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Design of New Turning Mechanism for the Cornell Ranger Robot

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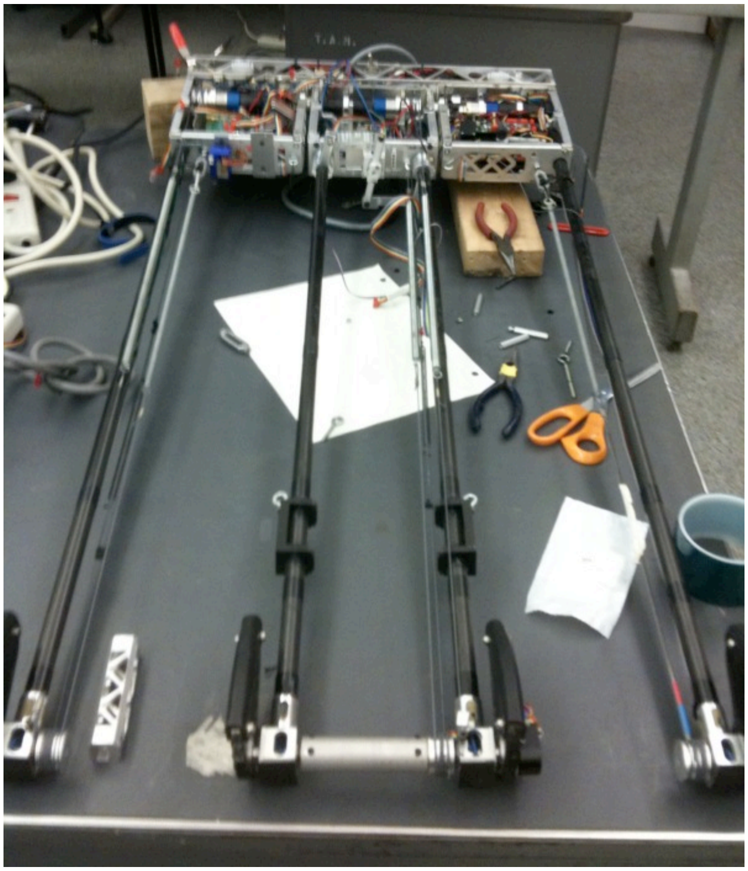

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Abstract

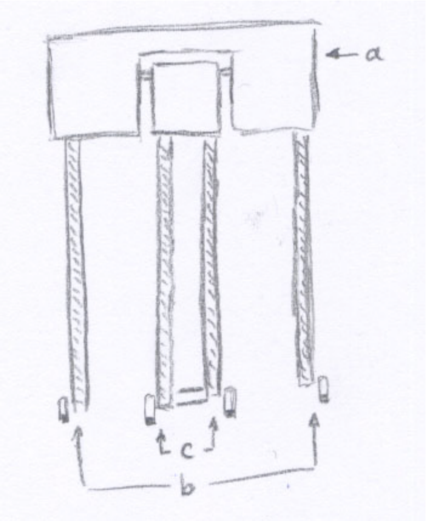
The Cornell Ranger's ability to walk long distances relies on its ability to turn. A turning mechanism had been designed for Ranger, but its ability to turn was inconsistent and it was deemed unacceptable. Therefore, a new turning mechanism was designed. It works by twisting the center legs, having them curl around themselves and generate a moment on the ground. They are controlled by a one center motor. The motor's position is measured by a magnetic sensor and its range is limited by two lever switches. The center feet can now turn approximately 10 degrees in both directions, giving the Cornell Ranger a new degree of freedom and potentially the ability to turn accurately.

Introduction

The Cornell Ranger is a robot has been designed to be a reliable, energy efficient robot which models biped walking. As of writing this, it has walked up to 5.6 miles in 5.5 hours without stopping. The Ranger must be able to turn since it is limited to flat spaces, and these spaces do not allow the Ranger to walk this full range in a straight line. The original steering did not perform adequately and was mechanically unreliable. It was re-done once before but was still deemed unsatisfactory. Therefore the task was to create a completely new way to make the Ranger turn, while trying to minimize its energy consumption. This paper will take the reader through the design process of that new turning mechanism.

The Design Process

The design process will be described chronologically, and for simplicity's sake I have broken the process into four phases. The phases are: identifying the problem and solutions, creating CAD models and fabricating the pieces, troubleshooting the design and assembling it, and, measuring the design's success.



