Fox Enterprises

Sidwell Friends School

Washington, D.C.

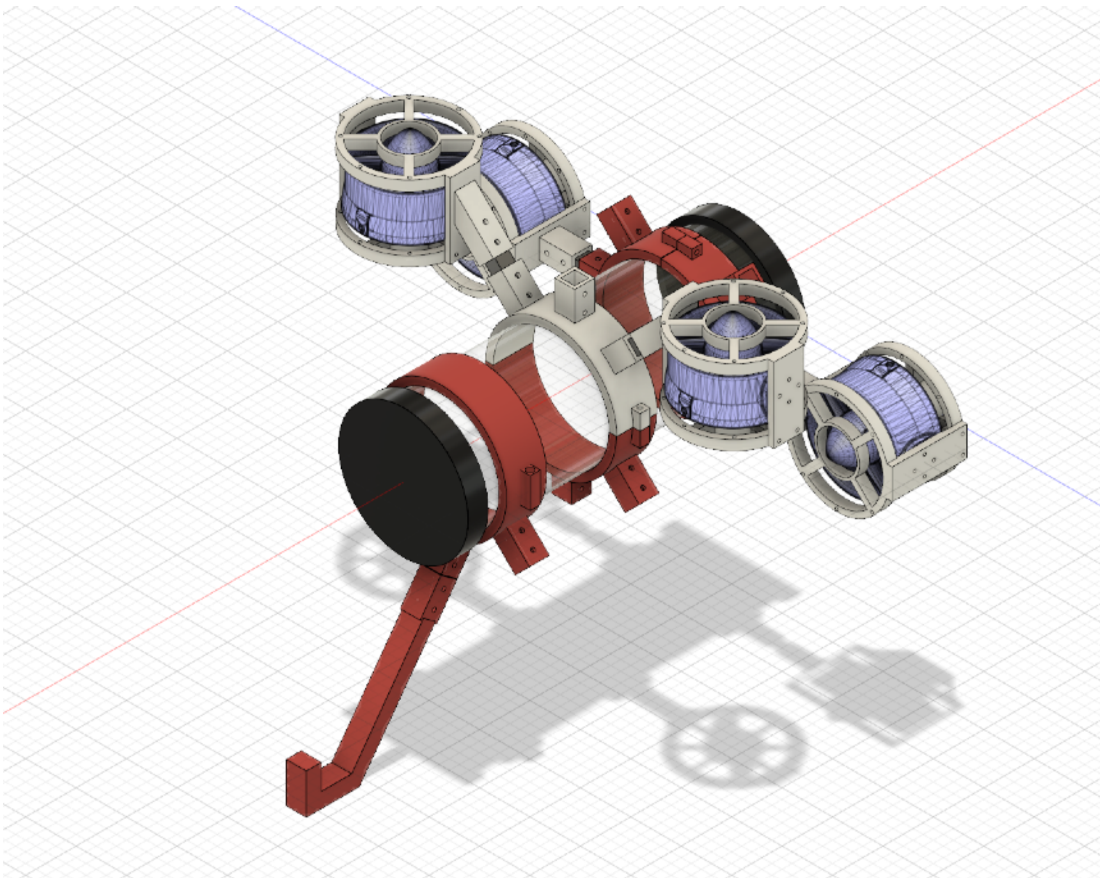

Figure 1: CAD of Sienna. (*CAD Credit: Luke Primis '20*)

Mentors: Darby Thompson and Marty Suresh (Robotics Club Leaders and Sidwell Computer Science Teachers)

ROV: Sienna

Pilot: Nicholas Spasojevic '20

CEO: Luke Primis '20
CFO: Golpari Abari '20
Chief Safety Officer: Ian Palk '20
Head Mechanical Engineer: Nicholas Spasojevic '20
Head Software and Electrical Engineer: Zachary Roberts-Weigert '20
Computer-Aided Design Specialist: Isabel Laguarda '21
Mechanical Engineers: Nate Aurbach '20, Arjun Thillairajah '20
Electrical Engineer: Lawrence Rhoades '21

Abstract

Fox Enterprises proudly presents Sienna, our latest remotely-operated vehicle (ROV). Created in response to the Eastman Company's request for proposals, Sienna is the perfect ROV to repair a deteriorating dam. Amongst other things, dams are vital to provide flood control and hydroelectric power. Fox Enterprises understands the importance of dams and has built Sienna to successfully address the problems presented by the Boone Lake Dam.

