# Milestone 9
# Final Design Report
# Approvals Sheet

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**Section Number: 0502**

**Contributions, Approval of Report, and Adherence to the University Honor Pledge:**

Andres Arbelaez: Programming and code, CAD representations and assembly, power information, writing and editing of report

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Khalib Baker: BOM updates, electrical schematic

Zack Dorsey: Structure information (chassis and arm), torque calculations

Kara Kirby: Programming and code, BOM updates

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Gregorio Zimerman: CAD representations of arm and depth sensor case, mission performance information

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***Executive Summary***

This report details how eight undergraduate engineering students at the University of Maryland have approached the proposed design problem of creating an autonomous over-sand vehicle (OSV). This autonomous OSV must meet the following objectives. First, this OSV must navigate to within 250 millimeters of a designated pool of water. Next, the OSV must measure and transmit the depth of the pool to within 4 millimeters. The depth of the pool will be range from 20 millimeters to 44 millimeters. The following objectives, while optional, should also be attempted: test the salinity of the water, transmit whether the pool contains freshwater or saltwater, and collect between 30 and 40 millimeters of water. Finally, the OSV should navigate back to the initial landing zone to complete the mission. The design of such an OSV is also limited by a number of specifications described in the design details of this report.

The design in this report employs an RF navigation system, two ultrasonic distance sensors, and control algorithms using Arduino software to complete the first part of the mission, navigation. Once the OSV arrives at the pool of water, the second base objective as explained above is met using a 3D printed arm that extends in front of the OSV over the water. At this point, a water depth sensor is employed to complete the mission. The OSV then navigates back to the initial landing zone using the same method as employed in the initial navigation to the pool of water.

Due to a number of unexpected setbacks, the prototype detailed in this report completed both base objectives, but failed to complete them in succession at the time of competition. With a few design modifications, this prototype would meet all objectives and specifications while integrating two main points of customer interest, specifically cost efficiency and mission success. These modifications are explained in the following sections.

There are a number of ways this design problem could be approached, many of which would bring success. However, the overall simplicity of this design reduced the chances of mission failure significantly. In addition, this design is highly cost effective, totalling $186.42 compared to the specified budget of $350. In general, this design meets all base objectives and specifications while integrating two main points of customer interest, specifically cost efficiency and mission success.

***Introduction***

This final design report details the progress achieved by a team of undergraduate students at the University of Maryland in creating an over-sand vehicle (OSV) that meets set design constraints and performs both general OSV vehicular actions, as well as mission-specific tasks. Constraints for this OSV include structural limitations such as a maximum vehicle weight of 3 kilograms, and a maximum overhead footprint size of 350 x 350 millimeters. Additionally, an RF communications system and Arduino compatible microcontroller are required for vehicle communication, navigation, and control. There was a $350 price cap for the on-vehicle components of the final OSV. Adherence to these design constraints will be discussed in this design report (ex: see weight and cost calculations in Appendix C). The final OSV must have been able to navigate through a sand-filled arena around a number of obstacles and perform tasks upon reaching a water-filled pool. The base objectives of this mission include navigating to within 250 millimeters of the pool of water and measuring and transmitting the depth of the water to within 4 millimeters. In addition to performing these base objectives, the OSV design detailed in this report was drafted to undertake the goal of completing the bonus objectives: (a) to determine if the water is fresh or seawater and (b) to collect a 30-40 milliliter sample of the water in the pool. Due to time and feasibility constraints these objectives were not completed.

To meet the structural and navigational constraints and standards, the OSV consisted of a double-decker polycarbonate chassis, four sand-paddle tread tires, two VEX motors, two ultrasonic distance sensors, one RF sensor, and an Arduino microcontroller. Mission objectives were met primarily through the use of a wooden arm component which was attached to the top layer of the chassis. The arm held a depth sensor enclosed in a 3D printed case and a servo motor to lower the arm-dependent components into the pool. These details will be discussed in the mission performance section of this report. Additionally, all electrical components were powered by a 7.2V NiMH rechargeable battery using the internal Arduino power regulator as needed. The weight of all on-vehicle components totals 1.72 kilograms, and the total estimated price was $186.42. An iterative and error-adjusting process was implemented in order for this design to be a successful end-product.

The most prevalent challenge in this engineering project was that plans rarely translated perfectly into reality. For example, even the most simple CAD-designed part, a spacer, erred during 3D printing, and a depth sensor transfer function calculation was not accurate due to a manufacturing flaw in the purchased sensor. The nature of this project also created challenges on the team dynamic level. With eight members on the design team, the team was bound to have conflicting ideas and interests. A successful design decision was achieved when all team members' ideas were evaluated objectively according to cost, efficiency, and completion of mission performance, and then implemented in the most effective manner. This challenge was encountered early in the design process, specifically with structural decisions regarding the arm. Because this component had the most room for creativity, a plethora of ideas emerged during brainstorming. The final arm design was chosen due to its ease of integration into the rest of the OSV, as well as its ease of construction by the use of 3D-printed CAD components and a wooden structure. The successful brainstorming and ultimate decision-making on the arm component served as an inspiration for the team to proceed according to this decision-making model throughout the rest of the project.

***Preliminary Design Shortcomings***

The preliminary design initially proposed for this OSV was followed closely in creating the final design and the resulting prototype. Two major changes were made to the preliminary design in order to simplify the mechanical workings of the OSV and increase the efficiency of the propulsion subsystem and mission performance.

**Stationary arm mechanism.** The first change involved simplifying the arm mechanism that carried out the second half of the mission, specifically measuring and transmitting the water depth in the pool. Originally, the design called for a pivoted arm that would begin facing the back of the OSV then rotate to the front to be situated over the pool of water. After considering the benefits of this mechanism, it was concluded that this design overcomplicated both the structure and the programming of the OSV without significant benefits. Thus, the decision was made to create a stationary arm permanently extending in front of the OSV. As this did not cause the OSV to exceed the specified overhead footprint restriction of 350 millimeters by 350 millimeters, this proved to be the best way to simplify the mission performance while remaining within the OSV specifications.

**Gear train.** While the preliminary design called for a gear train utilizing three gears (one at the motor and one at each of the two wheels) at a 1:3 ratio to decrease the operational speed from 9.01 rad/s to a more controllable speed of 3.26 rad/s, using just three gears proved to be unrealistic. In order to use three gears and have them span the space between the motor and the two wheels, the gears would have to be the same size if not larger than the tires. In order to resolve this issue, an intermediate gear was added to each side of the motor. This decreased the necessary size of each gear while still allowing the gear train to successfully span the space between the motor and the wheels. The updated gear train is shown in Figure 3. As the prototyping phase continued, the gear train created another problem. The gear train was under a large amount of outward torque, causing the gears to shift laterally significantly during operation. To keep the gears in place and decrease the shifting, axle hole platforms were designed, 3D printed, and riveted to the chassis. This solved most problems associated with the gear train.

***OSV Structure***

Designing a lightweight, compact, and functional structure was vital to the success of our OSV. In order to achieve this balance, we gave considerable thought to the following components of our design: a lightweight, durable chassis that maximized the space on our OSV, a functional “arm” that controlled our mission performance with ease, and a wheel system that was designed with the intent of traversing the terrain effectively and efficiently. The total weight of these components, along with the rest of the components on out OSV, was approximately 1.72 kilograms. The following sections of this report will address these design components in detail.

