Cornell University Snake Arm Team

Fall 2008 Semester Report

Mechanical Engineering

MechE Lead: Brian Johnson

Team Members:
Tristan Morris
Arjun Goyle
Shriram Subramanian

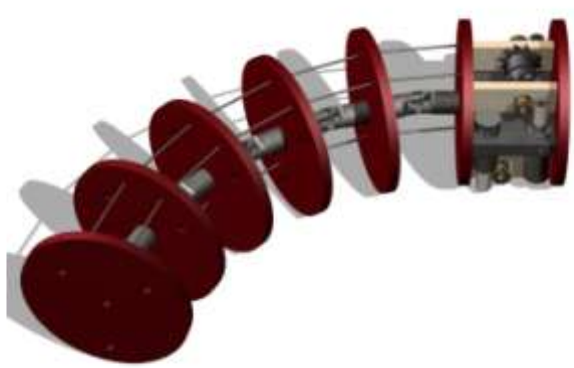
Brian Johnson
MechE Lead

Introduction

My work on the mechanical team this semester was focused on the design and construction of a proof of concept for the arm. This included basic modeling of the arm, design of the drive system, and fabrication of arm components. As mechanical lead, I was also responsible for managing and directing the mechanical team.

Design Summary

The current arm design is based on independent, self-contained segments. Each segment contains several "cells." A cell is defined as the space between two adjoining disks. Each segment is manipulated by three cables that pass through the disks. In previous versions of the arm, all of the cables originated at the base and terminated at points along the arm. All of the motors that drove the cables were housed at the base of the arm. In the current design, one cell of the segment contains the drive mechanism for the cables that control that segment. The picture below shows a single segment.



The use of independent, self-contained segments has several benefits. In the previous version of the arm, the cables for one segment pass through the previous segments. This means that control is very difficult considering that for a five segment arm, fifteen cables control the first segment. By using three cables that only span the length of one segment, three cables can be adjusted without changing the state of any other segments. This makes control of the arm much simpler than previous designs. The segments also make changing the length of the arm very easy. Segments can easily be added to the base of the arm. Since the tip segments are able to support themselves, the new segments added to the base need only to support the existing segments. The segments also use many standard parts, making manufacturing and assembly much easier.

The drive mechanism is made up of four main components, a motor, worm gear reduction, sprocket, and chain. The drive mechanism bends the rest of the segment in the desired direction, as specified by the user. The use of the three cables allows the arm to be bent in any direction. The desired direction of motion is accomplished by controlling the ratios between the changes in length of each cable. The degree of curvature is controlled by the magnitude of the changes in cable length.

The motor we have chosen is a small DC gearmotor. This motor has an internal 60:1 gear reduction that at 12V produces 71.44 oz-in at 410 rpm. The motor is 5/8" in diameter, 1.57" long and weights only 0.88 oz. This combination of small size, low weight and high torque makes this motor ideal for our application.

In the motor cell, there is also an external gear reduction from the output shaft of the motor. A worm gear is used to achieve a 20:1 reduction, which increases the available torque to 1429 oz-in. This also reduces the speed of the motor to 20 rpm. For rou application, this speed is acceptable, as only one turn of the output shaft is required for the full range of arm motion. At the reduced speed, the arm can band from straight, to the maximum curvature in three seconds. This is acceptable for our design goals. The worm gear allows this large reduction to take place in a relatively small space. It also makes it possible to mount the output shaft of the motor perpendicular to the driveshaft on which the sprocket is mounted. Another benefit of the worm gear is that it will not back drive when the motor is turned off. Because the teeth of the gears are nearly perpendicular, friction will not allow the load on the output gear to turn the gears. This means that the motor does not need to be left on once the sprocket has reached the desired rotation. This drastically reduces power usage and increases the lifespan of the motor and its controller.

