# Walking Robotics – The Cornell Ranger

# Fall 2006 Semester Report

Alexander Gates

Sophomore, Cornell University
College of Arts and Sciences, Math and Physics
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| School: | Home: |
|---|---|
| 140 Thurston Ave. | 22 Inningwood Rd |
| Ithaca, NY 14850 | Ossining, NY 10562 |
| (914) 525-5980 | (914) 525-5980 |

# Abstract

This paper details the author's contributions to the design and construction of the Cornell Ranger for Theoretical and Applied Mechanics 491. Specifically, presented here are the details for the design of the ankle, fabrication of the main crossbar and foot sensors, and analysis of foot signals and programming of software to determine foot contact. The ankle, main crossbar, and foot sensors were all directly used on the robot while the software required conceptual modification before its eventual implementation in the Ranger. Using these components, the Cornell Ranger recently set a distance record for walking robots, walking for a little over a kilometer.

# Introduction

One of the key traits that distinguish Homo sapiens from other animals is their ability to walk upright on two legs. Humans can move with extreme grace and speed, easily correcting their balance on uneven terrain. It has long been the goal of engineers to mimic human motion in walking machines. Many such attempts utilized actuators at every joint in the robot which, when coordinated properly, allowed a bipedal robot to walk. However, the gait for these robots is commonly jerky and extremely inefficient.

As an alternate design strategy, researchers in the Cornell Walking Robotics laboratory are developing passive-dynamic robots. Such a different design and control paradigm has already proven to efficiently impersonate human-like walking gaits in several completely passive machines [1]. Additionally, these passive designs have been extended to powered walkers; the newest of which is the Cornell Ranger pictured in figure 1.

The Cornell Ranger was designed with the goal of efficiently walking a long distance. It is made with two sets of legs, inner and outer. While technically this makes it a quadruped, the Ranger's gait closely resembles a true biped. Its extra two legs only serve to assist with balance and thereby simplify the walking problem. The Ranger is actuated on all five of its joints (4 ankles and hip) in order to

**Figure 1**. The Cornell Ranger walking robot. It has four legs split into two groups, inner and outer. Each step is made by striking the ground with the foot and then rolling forward into the next step.

increase the flexibility in control. It produces forward motion by striking the ground with an ankle actuation from one set of feet. These feet are then retracted and the robot rolls forward on the balls of the other feet.

The purpose of this report is to describe the work that the author did for Theoretical and Applied Mechanics 491 during the fall semester of 2006. Since the major project for the lab was the design and construction of the Cornell Ranger walking robot, the majority of this report focuses on the author's contributions to the development of this robot. These contributions fall into four main categories; design of the ankle base, fabrication of the main crossbar, installation of the foot sensors, and testing the foot sensors.

## Design of the Ankle Base

At the beginning of the semester, the overall design of the Cornell Ranger was essentially completed due to various efforts of students over the summer. However, there were several components whose details needed to be altered to account for unforeseen requirements. One such piece was the ankle base shown in figure 2. Since the beginning of the project, the ankle base had to be redesigned numerous times with different bearing configurations and sizes. It wasn't until other pieces were beginning to be machined that the final dual bearing design was settled upon. Following this design resolution, further alterations were made to reduce the piece's weight as much as possible while considering the strength and difficulty of machining. A reduction in the weight of the ankles was important to operation because it reduced the torque required to push the legs through one full step. The final design depicted in figure 2 places the two bearings on opposite sides of a small cube which is attached to the leg via the topping cylindrical mount. There are also four slits cut into the top cylinder with several holes machined into convenient areas near the bearings to reduce weight.

