Robot Report

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1 Overview of Robot

My group's design is a robotic arm. The base utilizes a turntable that yaws the robot arm. There's a motor at both the shoulder and elbow of the robotic arm that is able pitch each of their respective components. The design of these joints is based on a parallelogram four-bar linkage. The wrist of the robot is rigid and hold the gripper that is able to grasp the wooden cube.

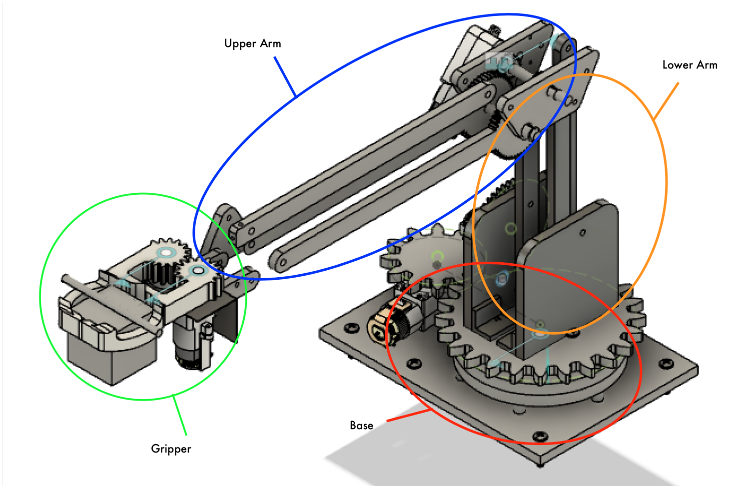

Figure 1: CAD of robotic arm

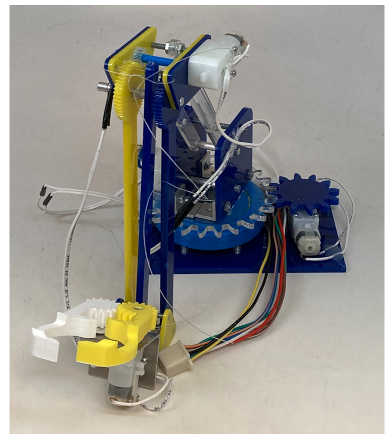

Figure 2: Physical robotic arm

During the competition, each part of the robot works sequentially to achieve its goal: place a wooden box from the field onto Geisel library. At its starting position, the base rotates the arm to position it in front of a box. The lower and upper arm work in unison to position the gripper at the correct location where it can grip the box. The gripper holds onto the box while the rest of the arm positions itself to allow gripper to place the box onto one of the floors of the Geisel Library.

2 Description of Component

The powered component I will analyze is the upper joint of the robotic arm. In figure 3, a motor will rotate a driving gear that rotates the driven gear on the linkage. The driven gear will pivot the linkage about the axis of the driven gear. Since this is a four-bar linkage, all the linkages will move to maintain the parallelogram shape. The role of the upper arm is to allow the entire robot to extend further. The lower arm's maximum height is constrained by the design constraint: 10 inches. The upper arm allows the robot to reach all the boxes on the field and the top floor of Geisel Library, which is 15 inches tall. Without the upper arm, the robotic arm would be severely limited in reach.

As I mentioned earlier, my design is based on a parallelogram four-bar linkage. The reason for this is because the gripper was designed in mind that it would be parallel to the ground when it was picking up boxes. The four-bar linkage allows the gripper to remain parallel at any height as shown in figure 4.