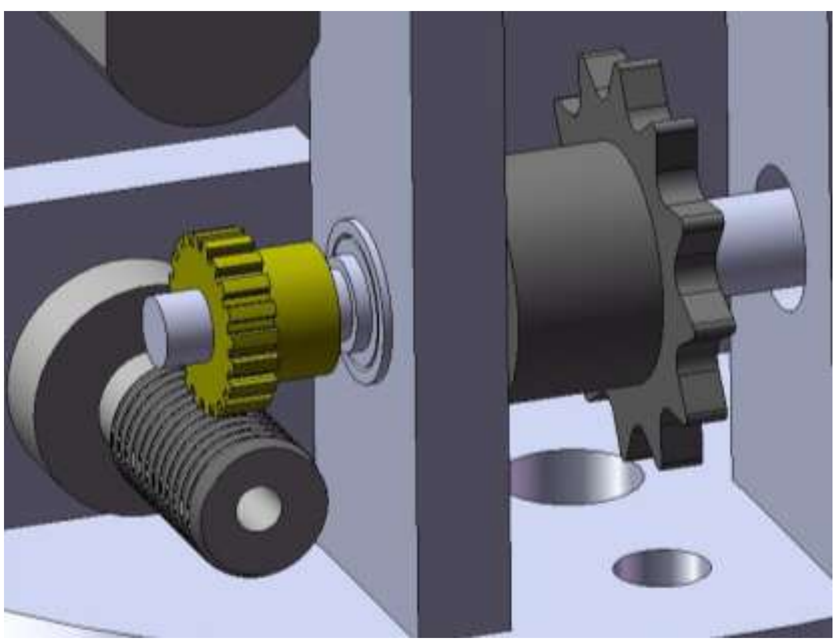
The output gear drives a sprocket attached to a chain that will pull the cable. The use of a chain and sprocket allows for a large amount of linear motion inside the relatively small thickness of the motor cell. The current sprocket has a pitch radius of

0.483 in. This radius corresponds to the distance from the center of the sprocket to the center of the chain. This arrangement generates an ideal linear force of 185 pounds at the cable. Even with a significant loss of force due to friction, this is more than adequate for our needs. The force calculation is described in the equations below.

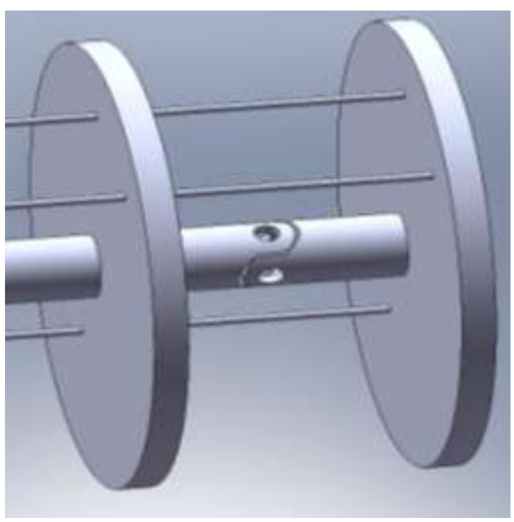
$$T_{out} = T_{motor} \text{ x } 20 = 71.44 \text{ oz-in x } 20 = 1428.8 \text{ oz-in}$$

$$F_{sprocket} \text{ x } 0.483 \text{ in} = 1428.8 \text{ oz-in} \rightarrow F_{sprocket} = 2958.2 \text{ oz-in} = 185 \text{ lbs}$$

The drive mechanism is show in the picture below. The chain and cable attachments are not shown in this figure. There are three separate drive systems in each cell for each of the cables.



The majority of the length of the arm is made up of body cells. A body cell is made up of adjoining disks and the universal joint between them. Without any stiffness, the arm would buckle any time a load was applied from the motor cell. In order to make the arm function, stiffness must be added to the body cells. This could be accomplished in several ways. One option is to use compression springs. These springs will placed around the drive cables or around the joint. Another option is to use a compliant mechanism instead of a kinematic joint. This mechanism would combine the motion of the joint and the stiffness of springs. This would also eliminate much of the play that is introduced by a kinematic joint. The body of the arm has a constant diameter. Tapering the cross section of the arm was considered in order to reduce weight of the arm. However, this would cause problems in operating the arm. Since the arm will be snaked through confined spaces, all segments need to have the same diameter as the tip segment. This ensures that any opening the operator navigates the tip through will not cause the rest of the arm to jam.



Applications

The previous arm was designed for applications that required a very small size. However, this arm design is intended for very different uses, given its larger size. This arm is geared towards situations encountered in industry that require working in very confined and inaccessible spaces. Inspection of spaces not accessible to direct human contact is well suited to the "snaking" ability of the arm. For example, in aerospace manufacturing, there are many spaces such as the wings and mechanical spaces that are not easily accessible. Over the lifespan of an aircraft, routine inspection must be carried out in order to detect fatigue cracks. A similar functionality can also be utilized in pressure vessels and other cyclically loaded situations.