Sienna uses a static hook to repair trash racks and recover a cannon, a multipurpose depositor to insert grout and release trout, a marker dropper tool to identify cannon shells, image recognition software to identify benthic species, and adjustable buoyancy to operate with ease at depth. It inspects dam damage with agility using an orthogonal motor configuration with a side-facing camera, and its 3D printed frame promotes a precise and flexible design.

The production of Sienna has pushed Fox Enterprises' design, scheduling, and construction capability to the limits. Company members put in an average of 100 hours of work over the past six months to ensure that Sienna is up to any task. We overcame several challenges in the engineering process and, in doing so, learned many lessons. This document details the creation of Sienna, decisions, reflections made in the process, and every aspect of Sienna that makes it the best ROV for Eastman.

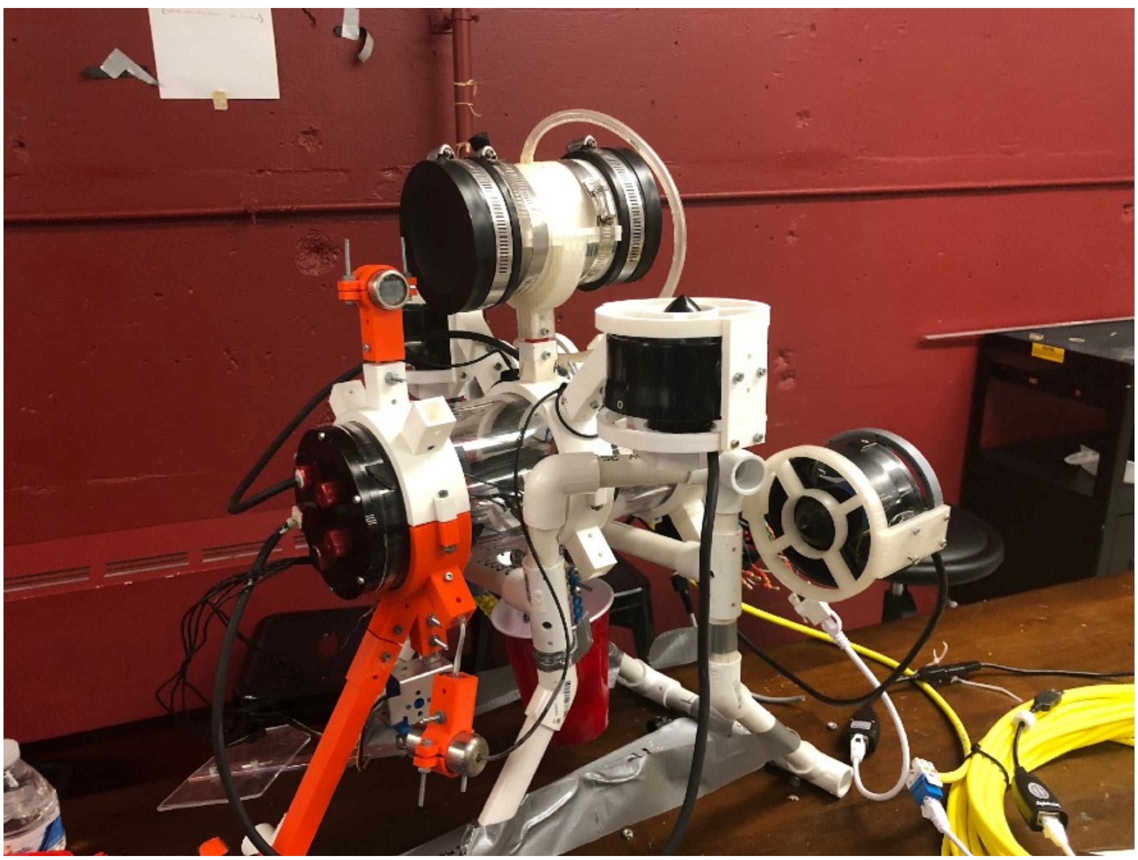

Figure 2: Completed Sienna on its stand. (*Picture Credit: Isabel Laguarda '21)*

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Theme Significance

This year competition tasks include ensuring public safety, maintaining healthy waterways, and preserving history. Eastman, a chemical company, has requested proposals for an ROV that will help the company better the community. The ROV requested will operate in Boone Lake, Boone Dam, and the South Fork of the Holston River to inspect and repair a dam, complete a study on the Holston river, and recover a Civil War cannon. The tasks discussed in Eastman's Request for Proposals are located in Eastern Tennessee, USA, an area known for its beautiful mountains, lakes, and rivers.