The picture to the right gives the reader a sense of Ranger's overall design. There are two pairs of legs, the inner and outer, and they swing together respectively. The original design allowed for four degrees of freedom. Three of them are labeled here; the hip angle, the angle of the outer feet and the angle of the inner feet (labeled here a, b and c respectively). The fourth is the relative angle of the outer feet, which was the Ranger's original steering mechanism.

Phase 1: Identifying the problem and solutions

Cornell Ranger is only modeled to walk on flat surfaces. Therefore, the Ranger is limited to the largest flat spaces at Cornell; the 400 meter outdoor track in the Robert J. Kane Sport Complex or the indoor 200 meter track in Barton Hall. The smaller and more reliable, the 200 meter track, has two curved 50 meter sections at either end. As the Ranger walks these 50 meters it must change its direction by 180 degrees. Since one step is approximately a foot, 50 meters would equate to 164 steps, or 82 full gaits. This means that the change in direction must be 2.19 degrees per gait. This small change in direction is the minimum the Ranger must be able to achieve to make it around the track.

There are two ways to get the Ranger to turn. One would be creating a torque on the ground, like a human pivoting on one foot as he walked. However, Ranger cannot simply pivot on one foot since at any point it has two feet on the ground. The other way would be breaking the symmetry of the Ranger's step. Take a rowboat for example, if the rower pulls on the oars in the same way, the boat will go straight. However, if the rower is asymmetric with his pulling, the boat will veer to one side. The Ranger is a symmetrical system, it is hardwired so that right side and the left side behave identically. If the left and right side behaved differently, the symmetry would be broken, and the Ranger would turn.

The prior strategy for the turning mechanism was to break the symmetry. To generate an asymmetry, a motor altered the angle of the outer left foot, relative to the outer right foot. The symmetry was broken and turning did result from the asymmetric behavior. However, the ground's surface created huge variations in the way that Ranger turned. For example, the angle difference that made Ranger turn left on the linoleum flooring of the lab might have made it turn right on the track surface in Barton Hall. This was described as Ranger turning by 'stubbing his toe', and exactly how much the Ranger would turn each time was unpredictable. In addition to the lack of precision, the wobbly steps while trying to turn were energy inefficient. Since the aim of Ranger is to be as energy efficient as possible, this is unacceptable as well.

The turning mechanism was considered one of the major design flaws in the Cornell Ranger. When the design problem was first introduced to me it was as something to consider and solve for the next iteration of the walker robot. However, it was decided that the current Ranger was to be perfected before moving on to another robot and the Ranger's inability to turn became an immediate concern. Therefore, a new design had to be made and retrofitted to the Ranger

The first design possibilities we discussed were ways to make Ranger's gait asymmetric again. Some ideas were dynamically changing the angle difference between the feet throughout the step instead of maintaining a constant angle difference. Having one ankle angled a little early at impact and then a little late on push off would generate a turn. Since the angle differences could be slighter, hopefully there would be fewer inconsistencies. A more extreme possibility would have involved changing the length of an outer leg. If a leg became longer before impact and shrunk in after push off to clear the ground, it would generate a turn as well.

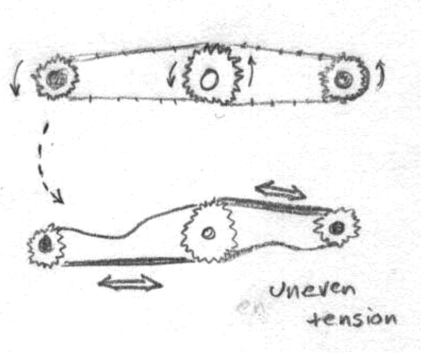
As mentioned above, the alternative to breaking the symmetry would be creating a torque on the ground while Ranger walked. There were no obvious options for this. Since the Ranger has two feet on the ground at any time, simply pivoting on one foot is impossible and twisting two legs at once would not result in the body pivoting. However, the two middle legs are connected by a small bar at the ankle, so twisting these two legs was not the same as twisting two separate legs. It made sense that the legs would twist around themselves and pivot over the midpoint of their connector.

