Design of an Instrumented Multifunctional Foot for Application to a Heavy Duty Mobile Robot Manufacturing System

by
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ABSTRACT

The design of a multifunctional foot for application to a mobile robotic system for heavy duty manufacturing is presented. The requirements for a target manufacturing task are presented and translated into requirements for the mobile robotic system, and specifically for the feet of this system. This includes: the ability of the feet to change frictional properties, the ability of the foot to operate without a direct power source, and load bearing requirements for heavy duty tooling. The mechanical design to meet these requirements for these feet is presented. Stability analysis is shown, and it is used to determine several design parameters to meet the goals of the project.

The development of a series of iterations of prototypes is discussed. Manufacturing techniques, choice of materials, alignment strategies and assembly practices are explained. Appendices include information about several of the important design milestones.

A sensing methodology is introduced. Computer simulations of magnetic fields to estimate the effectiveness of this methodology are performed. Experimental results are shown to match the simulations.

A final functional prototype is shown. Testing is performed on this prototype to verify that it meets the functional requirements desired for the system.

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My fellow lab members are a constant source of wisdom and insight as well as an often needed comic relief. I have never had the opportunity to work with so many selfless, creative, motivated and intelligent people as I have these past few years and I'm honored to be considered their peer.

Last, but certainly not least, I'd like to thank my family, especially my parents. It is difficult to put into words the gratitude I have for the way they have raised me. They are constant role models and teachers. They have given me an appreciation for math and science, food and art. They have taught me the importance of compassion and work ethic. They have given me the opportunity to live a full, happy life and I am forever indebted to them for it.

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List of abbreviations and symbols

KE	kinetic energy
PE	potential energy
BHmax	maximum value, product of magnetic field strength and flux density
MGOe	megaGauss Oersteds
EM	electromagnet
PM	permanent magnet
H	magnetic field strength
Ht	tangential component of magnetic field strength
kg	kilogram
lbf	pound-force
lb	pound
N	normal force
F_s	spring force
F_m	magnet force
mg	force due to gravity
l_1	length of lever arm 1
l_2	length of lever arm 2
R	reaction force
ABS	acrylonitrile butadiene styrene
FEMM	Finite Element Method Magnetics
FEM	finite element method
Amp	Ampere
m	meter

V	volt
mV	millivolt
mm	millimeter
CAD	computer aided design
A	Ampere

1. INTRODUCTION

1.1. BACKGROUND

The aircraft industry faces unique manufacturing challenges when compared to processes such as automotive manufacturing. In automotive manufacturing, the car or work piece is carried down an assembly line to a series of waiting tools. These stationary tools perform their tasks, and the work piece is sent further down the line. This is the standard paradigm for manufacturing operations in such an industry.

Airplanes, however, are too large to carry along an assembly line. There are many steps involved in building an airplane and such an assembly line would be prohibitively long. This makes automating such processes difficult. Unfortunately, there are many repetitive processes that manufacturers would like to automate. Most of these processes are currently performed by hand by factory workers. This is often unpleasant work, as it can cause repetitive stress injuries and is often dangerous and uncomfortable.

Because airplanes are too large to move down an assembly line, past a series of stationary tools, it is possible that a good way to automate their manufacturing could be to have the airplane itself stay still, while the tools move. This implies that tooling would have to be incorporated onto a mobile robotic system that traversed the airplane's surfaces, performing operations as it went. Such a paradigm introduces a host of complications, but solving it successfully could be a great boon to these industries. We are interested in the design of a system that can solve these problems. This work focuses on one very important component of such a mobile robotic system – the "foot" of the locomoting robotic system.

1.1. MOTIVATION

We start an exploration of manufacturing operations for automation with a specific task: fastener installation. Fasteners are used to attach thin sheets of material to one another; as an example, fasteners attach aluminum sheets to spars and strut flanges in the wing of the aircraft. There are hundreds of thousands of fasteners on an aircraft, and they are arranged in regular rows, making their installation an ideal choice for an automation procedure.

Currently, fastener installation is performed manually. In order to install a fastener, tooling must be brought together on both sides of the sheet metal, at the location that the fastener is to be installed. The "outer" tool is brought up against the outside of the wing box with relative ease, using a large movable fixture. However, the "inner" tool is brought inside of the wing box by an operator. This operator must climb into the wing box while holding a heavy tool, and then precisely position it with respect to its counterpart on the outside. There is little room inside the wing box so this is a difficult and uncomfortable task for the operator, as well as being time consuming.

In order to perform this operation automatically, it would be essential for a robotic system to climb along both sides of a sandwich of sheet metal parts. Because these fasteners are located all over the aircraft, this robotic system would have to work at any orientation – that is, it would have to be able to climb vertical walls as well as traverse horizontally. Thus we are interested in working to create a component of a robotic system with some climbing capabilities.

We expect that in addition to the fastener installation problem described earlier, such a system will also be applicable to a broad class of manufacturing, inspection and testing applications. This will be discussed in more detail later. In addition, we plan to develop control methodologies for this system. Based on our predictions of the design of the final structure, we will be working on the control of a switched system. The theory developed for such a system type could also be useful for a broader class of systems.

1.2. LITERATURE SURVEY

Climbing robotics is an active field of research. There is a great interest in bio-mimetic designs, utilizing adhesive materials or small "spines" such as those found in nature ([5], [12]). The mass production of such materials, however, is infeasible at this time. The use of magnetic adhesion has also been explored; however, these robots deal only with climbing walls that are of ferrous materials ([1], [13]). In general, the surfaces of the plane are not ferromagnetic. It should be noted, in addition, that very few of the climbing robotic systems in active research are designed to support the types of heavy duty manufacturing tools that we are interested in working with.

2. ROBOTIC SYSTEM

2.1. FUNCTIONAL REQUIREMENTS

As described previously, the task we are interested in automating is fastener installation. This operation joins portions of wing sheet metal to supporting strut and spar flanges. Instead of focusing on exactly this task, we choose to deal with a class of tasks that include this problem. In this way, we keep the important concepts for this system more general, and therefore more likely to be applicable to a large number of operations.

Figure 1 illustrates a class of tasks considered here. An operation must be performed using an end effector that is on the interior of some structure. It should be noted that for fastener installation, a pair of tools must mate with each other on the inside and outside of this thin wall. Automatic such a procedure is challenging. It is clear that in general, accessing the outer panel of a structure can be simple. Overpowered gantry systems or large robotic arms can reach the outside surface to bring in tooling. The challenge is found because, for our problem, it is necessary to control the locomotion and operation of a secondary end effector that sits on the inside of the panel. Furthermore, manipulation of this inner end effector must be possible when it is operating against a wall panel of any orientation.

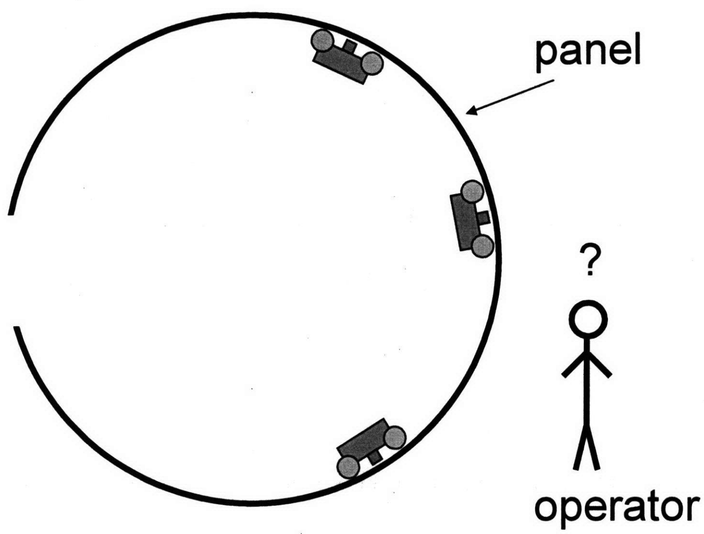

Figure 1 - Operation across a thin panel

Let us further define the problem. We assume that the inner tooling is heavy, and that it is working in a cluttered environment. This makes it difficult to use a long robot arm that would circumvent the wall to control the inner end effector. It also makes wireless operation very attractive, as a tether is likely to catch or tangle on the environment. In the worst case scenario, we would have no access to the inner robot except through the wall. This would mean that the inner end effector is not powered (passive). We assume that battery power would not be able to provide sufficient force to move the heavy duty tooling. In addition to these challenges, we assume that the tooling requires precise positioning ability and a significant amount of bracing capability while operating.

Given these requirements, the problem description for the overall robotic system is the *control of a heavy duty, passive end effector from across a thin wall at any orientation.*

2.2. ROBOTIC SYSTEM DESIGN

One proposed solution to the problem of manipulating a robot on the interior of a thin wall panel is a robotic system that is comprised of two robots – one on the interior and one on the exterior of this panel. The exterior robot can easily be controlled and powered using tethers or possibly an external robotic arm. The interior robot, however, is controlled by the exterior robot.

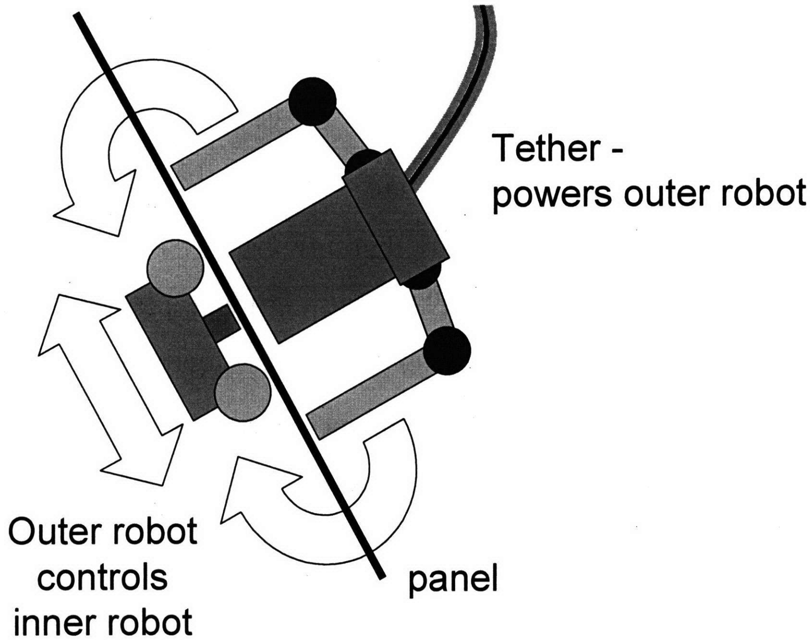

Figure 2 - Outer robot used to control inner robot

In order to allow these robots to operate at any orientation, a promising proposal is the use of a magnetic system to provide a holding force between the pair. By using strong electromagnets and permanent magnets, it is possible to exploit the field that penetrates through the panel to hold the inner robot in place, as well as to manipulate it using the Lorenz force. That is, by running a current through a wire loop that is sitting within a magnetic field, one can induce a force on the robot from across the panel. Figure 3 shows a possible location for a wire coil (powered by the outer robot) that could induce a force on the inner robot, much in the same way that a linear motor works.