**A lightweight, durable chassis.** In order to maintain durability and workability while keeping the OSV lightweight, Lexan polycarbonate was used to create the chassis of the OSV. Lexan polycarbonate proved to be a very durable material for the chassis of the OSV. In favor of simplicity and due to the lack of significant benefits of other shapes, the chassis was rectangular, measuring 20.32 centimeters by 25.40 centimeters by 0.24 centimeters. As illustrated in Figure 1, the chassis consisted of two layers of Lexan polycarbonate spaced to imitate a “double-decker” bus. Four 3D printed spacers as shown in Figure 1, each situated near a corner of the Lexan polycarbonate, were used to keep the two layers of the chassis distanced 5 centimeters apart. This gave the design flexibility as the top layer was easily removable, providing access to the lower level in order to allow visibility and ease when troubleshooting any electrical problems that arose. As such, the bottom layer was used to hold the electrical components, namely the Arduino and breadboard circuits. The top layer also served as the stabilizing support for the crane mechanism that was largely responsible for completing the mission objectives. In addition, the top layer was used to hold the identifying square which allowed for communication through the RF system. This double-decker design doubled the surface area of the chassis while creating a compact design for the OSV, maintaining a sufficient workspace while providing the OSV with ease of navigation. By building upward rather than outward, the overhead footprint of the OSV was largely reduced, minimizing the need for dramatic turns and corrections when maneuvering around obstacles. The main challenge with this design was creating a strong center of gravity, a challenge exacerbated by the second part of the structural design, a functional arm to control the mission performance. But since the arm used was very light, only .2 kilograms, this was not an issue.

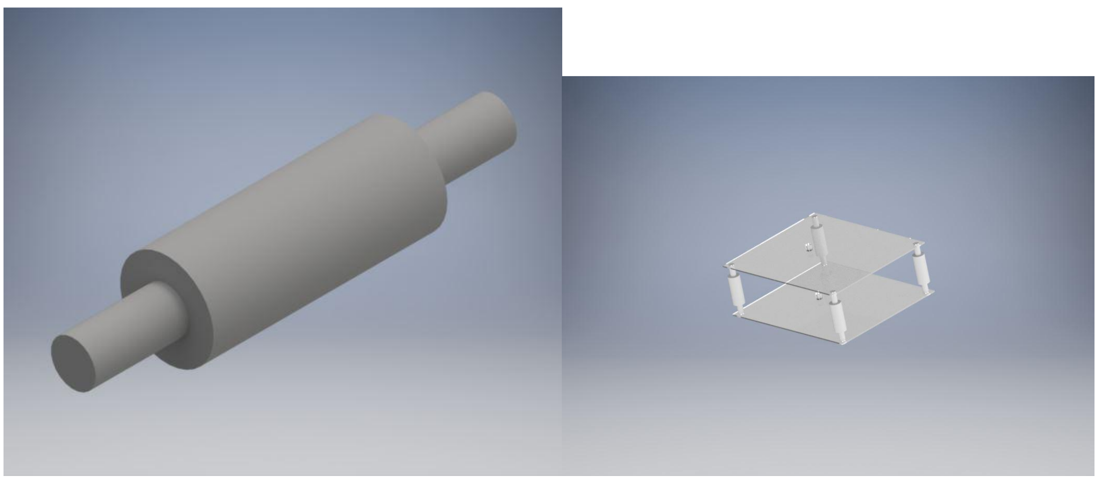


Figure 1
To the left is a rendering of the spacers we used to hold our chassis together. To the left is an assembly of the spacers and the polycarbonate which made up our chassis.

**Arm mechanism.** In order to complete the mission objectives, a crane mechanism was designed. To create the arm mechanism light weight, wooden planks approximately 2x3 centimeters thick and about 25 centimeters were used. These pieces were attached together in an L-shape. The arm was created by first attaching two identically shaped pieces together with a small piece of wood separating the two. Then, those two pieces were vertically attached to the third, horizontal piece of wood which served as the base of the arm. Then, the base of the arm was attached to the top layer of the OSV by Velcro with approximately 10 centimeters of the arm sticking off of the OSV. A pulley was then attached to the top of the arm in between the two pieces of vertical wood to act as a guide for the fishing line which lowered depth sensor case. Also, at the corner of the arm a T shaped clip was attached for the depth sensor case to allow the case to move consistently and repetitively. This design component will be discussed in further depth in the mission performance section of this report.

**Wheel system.** Effective wheels are critical in the design of the OSV, particularly in traversing sandy terrain. Paddle wheels were chosen to effectively travel across the sand to the site of the mission, the pool of water. While most wheels must rely on traction and friction on the surface of the loose sand, paddle wheels make use of the force lower in the sand (due to the weight and density of sand) to propel the vehicle forward. In addition, most wheels struggle on sand because they tend to sink into the sand and become stuck. The paddle wheels took advantage of this very characteristic of sand, allowing the paddles to sink into the sand and gain traction while the main body of the wheel remains above the surface. Alternating paddles increases this benefit while giving the sand an "exit path" as the paddles kick back the sand. In order to keep the body of the OSV well above the surface of the sand, the tires were 10.92 centimeters in diameter. The wheels shown in Figure 2 were 3D printed to fit inside the paddle wheel tires. No suspension was used in this design. Since the sand was relatively flat, suspension would have been unnecessary, only complicating the design. The purpose of suspension is to maintain maximum contact with the ground for accelerating, braking, and traveling on uncertain terrain. As the OSV moved at a slow enough speed to maintain overall control and travelled on relatively flat terrain, a suspension system was neither necessary nor extensively beneficial.

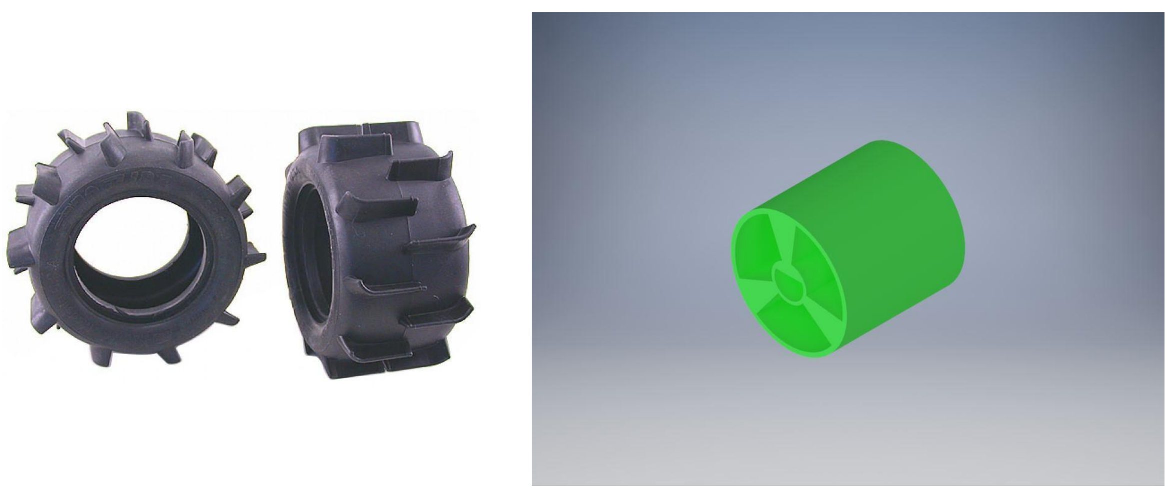


Figure 2
Shown left are pictures of the tires that were used on the OSV. Shown right is a rendering of the rim 3D printed to fit inside the tires.