In my opinion, the best two ideas were either adopting the current system to be more dynamic or to try and twist the middle legs to create a moment on the ground. Jason Cortell said that the former was not viable because dynamically changing the angle throughout the step was energy intensive and the motor that was currently installed was also too slow. He was unsure if the second idea because of the lack of applicable examples; we had nothing physical to base it on. It was not until late in the spring semester, when the legs on Ranger were loosened, that Jason got to twist the legs and see if it would work. The feet twisted with a far enough range under an acceptably low enough manual torque to satisfy Jason.

At this point it was decided to make Ranger turn by twisting its middle legs and creating a torque on the ground. The next question was how to twist them. Jason, Kevin and I discussed ways to design this new mechanism. The primary design goal is that it has to work. The secondary goal is that the mechanism be energy efficient, for this is the overall purpose of Ranger. Other design considerations were weight and longevity. We would have to install one or two motors somewhere that could twist both legs simultaneously. Preferably, we'd only need one motor to save energy and weight. Hopefully we would get it as close to the hip joint as possible, as it would add less angular inertia there. In addition, the motor would probably need to be anchored in the center box somehow.

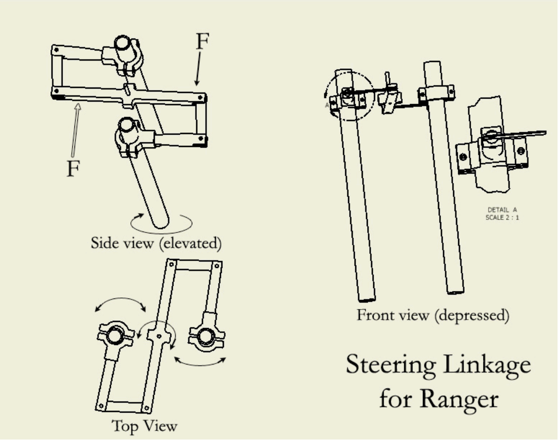
It was clear that we could not fit the mechanism entirely in the center box because of limited space, even though this would have been favorable. So we planned on placing it very close to the bottom of the center box. If we were only going to use one motor, we would probably have to orient the motor directly between the legs so it could evenly distribute its torque. We would have to design some type of linkage to transfer this torque to both of the legs.

Possibilities for transferring torque were using a four gear system or changing the rotational movement into linear movement. Converting the rotation to linear movement was preferred and we looked through options such as using something like a bike chain. However, using a rope or chain to transfer the movement would not acceptable because it allowed backlash to occur in the system. The tension in the chain could not be guaranteed to be the same coming and going to the motor, which could result in it falling off or a deduction in response time. So we looked for a way to rigidly transfer the motion. The easiest is simply changing the torque generated by the motor into a linear force down a solid linage and back into a torque around each leg. Its simplest form is shown in the picture to the



right. A design like this will probably require more energy than the former design, but hopefully use it in a more efficient way.

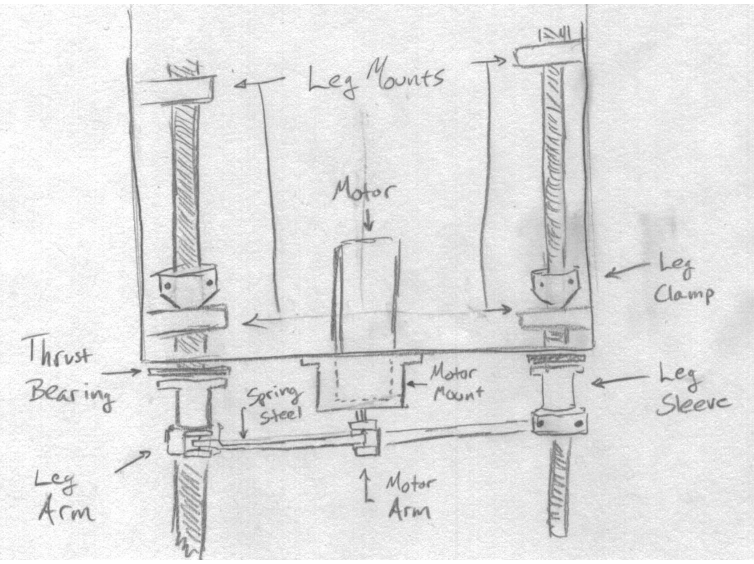
Our design also had to allow the legs to rotate. Originally, the legs were rigidly attached to the center box. Since the legs had to turn axially, and the legs need to sustain forces in the axial direction while walking, we used a ball bearing/ thrust bearing combination. Ball bearings do not handle axial forces well, so the thrust bearing is in place to receive the axial loads created as the robot walks.