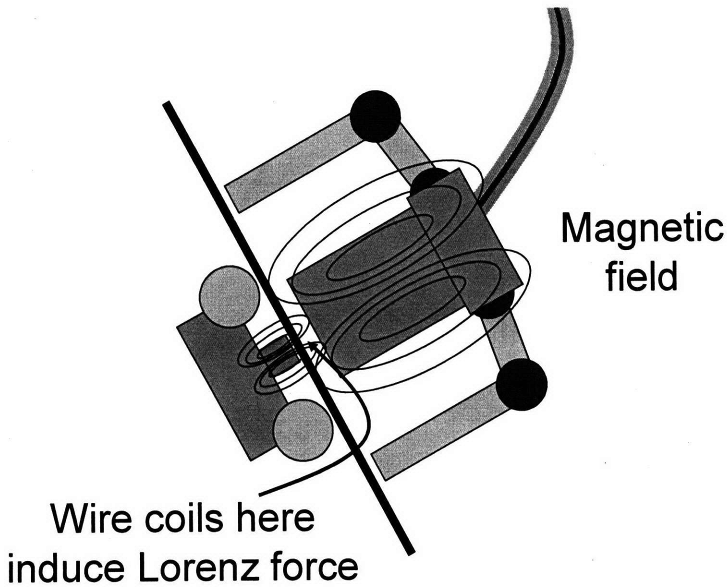

Figure 3 - Lorenz force actuation through panel

While the outer robot is easily accessible, the inner robot is working in an environment with cables, spars, and other obstacles that could snag a power cable. For such reasons, it is desired that the inner robot is tether-less. Using permanent magnets for the inner robot allows us to eliminate these tethers and saves power. However, locomotion remains a challenge, since this heavy, tether-less inner robot must be moved in any direction, often against gravity. This is a difficult but essential problem for our assembly operation of choice (fastener installation). The fasteners are several centimeters apart, and rows of fasteners can be separated by meters. While magnets can provide strong holding forces in the normal direction, it is difficult to induce traction forces along the wall surface that are large enough to lift and move the body against gravity. This is illustrated in Figure 4.

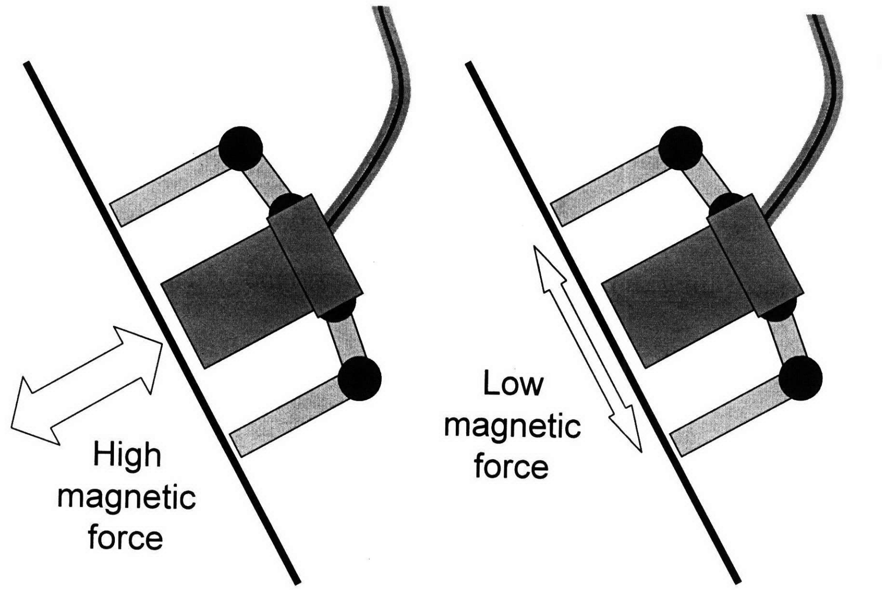

Figure 4 - Difficulty in inducing large lateral forces

Although it is difficult to induce a large lateral force on the inner robot, we can easily stimulate a series of smaller forces at a controlled frequency. By tuning this frequency to the natural mechanical frequencies of the inner robot, we can effectively dump large amounts of energy into the inner robot. The inner robot can then use this energy for locomotion, even while carrying a heavy payload. This is the key concept that allows for locomotion of the heavy tooling on the "inner" robot.

2.3. LOCOMOTION

The inner robot is designed to be tetherless. Its movement and position will be controlled by the outer robot. The outer robot will have a series of coils that sit close to the aluminum skin within a magnetic field that comes from the inner robot end effector. Running a current through these coils induces a small force on the inner robot, as shown in Figure 5.

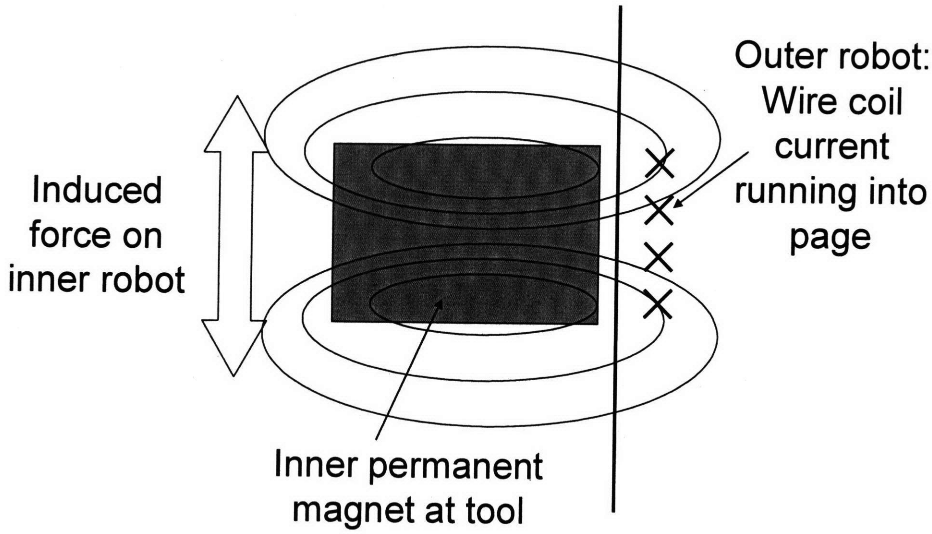

Figure 5 - Current from outer robot induces force on inner robot

The inner robot is expected to take the form shown in Figure 6.

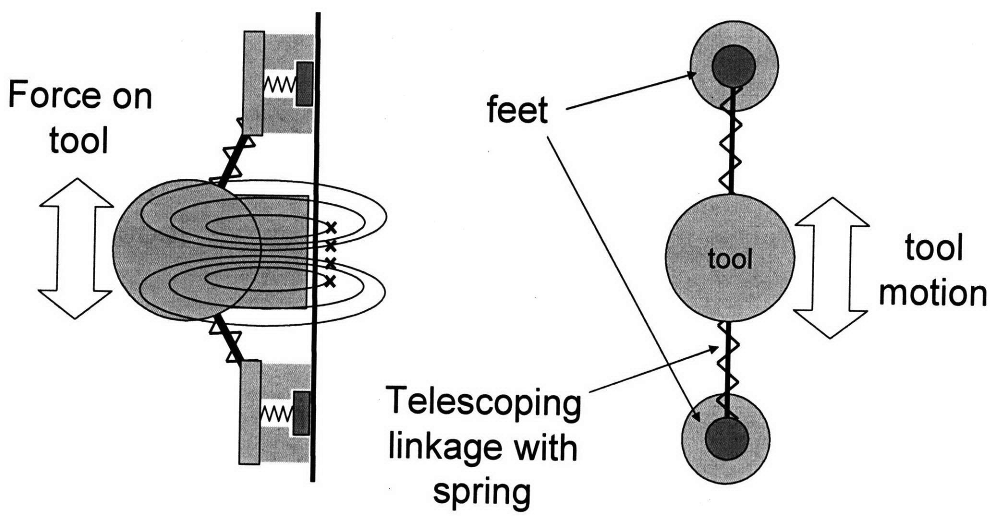

Figure 6 - Inner robot assembly

This robot will utilize an energy accumulation strategy similar to that often used in swing up control for a torque limited pendulum. As previously stated, it is difficult to produce a large force along the wall surface. However, it is possible to produce a small force at an easily controllable frequency. If the frequency of this repeated force is matched with the natural frequency of the forced system, we will be able to transfer a significant amount of energy to the inner robot. This energy will manifest itself in a large oscillatory motion of the end effector. It should be clear that as the outer robot applies small repeated forces, the inner end effector (tool), will oscillate back and forth along its telescoping linkages. Energy is stored as kinetic energy of the sliding mass and in spring potential energy during each cycle. Thus the inner robot accumulates a small amount of energy from each "push" in the same way as a child on a swing set.

As this inner end effector is oscillating, one can selectively detach and re-attach the feet in such a manner as to create locomotion of the inner robot, despite its significant payload. With a larger number of legs, gait control and path planning for such a system is a challenging endeavor. It is possible to gain some understanding of the type of motion available by considering the two foot case (see Figure 7). This figure shows an example of how such a system would take a forward step powered by the oscillation of the tool. The massive tool would be able to make a large slide forward against gravity because it is being run at resonance.

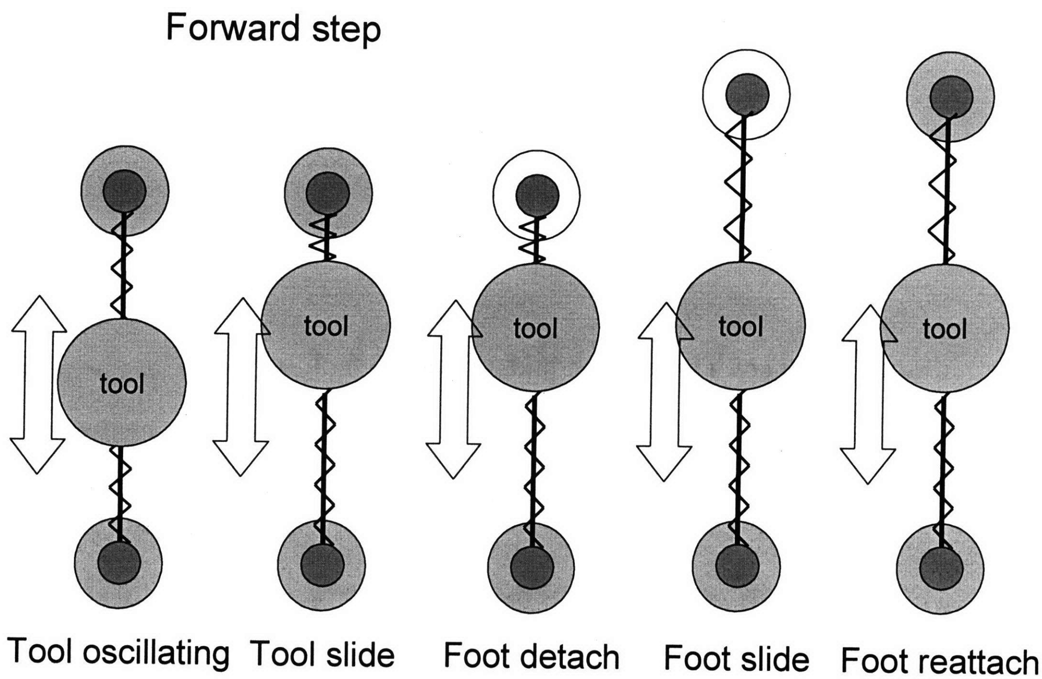

Figure 7 - Forward step motion of inner robot

The design of our foot described here should permit the robotic system to traverse the wall as described, as well as brace against the wall during tool operation or against the force of gravity.

3. CONTRIBUTIONS

The main contribution of this work is the design and development of the foot for the aforementioned robotic system. A static stability analysis of the foot to hold in several configurations was performed, and the results used to guide design parameters. Many iterations were assembled, tested, and dissected, leading up to a final fully functional prototype.