***Propulsion System***

An effective propulsion system is critical in a successful OSV. For this reason, this OSV design provides a simple yet efficient propulsion system consisting of sand compatible wheels, high torque motors paired with an effective gear train, and a simple steering system.

**Sand compatible wheels.** As previously discussed in the structure section of this report, paddle wheels were used on this OSV. As paddle wheels are specifically designed to handle sandy terrain, this automatically increased the efficiency of the propulsion system. The tires are 10.92 centimeters in diameter. While the estimated weight of the OSV is 1.72 kilograms, the following calculations used 3.00 kilograms as this is the maximum weight allowed for the OSV. This decision was made based on the fact that weight can easily be added to the OSV if needed, but cannot easily be removed. The OSV depends on two motors, a decision verified in the following section. Based on this decision, the load (L) on each set of wheels was 14.7 N. From this figure, the following calculations were made:

$$\square\square\square = \square\square/\square \qquad \square\square\square \approx 0.3\ \square\square\square\ \square\square\square\square$$

$$\square\square = 0.3\times 14.7\square = 4.41\ \square \qquad \square\square = \square\square = 4.41\square \qquad \text{Eq. 1}$$

$$\tau = \square\square\times\square \qquad \tau = 4.41\square\times 0.054\square = 0.23\square - \square \qquad \text{Eq. 2}$$

Using 3.00 kilograms for these calculations proved to be insightful as these calculations were used to evaluate the slippage of the wheels.

$$\square\square\square \leq \square\square/\square \leq \square \qquad \square\square\square\square\square\ \square\square\square \approx 0.3\ \square\square\square\ \square \approx 0.7$$

Eq. 3

As $\square\square/\square$ for $\square = 14.7$ (assuming an OSV weight of 3.00 kilograms) equals 0.3, lowering the weight brought $\square\square/\square$ more evenly between 0.3 and 0.7, thereby further reducing the possibility of slippage. From this information, it was determined that the weight of the OSV should be kept under 3.00 kilograms. The final weight of the OSV is 1.72 kilograms.

**Motors and gear train.** This OSV makes use of motors available through the vendor Vex Robotics. As these motors are designed to power autonomous vehicles similar to the OSV, meeting the torque requirement of the wheels was not a problem. While the original plan called for four lower torque motors with gear trains, the use of Vex motors with a stall torque of 1.67 N-m and a no load speed of 10.47 rad/s allows the OSV to depend on just two motors. One motor controls each side of the OSV. The reasons for this will be more explicitly explained in the steering system section. As stated above, the torque requirement is 0.23 N-m for each motor. As the stall torque exceeds this value by a large margin, a gear train was unnecessary to provide additional torque. However, the operating point of the motor without a gear train would put the angular velocity at about 9.01 rad/s. Therefore, to decrease the angular velocity and thereby increase the overall control of the OSV, a three-to-one gear ratio was used. This gear ratio, in the form of five gears--a small gear with 6 teeth attached to the motor, two large intermediate gears with 30 teeth, and two gears with 18 teeth attached to each of the wheels--as shown in Figure 3, decreases the operational angular velocity to about 3.26 rad/s or 17.80 cm/s, a much more reasonable speed given the size of the arena and the purpose of the mission. This is shown in Figure 3. This gear train improved the control of the OSV, allowing for better navigation and more reaction time in obstacle avoidance.

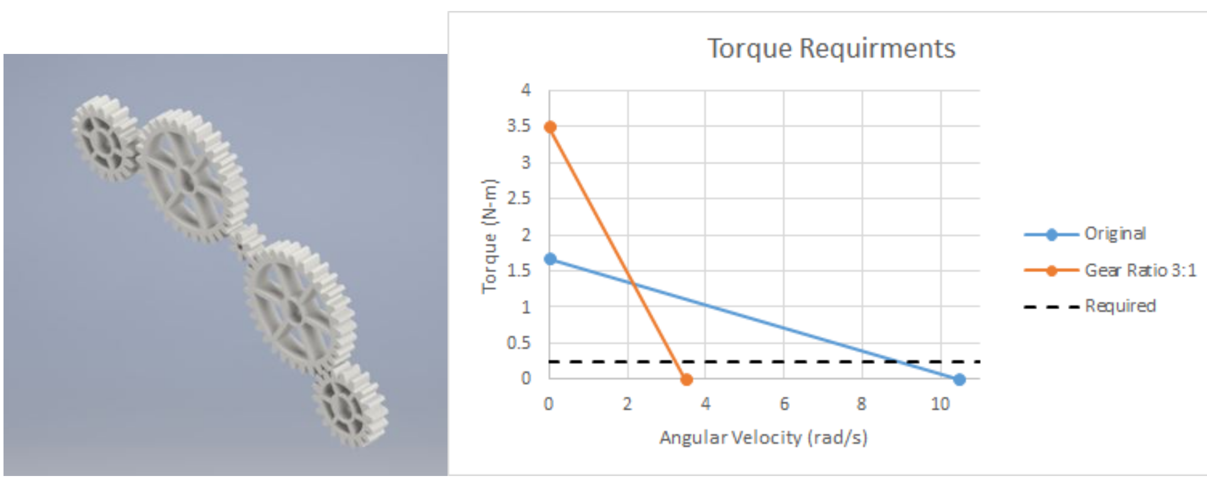



Figure 3
Shown left is a rendering of the gears used as our transmission. Shown right is a graph of the torque and angular velocity of the motors with and without a gear ratio.

**Steering system.** To increase the simplicity of the propulsion system and thus decrease the amount of troubleshooting during the prototype and fabrication process, the OSV used a simple differential steering system in which one set of wheels moved forward as the other set of wheels moved backward, making the OSV turn in place. As stated above, there were two motors controlling the movement of the OSV--one controlling each side of the OSV. This specific design was chosen to allow for this steering system. If the OSV needed to turn right, the left set of wheels moved forward while the right set moved backward. To further simplify the navigation and decrease the strain on the gear train, the OSV exclusively turned right when looking for a new orientation. This steering system allowed the OSV to travel through the arena to the water pool without overcomplicating the navigation.

### *Mission Performance*

This OSV conducted the water mission. The objective of the mission was to measure water depth. The design details for accomplishing this is explained in the following sections.