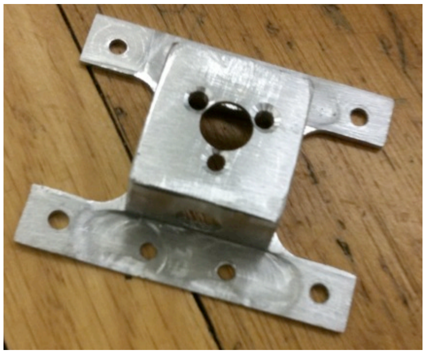
Another concern was how to attach the Leg Arms to the carbon fiber legs. Since we wanted them to be removable and adjustable, simply epoxying them on was not an option. Therefore, we were going to have to clamp them on. Initially we were worried that the clamp could crush through the carbon fiber. However, we determined that a previously installed, thin aluminum tube inside the carbon fiber leg extended far enough down to protect the carbon fiber from being crushed. The carbon fiber legs also had slight variations in diameter along its length, so we also would wrap tape around each leg at the point we wanted to clamp the Leg Arms onto to get a perfect fit.

Phase 2: CAD and Fabrication Phase

From this point forward, the design can be broken down into 14 different aluminum parts: a Motor Mount, 4 Leg Mounts, 2 Flex Linkages, a Motor Arm, 2 Leg Arms, 2 Leg Clamps, 2 Leg Sleeves. The Leg Mounts house the ball bearings. The Motor Arm generates a force through the Flex Linkages and into the Leg Arms. The Flex Linkages have small bearings on either end to reduce friction at the joints where they connect to the Motor Arm and Leg Arms. Each Leg Arm is rigidly attached to a leg and the Leg Sleeve bridges the distance between them and the thrust bearings. The Leg Clamps are on the inside, making sure the legs cannot be pulled out.



Kevin learned how to use the CNC machine and cut out the two Leg Arms. I machined the Flex Linkages, Leg Sleeves and Motor Mount with the mill and lathe. Around this point, the weight and bulk of the pieces came into question. Kevin and I went about slimming the pieces we had made, as well as altering the CADs of the unmade pieces. Kevin hollowed the Leg Arms. I shaved the Leg Sleeves down, and removed unneeded metal from the Motor Mount. I altered the design of the Motor Arm a little as well and learned CNC to make it. I also made the Leg Clamps.


The Motor Mount

Independently, Sergio designed and machined new leg mounts. He took his time on their design and fabrication, and made parts that have not needed any alterations. It should be noted that the legs are not rigidly attached to the ball bearings inside of the Leg Mounts. The ball bearings are press-fit into the Leg Mounts with retaining compound, but the legs themselves are only wrapped in a polyester/silicone tape and snuggly fitted to the ball bearings. All axial loads will fall on the thrust bearings.

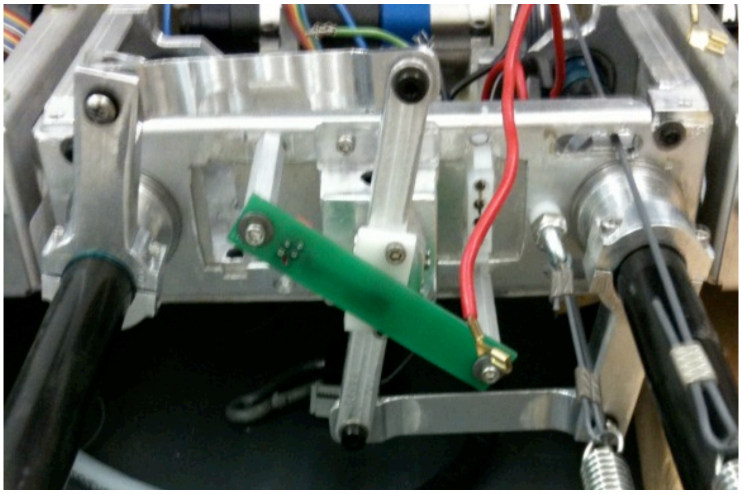
Phase 3: Fixing and Adapting

At the beginning of this semester, the parts for the turning mechanism had all been fabricated. We still needed assemble it and select a sensor for it. New problems arose during this stage and we had to adapt our design.