4. MECHANICAL DESIGN

4.1. TASK REQUIREMENTS

The foot for this robotic system must fulfill a variety of requirements. Much of the functionality of the robotic system as a whole is performed by these feet and they are crucial to the system's proper operation.

Normal holding force: The feet should provide a holding force in the normal direction (that is, *against* the wall) that is adequate to support the heavy tooling from falling due to gravity – at any orientation.

Tangential holding force: The feet should be able to provide a tangential holding force (that is, *along* the wall) that is adequate to support the heaving tooling from falling due to gravity – it should keep the robot from sliding down the wall. In addition, when the massive tooling on the robot is oscillating, this tangential holding force should keep the feet firmly in place.

Sliding: At times, the feet should be able to smoothly, and with little friction, move along the wall surface. This functional requirement is in contradiction to the tangential holding force requirement.

Switching: Because there are two contrasting functional requirements, it should be possible for the foot to switch between two modes – one with high tangential holding force, and one that slides easily.

Tetherless: In order to keep the inner robot tetherless, the feet should also operate without power. This means the *switching* ability must be actuated through some other method. In addition, the holding forces due to magnets must not come from electromagnets at the inner robot.

Lightweight: The feet should be lightweight enough that they don't contribute significantly to the mass of the tooling that the robot is carrying.

Sensing: It should be possible to determine the location of the feet from across the panel through some simple sensing method. This sensor, if it requires power, cannot be placed at the feet. Rather, it must be placed at the robot that is on the external surface.

4.2. DESIGN

The feet utilize off-the-shelf countersunk epoxy coated Neodymium Iron Boron permanent magnets. These magnets are extremely powerful (BHmax of 37 MGOe). Neodymium Iron Boron magnets are also known for their resistance to demagnetization as a result of impact. Their epoxy coating helps to further reduce the effect of these impacts. In addition, their geometry makes them easy to mount and work with. These permanent magnets are spring loaded into a custom housing as shown in Figure 8.

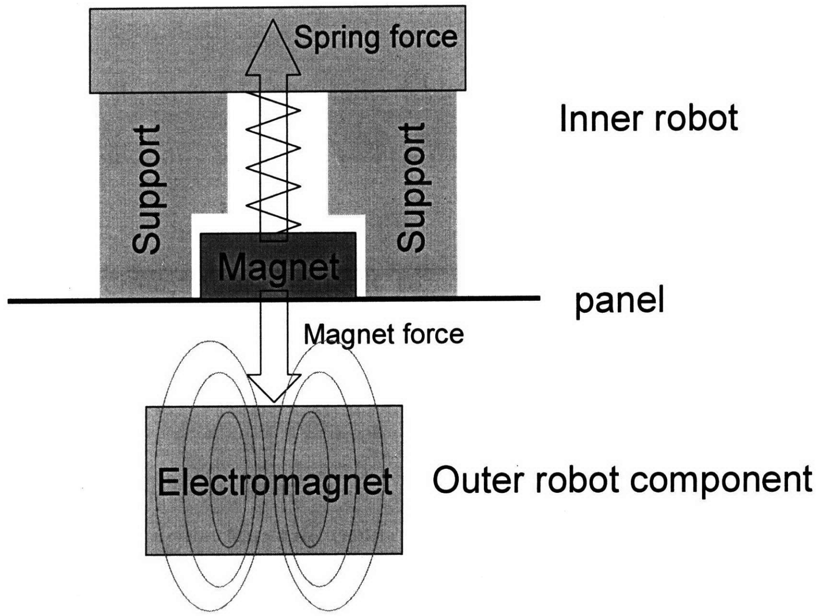

Figure 8 - Inner robot "foot" with outer robot electromagnet

On the outside of the skin, opposite to these feet, electromagnets are used to control the magnetic force that the permanent magnets feel. The electromagnets used for the final design are opposite pole electromagnets. This means the north and south pole of the electromagnet form on opposite sides. In most applications, this makes the magnetic circuit more difficult to complete. However, it helps us keep attractive force high even in the case of misalignment. By changing the direction of the current in the electromagnet, the permanent magnet either snaps back into the housing, or forward against the skin surface as shown in Figure 8. This bi-stable property is exploited in the operation of the foot.

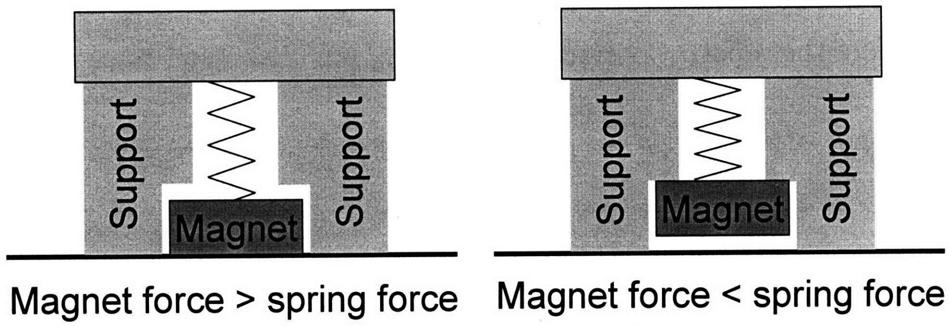

Figure 9 - Bi-stable foot

It should be noted that even when the electromagnet attempts to repel the permanent magnet, the flux density induced in the iron core of the electromagnet by the permanent magnet is larger than that induced by the coil of wire. That is, the permanent magnet is much stronger than the electromagnet. This means that there is always an attractive force between the two robots, so it is necessary to have a stiff spring to retract the magnet. This is beneficial to our design, as even when the electromagnet is disengaged, there is an attractive force on the inner robot (albeit a significantly reduced one) which helps to hold the robot in place.

Permanent magnets were used in the inner, passive robot foot because they have an excellent ratio of power to weight at the size scales we are interested in. However, we also desire the easy switching ability available in an electromagnet so that we can quickly control the magnetic force that the robotic system sees. The lightweight permanent magnets were used in the inner robot, as it is sensitive to weight and assumed to be unsupported, while the bulky electromagnets are used on the outer robot which is assumed to be controlled by some external mechanism. This allows us to have the benefits of both types of magnetic components.

The inclusion of a bracing mechanism is vital to the successful operation and locomotion of the robot. Consider the following robot configurations:

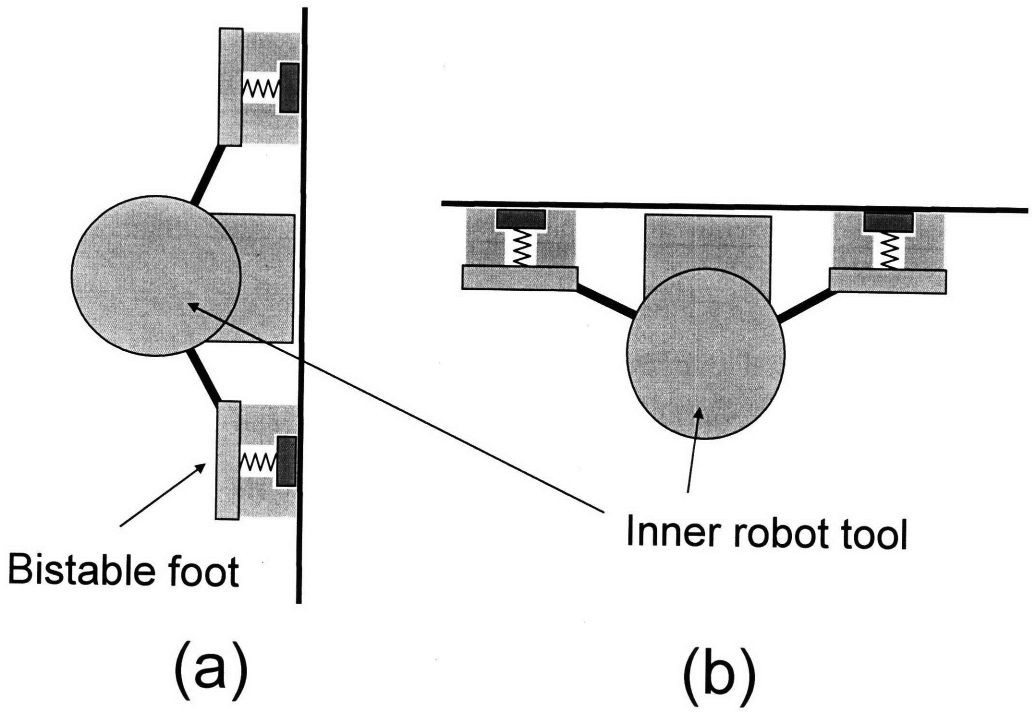

Figure 10 - Inner robot in two configurations

We can assume that the force holding the robot against the wall in Figure 10a is equal to the force on the permanent magnet. This force is not affected by the spring tension, so the robot is stable (i.e. will not fall). However, when the wall is vertical as in Figure 10b, the force holding the robot up is the frictional force. This is limited by the coefficient of friction of the surface in contact, along with the normal force at these contact points. Note that even when the magnet is fully engaged the normal force is distributed among the magnet and the supports – a result of the tension in the spring. When the magnet is fully engaged, the supports should be very high friction. However, because these are mobile robots, we would like the supports to have very low friction when the magnet is disengaged.

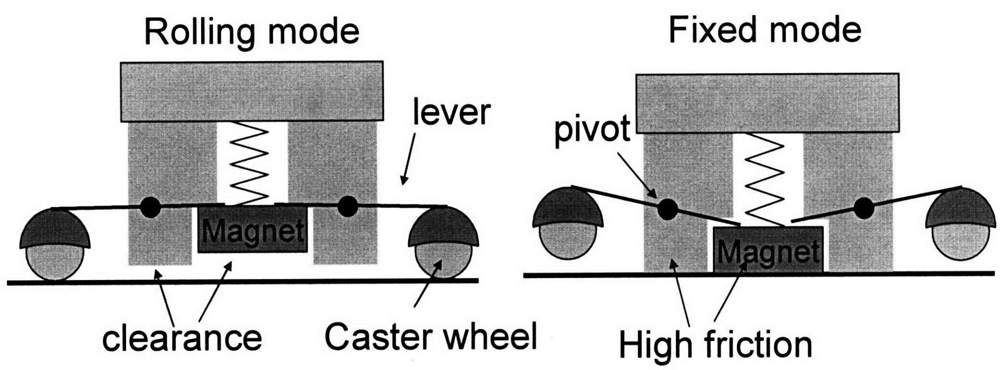

Figure 11 - High and low friction foot configurations

Figure 11 shows the design of the supports to meet such requirements. When the magnet is engaged, the wheels lift from the surface. The portions of the structure that bear normal force are the magnet housing and the aluminum supports – all rigid elements with high friction. When the magnet is disengaged, ball caster wheels are bearing the entire normal force seen by the robot, so it rolls almost without friction.

This bi-stable characteristic of the foot is necessary for its operation. A static analysis was performed in order to ensure its feasibility. We make several assumptions in this analysis. We assume that the travel on the magnet is small enough that the tension exerted by the spring remains constant at either configuration. Based on initial tests, we assume the attractive force on the magnet is either 11 kg (25 lbf) or 6.8 kg (15 lbf) (depending on the direction of current in the electromagnet on the opposite side). The mass of the system is assumed to hang from the "frame" of the system – the ball / level assembly is assumed to have zero mass.

We start with a static analysis of the "engaged" configuration.