**Navigation to pool.** The most basic objective of this mission was to navigate to within 250 millimeters of the pool. In order to do so, the OSV made use of the RF communication system, two ultrasonic distance sensors, and a programmed Arduino UNO microcontroller. An RF module was placed within the OSV and an identification square relayed coordinate information to the “eye in the sky” receiver. Given the schematic of the sand arena, a desired path was programmed into the Arduino. In addition to the RF communications system, ultrasonic distance sensors were placed on the two front-facing corners of the bottom layer of the OSV. These sensors measured the distance from an obstacle at any given time and relayed this information to the Arduino instantaneously. If the ultrasonic sensor read an object to be 30 centimeters away or less, a programming “if” loop was initiated to turn the OSV 45 degrees away from the obstacle currently blocking the desired path, move forward at this angle, and then continue on its course along the desired path. The Arduino was connected via digital PWM pins and motor controllers to the two VEX motors that drove the wheels. With the programs mentioned above, the Arduino dictated the motors’ output angular velocity. The OSV was able to turn in place as its steering system consisted of one motor spinning clockwise as the other motor spun counterclockwise. The respective angular velocity and duration at which these opposing motor actions occur dictated the number of degrees the OSV turned. Once the OSV reached the destination of the pool, the VEX motors were disabled and the next mission objective sequence was initiated.

**Water specific objectives.** The OSV had to measure and communicate the depth of the water to within 4 millimeters. This objective was met via the use of a wooden arm structure, a 3D printed PLA depth sensor housing case, and a servo motor which lowered the case into the pool. The arm was fixed on the top polycarbonate layer and extended directly over the front of the OSV, approximately 10 centimeters over the end of the OSV. The arm was 25 centimeters tall to sustain the entire sensor case. The sensor case depicted in Figure 5 is the 3D printed component that housed the depth sensor. The sensor case attached to the arm via a railing system in which a C-shaped component running the entire length of the case and 18 centimeters above fits into a small T-shaped component of the arm. This attachment system was used to keep the sensor case in a vertical position, perpendicular to the water surface. This point is essential to the depth-measuring objective as the depth sensor must be upright in order to provide an accurate reading. In order to ensure the maintenance of a vertical sensor position, many options were considered. One such idea included running wires along the four edges of the rectangular sensor. This idea was entertained for a portion of the design process, but was ultimately deemed unfit because there was no way to absolutely ensure that the wires would not cause the sensor case to sway and thus elicit an inaccurate depth reading. In the end, the "railing system" was determined to be most cost effective as 3D printing these small components is relatively inexpensive. Success of this mission relied on the successful lowering of the sensor case component into the pool of water. The lowering of the sensor case along the arm was performed by a pulley system. A spool attached to a servomotor at the base of the arm spun to feed fishing line, chosen for its strength and size, up the arm, over a pulley, and through a hole at the top of the depth sensor case. The unwinding of the spool by the motor causes the depth sensor to be lowered into the pool. The subsequent reversal of the motor's spinning retracts the fishing line in the spool and returns the depth sensor to its original, elevated position. A more visually intuitive understanding of this multi-faceted arm mechanism may be gleaned by referring to Figure 4.

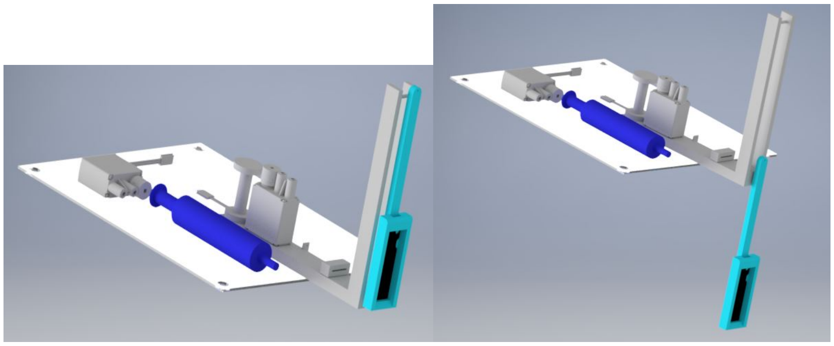


Figure 4
These two pictures show how the arm mechanism works. The case lowers into the water as shown by these images.

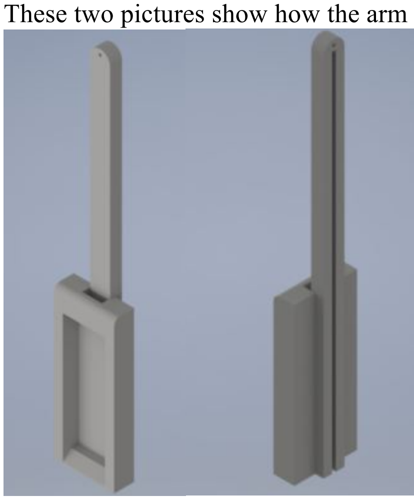


Figure 5
Shown above is a model of the case for our depth sensor and the clip on the back made to hold the sensor vertical. The left view shows the case where the sensor goes and the right view shows the clip that keeps it vertical while being lowered.

***Power***

Power for the whole OSV was provided by one 7.2V 1200mAh NiMH battery. This battery voltage was selected because the Vex Robotics motors, the components with the highest voltage requirement, chosen for the propulsion system require 7.2V to operate. Other power-consuming components of the OSV were the servo motor and Arduino UNO microcontroller. These components require a 5V input. Because of this, a switching voltage regulator was proposed to be used. In the final design this was not actually used. It was found that the Arduino actually had a 5V regulator built in to it. Due to this feature the Arduino was powered directly from the battery and then all of the 5V parts were powered with the Arduino. Originally this would have most likely drawn too much current through the arduino because there were many parts that required 5V. We initially had three servo motors planned instead of the one that was actually used. In addition to there being less 5V parts included in the final design, it was found that the switching regulator ordered did not function properly and so making the circuit without it was beneficial for time and cost reasons as well. By the end of the construction process the wiring schematic was much different from what we started with and is shown in Appendix D. The battery was also chosen for its mAh specification. The calculations that led to this decision are as follows:

$$\square\square\square\square\square\square = 2\times\square\square\square\square\square\square\square + 3\times\square\square\square\square\square\square\square + \square\square\square\square\square\square\square\square\square = 2\times 1\square + 3\times .817\square + .4\square = 4.85\square$$

$$\square\square\square(\square\square\square\square\square\square\square\square) = \square\square\square(\square\square\square\square\square\square\square\square)\times\square\square\square\square\square\square\square = \frac{1}{6}\square\square\square\times 4.85\square \approx 810\square\square\square \qquad \text{Eq. 4}$$

The minimum requirement based on the originally planned design was 810mAh. A higher rating was chosen for the battery in case parts drew more current than estimated or specified. During the construction process the battery held its charge for long enough to do everything that was needed. The battery never died while in use and because there were less electrical components in the final design, the battery specifications were definitely enough for the mission to be completed and to satisfy the requirement for all the systems to run at full power for 10 consecutive minutes. Without the two other servos the calculations look slightly different

$$\square\square\square\square\square\square = 2\times\square\square\square\square\square\square\square + 3\times\square\square\square\square\square\square\square + \square\square\square\square\square\square\square\square\square = 2\times 1\square + .817\square + .4\square = 3.22\square$$

$$\square\square\square(\square\square\square\square\square\square\square\square) = \square\square\square(\square\square\square\square\square\square\square\square)\times\square\square\square\square\square\square\square = \frac{1}{6}\square\square\square\times 3.22\square \approx 536\square\square\square \qquad \text{Eq. 4}$$

$$\square\square\square\ \square\square\square\square = \square\square\square(\square\square\square\square\square\square\square\square)/\square\square = 1200\square\square\square\ /\ 3220\square\square = 22.36\square\square\square$$

This shows that the battery that was originally selected would definitely satisfy the requirements after taking into account the change in electrical parts used. With the final design it shows that the final run time would be around 22 minutes, much longer than needed.