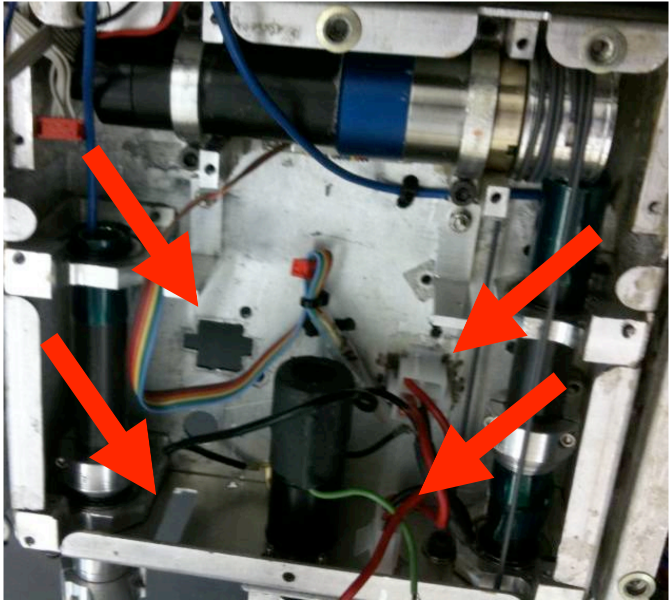
The first problem was with the Leg Arms. Specifically, the Leg Arm on Ranger's left inner leg did not clear the cables which run down the leg and control the ankle angle. The turnbuckle in the cable was removed to give the Leg Arm more space. Both Leg Arms were also trimmed as demonstrated in the photo to the right. The holes for the screws had to be moved closer to the center as well. Also, the notches in the Leg Arms which let the Flex Linkages swing were not made deep enough, and the Flex Linkages did not have enough freedom of movement. Only once we had installed them we could see that they were greatly limiting the turning range of system. So the notches were made deeper with a Dremel tool.

The initial CADs did not contain a sensor to judge the angle of the Motor Arm, so we had to choose what type of sensor and how to place it. We chose a magnetic encoder because it is not as energy intensive as some, does not have be rigidly connected to both the motor and the center box, and is fairly accurate. However, choosing a magnet encoder did mean that we had to mount a magnet on the axis of rotation of the motor. We made a small white polyethylene piece that we could connect to the Motor Arm to house the magnet. We also ordered a custom board to mount the sensor onto so that it could be attached and sit right above the magnet. Emily soldered the sensor onto its board and showed me how to use the soldering oven.

The sensor (above) is the small black component in the middle of the board. The board's orientation above the white polyethylene magnet holder is shown in the photo to the right. The initial angle of the encoder relative to the Motor Arm is arbitrary, all that is needed is its reading while the Motor Arm is in its neutral position.



It was also decided that the Motor Mount did not need the extra wings on it and that its holes had to be moved slightly further out so that it could be properly mounted. I altered the Motor Mount, drilled new holes in the Ranger and attached it. When the motor was in place, it became apparent that it would block the hole needed for one of the battery cables of the Ranger. I cut a new hole on the left side of the interior of the box. This hole was too far from the battery connector, and was going to be covered by the pc boards, so a third hole had to be cut as well. During the process of making holes and room for the motor, we had eliminated a large amount of the bottom wall of the center box. It was decided to remove the rest of the bottom wall and to put a new bottom plate in on the inside to renew its integrity. When the new bottom plate was put into the box, the sister battery hole had to be adjusted slightly as well.



In the picture you can see how the motor fits into the box, as well as the two holes for the input cables on the right side, as well as the input cables installed in their final holes on the right side. The new bottom is at the bottom f the photo.

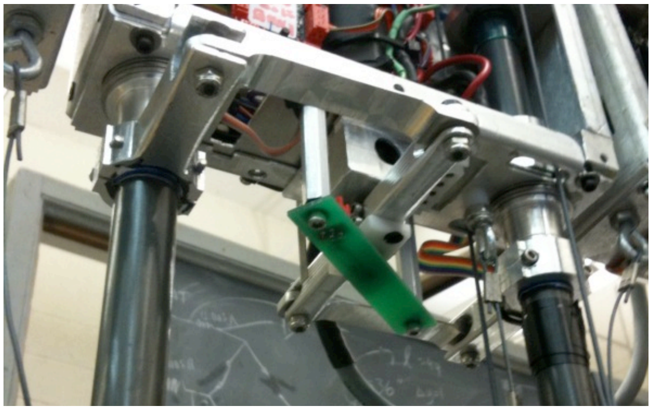
Mounting the PC boards in the center box also became problematic with the motor taking up space. There was no way that they could be mounted facing outward without overlapping. First we tried installing them perpendicularly which gave them plenty of space; but this created problems with wiring and programming. To program the boards we need to be able to connect to the face of the board, and when in place perpendicularly, this was too difficult. Instead, we installed them in an overlapping ‘L’ shape, with one above the other on spacers. This is a good example of how we learned what does not work from trying one design and adapting.