Future Work

Next semester, the primary focus will be on refining the prototype and producing a final design. Several aspects of the design will be especially critical. The drive system needs to be completed and integrated into the arm. This includes the addition of potentiometers for feedback from the drive sprockets. The joints and springs also need some attention. The buckling of springs is a major issue. Possible solutions include varying the spring constant or the location of the springs. Research will also be conducted into the use of a compliant mechanism instead of a kinematic joint. Refinement of the control system will also be important, and will be coordinated with the ECE team. A delivery method also needs to be developed for the arm. Without some method for introducing the arm into the confined spaces it will operate in, it is useless. Possible designs include a linear motion of the entire arm, or mounting the entire arm on a conventional robotic arm. This type of robotic arm is often used in snakearm applications. The figure below shows a snakearm and robotic base built by OC robotics.

Shriram Subramanian
MechE Team

Summary

I joined the CU Snakearm Project Team this semester in order attain some hands on research experience and some exposure to solving real and practical engineering problems.

My work in the team was directed towards two main projects: cable systems and end effectors. As a member of the Mechanical Team I also assisted in redesigning a mechanical arm that would have a higher degree of freedom and a higher payload capacity as compared to the previous versions of the arm. Our aim was to come up with a working single segment prototype of the arm over which we would have control and could obtain accurate feedback. In the process of building the arm, I also underwent machine shop training in Emerson Lab. One of the tasks that were assigned to me, as mentioned earlier, was to come up with different alternatives for cable-end attachments. I suggested the use of Open Wedge Sockets since they require the use of only one wire rope clip to secure the end of the wire rope. The pin fits in the socket to secure your wire rope or chain link. The pin also allows you to quickly add attachments to the end of wire rope for lifting or pulling applications.

Another alternative was to use Nylon Rope Clamps. The advantage with these clamps was that, they could easily fasten onto fibrous ropes.

However, it was decided that no cable-end attachments shall be used for the prototype, but rather it shall be pursued in the next semester when we start assembling 5 independently controlled segments.

The other task that was assigned to me was to research on different appropriate tools that could be attached to the end of the snake arm which would be further explored and pursued the next semester.

End Effector-Camera

Confined spaces exist by design (e.g. aircraft engine), by failure (e.g. collapsed building) or naturally. Confined spaces exist in nuclear reactors, aircraft, the human body, industrial processing plants, underwater environments, ship-building and even space. Actually, when you consider buildings, roads, pipelines and other man-made spaces, it becomes clear that the world is full of awkward confined spaces. The technical challenge in confined spaces is to avoid obstacles- to snake into cluttered environments without disturbing or damaging the environment. This is where a snake-arm with an end effector as a camera can come into use. Since the purpose of the snake arm is to introduce tools or sensors into a confined space, in order to maximize the benefit of the snake arm's path following capability, the diameter of the end effecter's envelope must be equal to or less than the diameter of the snake arm. Taking these factors into consideration, the requirements for a camera are as follow:

- Because of the limited payload capability of the end effector, the camera should be as light as possible, to allow as great a real payload as possible.

- Small size- A large bulky camera would interfere with the operations of the snakearm and would increase the chance of collisions. Hence the camera must be as small as possible to ensure that no such interference takes place.

- Low power consumption, preferably a mobile battery powered system.

- Built-in stabilizer- The camera should be able to withstand the shocks and vibrations associated with powered motion, and the occasional collision.

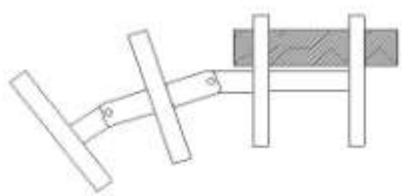
Of the many commercially available camera systems available, including brands such as Sony, Panasonic etc. only the Pulnix TMC-7 with detachable remote head was found to meet all of the requirements. *"The TMC-7 is excellent for applications such as pipe inspection, machine vision, aircraft cameras…"*[1]. The relevant specifications are tabled below:

Weight	7.3 oz.
Size (W x H x L)	1.65" x 1.26" x 5.74"

[1] http://www.avsupply.com/details/tmc-7.html

Power Supply	12 VDC, 500mA
Vibration and Shock	Vibration: 7G(200Hz-2000Hz), Shock: 70G

Since the camera is a bit too long (5.74"), it cannot be simply attached onto the last disk of the arm. Instead, in order to provide stability and steadiness to the arm, it has been decided to connect the last two disks with a solid bar instead of a Universal Joint and insert the camera through the last two disks as shown in the CAD drawing below.



End Effector-Gripper

Another tool for development that was chosen was the gripper, mainly because of its versatility and also since it could be manufactured by the team members in the Emerson Lab. Various designs are being considered and further more shall be explored next semester. Few of the designs that are being considered are as follows:

Pneumatic Grippers

We are considering pneumatic grippers mainly since these grippers don’t require the use of motors thereby, making them lighter and hence allowing the arm to carry as great a real payload as possible.