Boone Lake and Boone Dam are a popular recreational area; however, recently a sinkhole has opened underneath the dam, compromising its structural integrity. An ROV is required to inspect the dam from underwater to determine whether there is a public safety risk associated with the sinkhole. Sienna makes use of its maneuverable orthogonal motor configuration with a side-facing camera to inspect the dam and allow drivers to record the location of cracks. Sienna also uses an optimally sized depositor cup to insert grout into the void beneath the dam, and a hook to repair the dam's damaged trash rack.

Throughout the year, trash in the Boone River builds up, and an ROV is needed to pick up debris from the bottom of the river and to assess the health of the biome. Sienna uses its hook to pick up a water sample from the river bottom, and our drivers are trained to measure the pH of the water from this sample. Sienna can use its hook to lift a rock from the river floor and its image recognition technology to determine the number and type of benthic species present. Finally, Sienna transports trout fry using its depositor cup in order to restore the fish habitat on the river.

The Boone area is also famous for its history. Towards the end of the civil war, there was a large battle, and a cannon and some of its shells have been located in the watershed. The RFP asks that an ROV recovers the cannon, and marks the unexploded shells as either active or safe. Sienna can hook onto the cannon and use its adjustable buoyancy to return it to the surface. It also uses a marker depositor, which uses one servo to deposit four markers, to mark unexploded shells as active or safe.

Company Profile

In order to function efficiently as a team, Fox Enterprises delegated and taught skills based on the experience of each team member. The team is composed entirely of returning MATE competitors; however, some members have competed in MATE for two years, while others have competed for only one, and each member has different experience levels and skill sets. Those with more experience guided those with less.

Figure 3: Back row, left to right: Nate Aurbach, Isabel Laguarda, Nicholas Spasojevic, Lawrence Rhoades, Arjun Thillairajah. Front row, left to right: Golpari Abari, Ian Palk, Zachary Roberts-Weigert Not Pictured: Luke Primis

We assigned the role of CEO to the individual with the most knowledge of the workings of the ROV, Luke Primis. We wanted to make sure that our CEO had technical knowledge in all aspects of our ROV (mechanical, electrical, and developmental), allowing them to keep track of overall company progress and provide guidance to every company member, and Luke was well-versed for the position.

Similarly, we assigned other leadership positions to company members with the most knowledge in those fields. They oversaw the production of those areas and mentored fellow company members. Every other role was assigned on the basis of interest or past experience in the role. For example, Ian Palk was named Chief Safety Officer because he has field safety training including CPR training and other.

Scheduling and Project Management

Fox Enterprises began meeting in January of 2019. We meet each week on Fridays after school from 2:30 to 8:00 PM, and have weekend meetings either Saturday or Sunday from 12:00 to 4:00 PM. Many members of Fox Enterprises participate in multiple extracurriculars, and to avoid conflicts, we occasionally vary our weekend meeting time. Meetings take place at the Sidwell Friends School robotics lab, and, starting April 13, also at pools in order to run underwater tests.