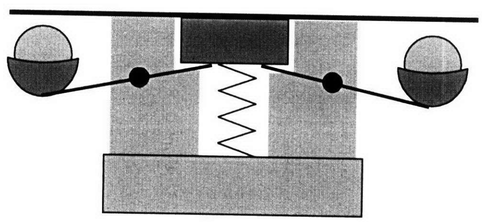

Figure 12 - Engaged configuration

Here we can break up the system into a collection of free bodies, as shown.

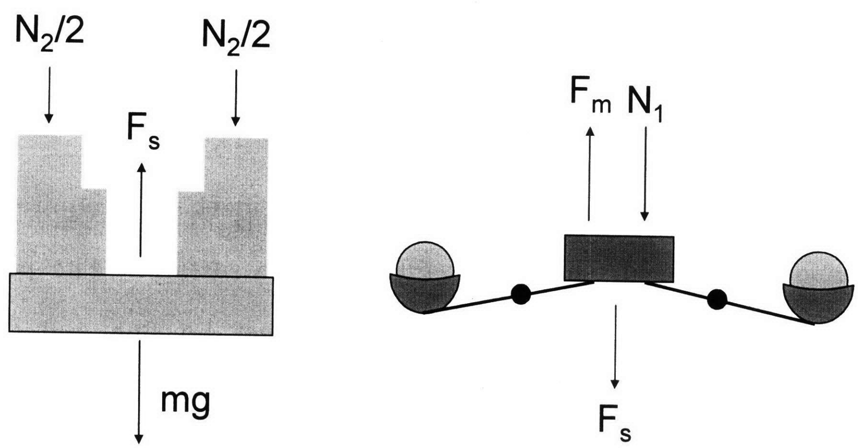

Figure 13 - Free body diagrams

Where N_1 and N_2 are normal forces from the surface, Fs is the spring force, Fm is the magnet force and mg is the force due to gravity. These free body diagrams produce a set of equations:

$$F_s = F_m - N_1$$
$$F_s = mg + N_2$$

This gives a condition on the required spring force:

$$\rightarrow mg < F_s < F_m$$

This condition must hold if the system is to remain statically stable.

Consider now the static analysis of the "disengaged" configuration

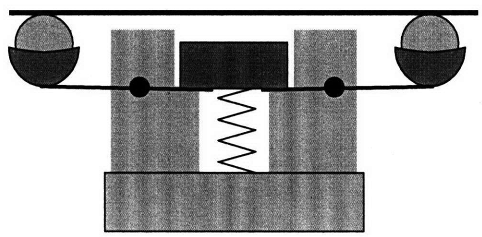

Figure 14 - Disengaged configuration

Again, we can form the free bodies

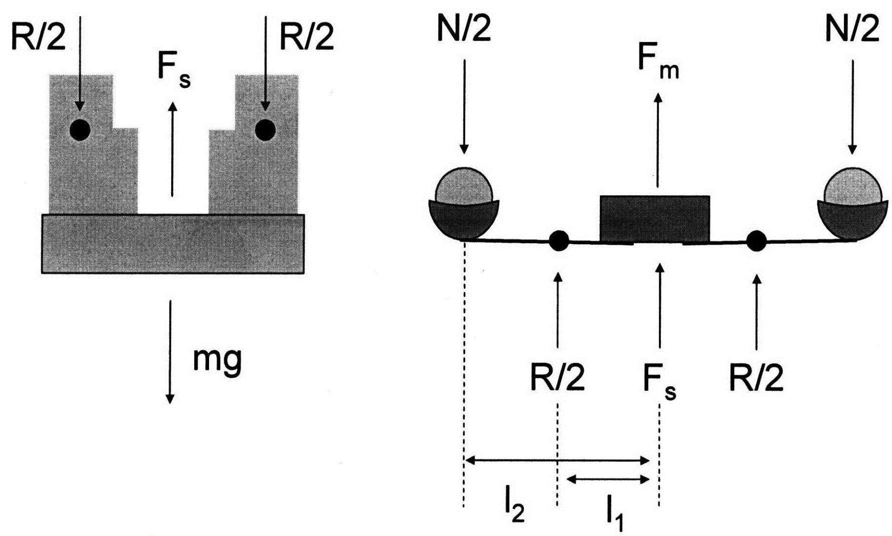

Figure 15 - Free body diagram

R here is the reaction force at the pivot point. l_1 and l_2 are lengths that determine the moment arm the magnet is pushing against. The resulting set of equations is:

$$mg + N = F_m$$
$$F_s = R + mg$$
$$Rl_1 = Nl_2$$

This gives the condition

$$(F_m - mg)(l_2 / l_1) + mg = F_s$$

These equations must also hold if the system is to remain statically stable. We plug into these equations the values of magnet holding forces found previously, and we assume that the mass (the support load required for that leg) can vary from 0 to 4.5 kg (0 to 10 lbf). We find that the ratio between the legs, l_1 and l_2 must obey the following relationship.

$$1 < l_2 / l_1 < 1.6$$

For safety, we choose a ratio of 1.25. A prototype of this foot has been built and tested, and will be described further.

5. MANUFACTURING

5.1. FABRICATION

It was necessary to develop a series of prototypes for testing and analysis. The fabrication of the parts required to build these prototypes come from a variety of manufacturing technologies. The "body" of the foot – the complex piece that holds the pivots and houses the spring was designed to be a complex, 3 dimensional part. It must be able to bear loads on the order of several hundred newtons without plastically deforming. This part was made using a 3-D printer –

a rapid prototyping machine that forms parts from acrylonitrile butadiene styrene (ABS) plastic. Small parts can be made in limited quantities in almost arbitrary geometries.

The ABS portion of the foot houses a pair of delrin bushings as shown in Fig. 16.

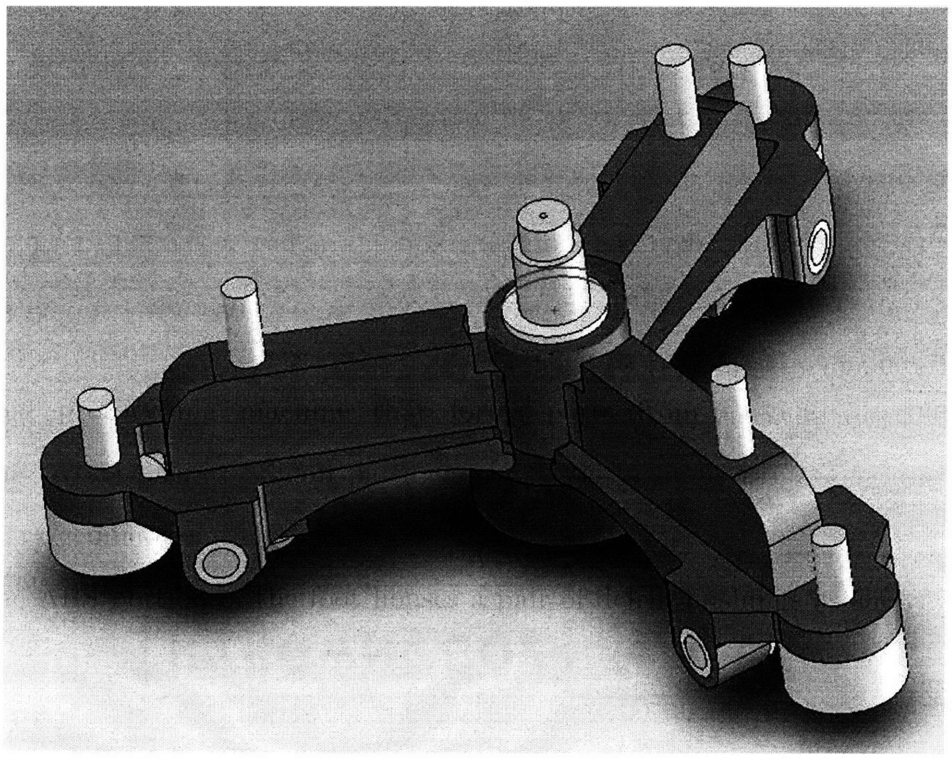

Figure 16 - CAD drawing of foot

These bushings bear against a ceramic coated (for reduced friction) center tapped aluminum shaft. An aluminum flat head screw is threaded through the countersunk magnet and into this shaft. Many of these parts were chosen to be aluminum in order to aid assembly in close proximity to the powerful magnets. The shaft slides in and out of the delrin bushing as the magnet moves towards and away from the surface the robot is sitting on.

Delrin bushings were also used to bear against the shafts that mount the "levers" (shown in Figure 16). These levers pivot by bearing against the top of the magnet surface. This pivoting is what brings the ball wheels into contact with the surface, or raises them away as desired.

When the ball wheels are raised from the surface and the magnet is engaged, the robot is bearing against the surface through three aluminum bolts that are mounted as shown in Figure 17 in addition to bearing against the magnet. These screws are aluminum in order to avoid interfering with the magnetic system, and also because of their frictional properties. This robot is designed to work on an aluminum surface and dry aluminum on aluminum has a coefficient of friction greater than 1. This allows these bolts to act as a high friction gripping surface when the magnet is engaged.

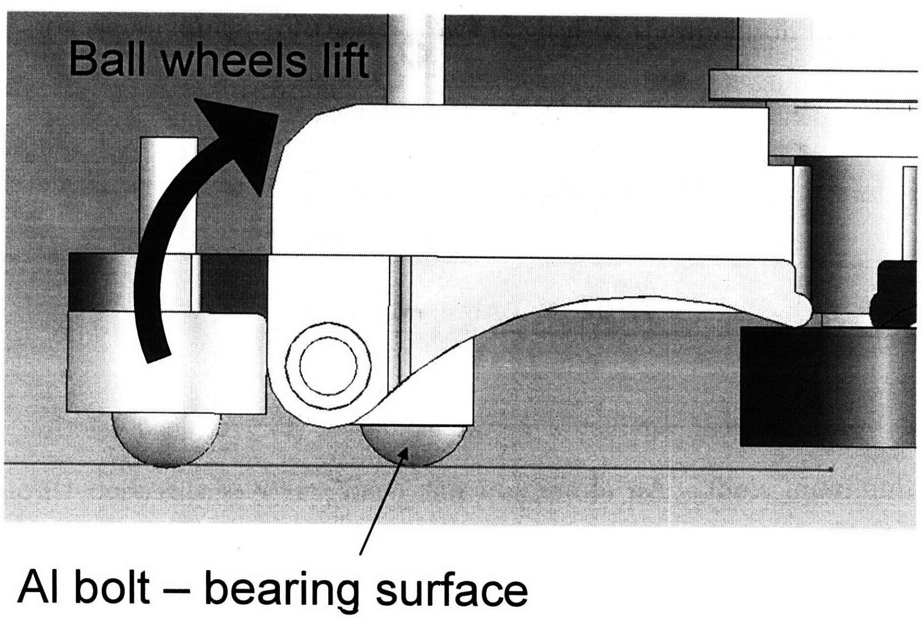

Figure 17 - Close view of foot bearing surface

The precise alignment of these screws is vital to the function of this foot, and will be discussed in a future section.

The aluminum shaft that holds the magnet in place is attached to a stiff spring that pulls it away from the surface. The opposite end of this spring is attached to a screw as shown in Figure 18. The screw can be tightened or loosened during assembly in order to adjust the force that the spring provides.