In the pneumatic grippers, we shall be using a piston-cylinder set up where compressed air shall be sent in to the cylinder of the gripper body. As pressure builds up, it shall force up the piston up and down. This linear motion of the piston, through a mechanical linkage, shall force the gripper jaws open and close. Two main motions of the gripper jaws are being considered: Parallel grippers and Scissor Grippers. In the parallel grippers, the jaws shall move parallel in relation the body. Parallel grippers are considerably accurate especially when lifting large objects. In scissor grippers, the jaws pivot about a common joint. Scissor grippers are ideal when limited space is available or when the jaws need to move up and out of the way.

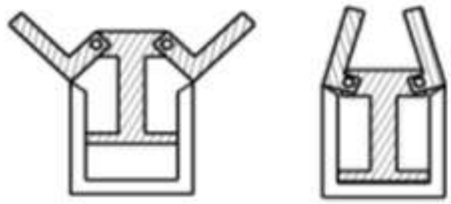


Figure: Scissor Gripper

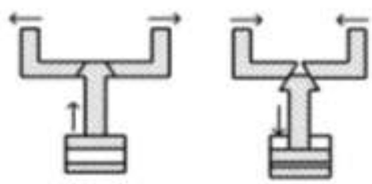


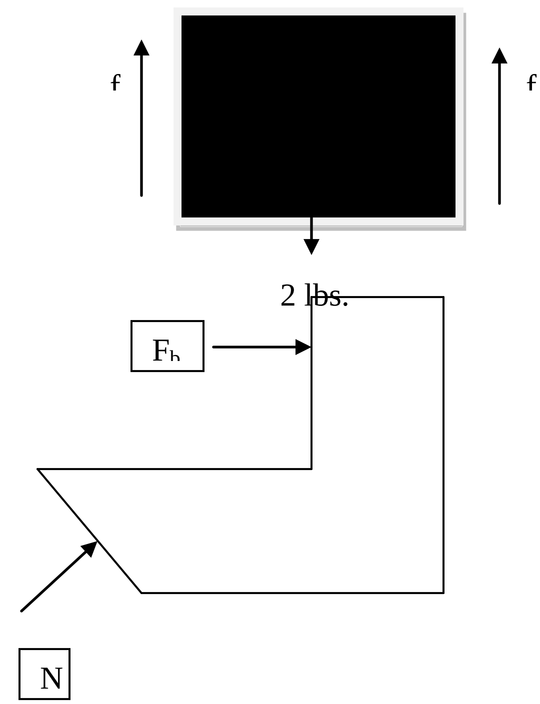
Figure: Parallel Grippers

Using statics we can calculate approximately the force that shall be exerted by the gripper jaws and as well as pressure required to move the piston.

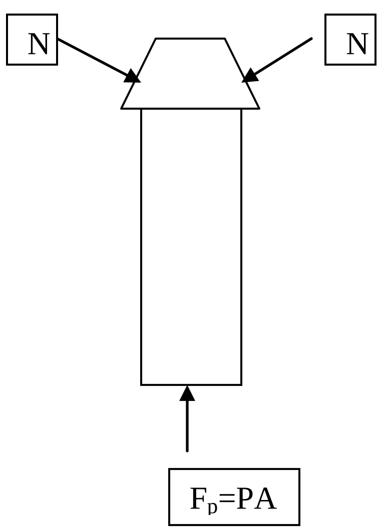
Assuming that the gripper picks up a load of 2lbs. then as per the FBD to the right, the friction force shall be

2f=2lbs.

=> f= 1 lb.



FBD of the jaw and piston:



f=µN The coefficient of rubber is between 0.6 and 0.85. Taking the lower limit to include all possibilities, we get

N=1/0.6=1.67lbs.

Force exerted by the jaws, F_b=1.67 Cos(60˚)= 0.833lbs.

Force exerted on piston, F_p= 2*N Sin(60˚)= 2.886lbf.

If the cross sectional area of the piston is between 0.0521in sq. and 0.064 in sq.

Then the required pressure would be between 45psi and 55psi.

Suitable air cylinders have been found in the market. One attractive possibility is the Stainless Steel Air Cylinders.