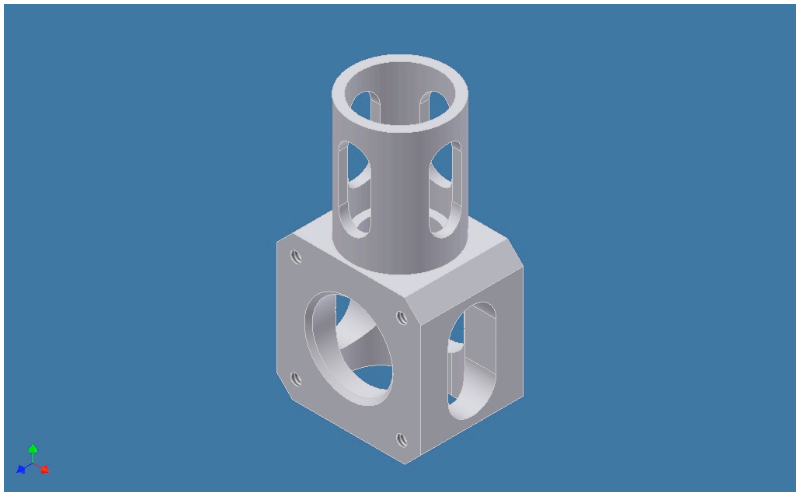

**Figure 2.** The ankle base on the Cornell Ranger. It supports two bearings to hold the ankle shaft and various holes to reduce weight.

## Fabrication of the Crossbar

Many of the parts on the Cornell Ranger were designed to reduce their weight while still maintaining functionality. This commonly results in a piece that is then very difficult to machine, especially for the amateur machinist. One such piece was the main crossbar shown in figure 3. There are two distinct features of this truss that made it such a challenge to machine; the recessed pocket with an intricate connector hole and the large number of triangular holes (used to reduce weight and keep the inner and outer set of legs as symmetric as possible).

Since machining this piece by hand would have been quite a tedious endeavor and would have greatly depended on the machinist's precision, it was decided that a NC (numerically controlled) mill should be utilized. The NC mill that the walking robotics lab had at their disposal was a small unit that ran on programs written in G-code. This particular machine has a couple peculiarities that made working with it a challenge. One of these peculiarities was the difficulty of changing the bit. Whenever the bench had to be zeroed, half an hour was spent loosening and removing collets with a hammer. Another problematic aspect of the small NC was the 14 inches of travel available on its x-axis. The truss is 20 inches long; therefore all of the cuts had to be programmed for only half of a side at a time. This meant that 8 different programs had to be written; one zeroed from the left-hand corner and the other from the right-hand corner for each of the four sides (top, bottom, front, and back).

The G-code for the truss was written based off of dimensions given by an auto-cad where all cuts were offset by the appropriate distance required for the mill width. Extreme care was taken not to accidentally have a travel path run at the same depth as the regular cuts. This would have been disastrous as the piece would have needed to be