***Sensors***

The success of this OSV relied heavily on sensors, specifically the ultrasonic distance sensor which assisted in obstacle avoidance and the water depth sensor which completed the main objective of this mission. These sensors did not depend directly on actuators such as servo motors. They were instead connected directly to the Arduino on the body of the OSV. All actuators used for other elements of the design will be discussed in the respective sections of the report. This section of the report will focus on how the sensors accomplished the mission.

**Ultrasonic distance sensors.** While the navigation of the OSV was primarily dependent on the RF system to travel from the landing zone to the pool of water where the bulk of the mission occurred, ultrasonic distance sensors were crucial for obstacle avoidance. There were two ultrasonic distance sensors situated on the front of the OSV. They were positioned on the front corners of the OSV. This allowed each sensor to detect obstacles in front of and immediately to the sides of the front of the OSV. These sensors operated by sending out sound waves above the frequency detectable by the human ear. They then measured the time it took for the echo to return to the sensor and related this value to the distance between the OSV and the obstacle. As the detection distance of these sensors is from 2 centimeters to 450 centimeters, they proved to be reliable obstacle avoidance aids. In order to provide the OSV with the necessary time to correct its path, the OSV was programmed to begin a secondary path as soon as an obstacle is sensed within 30 centimeters. Specifically, in the case that there is an obstacle within 30 centimeters of the OSV, the control algorithm would direct the vehicle to turn 45 degrees and continue around the obstacle, at which point the RF system once again began directing the OSV to the pool of water.

**Water depth sensor.** In order to complete the mission objective of measuring and relaying the depth of the water in the pool with just a 4 millimeter tolerance, an Arduino compatible water depth sensor designed to measure water of similar depths to the parameters provided in the mission specifications was used. In the initial designing process, a different depth sensor was considered but determined to be much more powerful than was necessary for the mission. It was better suited to discovering the depth of ponds, measuring up to two meters in water depth. This product was both beyond the scope of the project and would have taken over a fourth of the budget. The Arduino compatible water depth sensor, as shown in Figure 6, proved to be more reasonable and cost efficient. The sensor was connected to the Arduino through the use of the built-in three pin system, specifically voltage, ground, and sensor reading pins. This sensor had one major flaw--it measured water depths between 16 millimeters and 40 millimeters. At first, this posed a problem for the mission as the parameters in the mission specifications state that the water depth could be between 20 millimeters and 44 millimeters. While this sensor contained the correct range of readings, specifically a difference of 24 millimeters, it started the measurement 4 millimeters lower than needed for the purpose of this mission. This problem was solved indirectly. An additional design problem was keeping the depth sensor upright which would be critical to receive an accurate reading. In order to solve this problem, a thin sensor case was designed which, with the help of a T-shaped clip on the back of the case, kept the sensor perpendicular to the base of the water container while completing the reading. With slight adjustments to the design of the sensor case, it served two purposes. First, as stated above, it kept the depth sensor upright in the pool of water. Second, it provided the additional millimeters needed on the sensor. In the design of the sensor case, the sensor rested on a base of 5 millimeters as shown in Figure 6. The code, which interpreted the signal sent from the depth sensor, then added 5 millimeters to the sensor reading when printing the depth reading of the pool of water, moving the sensor reading range up to 21 to 45 millimeters. By making this adjustment, the reading range of the sensor was not altered; instead, the range was moved up to better accomplish the mission performance objectives. Between the precision of the sensor and the 4 millimeter tolerance, this sensor was able to successfully perform this part of the mission with accuracy.

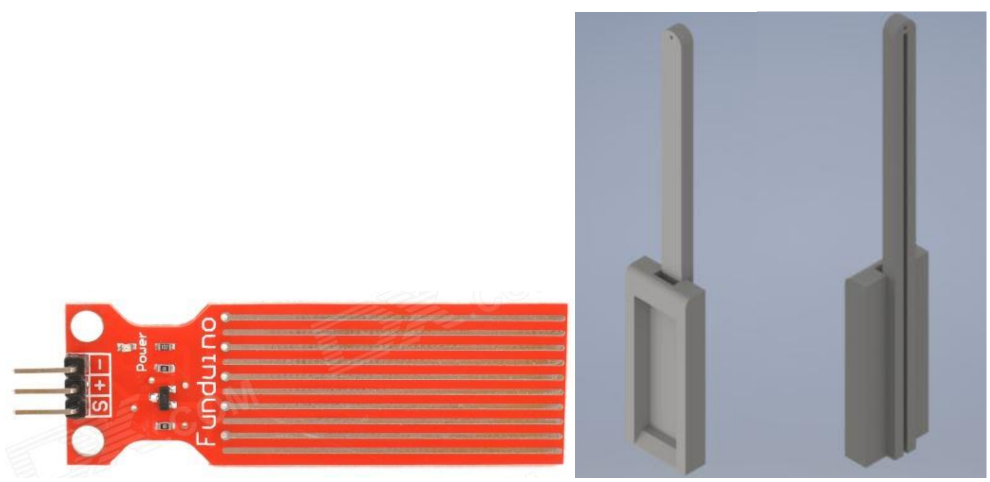



Figure 6

Shown left is the depth sensor we are using. Shown right is a model of the case for our depth sensor and the clip on the back made to hold the sensor vertical. The left view shows the case where the sensor goes and the right view shows the clip that keeps it vertical while being lowered.

### *Programming*

For this mission, the Arduino was programmed to navigate the terrain, operate the arm, and transmit the depth of the water pool. The final code design can be found in Appendix A; however, the basics behind the code will also be explained in the following sections.

**Navigation and obstacle avoidance.** The OSV navigated the course using RF sensors. Specifically, the code relied on a series of if statements dependent on the RF outputs for x, y, and theta. Once the RF reads values within the range specified in a certain if statement, the desired locomotion is determined and actuated. This can be more clearly seen in the final code design in Appendix A. While most obstacles on the course had fixed x and y-coordinates and could therefore be easily avoided using the RF coordinate system, the first two did not. They had fixed x-coordinates at 1200 mm; however, they had variable y-coordinates, presenting a significant challenge to the navigation of the OSV. In order to solve this problem, the navigation control algorithm was designed to minimize the likelihood of encountering these obstacles by going straight through the middle of the arena. This decision was made on the assumption that the two obstacles would likely be spaced apart rather than immediately adjacent to one another. However, this did not account for the slim chance that the obstacles were in fact near the middle of the arena. To combat this issue, ultrasonic distance sensors were used to determine if the OSV came within 30 centimeters of an obstacle. This part of the program begins running once the RF sensor has acquired the OSV's location and the OSV has oriented itself in the correct position for forward motion. Upon sensing an obstacle, the program sends the output, instructing the OSV to turn 45 degrees and continue past the obstacle, at which point the RF sensors redirect the OSV back onto the predetermined path to the pool of water. The OSV turns by rotating one motor (controlling one side of the OSV) forward while rotating the other motor (controlling the opposite side of the OSV) backward. This part of the code was written using the RF theta outputs to determine when the desired turning was complete.