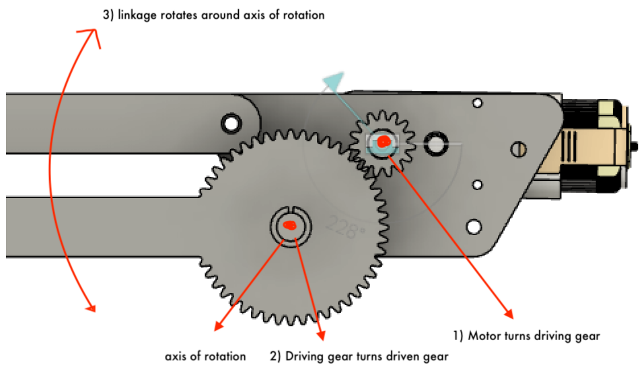

Figure 3: How my part works

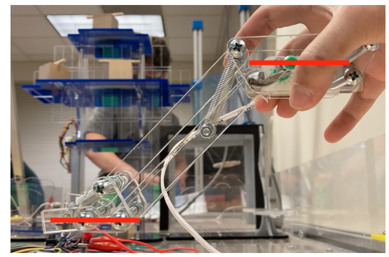

Figure 4: Red lines are always parallel

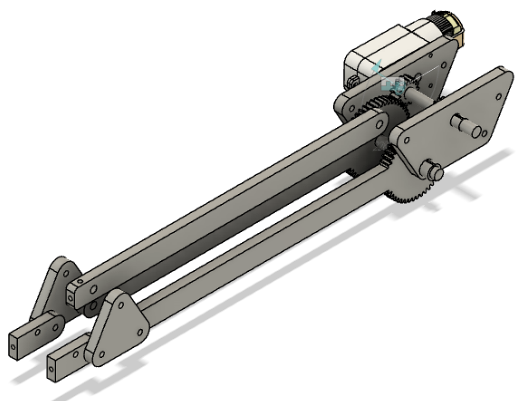

Figure 5: Isometric view of CAD

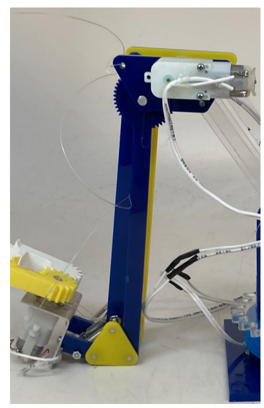

Figure 6: Physical component

2.1 Functional Requirements

- Upper arm must be greater than 4 inches in order to drop one box (38 g) on top floor of Geisel (15 inches)
- Must be collapsible to fit inside size constraints
- Upper arm must take less than 8 seconds to perform a 180 degree rotation

2.2 How It Functioned

The upper arm can do a rotation of 180 degrees in an average time of 3.7 seconds given three trials. The average angular velocity of the arm is 1.357 radians per second given three trials. It is long enough to reach all the boxes on the field and can drop boxes on the top floor of Geisel. This is important in order to score points and to not be restricted to certain boxes and floors. It can lift the wooden box without any stalling. Overall, these values make sense. The upper arm and gripper are relatively light and are mainly made of acrylic. This lightweight allows the upper arm to rotate quickly. Similarly, it was expected for the motor not to stall due to a factor of safety of 2.23.

3 Analysis of Component

The objective of this analysis is to calculate the maximum angular velocity of the upper joint around its axis of rotation as it moves against the force of gravity. How long it takes the upper arm to rotate around its axis of rotation plays an important role during the competition since this motion will occur when the robotic arm is trying to lift a box to a floor on Geisel Library. As a result, this will be the focus of the analysis.

3.1 Assumptions

- Gear teeth mesh perfectly and have 100% torque efficiency (optimistic)
- Motor operates at no-stall torque (optimistic)
- Mass of screws, nuts, springs, and fishing line is negligible (optimistic)
- Laminar flow (optimistic)
- Linkages can be reduced to rectangular prism since they are symmetric along the mid-plane of the upper joint (conservative; refer to figures 7 and 8)
- Linkages are not filleted at the ends and are rectangular prisms (conservative)

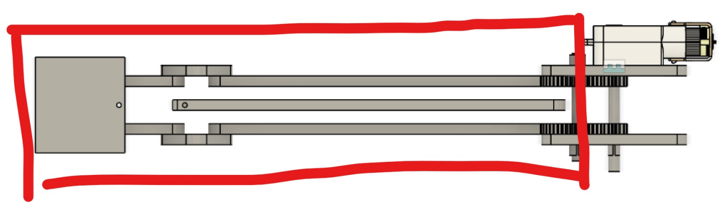

Figure 7: Section that rotates (enclosed by rectangle) excluding the screws is symmetric

