Report on Summer Internship
at
Locomotion and Biorobotics Lab
Cornell University

Design, Analysis, and Fabrication of Load cell for Cornell Ranger

A part of the
<u>Summer Undergraduate Research Internship Program (SURIP)</u>

Submitted by:
Pulkit Kapur
Junior Undergraduate,
Punjab Engineering College,
Chandigarh.

Supervised by:
Prof. Andy Ruina,
Biorobotics and Locomotion Lab,
Dept. of Theoretical and Applied Mechanics,
Cornell University

Foreword

This report talks about my summer internship at Cornell University, at the Biorobotics and Locomotion lab, in the Dept. of Theoretical and Applied Mechanics. This work is titled “Design, analysis and fabrication of a load cell for Cornell Ranger”, and was done under the guidance of Prof. Andy Ruina.

The aim of this report is two fold. It not only serves to inform the reader about the work done during my internship at Cornell, but also serves as a guideline for people who shall continue on the research project I worked on.

This report is divided into six chapters. Each chapter delves into the details about specific aspect of the project such as fabrication, calibration etc. An appendix at the end describes briefly, the short work done to eliminate the noise in the output of the gyroscopes on the Cornell ranger.

This project was completed during one month of my stay in Cornell. This would not have been possible without the constant support, encouragement and feedback from Prof. Andy Ruina, Lab manager Jason Cortell, and every member of the lab. I thank everyone, for their support, and advice and the bond of friendship I developed with every member of the lab.

Contents

Chapter 1: Introduction and Background

The Cornell Ranger is a four legged, knee-less statically stable biped. Weighing five kgs, and using 40 Watts of energy, it is developed at the Biorobotics and Locomotion Lab, Department of Theoretical and Applied Mechanics, Cornell University.

In contrast to Collins robot, which is very energy efficient, and uses only 11 Watts, the Cornell Ranger uses 40 Watts, with a 80 watt hour battery pack. However, this is justified as unlike Collins robot, the Cornell Ranger is designed for reliability. It is designed to run in a repetitive reliable gait. It is steered by a hobby remote control which slightly, biases the steering to one side or another by lifting one of the four feet slightly.

There are a number of design modifications which are needed to improve the reliability and aim for the record of the longest walking robot, which the Cornell ranger strives for. Some of them are:

- There is a lot of noise in the output of the gyroscopes which might be electrical or mechanical noise. Reducing this noise might improve the gait.
- Possibility of adding hip springs, as a lot of energy is wasted in firstly accelerating the robot, and then de-accelerating it. However, problems might be caused by motions which are not at natural swing period of the leg.
- Design of arrangement to add ankle and hip encoders.
- Ankle Springs are needed to get uniform spring constant in all the legs.

The first task in the design modification stage was to get uniform spring constant in all the legs, by adding ankle springs. In order to estimate the stiffness values for ankle springs, we need to determine the tension in the string that operates the toggle arrangement at the feet.

We conducted an experiment on the Cornell ranger, whereby we controlled the input torque at the hip, and found out the angle turned by the right outer leg, for increasing and then decreasing values of hip torque (max 2N-m). However since the values were very close, we needed some other means to find out the force in the strings. In order to measure the spring tension, a Load cell is needed.

The following section describes the design issues related to Load Cell for measuring the string tension in the Cornell Ranger.

Chapter 2: Design of Load Cell

In order to measure the string tension, using a load cell, there are two alternatives. Either to buy commercially available load cells or to design and fabricate a custom made load cell. The following factors contributed to the choice of a custom made load cell:

- Commercial load cells are sensitive to a lot of noise which can lead to errors in the measurement of the sensor.
- Commercially available load cells are very costly (around $500-$1000).
- Mounting and attachment problems with commercial available load cells.
- Commercial load cells require additionally good amplifiers.

During the design phase many alternative designs were reviewed among them were, small proving ring, linear pulley arrangement, S shaped load cells etc. The load cell consists of a flexing member such that only the tension component gets through and a optical sensor to measure the deflection. This deflection will then be calibrated against the tension in the string.

In contrast to a simple tension load cell that moves up several inches up and down and bounces with the motion of the ranger, we choose a load cell that is fixed on the ranger’s leg with its electrical connections, which might be more reliable.

The following points were kept in mind while designing the load cell:

- The material chosen should have low creep and hysteresis.
- Acc to St. Venant’s principle at the attachment point the details of how the load is transferred must not affect the reading.
- Bolted connections will have contact non-linearities and frictional hysteresis, they should either be avoided or at such points so that they do not affect the sensor reading.
- There must be no contacting pieces in regions of deformation that affect the sensor. Contact will almost inevitably lead to non-linear and hysteretic effects.

- The pulleys should be in plane of the Load Cell so that there is no out of plane bending of the load cell.

The Design Procedure:

The design procedure for the fabrication of Load cell consisted of following steps:

- Pencil Sketches and cardboard models to come up with different feasible designs.
- CAD modeling of potentially useful designs in INVENTOR.
- Assigning proper material properties and making design changes to reduce the mass.
- FEA analysis of CAD model to determine stresses and deflections.
- Generating the part drawings for fabrication.

During the FEA analysis, a bearing load of 100 N was applied on the top pulley, a pin constraint was added on the left pulley and a frictionless constraint was added on a bump, parallel to the bottom surface. The FEA analysis was done in ANSYS inbuilt in AutoCAD Inventor. The deflection that we get from FEA analysis should be in the linear range of optical interrupt sensor. The details about the sensor and its range will be covered in the next chapter.