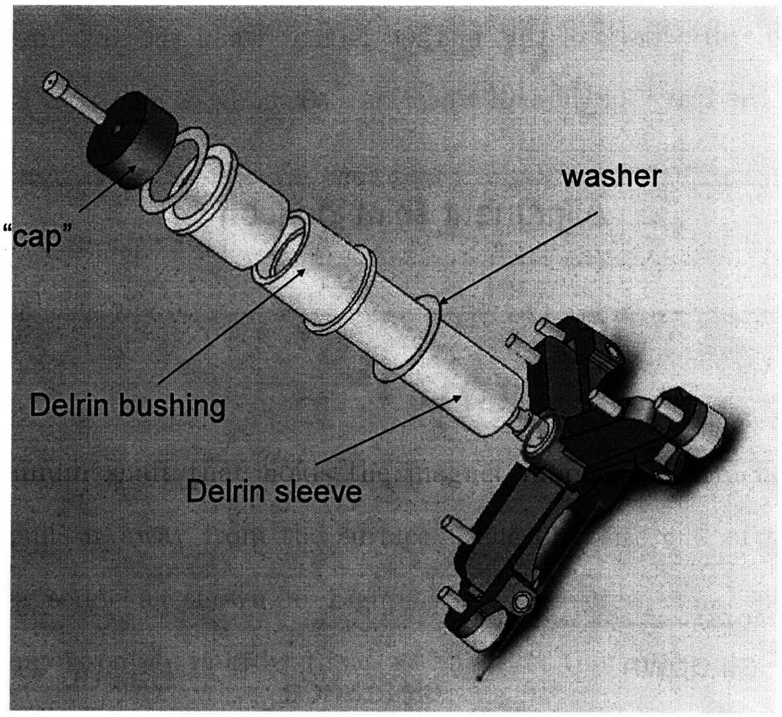

Figure 18 - Exploded view of foot

This screw is mounted against a cap, which is in turn mounted onto a delrin sleeve. The sleeve sits on the ABS plastic portion of the foot. The delrin sleeve has several large delrin bushings on it that bear against the sleeve and against thing steel washers so that they can spin with low friction. The washers are thin enough that the magnet does not exert significant forces on them. The large delrin bushings are designed to be mounting points – locations for each foot to attach to the main body.

5.2. ALIGNMENT

A previous section described how the ratio of leg lengths for the ball wheels was chosen. In the interest of keeping the foot light weight, we would like to maintain the required ratio while keeping the absolute leg lengths as small as possible. One drawback of this method is that when the absolute leg length is fairly small, the travel of the ball wheels is also small, as shown in Figure 19.

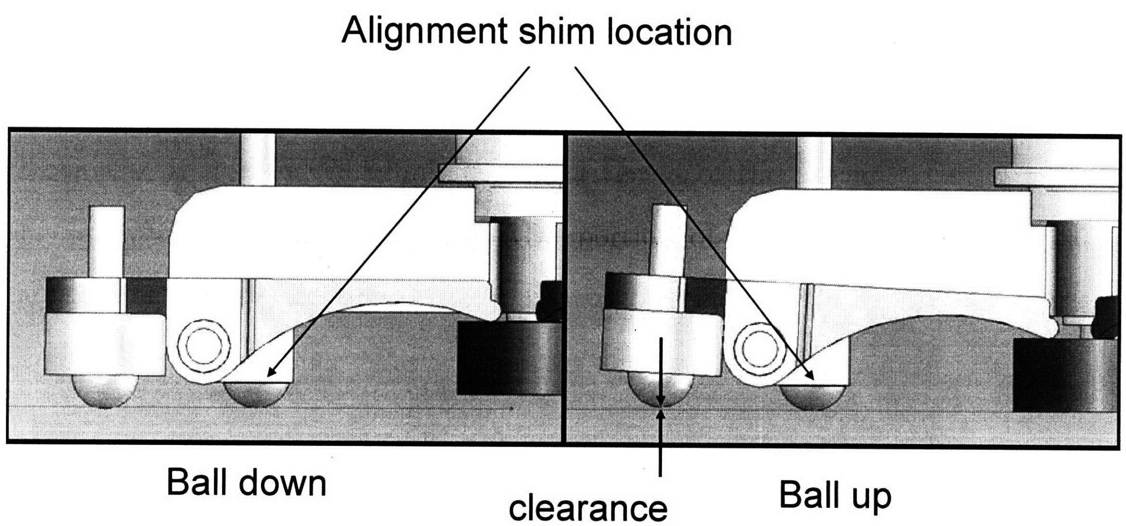

Figure 19 - Alignment in foot

As this travel decreases, alignment becomes increasingly important. That is, the ball wheels should not bear a load in the "engaged" configuration, while the supports should not bear any load in the "rolling" configuration. The precise location of this screw will limit the effectiveness of this design. Unfortunately, the screw is mounted against the ABS portion of the foot. This portion was made by a rapid prototyping machine that had poor spatial resolution - on the order of 0.5 mm – which is approximately the resolution we require. In order to perform fine adjustment, the height of these screws is adjusted using shim washers that have a thickness on the order of 0.1 mm.

5.3. ASSEMBLY

Figure 18 shows the layout used to assemble the prototypes. Kevlar cables were used to tie to the springs, attached with a non slip bowline knot. These cables were threaded through vented screws in a manner so that tightening the screw adjusted the tension on the cable. For most iterations of this prototype, the assembly procedure was the same: (1) parts assembled (2) knots tied (3) vented screws tightened. This multi step assembly and alignment process allowed for good control over spring tension and ease of manipulation while testing.

6. SENSING

6.1. SENSING GOALS

It is crucial to the operation of this system that the outer robot creates a holding force on the inner robot. In addition, it needs to apply small lateral forces for locomotion at the appropriate time as the inner robot oscillates. In order for both of these tasks to be accomplished, the outer robot needs to be able to sense the position and velocity of the inner robot. This sensing must occur across the thin panel, and it should be accomplished without the aid of any power from the passive inner robot.

We focus here on a method to accurately find the position of the *feet* of the inner robot, so that the electromagnets of the outer robot can align with their existing field. Because the feet of the inner robot are fitted with powerful permanent magnets at their center, it is reasonable to use Hall Effect sensors to detect the magnetic fields, and therefore the position of these feet. Hall Effect sensors will be mounted to the outer robotic assembly in pairs as shown in Figure 20. By taking differential measurements over pairs of these sensors, the location of the feet of the inner robot can be found with good accuracy.

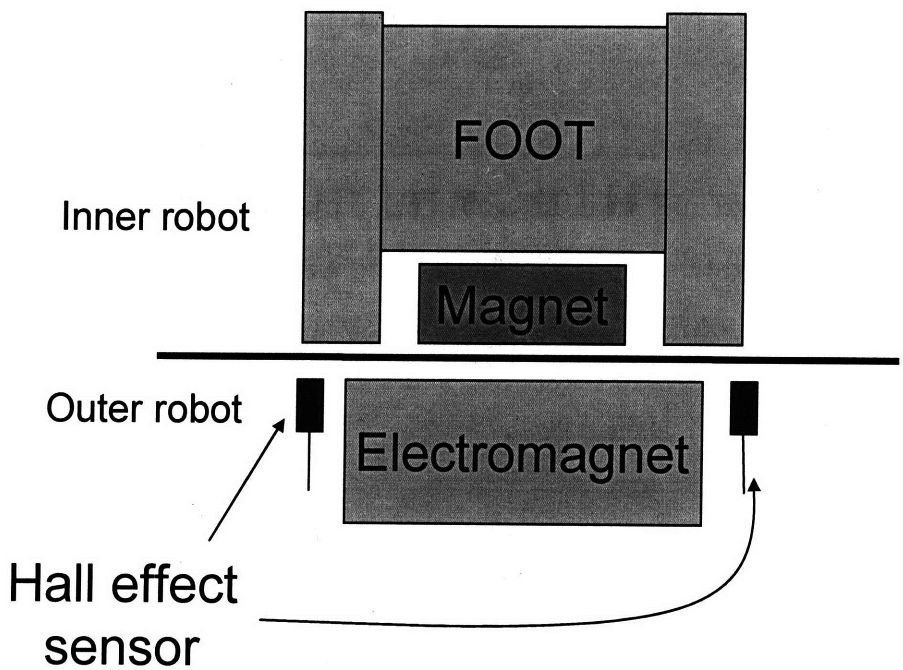

Figure 20 - Hall effect sensor location

6.2. FINITE ELEMENT ANALYSIS

Before performing experiments, the properties of the field were explored using Finite Element Method Magnetics (FEMM). This software package models magnetic fields due to permanent magnets or coils of wire. The layout used, along with the derived field lines, is shown in Figure 21.

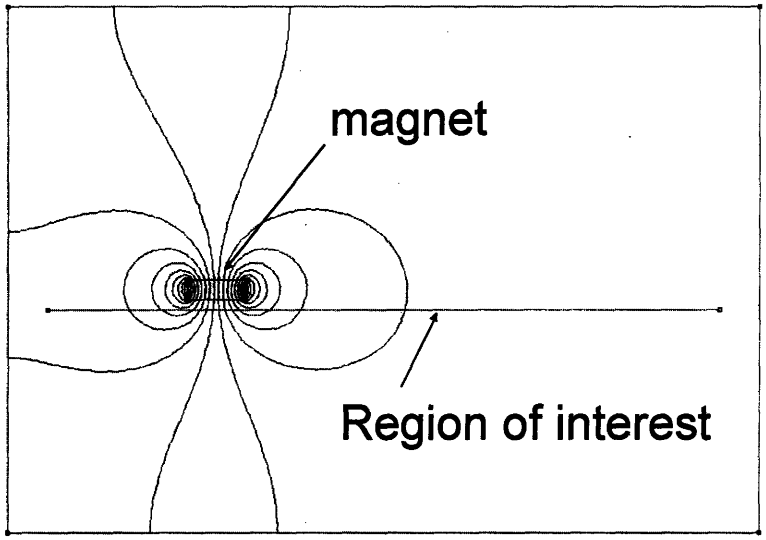

Figure 21 - FEM field results

We are interested in the field along the red line as that is the location that the Hall Effect sensors will be placed. For ease of mounting, we would like to place the sensing axis *tangent* to the line of interest. The field tangent to this line can be determined from FEMM, and is shown in Figure 22.

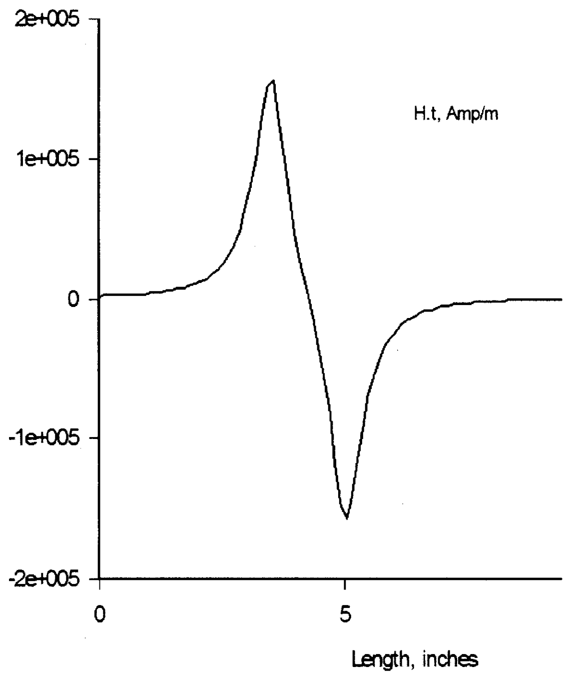

Figure 22 - FEM tangential field results

We are interested in the slope of the field near the region when the magnet is slightly misaligned (on the order of several centimeters). Note that due to the location of the sensor as shown in Fig. 20, the region of interest is when the sensor is about 4 cm from the center of the magnet. The slope of the field here is small, but enough to get precision on the order we desire.