> *"Both are single acting with a spring return—they have one compressed air port to extend in the "push" direction; an internal spring retracts in the "pull" direction."*[2]

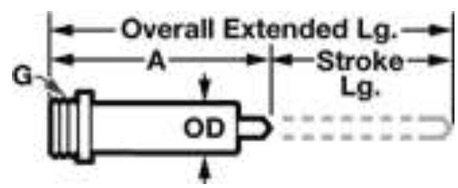


Figure: Stainless Steel Air Cylinder

Motor Powered Gripper

Another possibility we are considering is to use a parallel jaw gripper of a different design powered by a motor. The jaws of the gripper shall be held by a 4-joint mechanical linkage. In this model, two parallel plastic rods shall be used as a link between the jaws and the gripper body, while a linear actuator actuates the gripper.

[2] http://www.mcmaster.com/

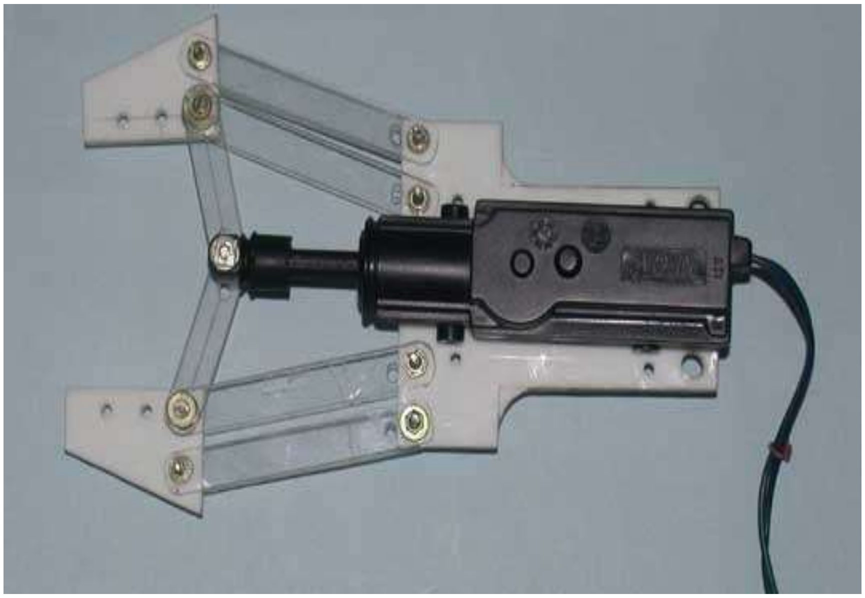
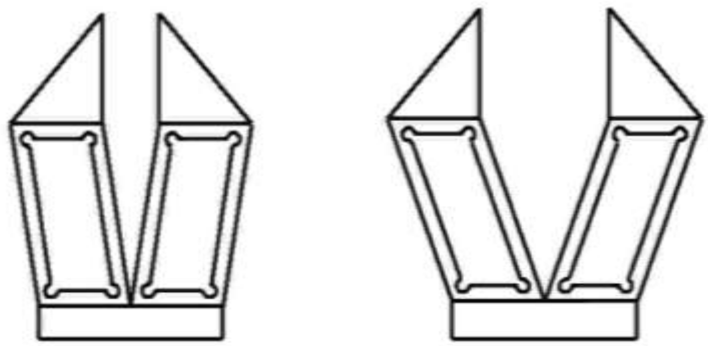
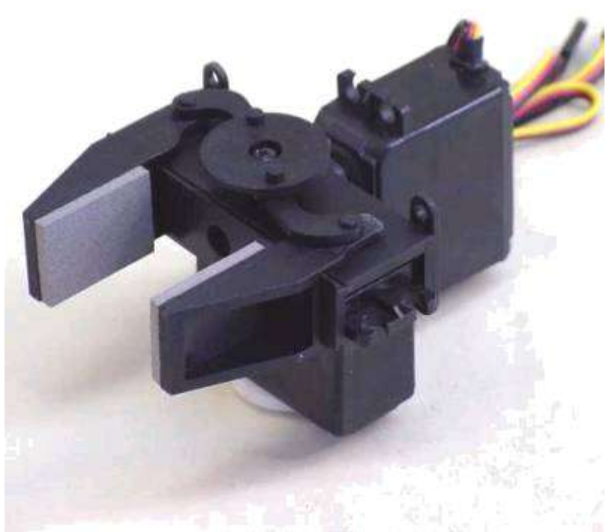


Figure: Motor powered Gripper.

Another idea that is in its infant stages of development is the concept of compliant mechanism. Unlike the 4-joint parallel mechanism which uses rigid plastic links, a deformable plastic may be used instead. In this way we can gain some mobility from the deformation of flexible members rather than only from the movement of rigid links and joints. One of the advantages why a compliant mechanism may be considered is that there is potential for a reduction in the number of parts required to accomplish a specified task. It also reduces wear and tear and hence the need for lubrication. An elementary CAD drawing is provided below:



Another possibility would be to actually buy a mini-gripper from the market. One viable option is the Gripper LG-KT distributed by RoboShop.