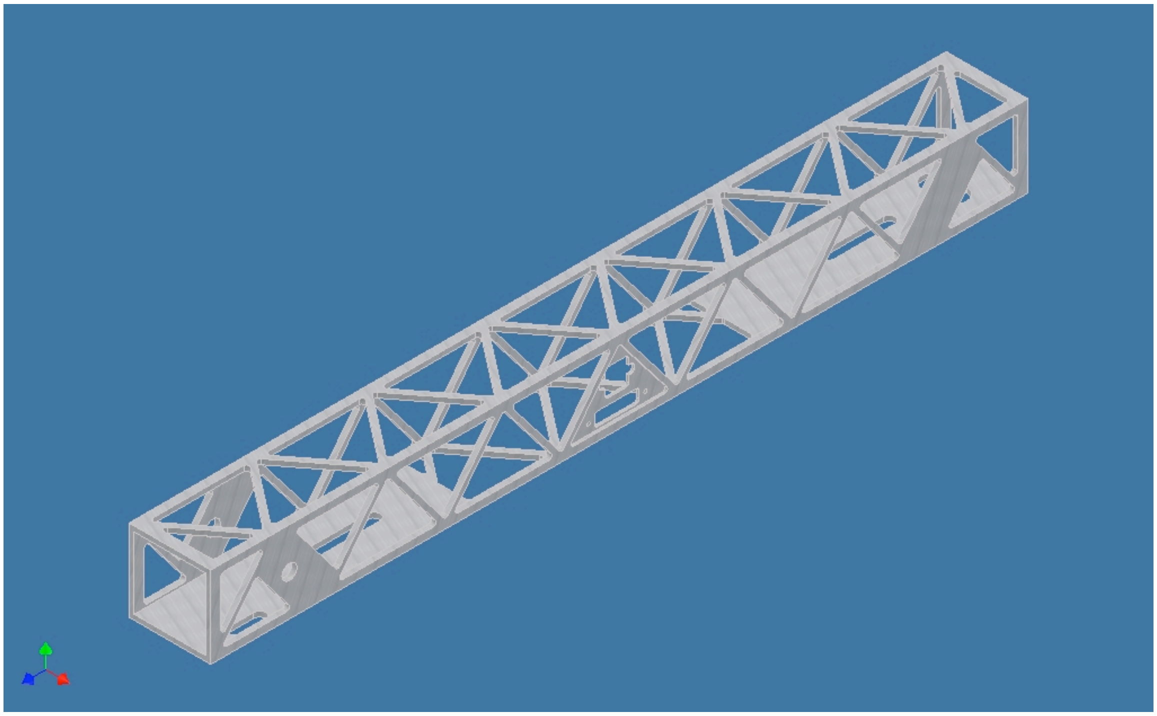

**Figure 3.** The main crossbar on the Cornell Ranger. The 42 triangles were cut out using an NC milling machine to reduce weight but maintain the strength of the piece.

restarted from scratch. To assist with the elimination of such mistakes, a G-code simulator was used to simulate the cut before each program was actually machined. This simulator was extremely valuable as it caught some unexpected problems before they ruined the project. One such problem involved resetting the radius for circular cuts. All of the code accounted for resetting the i-component of the radius but it was not known until the simulations that the j-component also needed to be reset before each cut. Through the use of such simulation techniques, the machining process was carried out without any significant errors.

## Installation of the Foot Sensors

Before the Ranger could take its first steps, the program needed some way to detect when a foot has made contact with the ground. This was achieved through the use of sensitive optical sensors illustrated in figure 4. These sensors worked by emitting a low power infrared beam that was then received by a diode. When contact is made with the ground, a small blocking element is moved between the emitter and detector, blocking some of the light. Since the diode is very sensitive and can detect small changes in the intensity of the infrared light, care had to be taken in making the blocking element at just the right initial height to provide a clear signal on heal strike. A hand file was used in conjunction with an ohm meter to hand craft the blocking elements for each of the four feet shown in figure 5.

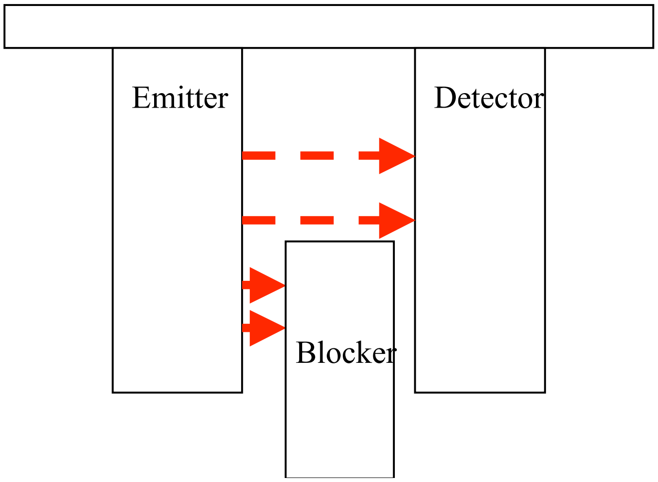

**Figure 4**. The optical foot sensor. When contact is made with the ground, the blocker is pushed in-between the emitter and detector, altering the voltage between the two terminals of the detector.