6.3. EXPERIMENTAL CONFIRMATION

A test setup was built using A1301EUA-T Hall Effect sensors. These sensors were chosen because of their good sensitivity and their linear voltage to field strength relationship. In addition, they are low cost and easily mountable.

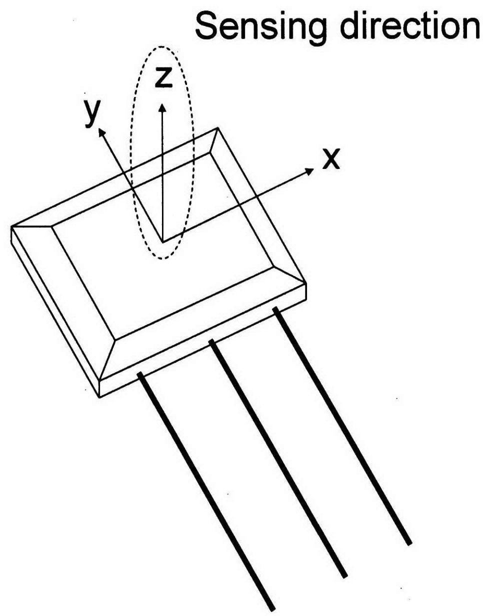

Figure 23 - Sensing axis

The output of the Hall Effect sensor is proportional to the magnitude of the magnetic field *through the z axis of the sensor.* This is shown in Figure 23. Figure 24. shows the experimental stage used to test the effectiveness of these sensors at the distances we expect to be important for the final robotic system.

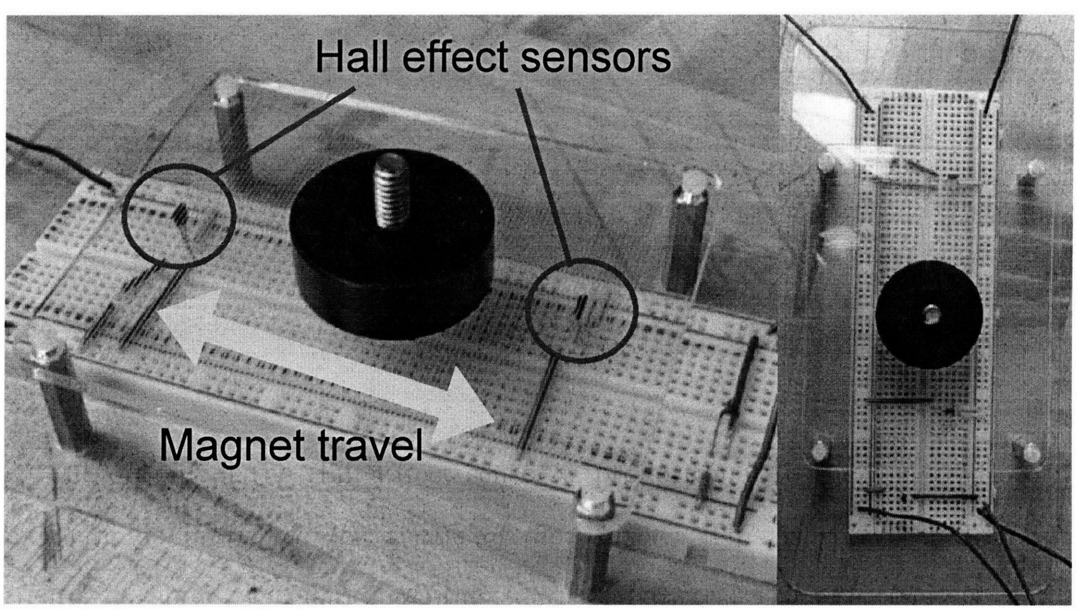

Figure 24 - Hall effect sensor testing experimental setup

Data was taken from the experimental setup to verify the accuracy of the predictions from the FEMM calculations. Two sensors were used, and the output of these sensors as the position of the magnet was varied is shown in Figure 25.

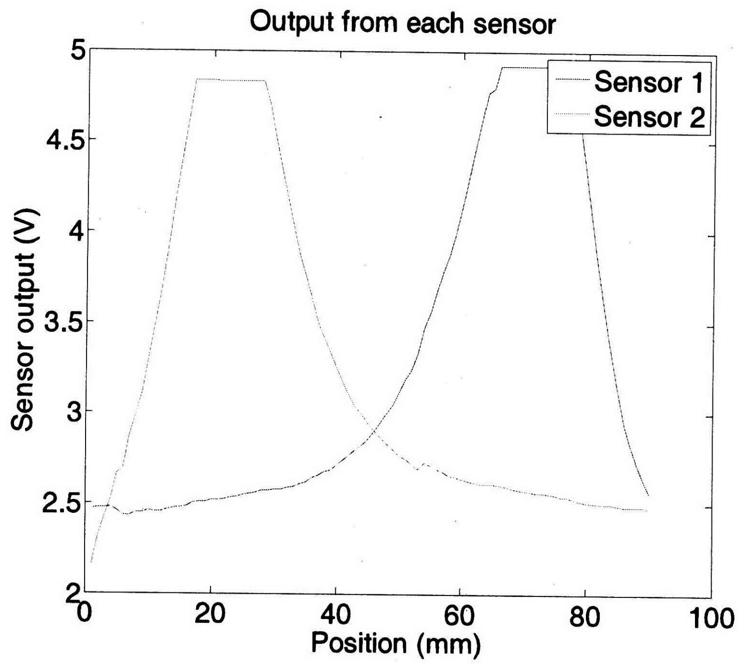

Figure 25 - Results from sensor tests

Note that the output of the Hall Effect sensors saturate as the field gets very high. The output we consider is actually the difference between these sensors, which is plotted in Figure 26.

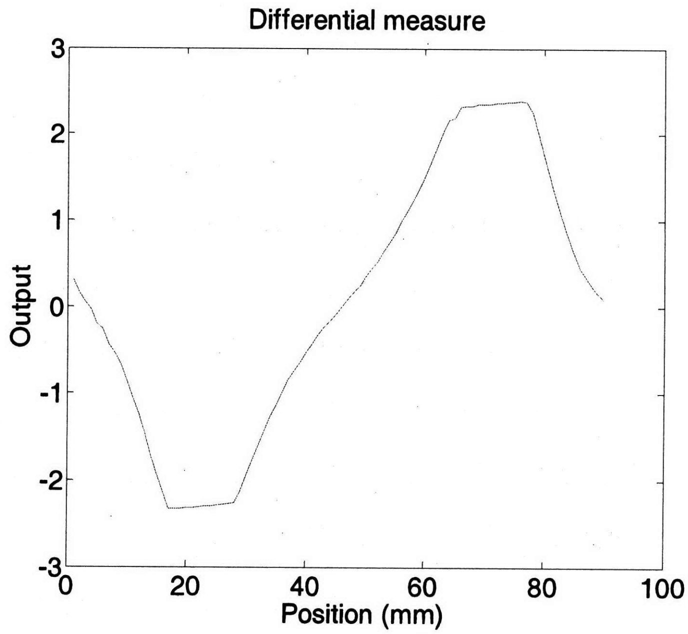

Figure 26 - Differential sensor measurement

The sensitivity of the system near the "aligned" position is on the order of 100 mV / mm. The noise in the sensors is generally on the order of 50 mV / mm. This means we can get mm sensitivity, which is more than adequate for our purposes. The required sensitivity only requires aligning the feet well enough such that the magnetic field from the permanent magnet overlaps well with the field from the electromagnet. This corresponds to a resolution on the order of 5 mm.

The methodology described here shows how Hall Effect sensors could be used to detect the location of the feet of the inner robot in order to match their location with the electromagnets of the outer robot. We expect to use a similar method to locate the position of the tooling on the inner robot.

7. PROTOTYPE

The tooling required for the fastener installation procedure weighs approximately 13.6 kg (30 lbs). We predict the final robot will have 3 feet. If each foot can bear a load of 20 lbs, we feel comfortable that the robot will not fall from the wall. Each permanent magnet used can bear about 25 lbs, and the mass of the foot is $<$ 5 lbs, so the feet were designed to be able to bear this load.

A functional prototype of the foot for this robot has been built based on the specifications from the static analysis. Figure 27 shows the CAD drawings of the lever / pivot / magnet assembly. The magnet is attached to a ceramic coated aluminum shaft that allows it to slide vertically in delrin bearings. The larger parts are made from ABS plastic from a rapid prototyping machine.

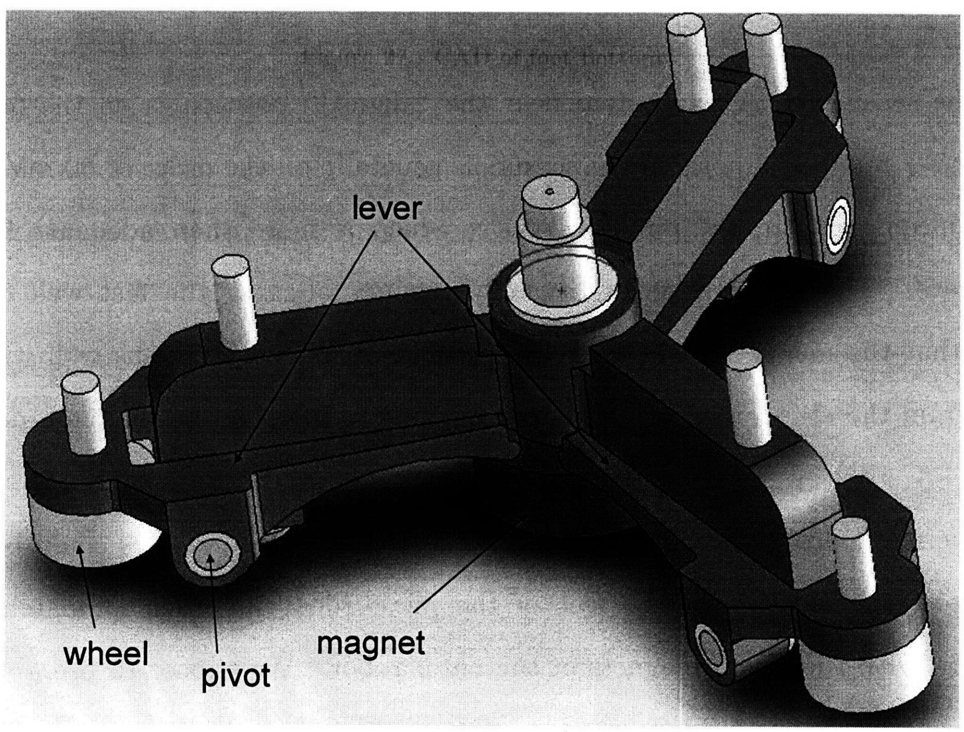

Figure 27 - CAD of foot bottom

Previous versions of the foot had difficulty releasing from the surface (transitioning to "disengaged" mode) unless there was a significant weight on the structure to assist the disengagement. The design should not rely on this weight, as its effective magnitude may vary depending on the orientation of the robot.

By following the design constraints found in the static analysis, we were able to build a prototype that was able to completely disengage and re-engage quickly, repeatedly and reliably with no applied load. Figure 28 shows this prototype.