There were a number of designs suggested and following an iterative process to achieve the desired deformation, size, weight etc. Some of them are mentioned below:

Three Pulleys, Triangular Design:

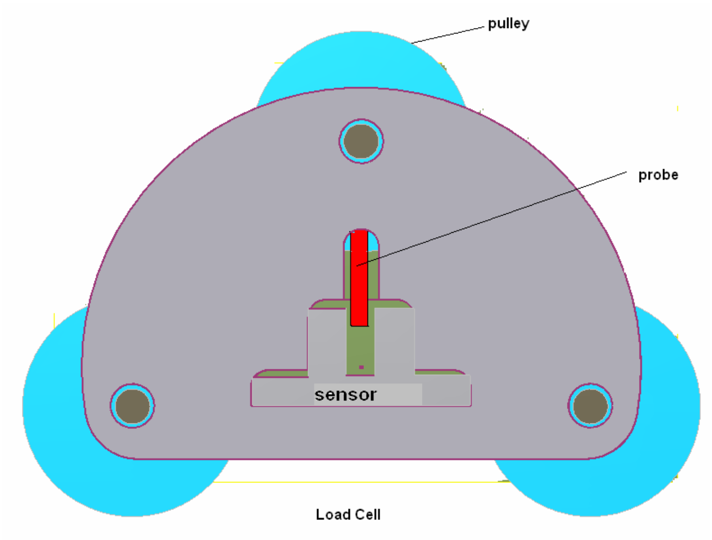


Fig.1: CAD model showing front view of load cell

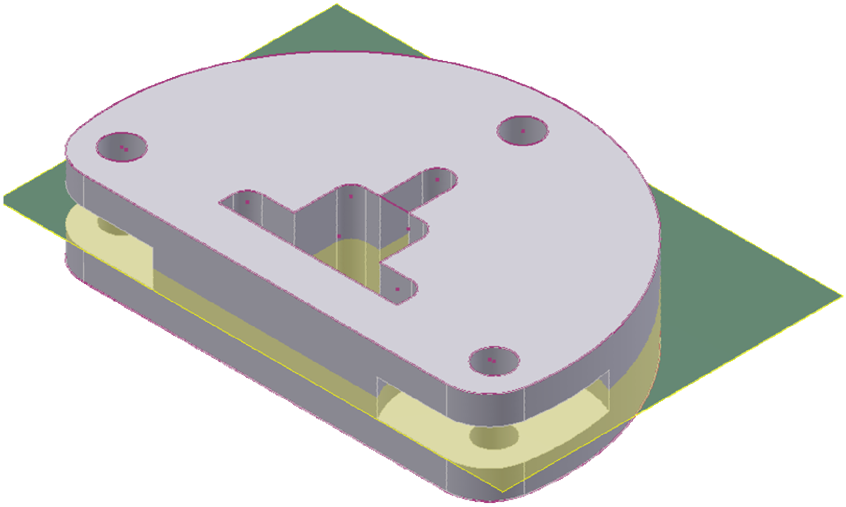


Fig 2: CAD model showing isometric view of triangular load cell

The Load cell is a triangular piece of aluminum, hollow inside to hold the pulleys. The optical interrupt sensor is mounted in a slot made for it. A probe is attached to the top pulley which can move longitudinally inside the sensor.

Working of the Load Cell: Due to tension in the string, the load cell is stressed, causing it to deform in the vertical direction. As the load cell deforms, the pulley and the probe moves vertically down. This motion is noted by the optical sensor.

Since the load cell is made of single piece no bolted connections are needed.
FEA Analysis reveals that deformation required to cover the range of the optical sensor can be achieved by a load cell made of polycarbonate but with low creep properties.

Reduced weight three pulley triangular design:

Since the motors have to work against lifting the weight of the ranger, it was imperative that the mass of the load cell should be reduced as much as possible. Hence, some changes were made in the previous design to remove a lot of chunk of metal. FEA analysis was then done to see the stresses and deflections. It was found that the thin region between the bottom two pulleys had high stresses and considerable deflection, which was not desired. In order to assemble, two such thin plates can be bolted together.

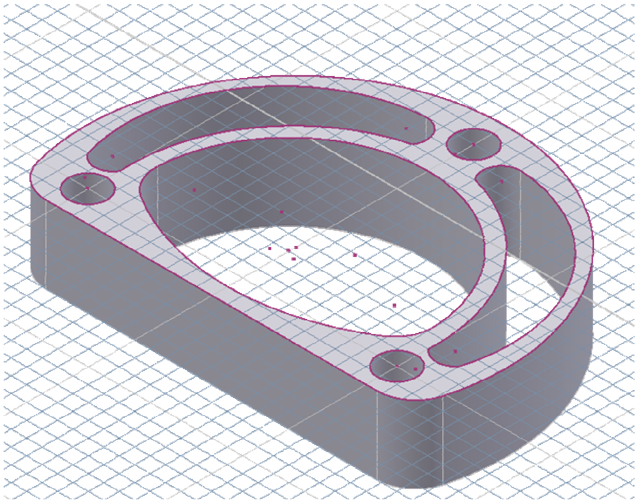


Fig 3: CAD model of reduced weight triangular load cell

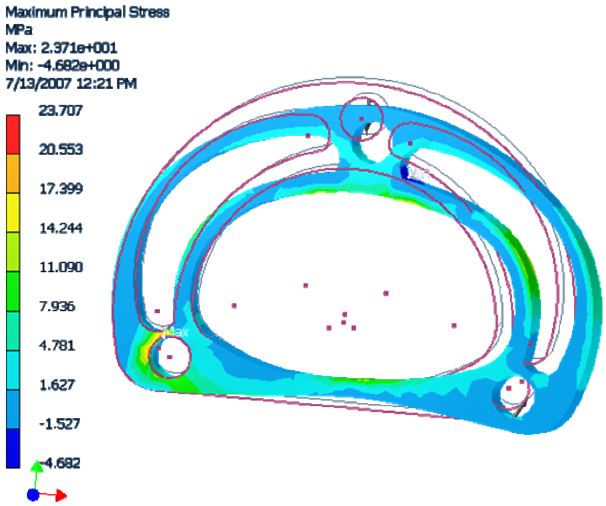


Fig. 4: FEA results showing stresses in the model

Rectangular three pulley design:

In order to facilitate mounting of the load cell on the ranger's leg, a rectangular three pulley design was included. Also, inorder to reduce the stresses a stress relief hole, and a cut is added. This design handles stress better, gives the desired deflection, and is light in weight.