**Mission performance.** As most of the mission depended on the success of the arm, perfecting the programming involved in this design aspect was critical. Once the OSV successfully navigates to the pool of water, the code instructs the servo motor, attached to the spool holding the fishing line connected to the depth sensor case spine, to begin rotating, lowering the depth sensor case into the water. This mechanism was timed to determine the amount of time necessary for the depth sensor case to reach the bottom of the pool and a small amount of slack to build up. At this point, the depth sensor was programmed to begin reading values. As discussed in the sensors section of this report, this depth sensor works with a number of resistors. Thus, the sensor output is in voltage. Through a series of tests, the depth sensor code was calibrated to relate voltage to specific depths. This proved to be very successful as the readings were always within 1 millimeter of the actual depth, much more accurate than the specified accuracy of within 4 millimeters. At the end of the mission, the servo motor is then activated in reverse, bringing the depth sensor case back up to its initial position.

***Construction Details***

Construction of this OSV began with planning the layout of all of the components on the double decker. This was where using a polycarbonate chassis proved helpful as dry erase marker was used on the chassis to mark the projected locations of components such as the battery, the Arduino microcontroller, and the VEX motors as shown in Figure 7. As component spacing on the chassis was optimized, the old markings could easily be replaced by new ones using the dry erase marker.

Figure 7

Shown above is the Lexan Polycarbonate chassis with initial proposed locations of OSV components.

What followed the layout design of the chassis was a series of iterative 3D print jobs that eventually resulted in the inclusion of 3D-printed axles, axle holders, base spacers, wheels, and arm components in the final OSV product. Test prints of all parts were conducted first in order to ensure the successful print and integration of these parts into the vehicle. For example, an initial test print of the arm clip railing and its complementary sensor case spine informed the team that a thinner clip would need to be designed on CAD in order to ensure the smooth travel of the sensor case spine along the arm clip. Changes to the part were made accordingly and the resultant print job successfully allowed the the sensor case and clip to interact smoothly, without much friction. The printing of gears, axles and their holders, and wheels followed this same process until all parts met a satisfactory level of structural and functional integrity. Next, the eight axle holders were fastened to the chassis using rivets in order to prevent the axles or their attached gears and/or wheels from moving around freely. The addition of motors on the chassis resulted in an OSV that was powered by two motors, guided by differential steering, and kept at a reasonable speed of movement by a 5-gear gear train. During the construction process, super glue was used to combine 3D-printed parts, such as an axle and a gear, in addition to epoxy to cement the VEX motors in their respective place. Velcro was also used for parts that demanded constant removal and attachment, such as the battery, for charging and replacing, and the wooden arm for testing the mission performance aspect of the project separate from the rest of the vehicle. The circuitry was constructed as shown in the circuit diagram in Appendix D.

***Product Performance and Evaluation***

The final OSV was able to meet many of the product specifications as a result of the adherence to the product development process. Basic specifications that were met included having an OSV that weighed less than 3kg and had an overhead footprint less than 350mm x 350mm, as well as one which was able to transmit and receive RF communications using the APC220 Radio Communication Module. Performance, control, and navigation requirements, however were not all completely met. Code, using the Arduino IDE, was successfully written to navigate the OSV to within 250 mm of the mission site and conduct the base performance task of measuring the depth of the water. Although the final OSV did make some successful trips to the site, structural failures eventually resulted in an OSV that was unable to complete the navigation and base mission requirements on the day of the course-wide competition. The structural component of the OSV that led to the majority of its failures was the 3D-printed gear train. During the preliminary design stages of the OSV production process, the implementation of a gear train was proposed, and eventually carried out, with the intention of slowing down the motors to operate the OSV at a controllable speed. Although a valid idea, problems arose with the use of these gears, mainly due to the inherent nature of 3D printing: there is very little room for error, especially pertaining to small parts that are needed to constantly interact with each other at a very precise speed and position. Because of this, any imperfection in a printed gear translated to an imperfection in its interaction with another gear. This accumulation of error eventually led to a gear train that did not run smoothly, with gears being unable to consistently maintain contact with one another. This thus impeded on the OSV's ability to navigate around the arena. In hindsight, the integration of a gear train into the OSV led to many difficulties that could have been avoided had the team chosen not to use one. Instead, in order to slow down the OSV while using the VEX motors, the code for the motor controllers could have been altered to operate these motors at a slower speed. Had the implementation of a gear train been deemed absolutely necessary, a better option could have been to purchase gears. These purchased gears would have been created and designed under standardized conditions with more precise instruments, which could have resulted in a gear train that operated without failure.

