

1. Normal Human Walking Gait
2. Max deflection is 90°
3. Moment arm = 2 in. because that is average length (from McMaster-Carr)

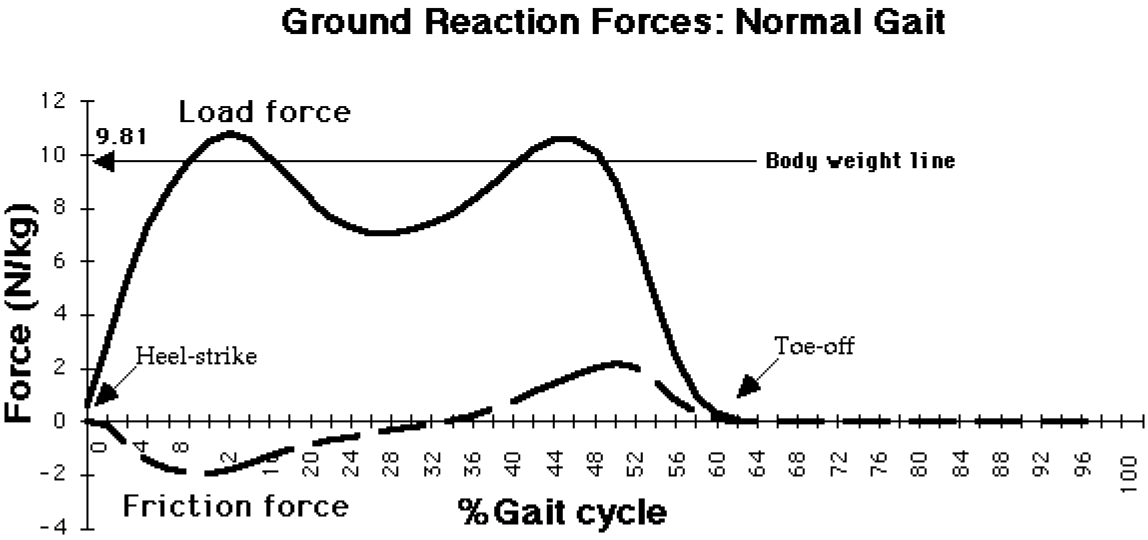


Figure 10 – From website: http://www.univie.ac.at/cga/teach-in/friction.html "Resolution of Forces, Friction, and the Ground Reaction Vector"

Robot = 100 lbs. = 45.36 kg

Energy Released ≅ 11 N/kg (From Figure 1 above)

F = (11 N/kg)(45.36 kg) = Force from toe off

F = 498.96 N = 113.4 lbs.

M = 2 in.

D = 90°

$$\boldsymbol{k} = \frac{(113.4\ lbs.)(2\ in.)}{90^\circ} = \boldsymbol{2.52\ in * lb/deg = 144.4\ in * lb/rad}$$

Calculation of Some Custom Spring Specifications:

$$k = \frac{Ed^4}{64nR} = \frac{(Young's\ Modulus)(Wire\ Diameter)^4}{64(\#\ of\ Coils)(Radius\ to\ Outside\ of\ Coil)}$$

$$E = 193\ GPa\ for\ Annealed\ 304\ Stainless\ Steel = 27992283.38\ psi$$

<u>Try 6 coils with a 0.4 in outside diameter (O.D.):</u>

$$144.4 = \frac{(27992283.38\, psi)(d)^4}{64(6)(0.2\ in.)}$$

$$\boldsymbol{d = 0.141\ in.}$$

$$\boldsymbol{l} = body\ length = (0.141)(7) = \ \boldsymbol{0.987\ in.}$$

This analysis was performed in order to determine exactly which kind of torsional springs were used. Based on the normal ground reaction forces for a normal human gait, the return force the springs should yield at 90 degrees was determined. The spatial constraints of the springs were also determined. In the event that a custom spring manufacturer could not create a spring or springs that met these conditions, the information to create a proper spring in house is available.

Appendix 3: Test Plan

Pulley/Tension belt:

1. Apply force to tension belt to ensure that it can withstand the required tension
2. Connect pulley/timing belt to fit and check at different rotations of the toe to see if displacement is constant or if force varies.
3. Make sure bore in pulley is centered so as to minimize errors in data.

Assembled Foot:

1. Mount foot for testing in a vice at ankle joint. Hang load from axle to measure deflection and compare with FEA results.
2. Apply known vertical load to each sensor at its center. Check results from each sensor to see how load distribution in foot compares to theoretical distribution.
3. Check how accurately the foot measures CoP on an even, then uneven, surface.
4. Check sensor measurements of foot on edge.

Rubber Samples:

1. Test samples in Dana 22 by putting a weight in the center of the sample and pulling the rubber along the floor with a force gage attached to the rope. Pick the rubber sample which requires the greatest amount of force to pull it along the force.