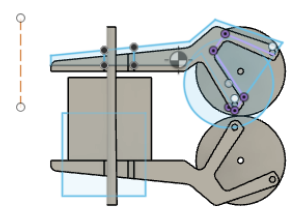

Figure 8: Gripper and wooden block is nearly symmetric

3.2 Free Body Diagram

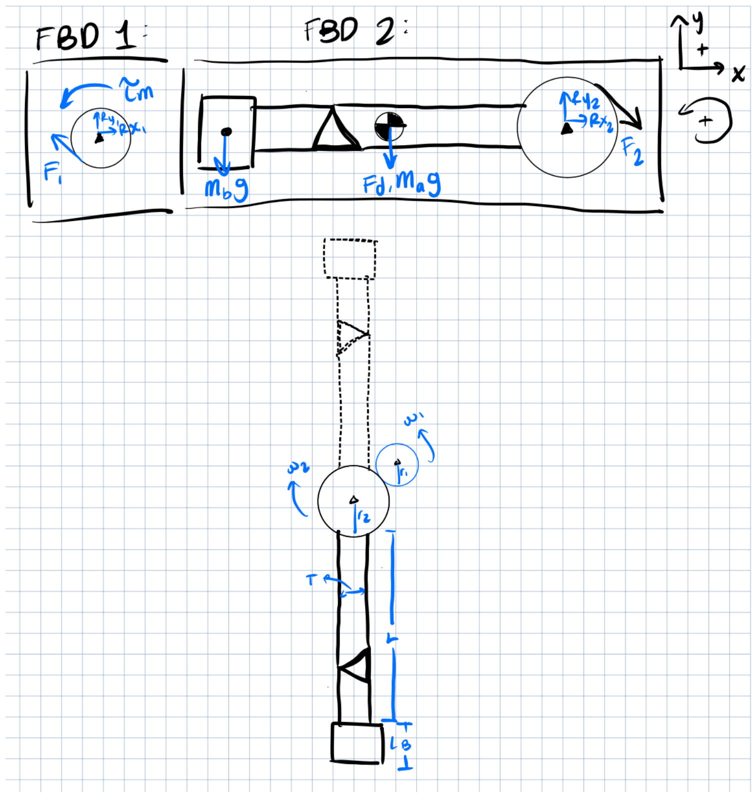

Figure 9: Free body diagram of Upper Arm

3.3 Calculations

Design Parameters:

Density of Acrylic	1.18 grams/cm^3
Thickness of Acrylic	0.53 cm
Height of Acrylic	1.27 cm
Mass of Upper Joint and Gripper that Rotates	221.28 grams
Mass of Wooden Box	38 grams
Horizontal Length from Pivot Point to Center of Mass of Upper Arm	0.15 m
Distance from Axis of Rotation to Gripper	15.0134 cm
Cross-sectional Area with respect to Top Plane of Upper Arm and Gripper	69.798 cm^2
Length from Axis of Rotation to Gripper	36.793 cm
Angle of Rotation	180 degrees

In order to solve for the maximum angular velocity, we will use the equation $\sum \tau = I\alpha$. First, I will solve for the rotational inertia about the axis of rotation. Since the rigid body is assumed to be completely symmetrical about its mid-plane as shown in figure 7, we can condense the body into one linkage on the mid-plane as shown in figure 10 where the thickness is 3 times the thickness of the acrylic because there are three linkages.

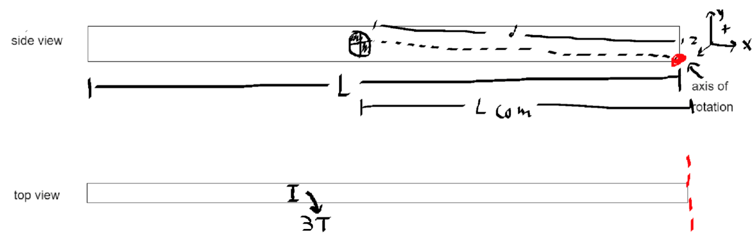

Figure 10: Rigid body diagram of Upper Arm

I can then solve for the rotational inertia by first using the equation $I_{com} = \int r^2 \, dm$ and simplifying the linkages to a rectangular prism.

$$I_{com} = \rho \int \int \int (x^2 + y^2 + z^2) \, dx \, dy \, dz$$
$$I_{com} = \rho \int_0^{1.59} \int_0^{1.27} \int_0^{36.793} (x^2 + y^2 + z^2) \, dx \, dy \, dz$$
$$I_{com} = 39681.09616 g * cm^2$$

This is the rotational inertia about its center of mass. In order to find the rotational inertia about the actual axis of rotation, I will use the parallel-axis theorem: $I = I_{com} + Md^2$

$$I = I_{com} + Md^2$$
$$I = 43003.26 g * cm^2$$

Next, we will find the sum of torques. In the free body diagram, the torque acting on the rotating linkage are: the torque due to gravity at the center of mass, the torque due to drag force at the center of mass, the torque due to the weight of the wooden block, and the torque provided by the driving gear.