The FEA analysis shows that, the maximum equivalent stress is higher near the stress relief hole, however stress is low otherwise. The deflection is in the range of 1-2 mm.

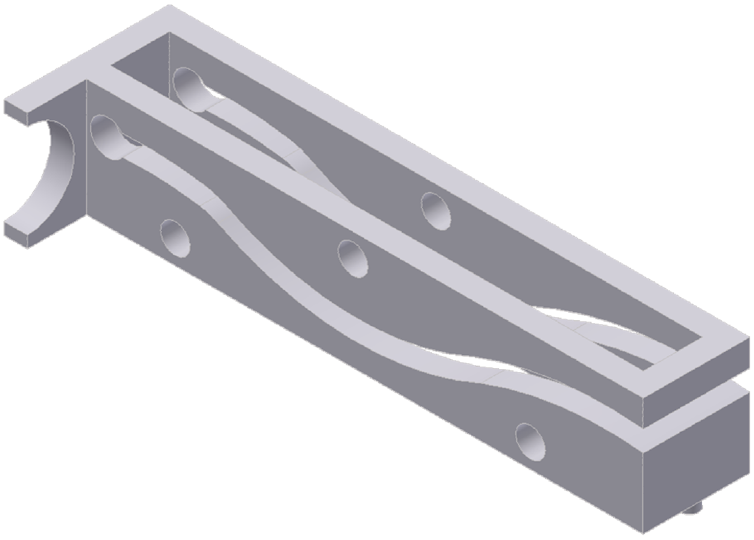


Fig. 5: CAD model of rectangular load cell

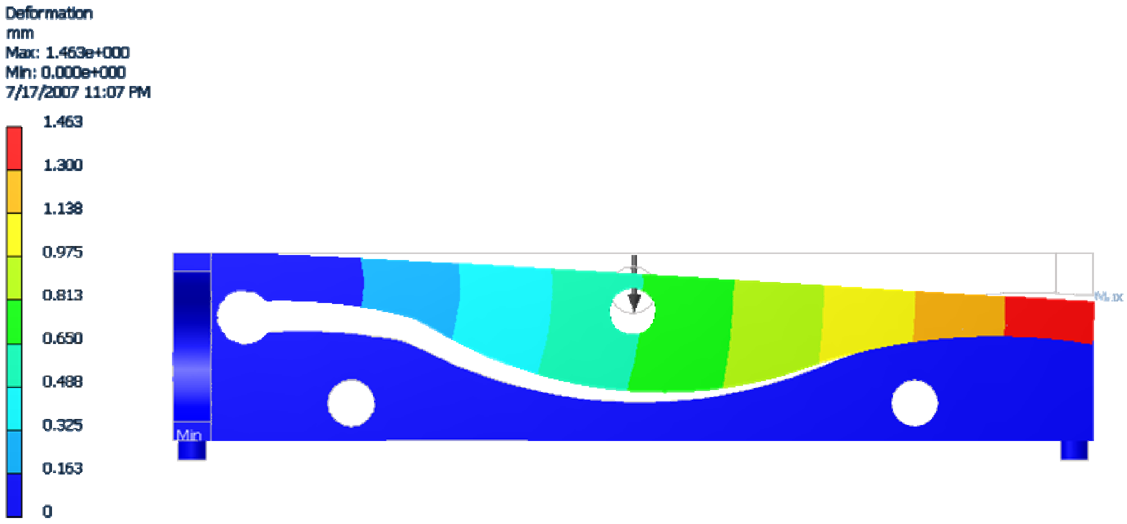


Fig. 6: FEA results showing the deformation of load cell under

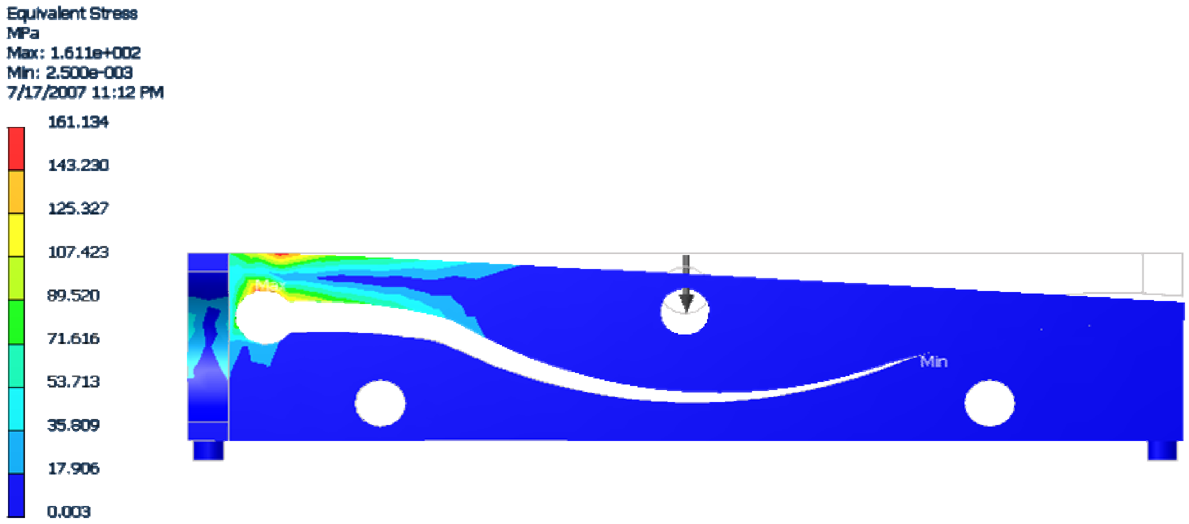


Fig. 7: FEA result showing Equivalent stress in rectangular load cell model

Modified rectangular load cell:

The rectangular load cell was modified because the bottom thin ligament, would be considerably stressed and show some deflection. However, this is not seen in the FEA results in ANSYS. Hence The bottom pulleys are housed in a firm aluminum member which can be mounted rigidly to the leg. The weight of this model is 60 grams.