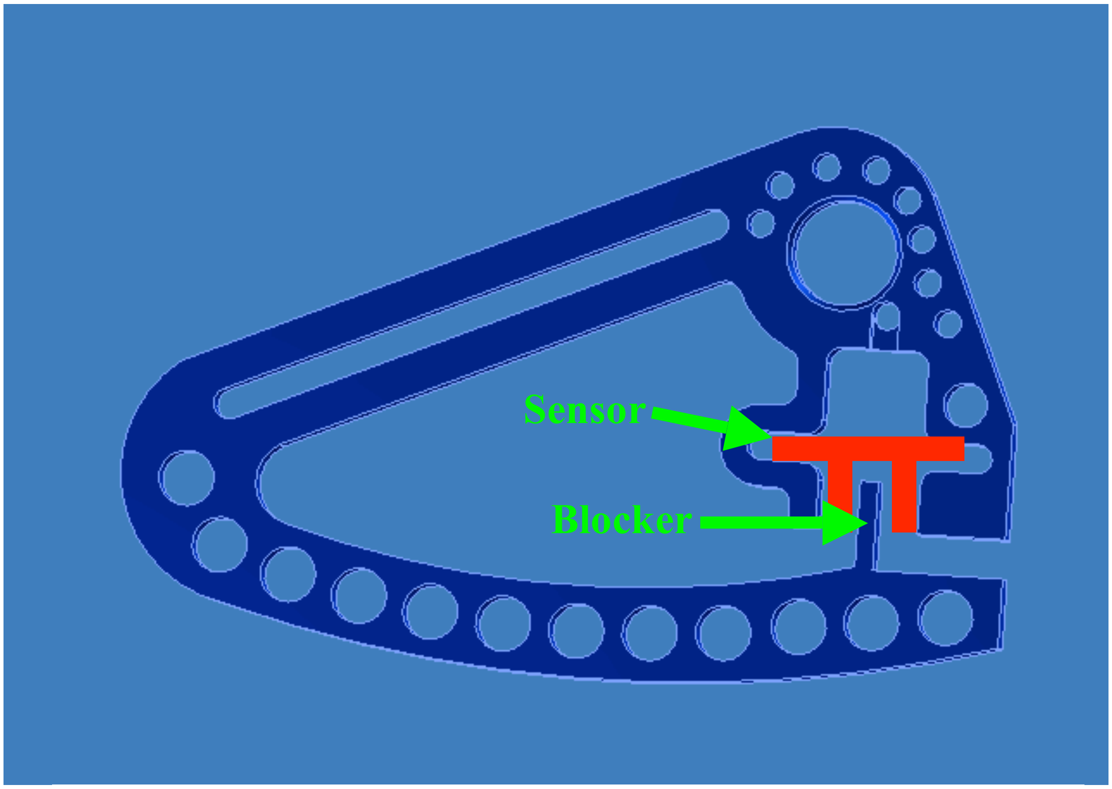

**Figure 5**. Schematic of the optical foot sensor installed in the Ranger's foot. The blocker extends upwards from the bottom of the foot between the elements of the sensor. When the heal touches the ground, the blocker is forced upwards and the displacement is detected by the infrared sensor.

## Foot Contact Signal Analysis

Once the feet were made, a function had to be written which could analyze the output signals from the four feet and determine whether or not a set of feet were on the ground. As an initial step, the output signals from the foot sensors were analyzed for signal integrity and continuity.

**Experimental Design**. Each foot was attached to a wooden leg using nails through the same holes designed to hold the feet to the actual ankle. This system was then manipulated by the researcher to simulate a variety of different contact conditions. One side of the sensor was connected to a power supply which provided a constant 3.3 volts while the other side was connected to the LabView program on the computer. A research assistant ran the computer so the researcher had his hands free to control the foot-leg system. There were three different contact situations simulated using this technique:

1. *Free Fall* - The foot was raised approximately a foot off the ground and then dropped straight down. There was no interference by the researcher during the process.
2. *Guided Forward Roll*- Here, the foot was guided to the ground by the researcher. Once contact was made with the ground, the foot was rolled forward before it was finally lifted up.
3. *Free Fall and Forward Roll*- The third trial situation combined both the free fall and the guided forward roll situations. The foot was dropped from around twelve inches off the ground and then guided into a forward roll by the researcher.