In order to calculate the drag force, we need an equation to represent the surface area as a function of degrees. At 0 and 180 degrees (the minimum), the surface area is the face of the arm linkages parallel to yz plane plus the face of the gripper linkages parallel to the xz plane. The gripper linkages will always be parallel to the xz plane because the four-bar linkage mechanism ensures they will be as shown in figure 4. While at 90 degrees (the maximum), the surface area is the face parallel to the xz plane. We can use these points to write an equation for surface area as a function of degrees. Using MATLAB's fit function to perform quadratic regression, the equation was found to be $SA = -0.0007453\theta^2 + 0.1341\theta + 0.6732$ and it was plotted against the reference points as shown in figure 11.

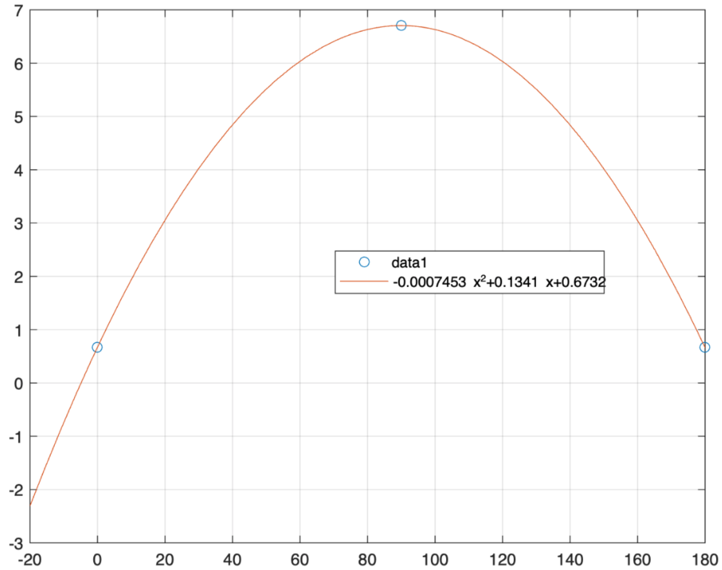

Figure 11: Surface area as a function of degrees

We can model the equation for drag force using the simplified equation $F_D = \frac{1}{2}C\rho A v^2$, where ρ will be the density of air at STP and C will be the drag coefficient for a cubic face (1.05).

The force due to gravity and the weight of the block can be modeled as $F_G = Mg$ and $F_b = m_b g$ respectively. The distance from each force vector to the pivot point is already known, so the moments can easily be found using $\tau = r \times F$. The torque provided by the driving gear is 0.9088 Nm with a gear ratio of 16:5. When we sum the torques, we get

$$\sum \tau = \tau_{motor} - r_1 \times Mg - r_2 \times m_b g - r_3 \times F_D$$

$$\sum \tau = \tau_{motor} - r_1 Mgsin(\theta) - r_2 m_b gsin(\theta) - r_1 \frac{1}{2} C\rho(-0.00074530\theta^2 + 0.13410\theta + 0.6732)(\omega/r_1)^2 sin(\theta)$$

Finally, we will solve the angular velocity using $\tau_{net} = I\alpha$. We will rewrite this equation as $\tau_{net} = I\frac{d^2\theta}{dt^2}$ and simplify the ODE.

$$\tau_{net} = I\frac{d^2\theta}{dt^2}$$

$$I\frac{d^2\theta}{dt^2} + \frac{C\rho(-0.00074530\theta^2 + 0.13410\theta + 0.6732)sin(\theta)}{2r_1}(\frac{d\theta}{dt})^2 - (\tau_{motor} - r_1 Mgsin(\theta) - r_2 m_b gsin(\theta)) = 0$$

The initial conditions for this differential equation are $\theta(0) = 0$ and $\omega(0) = 0$. We will solve this using MATLAB.