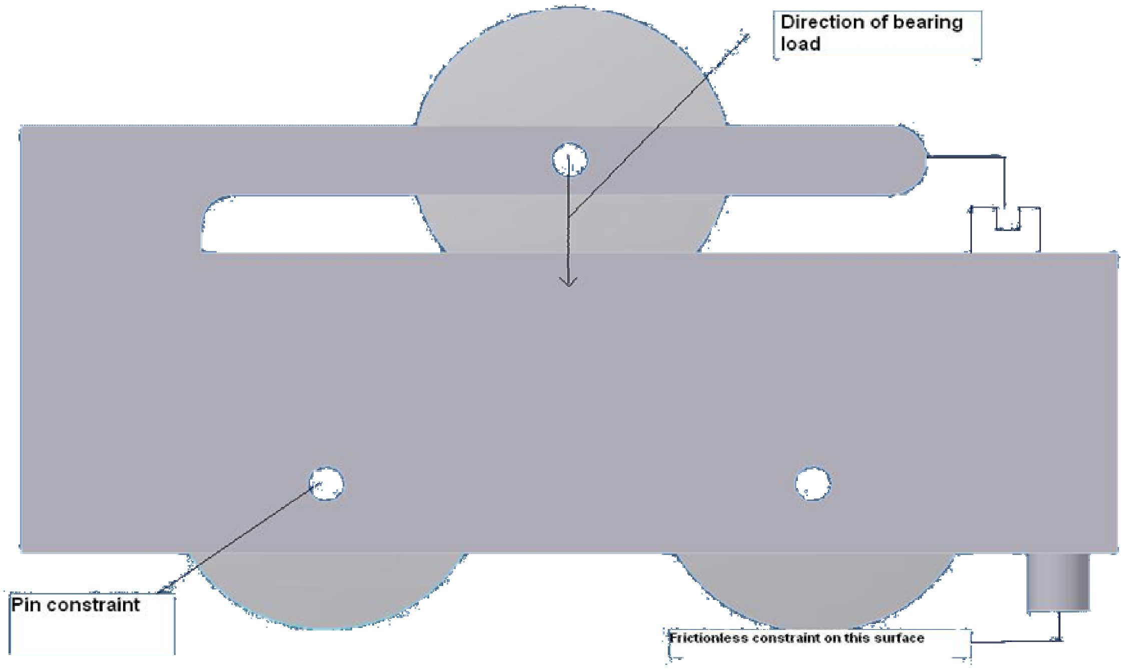


Fig. 8: CAD model of modified rectangular load cell

Proposed Rectangular Design:

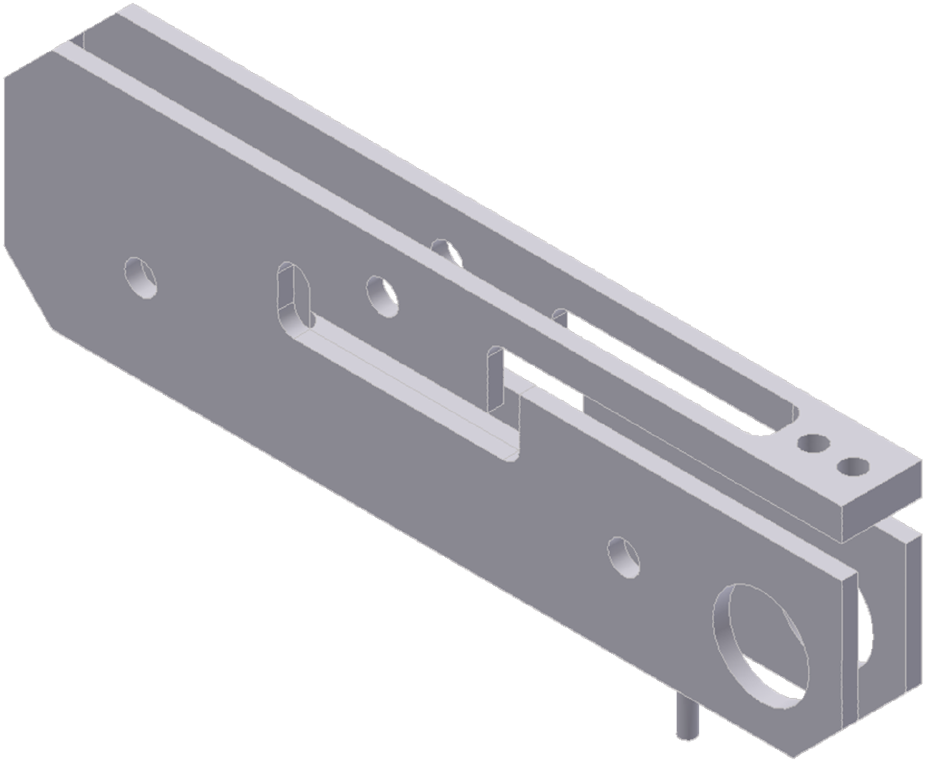


Fig. 9: CAD drawing of Load Cell

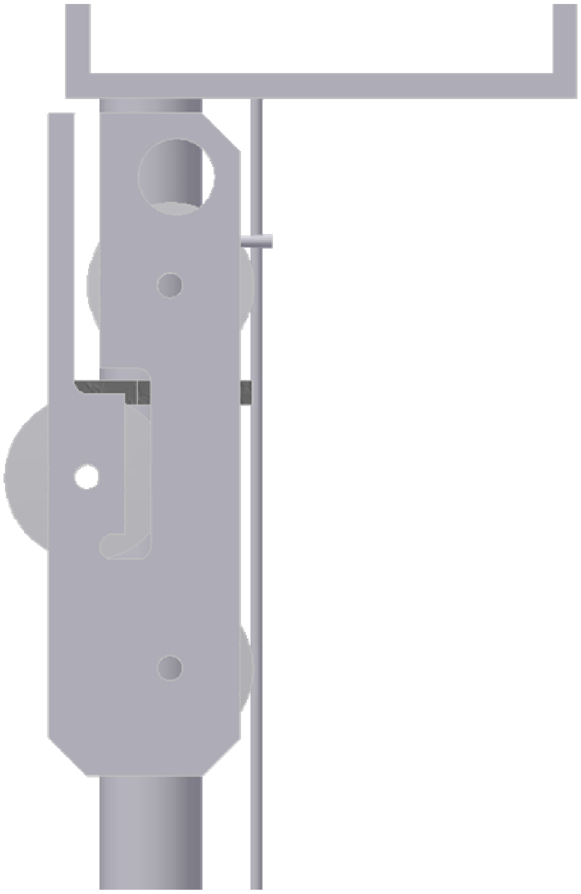


Fig. 10: Isometric View of Load Cell mounted on ranger's leg

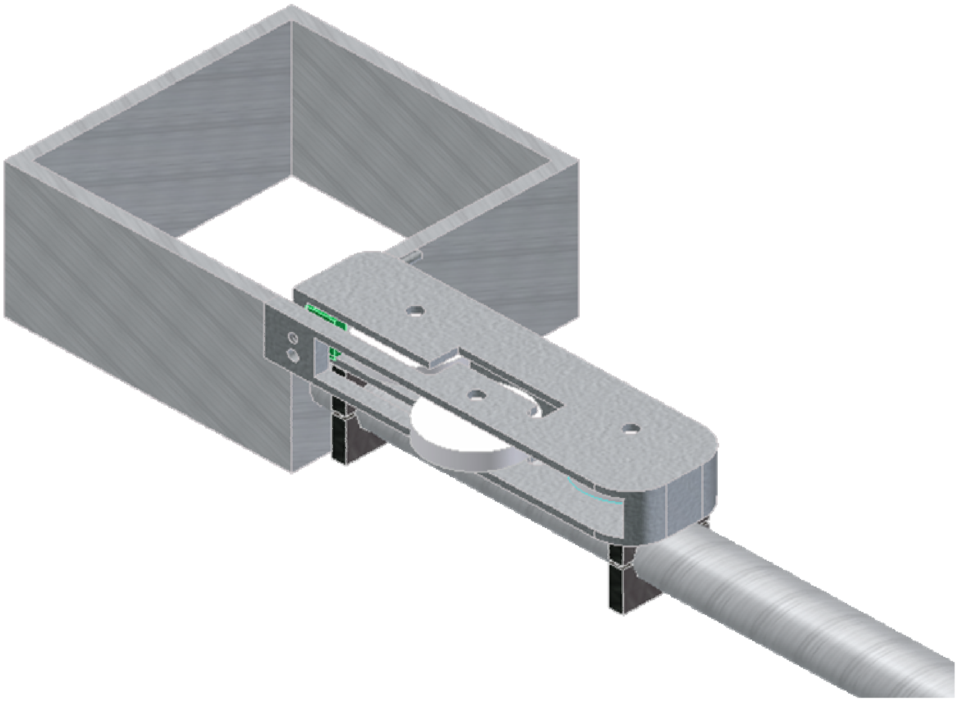


Fig. 11: Load Cell in context on ranger's leg and body.

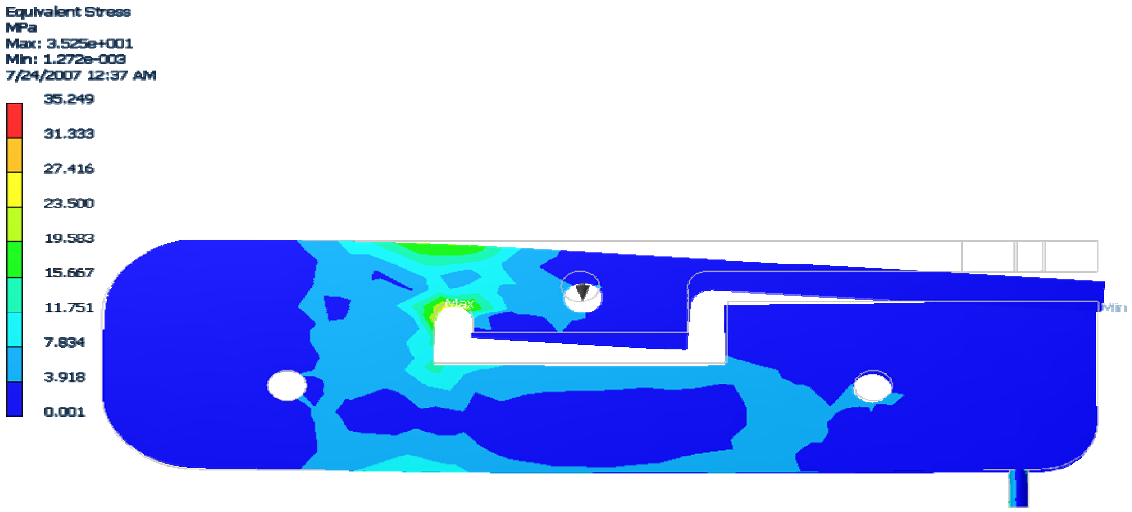


Fig. 12: Distribution of stresses on application of load

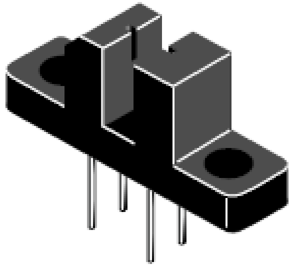
We observe that in the final design, the stresses are well distributed, and are not dangerously high. There is a reasonable safety factor in this design. Also, the desired deflection can easily be achieved by changing the length and profile of the cut.

Thus, we have arrived at a design which gives us the required deflection, and at the same time remains fixed to the ranger's legs, thus improving the reliability of the results.

Next, we shall discuss about the sensor used to measure the deflection and the sensor mount to fix it on the load cell.

Chapter 3: Optical Sensor

An optical interrupt sensor was used, to measure the deflection of the load cell under the load. The deflection must be calibrated in terms of change in output voltage across the optical sensor. The reason to choose an optical interrupt sensor was because the ranger's P.C board has enough analog inputs, to directly connect the interrupt sensor.