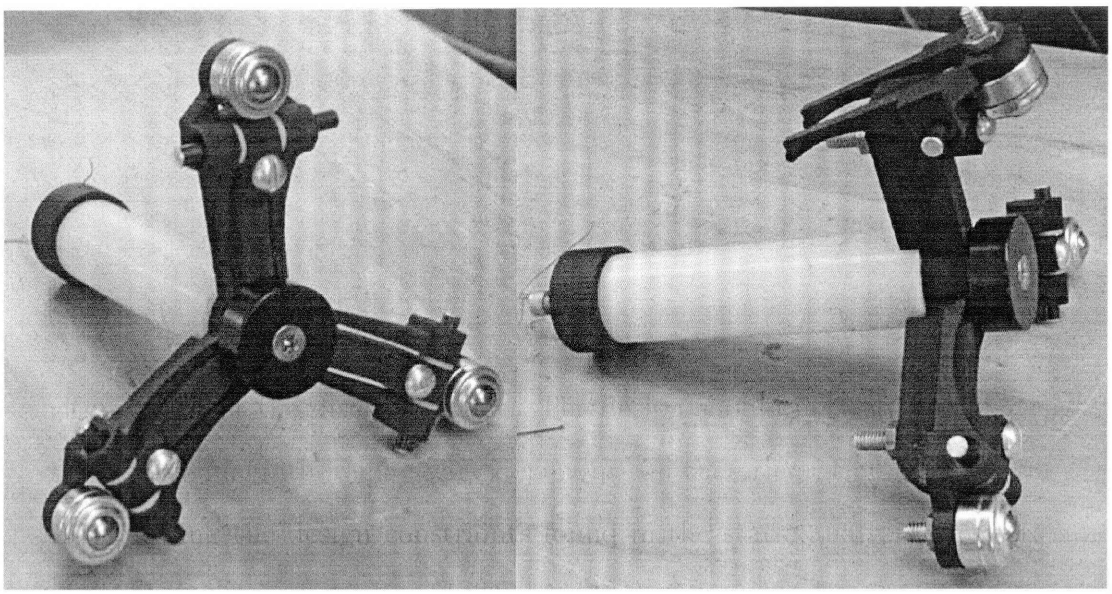

Figure 28 - Prototype

During testing it was found that this version of the foot can hold 9 kg (20 lbs) when "engaged" and the mass of the foot is around 0.5 kg (1 lb). When "disengaged" the foot rolls with almost no friction, holds itself to the surface, and can even bear a load of around 2.3 kg (5 lbs). These values correspond to a panel thickness of 1/8'' and the electromagnet running at a modest 6V (4A). In practice we would have multiple feet holding the payload while one foot moves. The successful production of this component is an encouraging and significant point of progress in the development of the larger robotic system.

8. CONCLUSIONS

8.1. SUMMARY

We have presented the design of a "foot" that is an essential component of a mobile robotic system for heavy duty manufacturing operations in aircraft assembly. The design concept for the robotic system utilizes a pair of robots in which a primary, easily accessible robot is able to control an inner robot from across a thin panel. This control is performed using magnetic fields and a Lorenz force. The locomotion of the inner robot, even when it carries a heavy payload, can be accomplished through the thin panel by utilizing an energy accumulation strategy.

Analysis of the design parameters for this foot have been presented and verified through a functional prototype. The foot is able to hold itself in place and bear high loads, or alternatively, it can roll with little friction across a surface. This switching of frictional capabilities is controlled from across a thin panel. In addition, it was found that it was possible to detect the position of the foot to considerable accuracy.

8.2. OTHER APPLICATIONS

This design of this robotic system may also be useful for a broader class of applications. In addition to airplane manufacturing, such a system might be a boon to ship or building construction – these are other examples of large manufactured objects. It may also be possible to use such a system in fuel tank or pipeline inspection – in these tasks, we are trying to glean information about a space that is on the opposite side of a thin wall. Other examples of this concept include nondestructive testing of storage or shipping containers. In many of these applications, the design of the foot will have to be altered to fit the requirements of the specific task (load requirements, size constraints), but the concepts and designs developed here are still valuable.

8.3. FUTURE WORK

Future work involves the assembly of several feet into a functional inner robot prototype. The first such prototype is expected to have only two legs with the tooling able to slide back and forth between these legs as they lock and unlock from the surface. Future versions could have multiple legs, depending on load bearing and locomotion requirements. In addition, the development of an outer system that mates with this inner robot should be constructed. While not as novel of a concept, it is a necessary component that will allow us to perform testing on aspects such as gait control, holding forces, stability and sensing. The continued development of this project is an exciting and challenging pursuit.

9. APPENDIX A: DESIGN MILESTONES

9.1. PNEUMATIC FOOT

This is an initial version of the foot designed for the robotic system. At this point in the design process, it did not seem reasonable to have a foot that could attach and detach itself from a surface without power. The actuator chosen to enact this attachment / detachment was a pneumatic actuator. Pneumatic actuators are very lightweight (air is the actuation material) but can deliver extremely high forces. Most of the mass in the actuator chosen was contained in the bulky linear bearings packaged along with the actuator. Figure 29 shows a CAD drawing of this foot.

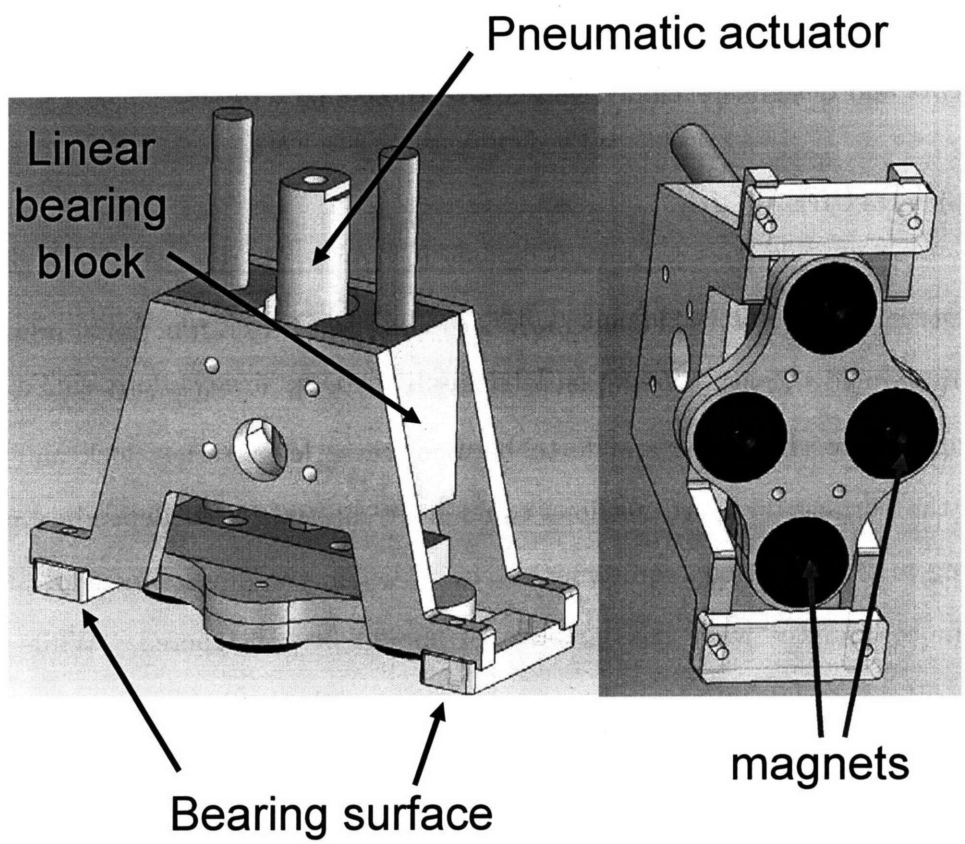

Figure 29 – Pneumatically actuated foot

The pneumatic actuator provided enough force to detach these very powerful magnets. While in contact, the array of four magnets could resist substantial loads. This prototype is an over designed first pass at the problem, using far bulkier actuators and heavier components than is needed. A picture of a partially assembled prototype of this foot is shown in Figure 30.

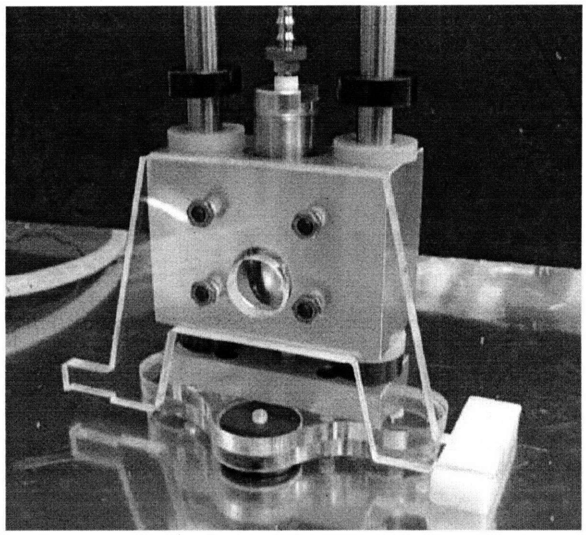

Figure 30 – Pneumatically powered foot prototype

The clear plastic parts are laser cut acrylic sheets, and the bearing surfaces were chosen as delrin due to its machinability properties, as well as its low friction. This design worked adequately, but it was abandoned when the importance of having a passively actuated foot became apparent.

9.2. STATIONARY TETHERLESS FOOT

This iteration marks the first tetherless version of the foot. This foot has a spring loaded detachable magnet. As in the final version, the position of the magnet is controlled by an electromagnet on the opposite side of the thin aluminum surface. In this iteration, we first introduce the idea of using a single tapped ceramic coated aluminum shaft attached directly to the magnet that is also connected to a vented screw. These vented screws are used to tie to kevlar cables to springs and help for easy assembly and quick prototyping of these designs which sped up the development of the system. A CAD drawing of this iteration is shown in Figure 31.

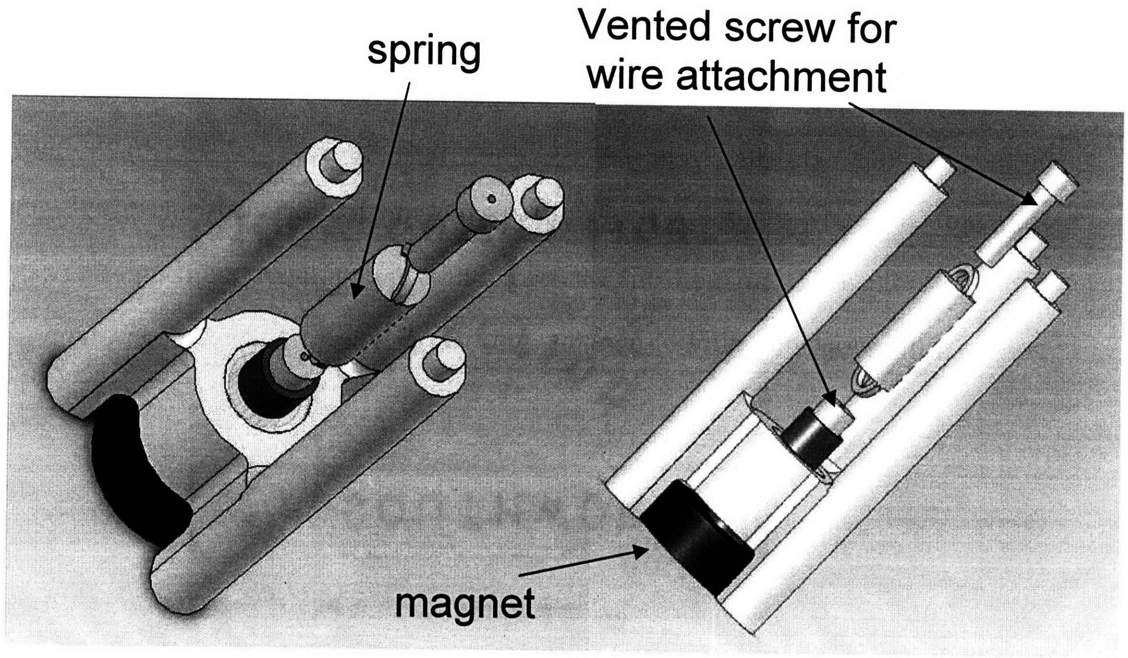

Figure 31 - CAD drawing of first untethered foot

This prototype was significant because it proved the concept of having a bistable spring loaded magnet that could be actuated entirely from the outside. By changing the direction of current in the electromagnet, we were able to see the permanent magnet snap back and forth in the housing of the foot, *while the foot remained attached to the aluminum surface.* This functional prototype is shown in Figure 32.