"The gripper features injection molded components and tow HS-422 servos for open and close and wrist rotate. The jaws open to 1.3" and the wrist rotates approximately 180 degrees. It needs only a screw driver for assembly."[3]

[3] http://www.roboworld.com.sg/roboshop/product.aspx?RecordID=82

Future Work

The most important work to be done is to develop complete control of the arm and then assemble 5 independently controlled segments (1 foot each) with the help of joints. Efforts must be taken in making the snakearm lighter by using lighter materials and by trying to increase the payload capacity of the arm. Comprehensive testing needs to be done on the arm, to ensure that the arm can withstand all environments. Further research and development is also needed into end effectors, so as to increase the tasks that can be accomplished by the arm. The field of compliant mechanism must be seriously explored, as it would significantly simplify the task of assembling a gripper, while also increasing the real payload capacity that the arm may be able to carry.

Arjun Goyle
MechE Team

Summary

I joined the Mechanical Team of CU Snake Arm to gain some hands on research and manufacturing experience. The objective of the team was to come up with a new design for the arm by overcoming the complexities faced in the previous versions of the arm.

As a member of the Mechanical Team we had to design the entire structure of the arm and come up with a plan for installing the motors and sensors on individual segments of the arm which would be assembled together to give high degree of flexibility and higher load lifting capability.

We have utilized acrylic sheets as the main base structure of the arm as it makes the arm at least 5 times lighter and it is also easy to machine. We utilized the services of Cornell Computational Synthesis Lab (CCSL) to laser cut the circular 3” diameter acrylic base plates.

The idea is to assemble 5 independently controlled segments (1 foot each) with the help of joints and control them with steel cables attached to a chain-sprocket-motor control unit.

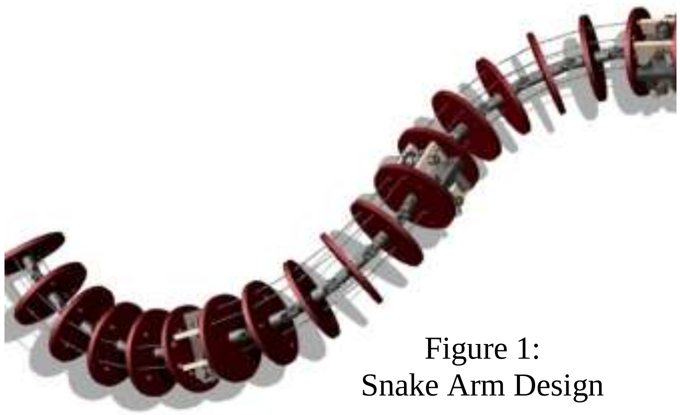


Figure 1:
Snake Arm Design

One problem we faced was in deciding the joints needed to put together the circular acrylic plates, I suggested the use of Universal-Joints with internal threads (5/16"). These joints consist of a pair of hinges located close together, oriented at 90° relative to each other, connected by a cross shaft. The following joints were procured and used for the current design:

Description	Universal Joint
Distributor	McMaster-Carr
Part Number	6445K1
Price	$11.39
Bore Diameter	0.25”
Bore Depth	9/16”
Joint Diameter	9/16”

Overall Length	2”
Material	Die Cast Zinc
Max Angle	15º

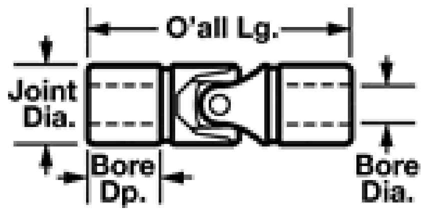


Figure 2: Universal Joint

In the future we plan to use polymers to manufacture light weight universal joints to complement the acrylic base.


Figure 3: Future Acrylic Universal Joint

Another issue we have faced during the assembly process is in connecting the potentiometer shaft to the gear-sprocket shaft. Both the shafts are of different sizes and materials thus negating the option of welding them together. Since is potentiometer sensitive devise used to measure the amount of rotation of the shaft, it is necessary to have it securely bound to the shaft.

I suggested that we cut small keys on both the shafts and paste the matching sides together with epoxy; this will ensure that the potentiometer is secured to the shaft and hence minimizes the problem of error in the readings. For this purpose I underwent workshop training in the Emerson Lab.