For the initial Triangular and Rectangular Designs, we used the H21A1 optical interrupt sensor. The H21A1, consist of a gallium arsenide infrared emitting diode coupled with a silicon phototransistor in a plastic housing. The packaging system is designed to optimize the mechanical resolution, coupling efficiency, ambient light rejection, cost and reliability. The gap in the housing provides a means of interrupting the signal with an opaque material, switching the output from an "ON" to an "OFF" state.

The working of the sensor is useful only in its linear range. In order to determine the linear range of the sensor and to calibrate it, we conducted an experiment and plotted its Displacement v/s output voltage graph.

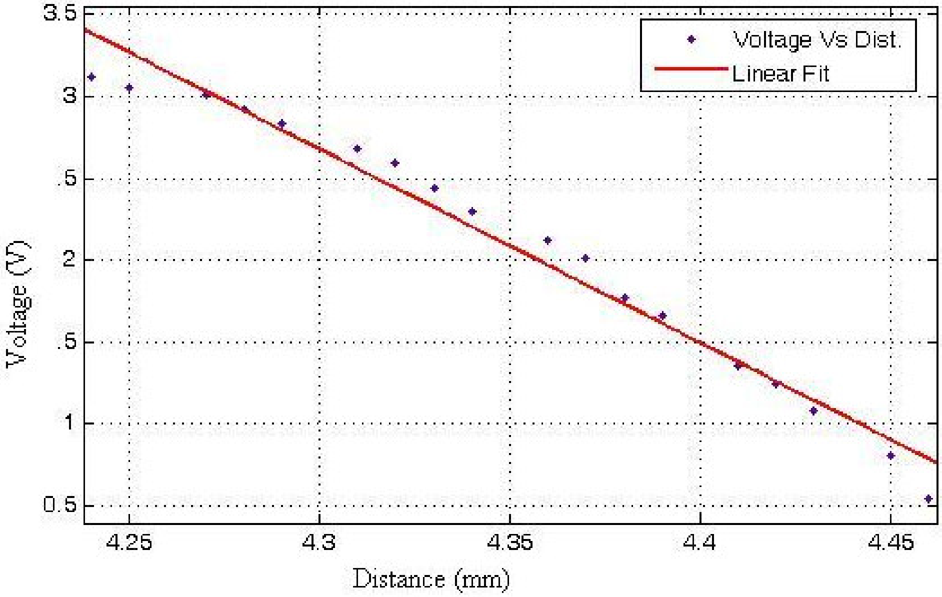


Fig. 13: Calibration plot of Optical sensor H21A

The scatter shows the data from the sensor, which has been superimposed by a linear fit. The error results show that, within the 0.2mm range, the sensor behaves very close to the linear behavior. Thus, this is the region where, the sensor data should be recorded from.

For the Modified Rectangular design and for the Final Load cell designed, to choose a more reliable and smaller optical interrupt sensor. The same exercise was repeated in order to get the displacement v/s output voltage plot.

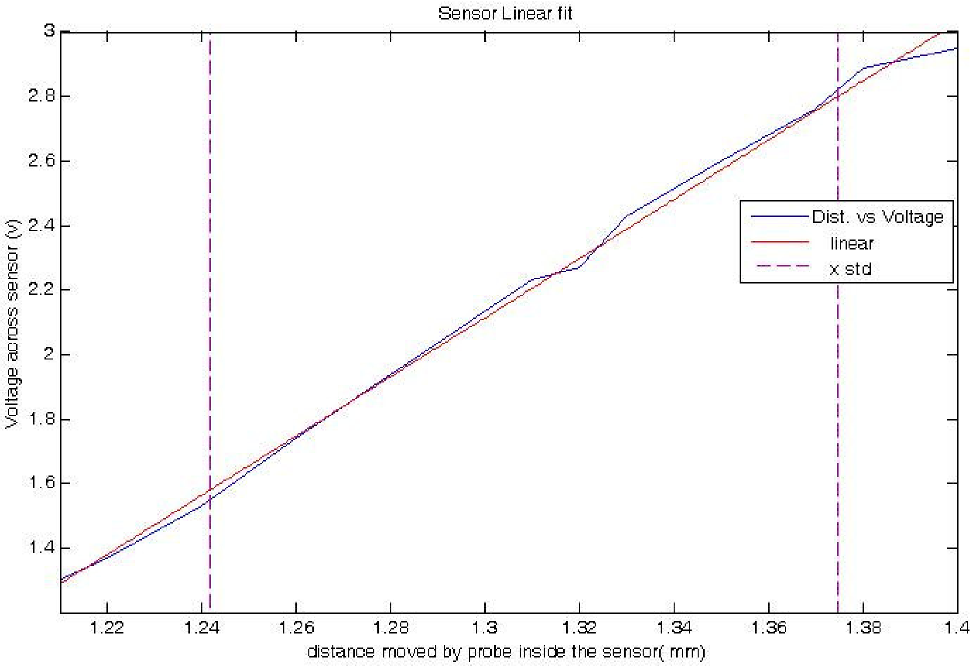
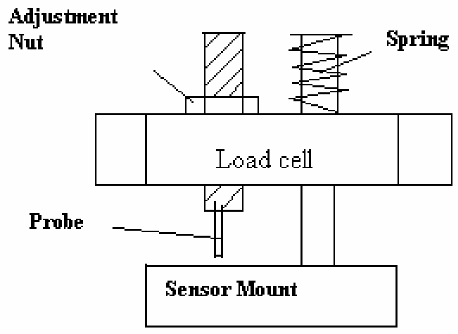


Fig. 14: Calibration plot of distance v/s output voltage

The blue line respresents the sensor data and the red line the superimposed linear fit on it.

<u>Mechanisms for adjustment of the probe:</u> There are two Screws used for adjustment of the Probe. A coarse adjustment screw and a fine adjustment screw(with spring). The coarse adjustment screw is used to put the probe in the center of its linear range. The second screw is used to make finer adjustments. It has a compressed spring element, and is fixed (glued) to the sensor mounting plate.