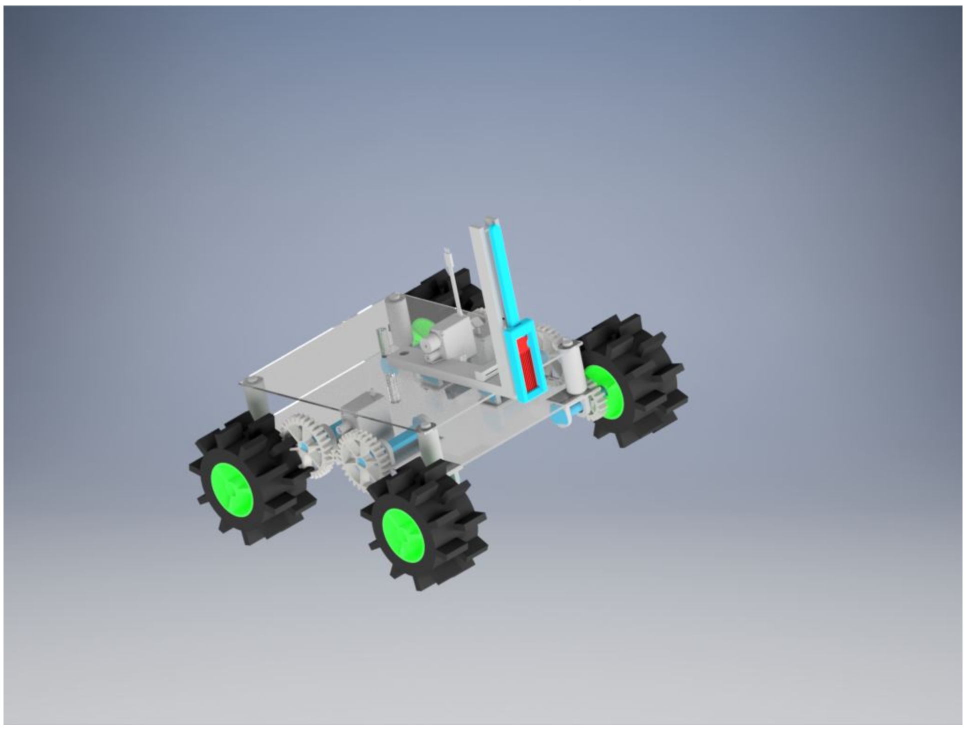
***Lessons Learned***

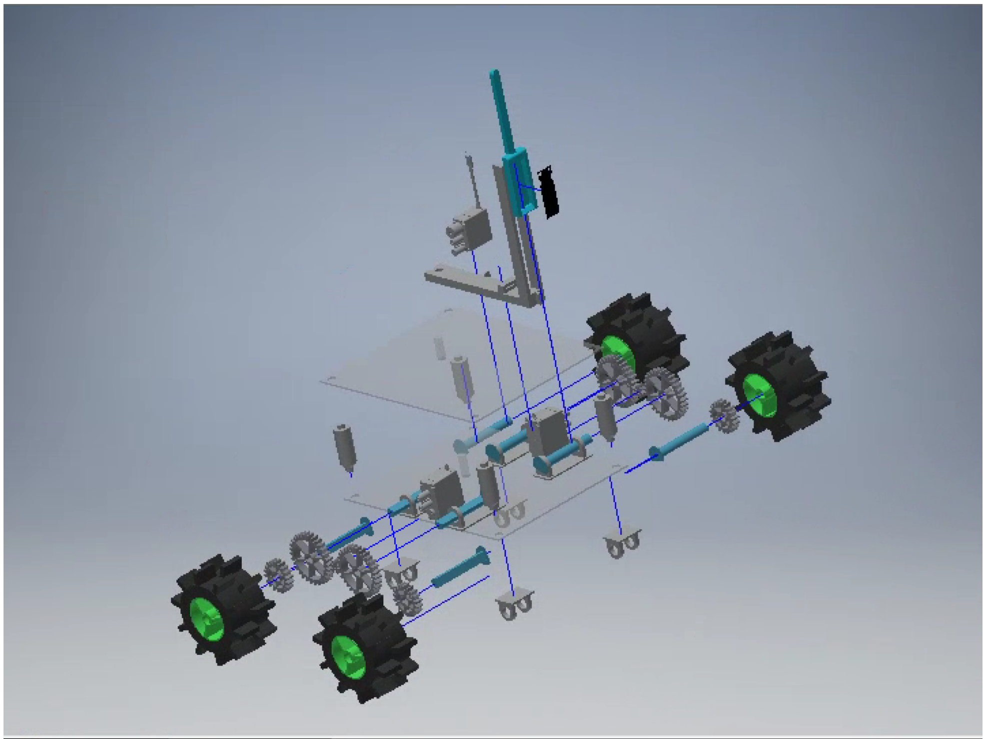
This mission and the resulting OSV design detailed in this design report provided these undergraduate students with a more involved opportunity to learn about the engineering design process from experience rather than lecture. This proved to be a successful way to expose the students to the iterative processes involved in engineering projects. While a number of mission-specific lessons were learned, two general lessons along with proposed changes to the final design to maximize success are explained in the following sections.

**An iterative design process.** Soon after beginning the initial design phase, it became obvious that the design process was not a checklist of step-by-step activities, but rather an iterative process in which design led to prototyping which led back to design for further adjustments. In this cyclic process, the OSV detailed in this report underwent a number of small design adjustments during prototyping to increase the efficiency and efficacy of the OSV. This continued through the testing phase, concluding with a few final adjustments on the day of the final testing of this OSV. Ultimately, the OSV was unable to complete the entire mission at the time of the final OSV test. While the programming had been tested many times and proved to be effective in navigating to the pool of water, lowering the depth sensor, and transmitting an accurate reading of the depth of the water, structural challenges ultimately prevented the OSV from completing the mission at the time of testing. Provided more time, a number of structural changes would have been made to ensure success.

**Proposed design changes.** The following design changes are proposed to improve the overall function and ensure the successful performance of the OSV. The main structural challenge in this design is the gear train. As the OSV depended on just two motors, a gear train was necessary to connect each motor to the two wheels on the respective sides of the OSV. The gear train was also chosen to lower the operational angular velocity to increase the overall control of the OSV. However, as prototyping continued, it was clear that any control gained from lowering the operational velocity of the OSV was then lost by the lateral movement of the gears caused by the strong torque of the motors. To combat this issue, it is proposed that the design of this OSV changes from using two gears to using four gears, each controlling one wheel. This would not drastically change the design or function of the OSV as differential steering would still be utilized to control the locomotion of the OSV. This change would simply increase the control as the propulsion system would no longer suffer from lateral movement. Along with the structural construction of the OSV, the electrical wiring of components also proved to be a challenge. As testing began, it was difficult to follow the electrical components through the crowded breadboard and Arduino to troubleshoot problems that arose. In addition, the small number of digital pins on the Arduino Uno proved to be limiting, particularly when the servo motor was added. Originally, the locomotion motors were controlled by pins 10 and 11. However, the servo function required in the code disabled the PWM function of pins 9 and 10, making it impossible to run a motor on pin 10. As other PWM pins were evaluated for use, it became clear that this created more of a challenge than expected. As the other PWM pins ran at different frequencies, the motors began to run intermittently and spontaneously. This was solved by finding two pins that ran at similar frequencies. However, this would not have been a problem had an Arduino Romeo been used rather than the Arduino Uno. Thus, it is proposed that the final design of the OSV changes to use an Arduino Romeo to increase the electrical capabilities of the OSV and a solderable breadboard to increase the visibility of the wiring. Given the time and ability to change the design, these changes would help optimize the performance of the OSV.