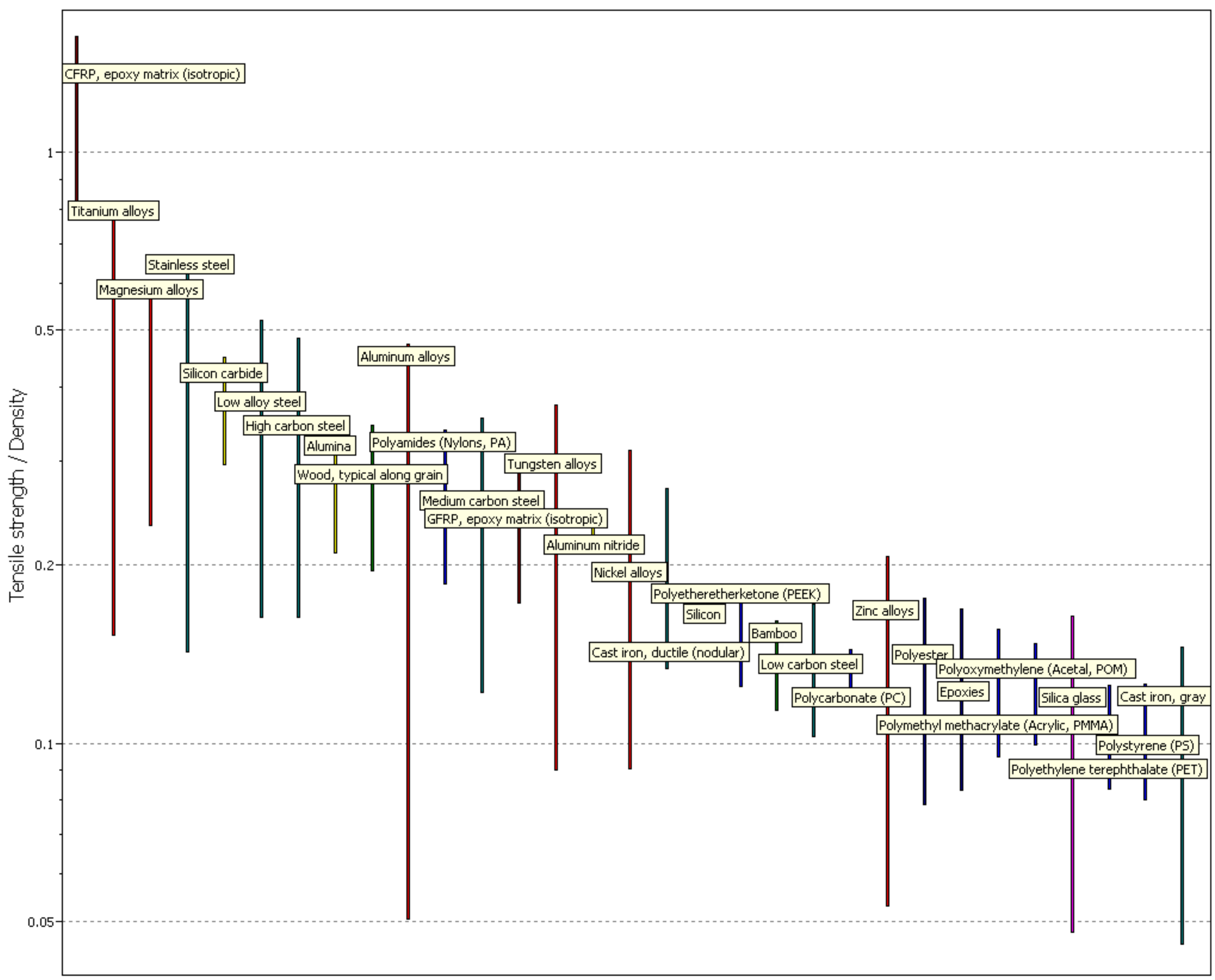
Since the design’s implementation is in preliminary stages we are trying to come up with more and more solutions to make the arm lighter and its operation more efficient.