Chapter 4: Fabrication of Load cell

After the design of the load cell was finalized and agreed by FEA results, it was required to fabricate the load cell. The material of the load cell was chosen to be aluminum, because of its excellent machineability and high tensile strength.

The fabrication of the load cell was carried out on a milling machine in the TAM workshop.

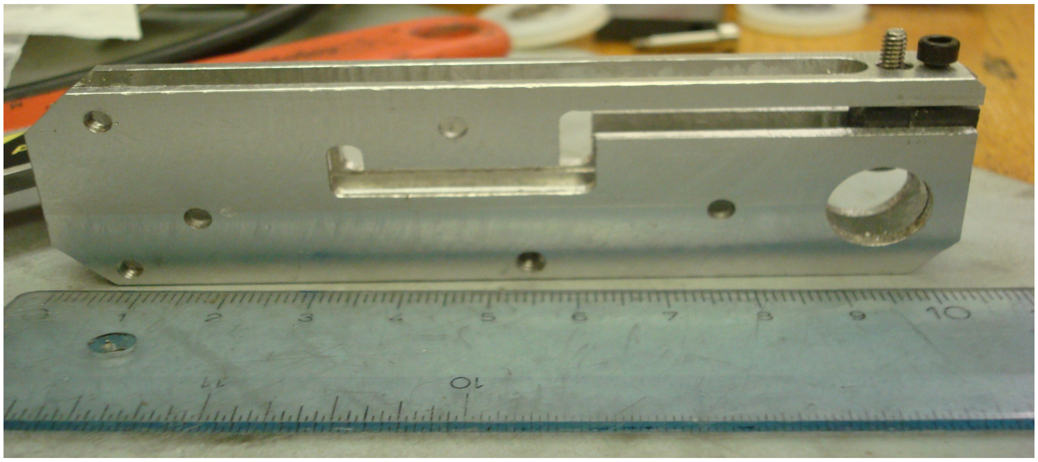


Fig. 15: Fabricated model of Load cell

The weight of fabricated load cell was 37 gms. The Fig. 16 shows the sensor mount with the adjusting screws in place.

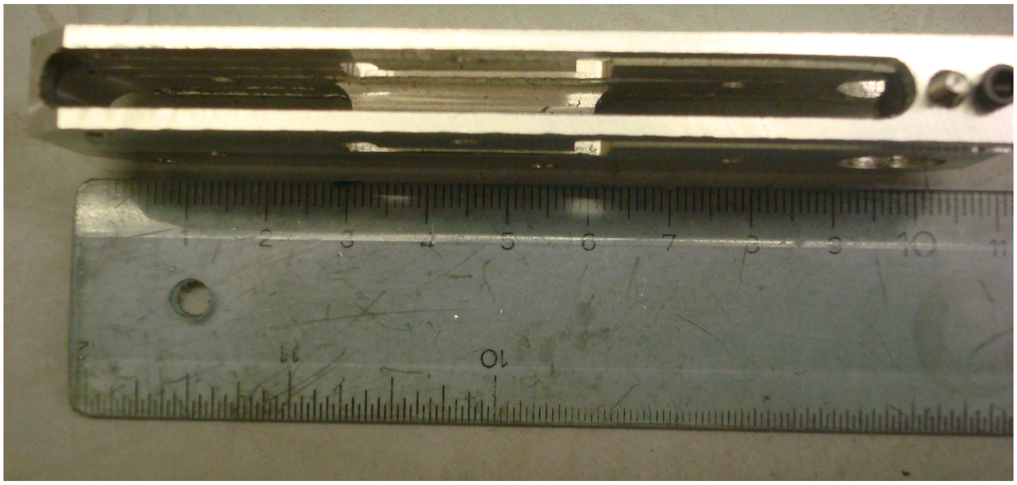


Fig. 16: Top view of load cell showing the space for pulleys and bottom thick section

Chapter 5: Calibration of Load Cell

Once we know the linear range of the sensor, and have set the probe in this range using the adjusting screws, in order to measure the tension in the cable's we need to calibrate the force in terms of the output voltage. We would like to see a linear relation between the force and the output voltage.

In the experimental setup, a string was passed over the pulleys and a load was applied vertically downwards. Different weights were loaded gradually and the output voltage from the voltmeter was recorded. The following results were obtained:

Table1: Calibration of Load cell

Force (N)	Voltage (V)
0	.78
3.6	.89
6	.94
8.6	.97
15.8	1.06
20.6	1.22
31.4	1.4
36.4	1.6
50	2

The data from Table 1 was used to plot the calibration curve for the load cell between Force applied and the output voltage at the sensor. This curve is then superimposed with a linear fit and the plot of residual error plotted to estimate how close is the fit.