**Experimental Results.** The experimental results from the left-outer foot are shown in figure 6. Figure 6a) depicts the output from the first trial. The signal initially spikes on impact and then evens out to a stable value around 2.6V before quickly dropping to the baseline at 0.4V. Both transitions (from baseline to high and then back down again) took 0.2 seconds to complete. Figure 6b) illustrates the results from the second trial. There is a similar initial spike when the foot makes contact with the ground. However, the signal then stays at the same high value of 2.6V for only a tenth of a second before it begins to transition to the baseline value. The initial transition from baseline to high took 0.2 seconds while the transition from high down to the baseline took 1.2 seconds. The final trial is shown in figure 6c). Here, the signal starts out at a stable high value and then

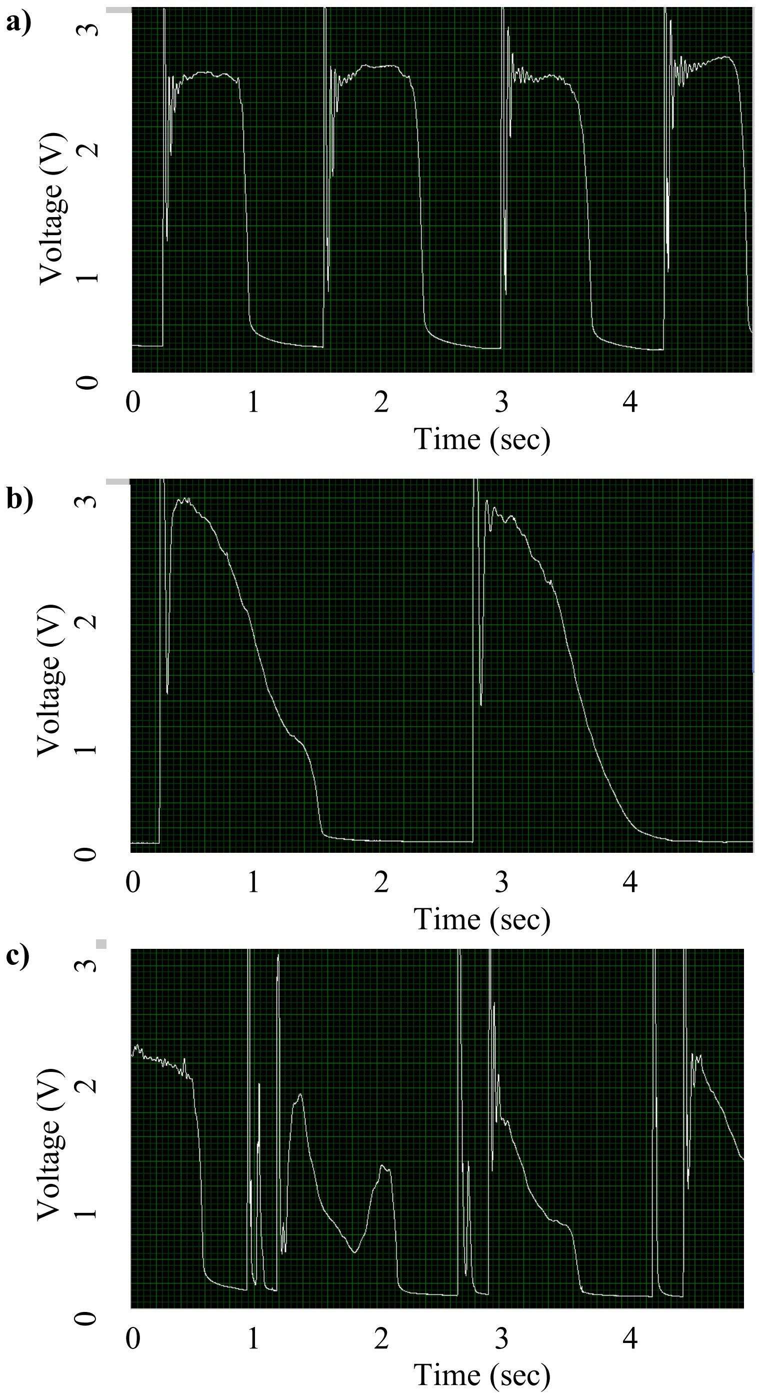

**Figure 6**. The output signals from the foot sensor during testing as functions of voltage vs time. a) shows the signals when the foot was dropped from approximately 12 inches off the ground. b) depicts the voltage while the foot is guided to the ground and then rolled forward. c) pictures the signal as the foot is dropped and then guided into a forward roll, combining the actions of the previous two trials.

drops to the baseline. It then quickly spikes in the first tenth of a second, returns to the baseline and then spikes again 0.1 seconds later. The signal then slowly decreased back down to baseline over 0.8 seconds.

**Discussion.** The signals produced for both the free fall and guided forward roll trials were relatively smooth continuous curves that can be easily handled by a somewhat simple processing algorithm. Moreover, the fact that the voltage spikes only on the initial contact and then performs a continuous transition back to the baseline means that the system could reliably handle the signal with simple averaging routines that require only a small data set taken over a short period of time. On the other hand, the signal produced during the combined free fall and forward roll trial is just choppy enough to require a slightly more complicated program to eliminate false contact decisions. The double spike at the onset of the signal means that averages will have to be computed over larger time samples of the signal.

**Conclusion.** Considering how the simulated gaits for the Ranger, the second trial of consisting of a guided forward roll is the most realistic of the three attempts to mimic an actual step. Because of the relatively small number of oscillations on the initial contact with the ground, the program written to process the foot signal will not have to take into account long temporal averages into order to accurately determine when foot contact has been achieved.