Tristan Morris
MechE Team

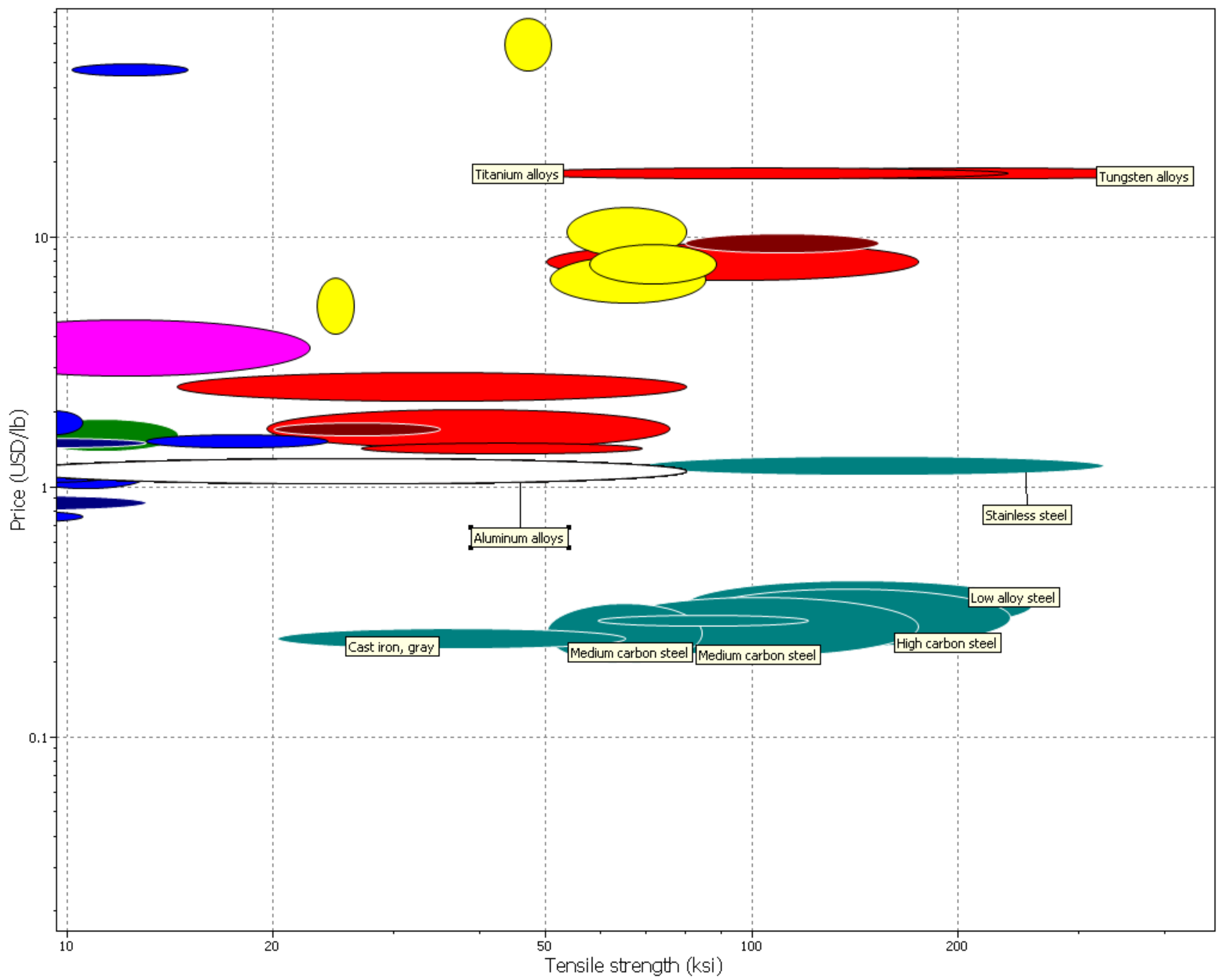
Materials for Snake Arm Construction

One aspect of my work for this semester was selecting materials to construct the complete version of the snake arm. Although our demonstration model was made out of laser cut plastic for ease of construction and demonstration, the hard plastic employed is unsuitable for production of a final model. It has a low tensile strength, high cost for the tensile strength it possesses, and suffers from fatigue extremely quickly under the stresses of the arm, making any long term use impossible. While good for prototyping, the final model of the arm will require a different, more resistant material.

In selecting a material, our first requirement is a high tensile strength vs density ratio. This is because the amount of weight the material is required to support is directly proportional to the weight of the arm, and so the absolute strength of the material is not the only factor. Using CES software, we plot this ratio and get a list of possible materials.



With this list of possible materials, our next concern is cost, plotting Cost vs Tensile Strength, we find a second standard by which to select our materials.



Comparing these two graphs, we see there is a highly convenient solution. High carbon steel can be seen to have high tensile strength – comparable to titanium, for less than 1/10th the price. Looking at our first graph, we see that high carbon steel has an excellent tensile strength to density ratio. Low alloy steel has a slightly higher price and, by roughly the same percentage, a slightly higher ratio. The tiebreaker comes in that Low Alloy Steel has a significantly higher yield strength and fatigue strength. Easily machined, and with a market price of only \$0.42/lb, it is a material convenient for both machining and ease of ordering.