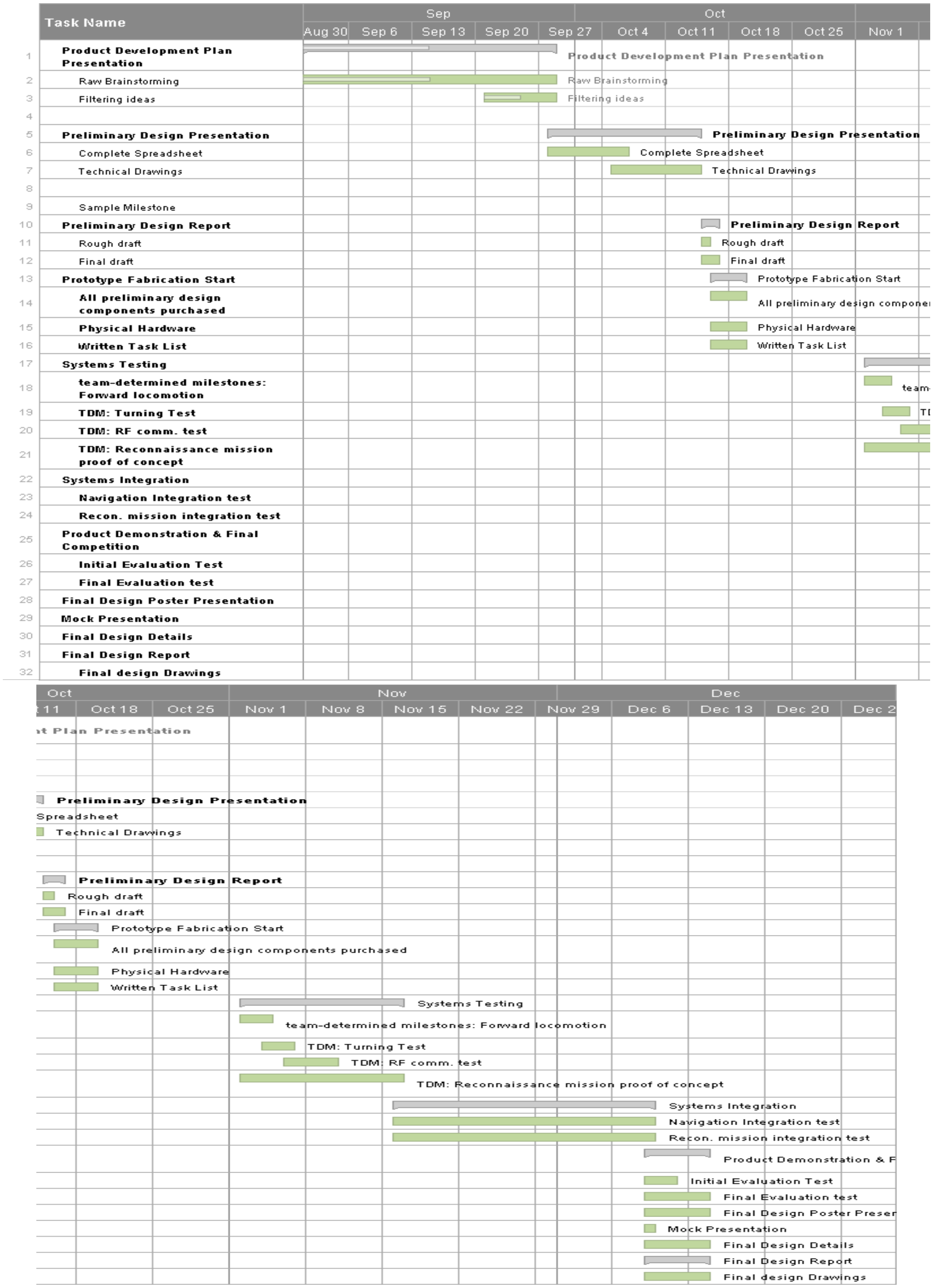
## *Appendix A:*
## Final OSV Design





***Appendix B:***

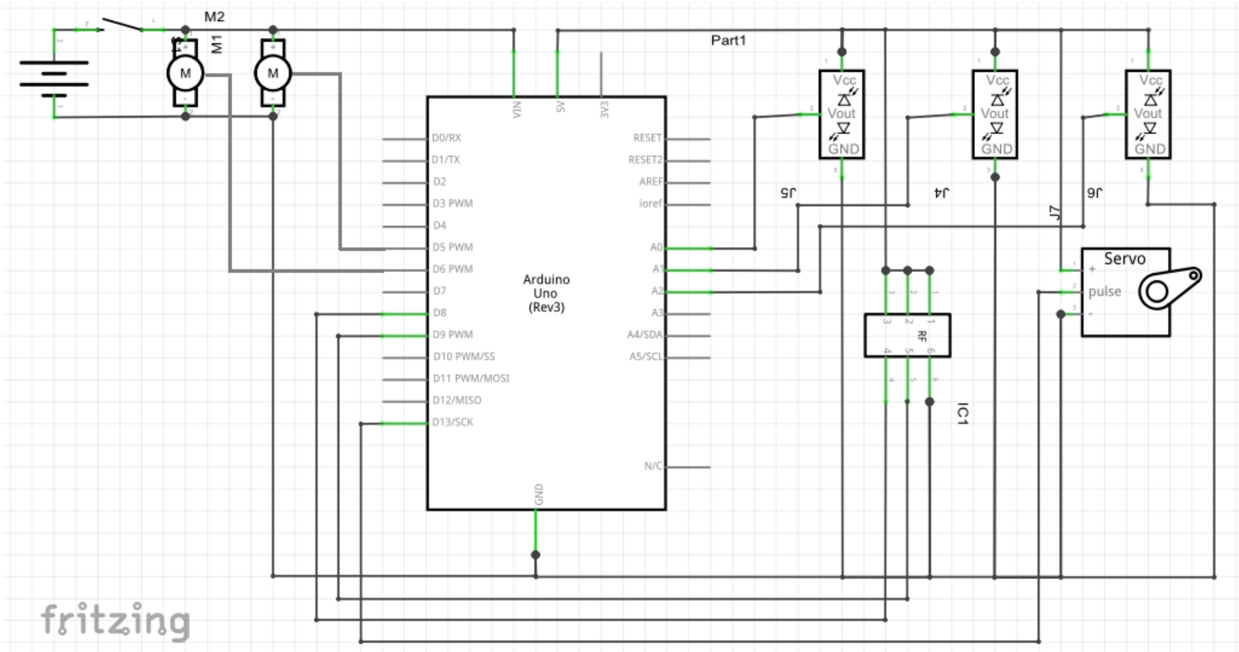
## Preliminary Gantt Chart




### *Appendix C:*
### Final Bill of Materials

| Final Bill of Materials | | | | |
|---|---|---|---|---|
| **Part Name** | **Unit Cost** | **Quantity** | **Cost** | **Weight (kg)** |
| Wood Arm | 3.12 | 1 | 3.12 | 0.03 |
| 3-D Printed Depth Sensor Case | 1.51 | 1 | 1.51 | 0.02 |
| 3D Printed Gears | 2.91 | 8 | 4.85 | 0.29 |
| Venom 7.2 1200mAh | 13.48 | 1 | 13.48 | 0.18 |
| 10" x 8'' Polycarbonate Sheet | 4.1 | 2 | 8.20 | 0.29 |
| 3-D Printed Spacers | 0.56 | 4 | 2.25 | 0.02 |
| Breadboard Jumper Wire | 4.9 | 1 | 4.90 | 0.05 |
| Solder-able Breadboard | 1.99 | 1 | 1.99 | 0.01 |
| Vex Motor Controller | 9.99 | 2 | 19.98 | 0.02 |
| 2-Wire Vex Motor | 14.99 | 2 | 29.98 | 0.17 |
| Fishing Line | 2.68 | 1 | 2.68 | 0.02 |
| Bobbin | 1.84 | 1 | 1.84 | 0.02 |
| Velcro | 3.99 | 1 | 3.99 | 0.01 |
| Water Sensor Liquid Depth Det. | 2.72 | 1 | 2.64 | 0.01 |
| Ultrasonic Distance Sensor | 1.83 | 2 | 3.66 | 0.02 |
| Arduino UNO Controller | 25 | 1 | 25.00 | 0.01 |
| Sand Paddle Tread Tires (2) | 17.19 | 2 | 34.38 | 0.36 |
| 3D Printed Axles | 0.24 | 4 | 0.96 | 0.01 |
| Continuous Rotation Servo Motors | 10.99 | 1 | 10.99 | 0.04 |
| 3D Printed Axle Holes | 0.12 | 4 | 0.48 | 0.01 |
| 3D Printed Wheels | 3.17 | 4 | 12.66 | 0.13 |
| | | 24 | 186.42 | 1.72 |

## *Appendix D:*
## Wiring Schematic


M2
M1
Part1
VIN
5V
3V3
D0/RX
D1/TX
D2
D3 PWM
D4
D5 PWM
D6 PWM
D7
D8
D9 PWM
D10 PWM/SS
D11 PWM/MOSI
D12/MISO
D13/SCK
RESET
RESET2
AREF
ioref
A0
A1
A2
A3
A4/SDA
A5/SCL
N/C
GND
Arduino
Uno
(Rev3)
Vcc
Vout
GND
J5
J4
J6
J7
Servo
pulse
RF
IC1
fritzing