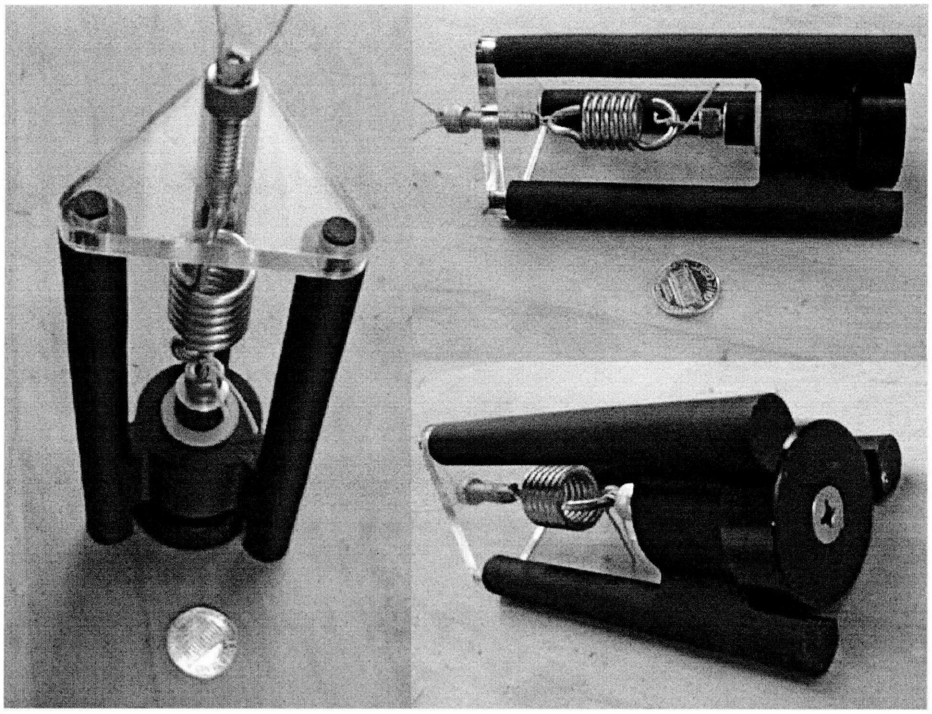

Figure 32 – First tetherless foot prototype

The black portion of this prototype was built with the 3-D printing machine. This machine proved valuable in rapidly prototyping many versions of this device. The spring shown in the prototype was later abandoned for a softer spring, due to space constraints. Here we also first see the delrin bearings and threaded vented screws that proved to be a useful tool for many future iterations.

9.3. OMNIDIRECTIONAL FOOT

This iteration marks the first usage of omnidirectional caster wheels. It also marks the first attempt at having detachable wheels in order to provide the mechanism with dramatically different frictional properties. Previous iterations had fixed caster wheels and they showed promising results – the magnets attached and detached when desired, and the foot could roll while still holding to the ceiling when the magnet was disengaged. Unfortunately, those versions did not have high frictional holding forces when the magnet was engaged, so this prototype was built with wheels that were designed to be detachable. Figure 33 shows the CAD drawing of this foot.

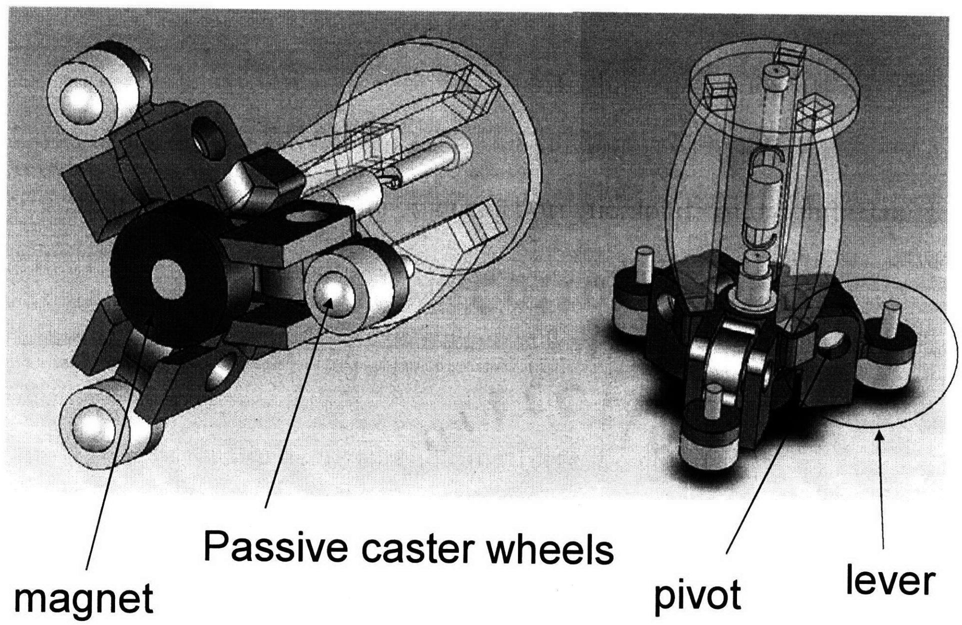

Figure 33 – CAD drawing of first omnidirectional foot

It turned out that it was possible for us to have the foot attach and detach simply by changing the current in the electromagnet. This was very promising – while the foot was attached, the wheels bore no load, and while the foot was detached, it rolled with almost no friction while holding itself in place. Unfortunately, this was only possible when the electromagnet was moved a significant distance away from the surface it was sitting on. This was a bad development, as it meant that the holding force we could get was greatly reduced. This prototype forced the stability analysis shown in the body of this work (chapter 4.2) in order to adjust the lever lengths for the caster wheels to appropriate values.

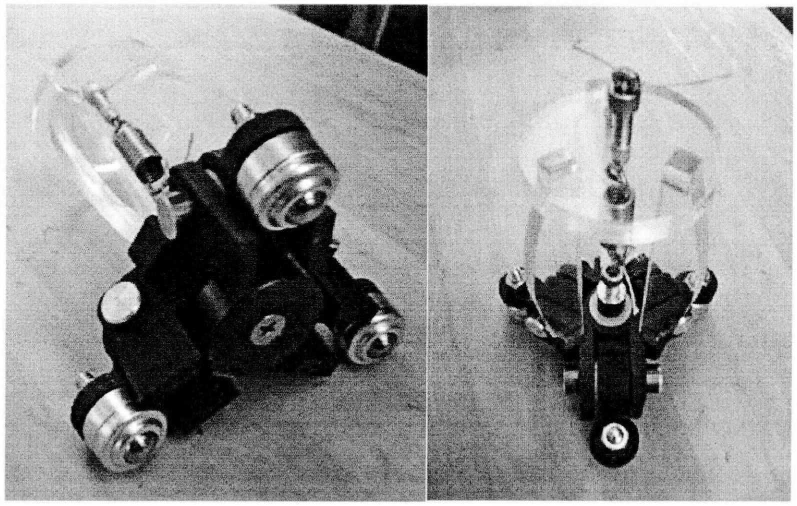

Figure 34 – First omnidirectional prototype

Figure 34 shows the completed prototype. The supports for the vented screw that holds the spring taut were made from laser cut acrylic. This turned out to be a bad idea as there were significant alignment issues and the acrylic was prone to cracking. In addition, it was difficult to assemble. Overall, however, this prototype taught many valuable lessons and provided much needed insight into the direction that the design should take.

10. APPENDIX B: OMNIDIRECTIONAL ELECTROMAGNET

The actuation of the electromagnet on the outside of the structure is a problem that should be addressed in future work. At this point, it was essential, for testing purposes, to build an electromagnet housing that could be rolled over the surface easily. This electromagnet was manipulated manually to simulate the motion it would undergo in a finalized version of the robotic system.

Figure 35 shows a CAD drawing of the omnidirectional rolling electromagnet. The hexagonal supports are aluminum standoffs and they are sandwiched by two pieces of acrylic. The ring of acrylic near the bottom of the electromagnet is largely to increase the stiffness of the housing. There are three omnidirectional caster wheels that bear the load of the electromagnet. Fine alignment is done by adding thin spacers between the top of the electromagnet and the top acrylic plate.

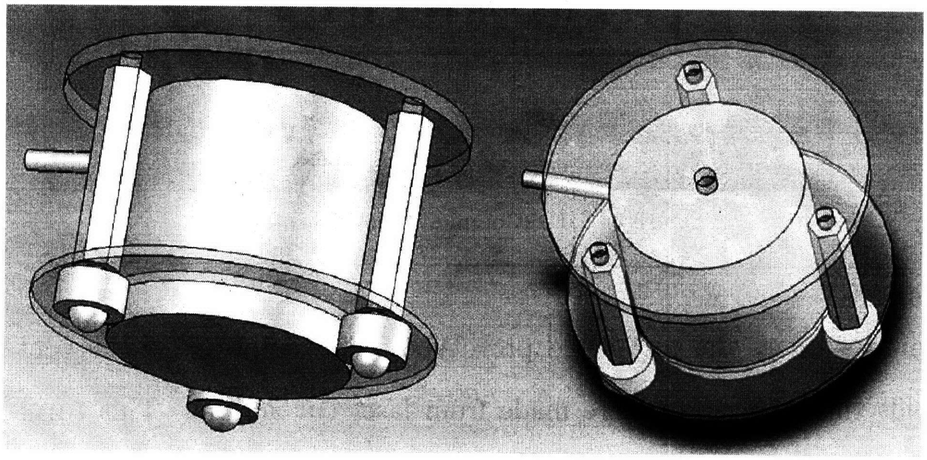

Figure 35 – CAD drawing of omnidirectional rolling electromagnet

Figure 36 shows a built version of this rolling electromagnet. This tool will eventually be mounted into a gantry or robotic arm type system in order to control its position, which in turn, should control the position of the passive robot on the inside of the structure.

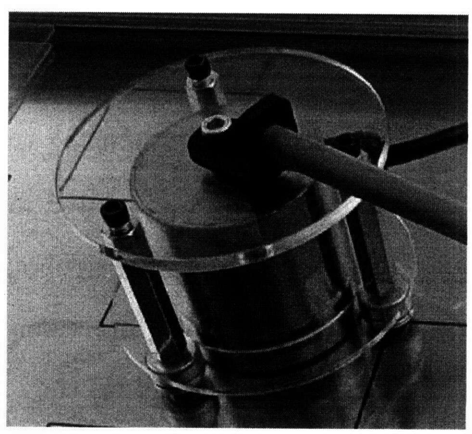

Figure 36 – Rolling electromagnet

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