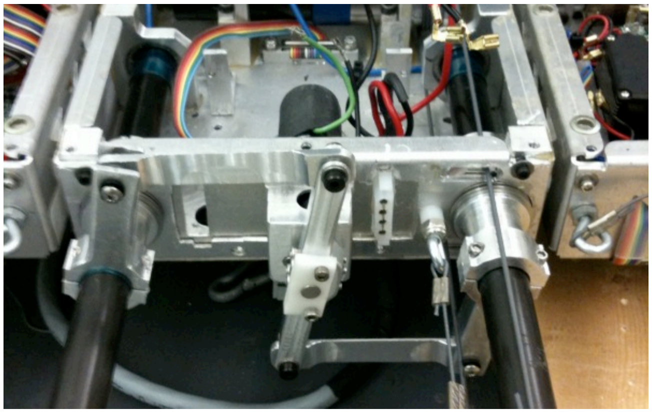
On top of the sensor, a hardware limiter was recommended to prevent damage to the legs. Sergio selected two separate lever switches that would trigger when the Motor Arm swung too far in one direction. When triggered, the lever switch would run the current through diodes and only allow the motor to swing the Motor Arm in the opposite direction. The lever switches were attached on the back of Ranger as shown in the picture.

The Leg Arms were designed with a small gap in between them and the carbon fiber. This gap was to be filled with a silicon tape, to help distribute the stress on the carbon fiber. However, Professor Ruina raised the concern that the adhesive layer in the tape could act as thin layer of viscous liquid. This means that a slow creep could result from any force placed on the tape, in the plane of the adhesive. Once clamped on the tape, each Leg Arm applied radial compression, a torque during turning and an axial force while the Ranger walked. Since two of these forces are in the plane of the tape, the Leg Arm could possible slowly creep away from its intended position and let the legs slip into the center box. I ran an experiment to see if the tape’s adhesive really would act like a thin viscous liquid. The photo on the right displays the results, the black lines indicate the original position of the tape and the two white blotches indicate its position after twelve hours of force. The tape only slid a couple millimeters but enough to demonstrate that the silicon adhesive would act as a viscous liquid. The tape had to be replaced by a ‘dry’ alternative. Aluminum shims were used instead to fill the gap between the Leg Arms and carbon fiber legs.

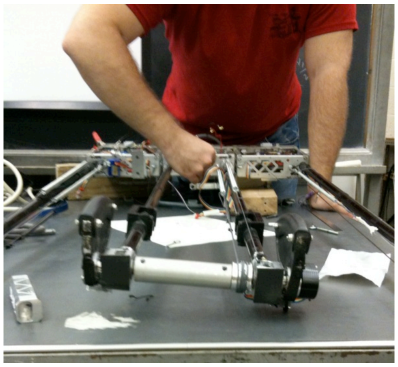
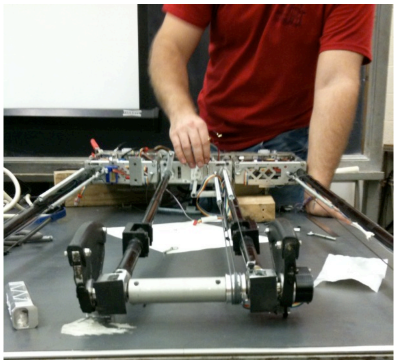
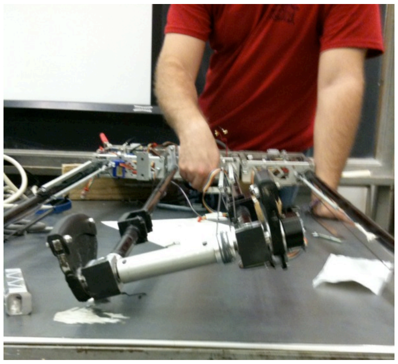
Phase 4: Results and Testing

Here are a few pictures to displaying our design, with the improvements that I have discussed:





The first test we had to see if the mechanism would actually work was manually twisting the Motor Arm, which was successful.