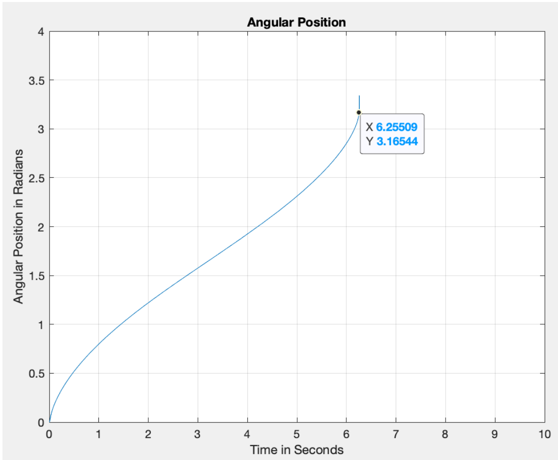

Figure 12: Angular position as function of time

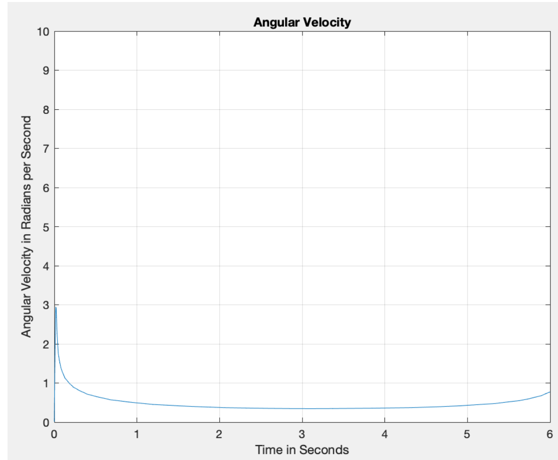

Figure 13: Angular velocity as function of time

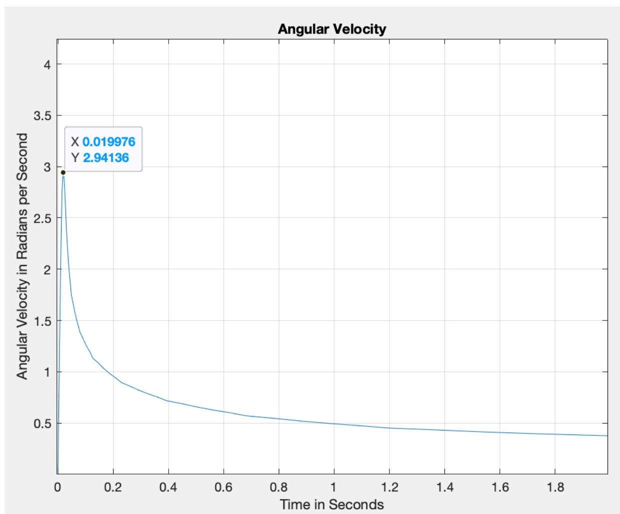

Figure 14: Angular velocity zoomed in

From figure 14, we can see the angular velocity plotted versus time. This maximum angular velocity is 2.94136 radians per second.

3.4 Experimental Results

Experiments were done in order to compared to calculated values. The expected time for a 180 degree rotation is approximately 6.3 seconds; however, the actual time is 3.7 seconds (averaged from three trials). The expected maximum instantaneous angular velocity is 2.94 radians per second and the expected average angular velocity is 0.5067 radians per second. Experimentally, I could not find the instantaneous angular velocity due to human error. As a result, I found the average angular velocity where the arm rotated 45 degrees. The average angular velocity is 1.357 radians per second (averaged from three trials).

The realized factor of safety for angular velocity is 3.46 using the experimental value. This means that the upper arm's maximum speed is approximately 2 times slower than what was expected. The percent error when comparing the instantaneous angular velocity with the experimental average angular velocity is 117%, and the percent error when comparing the calculated and experimental average angular velocity is 168%.

3.5 Maximum Performance of Robot

The results of my analysis showed that the upper arm was going to be slow. It would take approximately 6 seconds to do a 180 degree rotation and the expected maximum instantaneous angular velocity is 2.94 radians per second. The experimentally values showed that the upper arm was slower with regards to instantaneous angular velocity, but it would be faster with regards to overall rotation speed. The reason for the angular velocity discrepancy is due to how the experimental value was calculated. I found the average value over three trials. This is guaranteed to be much slower than a maximum instantaneous speed. Some possible sources of error that are causing the arm to take longer to rotate is the conservative consumption with the rigid body. I assumed a rectangular prism when it actuality, the body is closer to a rectangular ring where the inner cavity is empty. This extra weight most likely caused calculations to be much slower. This is verified with MATLAB; when I decrease the rotational inertia, the position function converges to pi much faster.