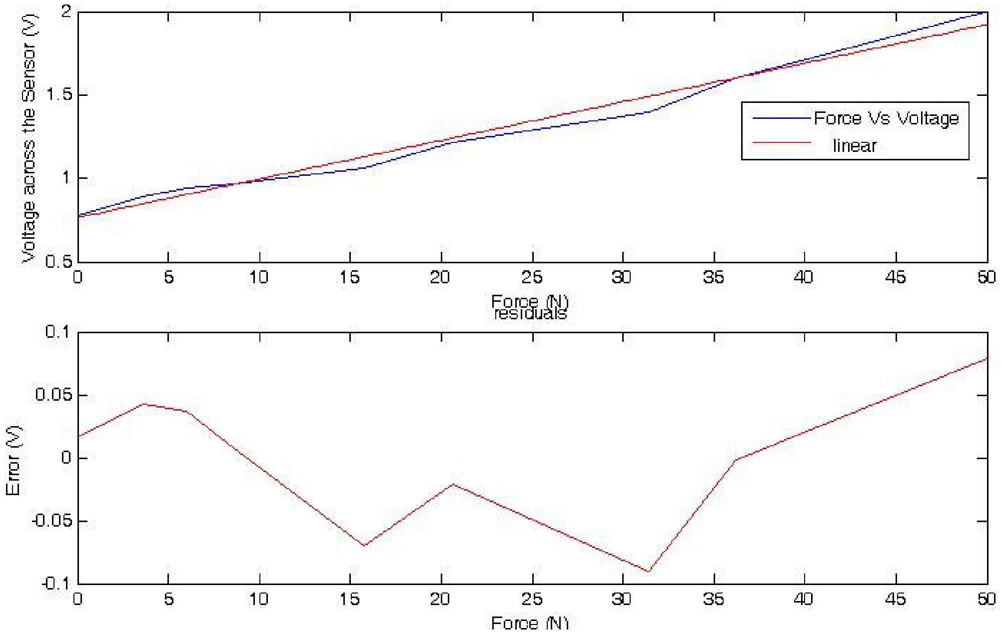


Fig. 17: Calibration plot of Force v/s Output voltage of sensor with residual error from linear fit

It is observed that the curve is nearly linear as theire is very little residual error from the linear fit. This is useful as it prevents tedious non-linearities and makes the load cell easy to use.

Chapter 6:

Conclusion & Scope for future Work

This report describes the design, fabrication and calibration of a load cell. The load cell was made in order to measure the force in the legs of the Cornell Ranger (string tension). The string tension was essential to get uniform spring constant in all the legs and hence improve its reliability. The main requirements for the load cell were:

- Simple Design to have reliable mechanics
- Ease of manufacturing
- Light weight
- Easy to remove and fix to the ranger's leg

The things achieved during this internship are:

1. We estimated the regions where there was scope for improvement in term of reliability for the ranger.
2. We tried to provide mechanical damping to reduce the noise in output of gyros.
3. We calibrated the optical Interrupt Sensor, and estimated its linear range.
4.. Designed and analyzed the load cell to get desired deflections and minimize stresses and any out of plane bending.
5. Fabricated the load cell and subsequent mounting of sensor and adjusting mechanism.
6. Finally, Calibration of load cell and force v/s voltage being close to linear range.

After a month of intense hard work, the load cell was successfully fabricated and calibrated. There is however, a lot of scope for future work, in following areas:

- Fabrication of two other load cells for other two legs.
- Estimating the force in the ranger's leg upon mounting the loadcell and making the ranger walk.
- Finally using the data for tension in the strings, making the spring constant in all the legs uniform.

Appendix:

This section describes the small experiment done on the cornell ranger. It was observed that there was a lot of noise in the output of the gyroscopes and accelerometers mounted on the ranger's pc board. This could be due to two reasons:

- Electrical noise from the P.C board
- Mechanical noise due to vibrations of the P.C board

In order to eliminate the mechanical noise due to vibrations of the P.C board, we replaced the aluminum spaces joining the P.C board with the ranger's body with compliant rubber spacers. These act as dampers, and reduce the vibrations received by the P.C board.
We expect to see some smoothening in the output of the accelerometers.

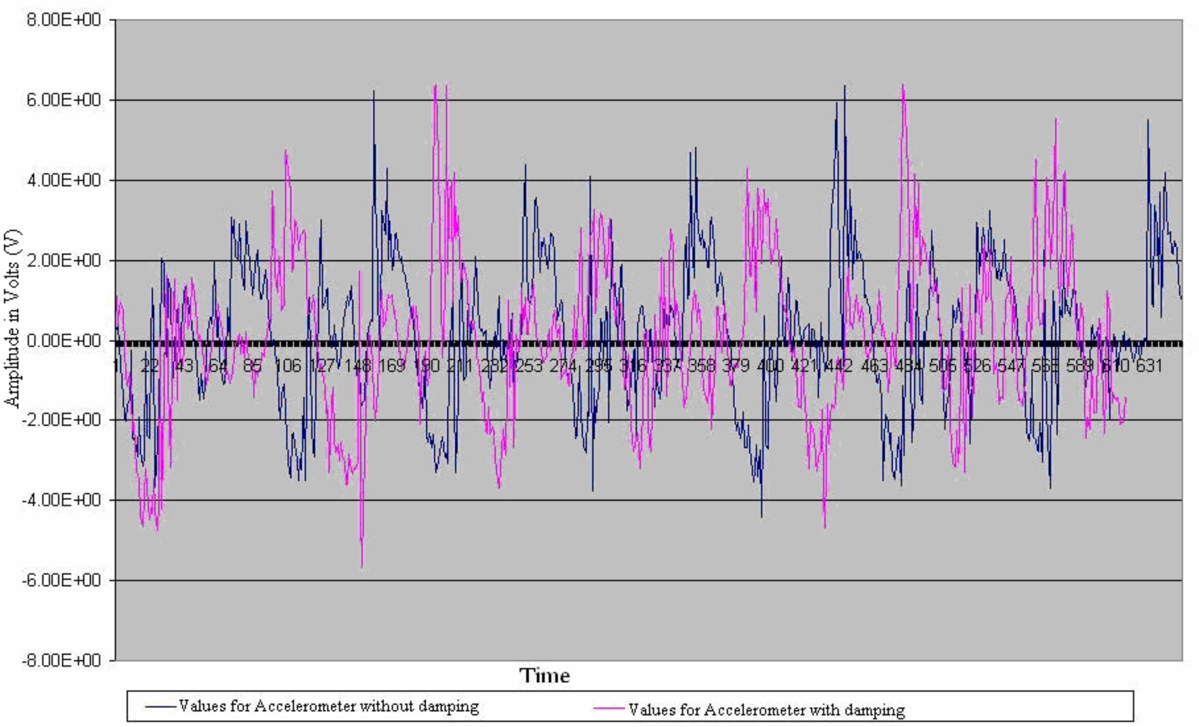


Fig. 18: Accelerometer data with and without damping

We observe from Fig. 18 that there is not much change is the accelerometer output in terms of noise. Hence, the main reason for noise in accelerometer and gyroscopes could be electrical noise.