# Foot Contact Detection Function

In order to reliably determine when the feet have touched the ground, a function was written to analyze the foot sensor signals and indicate when heel strike occurs. As input the function would take the foot signals from each of the four feet on the Ranger. The output for the program were two boolean variables (one for the outer set of legs and one for the inner) as well as several error messages. There were two programming restrictions placed on the function:

- *Reliability* - The function must be extremely reliable since each step depends on the successful detection of contact.
- *Low Computation* – The microcontroller used on the Ranger had a limited number of clock cycles available for runtime routines. Therefore, the contact detection program could not exhaust a huge number of these cycles.

The contact detection function written by the author split the two legs of the robot into two different cases, treating the inner and outer legs separately. It would then compare the signals for both feet of a leg set. If they were both over a predetermined threshold value then the leg set was considered on the ground. However, if only one of the feet was over the threshold value then that foot was averaged over 5 time steps of a millisecond. This assured that when the robot was turning, and the feet were out of phase, contact detection was still reliable.

This program failed to take into account is the case where the feet do not agree for an extended period of time. In this case, the function would bounce between contact and no contact every 5 milliseconds. Therefore, before the function was implemented on the Cornell Ranger, it was modified to taken into account the previous state of the foot.

Using this information, the function was much more stable under instances where only one foot was in contact with the ground.

## Conclusion

On December 3rd, 2006, the Cornell Ranger entered the record books as having walked the farthest of any walking robot [2]. Its record breaking stroll was a full kilometer. Throughout the Ranger's saunter, the ankle remained light and sturdy, the main crossbar stayed structurally sound, and the feet reliably detected contact with the ground. The success of the Ranger represents a significant landmark in the design of walking robots; proving that with an increase of reliability, energy efficient walkers based off of passive-dynamic concepts could march to the beat of their own drum.

## Bibliography

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2. Ruina, Andy http://ruina.tam.cornell.edu/research/topics/locomotion_and_robotics/papers/CornellRanger/index.html, last accessed: 12/14/06.