Hinges:

1. Evaluate k of each spring by applying force and measuring deflection. Check to see if k-value of the springs matches manufacturer given k-value.
2. Check to see if there is any slop in the hinge after it is screwed into the foot. Apply vertical force and check to see if deflection is within accepted safety factor value.
3. Set toe to given angle and check to see if encoder accurately measures the angle of deflection.
4. Check to see if limit stop actually limits motion to 90°.
5. Check to see if no stress on encoder when foot is supporting weight on toe section.
6. Check to see that belt tension doesn’t give an error to deflection measurements.
7. Examine impact loading on limit stop both in FEA and in testing.

Electrical Test Plan:

1. Get results about power from Jerry
2. Give specifications to Tom Thul and design electrical components and amplifiers if necessary
3. Write and test code for recording output (possibly Labview)
4. If labview check with Professor Mastascusa for help
5. Measure electrical output of sensors and check to see if the robot can read that output.

Sensors:

1. Check wiring of sensors to make sure that it reads zero when no load applied.
2. Apply known loads and check accuracy.
3. Test side loading to see how recalibration works. Combine vertical and horizontal components to a single sensor to how accurately it measures the vertical force.
4. Check to make sure amplification of signal output doesn't affect reading.
5. Measure how accurately a preload can be applied to each sensor. Examine preload on each sensor. Determine if the same preload can be applied to each sensor.

Encoder:

1. Apply known displacement to encoder to determine if it measures proper angle.
2. Apply small side load (similar to that of tension belt) while rotating to make sure it doesn't affect measurements.

Appendix 4: Memos

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MEMO

MEMORANDUM

DATE: January 26, 2009

TO: Professor Stryker

FROM: Lee Markison, Jerec Ricci, Chris Shake, Chris Slavin

SUBJ: Senior Design Project: Robotic Foot

ATTACHMENTS: Gantt Chart

The foot design that utilizes the force/torque tri-axial sensor is completed. However, Jerry Pratt of IHMC requested that another design be developed using load cells. After the foot design with load cells is complete, a decision will be made on which foot to build. Once the foot is built, rubber traction will be added to the bottom.

A phone conference was held on Friday, January 23rd with Jerry Pratt. User requirements and engineering specifications were determined for the alternate foot design. Jerry specified a maximum height and weight for the new design. The maximum height from the ankle Universal bearings to ground was determined to be about 2.5 inches and the maximum weight of each foot should be about 2.5 pounds. Although the force/torque tri-axial sensor would provide the most accurate CoP (center of pressure) measurement, it would fail under fatigue if loaded with the full force of the ankle actuators. This limitation is one reason that an alternate load cell foot design could be an improvement over the force/torque tri-axial sensor design. Additionally, the tri-axial sensor weighs about 2 pounds. A foot cannot be designed to weigh less than 2.5 pounds with this sensor.

The Gantt chart was updated to reflect the progress and schedule of the project. The deliverables and specific tasks for each week are outlined within the Gantt chart. According to the Gantt chart, a finalized foot design will be chosen within the next two weeks and parts will be ordered and fabricated to build the best design.

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MEMO

MEMORANDUM

DATE: February 9, 2009

TO: Professor Stryker, Professor Buffinton

FROM: Lee Markison, Jerec Ricci, Chris Shake, Chris Slavin

SUBJ: Senior Design Project: Robotic Foot

ATTACHMENTS: None

After talking with the customer, Jerry Pratt of IHMC, a decision has been made on one foot design to be built. The load cell foot design will be built and parts will be ordered promptly.

There is no longer a requirement for the foot to be contained within a shoe. Thus, the feet will require rubber tread on the underside to provide traction. To determine which rubber material will have the most friction on concrete (the target surface), a sample pack of 14 different rubber and foam varieties will be ordered and tested. Once a material is selected and approved, an appropriate quantity will be ordered for assembly with the rest of the feet.

The FE analysis is in progress, but the feet currently weigh more than the target value of 2.5lbs. The working design is 2.77lbs without the ankle distal, and it appears from the FEA that the material around the hinge bearing will need to be thicker to support the weight. More tests are being run, and hand verification of results is also being used as a check.

A conference call with Jerry Pratt and Steven Shooter on 2/6/09 revealed several important ideas to our group. Professor Shooter suggested buying springs of different stiffness, so that the team can run tests to determine the best. The customer service representative at Futek will be contacted soon to verify if washers above and below the load cells will eliminate shear loading. The specification for allowable shear load on the cells also needs to be found. The team needs to allow for wiring all 4-7 load cells on each foot. The wiring must be properly channeled up the robots legs, and more importantly through each foot. Signal amplification from the raw data needs to be determined before wiring can be completed. Rough drafts of a testing procedure for the feet have been made, but need to be improved and verified before any parts are ordered.