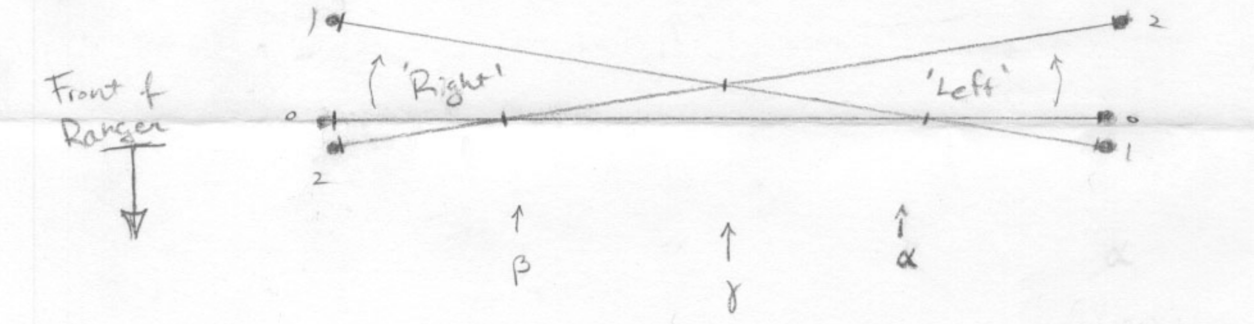
We then tested it by running current through the motor, which also worked. Finally, Nic Williamson and I went about accurately gauging the performance of the turning mechanism. I adjusted the toggle switches until they were even on both sides. The desired result was a maximum turning range of 10 degrees. Nick worked with the PC board and found the current and related PWM limits for the motor right before it triggered the toggle switches. One of the surprising things that we discovered is that there is a point where the lever switch is not fully on and not fully off. Usually, when the motor moved further than the toggle switches allowed, they would start click off momentarily, cutting the current, and let the motor arm swing back towards its neutral before clicking on and letting current flow again. However, there were times when there was no clicking; instead the switch reached an equilibrium, where they didn't let the motor arm swing any further but also didn't cut the current to the motor completely. We set the software current limits to trigger before this point, therefore this unexpected behavior will not affect normal operation.

The results from Nic's testing is are follows

	Left Turning Maximum	Neutral position	Right Turning Maximum
Sensor Output	2535	2415	2295
Current	.16 amps	N/A	-.23 amps
PWM	140	N/A	-200

We have also tested the new turning mechanism with the feet touching the ground. While supporting most of the weight from above, we rested the feet on the ground and activated the turning mechanism. The Ranger's body did rotate around its feet and demonstrated that the mechanism is working the way we expected.

Additionally, I taped a piece of paper below the Ranger while it was completely suspended and marked the physical results of the turning mechanism. I marked the position of the feet at neutral, and at both of its turning extremes. Here are those results.



There are three angles, marked Beta, Alpha and Gamma above. Alpha is how far the feet turn to the right, Beta is the angle to the left, and Gamma should be the sum of these two angles, the full range of motion of the feet. Using the law of cosines, I estimated the angles finding Alpha ~ 9.522°, Beta ~ 8.7° and Gamma ~ 19.09°. There is obviously some precision lost when calculating this with pencil and ruler. However, these results are very close to what we were hoping for. Also, looking at the picture above, it seems that Ranger's feet do not pivot around their center point. At these small angles, the turning of the feet can hopefully be predicted linearly between the angle encoder on the Motor Arm and the feet's actual angle relative to its neutral.

Discussion

The new turning mechanism seems to be functional and well designed. The amount it turns is highly consistent and predictable. The mechanism has been completely assembled on the Ranger and now the feet can turn much further than needed. However, there are plenty of unknowns left in the design. We have yet to see how the turning works while the Ranger is walking. We also do not know how the inertia of the body will affect the turn. When we tested it with its feet touching the ground, the angular momentum carried in the rotating body was enough to swing into the lever switch. Smaller angles and smaller currents should not generate as much momentum when the Ranger is actually walking, however we will not see the effects until then. We also have not seen how energy efficient it is, which could be a large problem. Future design concerns are how the turning affects the IMU, and how to remove the old turning mechanism to reduce weight.