A significant limitation of the upper arm that comes to mind is how flimsy and wobbly it is. When the upper arm had 4 inch linkages, this problem did not exist. When the length was increased to 7 inches, the arm became a lot more unstable. This makes it extremely hard to grab the dangling box and the box on the pier, as well as any other box. This also makes it difficult to control, which is a prominent challenge to our robot. If I had more time, I would find ways to make the arm less wobbly. If I had a second chance to redo the entire robot, I would try a drive train robot with a scissor lift and gripper.

The biggest technical lesson I learned from this project is the importance of hand calculations and analysis. The reason this is important is to save time and resources. In one of my early prototypes, I did a torque analysis test and used a gear ratio that had a factor of safety of 1.4. I thought this would be good enough, but my component wasn't able to rotate a complete 180 degrees. It stalled when it hit the 90-100 degree mark. When I changed the gear ratio to have a factor of safety above 2, the part worked well. If I had decided to use a higher factor of safety, I could've saved two days of work. Nevertheless, I learned analysis still played an important role in designing. When I did my torque analysis, I wasn't just guessing how much torque I needed; I did calculations to better estimate this value. Throughout this entire project, I learned that analysis allows you to make better choices when designing rather than relying on trial and error.

Overall, the robotic arm performs well. During our first few attempts of scoring under 60 seconds, we were able to consistently get above 60 points. There is not stalling in any of the parts and similarly, none of the parts move slowly. With practice, we should be able to score higher. My component, specifically, performs well. With a gear ratio of 16:5, it doesn't stall and with a factor of safety above 2 and risk reduction tests, I was confident in my design.

4 Design Process

4.1 Concept Generation and Creativity Methods

When brainstorming ideas for the robot during week 4, I was stuck with how the robot should be designed. The lack of controls pushed me away from a drive-train design and I wanted a relatively simple design that was easy to control. I thought about using a robotic arm and was having trouble with how the arm structure would be designed. My conceptual breakthrough happened when I remembered that I had a lamp that used a four-bar linkage at home as shown in figure 15. I used this design to guide the design of the robot.

Figure 15: Lamp arm design

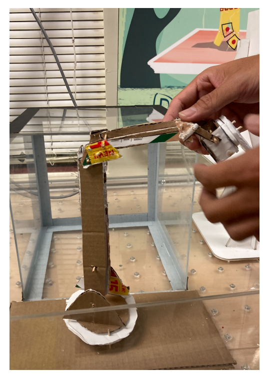

Figure 16: Cardboard design

4.2 Risk Reduction Test

I built two different prototypes to validate my design. The first prototype was built out of toothpicks, foam core, and cardboard. I used this model to verify that the design would work and it did. This didn't have a power part for my component, so I did an actual risk reduction test with an acrylic prototype.

Since the design moved as expected without a motor, I fabricated a design with clear acrylic to better simulate the actual weight and tested to see how it worked dynamically. The weight of the gripper was expected to be 80 grams and the wooden block was 38 grams. Using these values, I tested the design to see if it could carry the weight. In the end, it worked and this led me to continue with this design. Future designs would tweak the design parameters like arm length and gear ratio, but the overall design would be kept similar

4.3 Prioritization and Scheduling

I prioritized tasks based on importance with respect to assignments and the importance of certain components in the design. For example, during the week we had to do the risk reduction test. I prioritized the power component that yaw-ed the arm. This was important because it supported the entire structure. It utilized a turntable design that was complicated and needed to be 3d printed. Testing this component first was necessary to see we should abandon this approach. For the functional component lab, I prioritized the gripper since this was a component that was relatively easy to make and was important to grab boxes. I wanted to make sure that the teammate working on the gripper was able to prototype different gripper designs. Personally, I didn't use the Gantt chart provided by the MAE 3 team. I created a notion that had used a kanban board that I prefer much more to the spreadsheet. The reason being is that it's much easier to create new tasks for members and allows for greater customization.