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MEMO

MEMORANDUM

DATE: March 17, 2009

TO: Professor Stryker, Professor Buffinton

FROM: Lee Markison, Jerec Ricci, Chris Shake, Chris Slavin

SUBJ: Senior Design Project: Robotic Foot

ATTACHMENTS: None

Over the past week, our team has machined the top and bottom plates of the back of the foot. The plates were machined out of Aluminum 6061-T6. The team has completed all part drawings for future machined parts. We are currently on track to complete the remaining plates by the end of next week. Most of the required parts have been both ordered and received in the past two weeks, including the Omron rotary encoder, the bearings, the axle, and a variety of springs and rubber sample sheets.

Due to a unit error conversion, new springs must be purchased with an expected lead time of two days. A different encoder than initially specified was purchased, because the original encoder had a 7-8 week lead time, which would take too long. The new encoder can be adapted to give the same output of the same encoder with a 2-kΩ pull-up resistor. We have been in contact with Tom Thul in the past two weeks regarding implementation of the encoder and wiring of all sensors to the robot. We will speak with him again to work on wiring once the Futek load cells arrive. The load cells have been ordered, but their current status is a mystery since Dan Johnson could not be contacted in the past week. We will also get in touch with him in order to finalize this order.

Once the front plates are machined, the encoder, axle, and new springs can be tested. The rubber sample sheets will be tested on concrete to determine the samples with the highest friction coefficients. Professor Brungraber's friction testing apparatus may be used in order to obtain more controlled friction coefficient data if he can be contacted.

A rigorous test plan detailing testing methods for the above products is on track to being completed by the end of the week. Dummy load cells may have to be machined in lieu of in transit sensors in order to complete testing on time. Machining should be completed in the next week, and testing should begin in the mean time.

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MEMO

MEMORANDUM

DATE: March 30, 2009

TO: Professor Stryker, Professor Buffinton

FROM: Lee Markison, Jerec Ricci, Chris Shake, Chris Slavin

SUBJ: Senior Design Project: Robotic Foot

ATTACHMENTS: None

All fabricated parts have been machined and the aluminum components of the foot are fully assembled. The center of the pulley needs to be bored out to fit on the axle between the hinges. A minor modification has to be made to the foot plate to allow the timing belt to move freely without rubbing on the bottom of the foot. The sensors have arrived earlier today, but dummy load cells were machined in the past week in lieu of the in-transit sensors in order to complete testing on time.

New springs need to be purchased to satisfy the load specifications of the foot. Multiple custom spring manufacturers have been contacted to make a spring that meets the given specifications. Unfortunately, the new spring must be 57 times stronger than the old spring but must be the same width to fit on the axle. The team needs to modify the encoder to produce the same output as the unavailable encoder that was specified. The new encoder can be adapted to give the same output of the same encoder with a 2-kΩ pull-up resistor. We will meet with Tom Thul on Tuesday to discuss adapting the encoder and amplifying the signal from the encoder and the load cells to get viable output for the robot.

The mechanical test plan is completed and testing will begin this week. We will contact Professor Mastascusa of the electrical engineering department once we have the electrical system complete to discuss writing a labview code. We spoke with Professor Brungraber and he told us to send the rubber samples to him. He will use his friction testing apparatus to obtain the friction coefficient of each rubber sample and we will use the sample with the greatest friction coefficient, provided it is hard and strong enough.

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MEMO

MEMORANDUM

DATE: April 13, 2009

TO: Professor Stryker, Professor Buffinton

FROM: Lee Markison, Jerec Ricci, Chris Shake, Chris Slavin

SUBJ: Senior Design Project: Robotic Foot

ATTACHMENTS: None

The foot is fully machined and assembled. All purchased parts have been received. Preliminary load testing has been completed.

A new spring was spec'd and purchased to replace the old, 57 times too weak, springs. The new design features a single spring as opposed to two springs, but the single spring is now only 14 times weaker than specified. Custom manufacturers were contacted to make a spring that meets specification. The manufacturers have responded that they require an order larger than one spring, and haven't given a price quote, but a custom spring might likely be prohibitively expensive.

Mechanical testing on the foot has been completed. A series of increasing weights was hung over the hinge of the foot to determine the deflection. Weights were added in 25 lb increments with the largest load being 100 lbs. The foot deflected linearly with increasing weight, so the deflection results for a 500 lb load can be interpolated from the data. The 500 lb load deflects the foot 0.5 inches, assuming elastic deformation.

The next step is electrical testing of the foot. Tom Thul attached two 1000 Ω resistors to the encoder wires to serve as the 2 K Ω pull-up resistor to match the purchased encoder output to that of the unavailable spec'd encoder. Tom Thul also suggested ordering an AMP 04 to amplify the strain gage bridge in the load cell to a readable voltage level. The AMP 04 has arrived and a meeting has been set up this week with Tom Thul to wire the AMP 04 to the encoder.

Professor Brungraber sent back the results of the friction tests of the rubber samples. The best rubber to use for the foot tread, based on durability, friction coefficient, and cost, is Butyl.

In the next week, the team will have completed the poster, electrical testing including writing a Lab View or MATLAB program to analyze the output of the sensor to see if the center of pressure can be resolved.