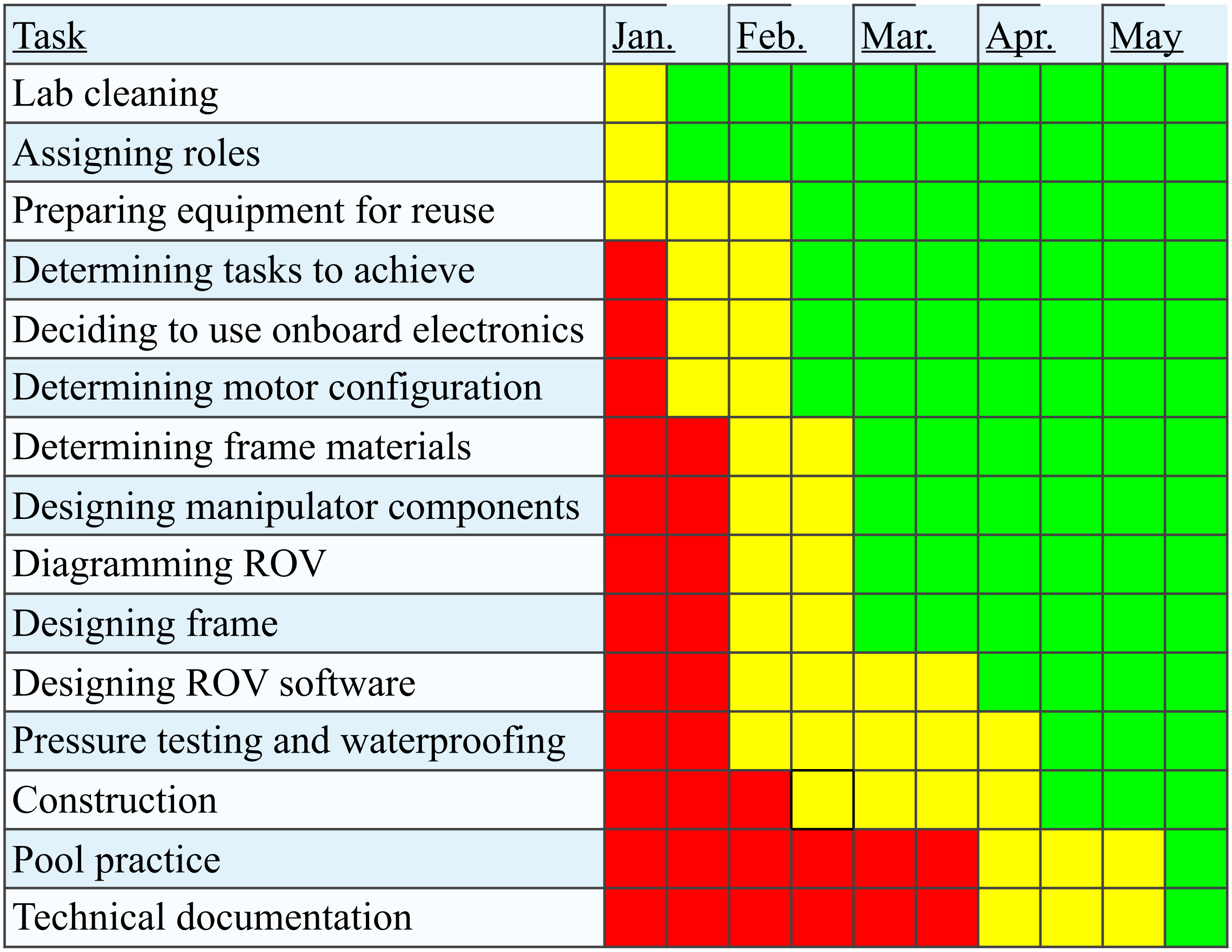
To organize meetings to be as efficient as possible, Fox Enterprises delegated and taught skills based on the experience of each team member. The team is composed entirely of returning MATE competitors; however, some members have competed in MATE for two years, while others have competed for only one year prior to joining Fox Enterprises, and they have more experience or different skill sets. Accordingly, we assigned leadership roles, such as CEO, to members with more experience, in order to provide supervision and guidance to less experienced members and to ensure that all team members could be their most productive.

When company members had conflicts that required them to miss meetings, they received updates on the status of the ROV via our group message, and if at any point we felt we needed members to work on the ROV outside of scheduled meeting time, we used this group chat to delegate tasks to prepare the ROV for the next meeting. In order to maximize efficiency, we used chalkboards to delegate tasks for each meeting to different company members according to experience level. These chalkboards would also remind us of the most pressing tasks currently facing our company, and held important messages for other team members to read later.

To stay on task, we set multiple self-imposed deadlines in the process of making our ROV. Our most important deadline was the first weekend meeting of April when we had set a goal to have a waterproof-tested, swim-ready ROV to allow our drivers to practice in the weeks leading up to the product demonstration. In order to meet this deadline, we determined to finish deciding what our ROV would accomplish and to finish designing the basic framework of the robot within the first two weeks of starting the season. We diagramed thoroughly to avoid later alterations on the ROV that would be costly in terms of time and preparation.

Progress Chart

Key	Incomplete	In Progress	Complete
Color	(red)	(yellow)	(green)



Safety

Philosophy

Fox Enterprise's goal is to create the best product efficiently, and we believe that will be best achieved in a safe and dynamic working environment. We consider safety an integral aspect of our setup while assembling our ROV, so we use a thorough job safety analysis (JSA) when working to ensure all tasks are carried out in the safest ways possible. The JSA contains information on how to operate, and what to do in the case of injury. We unremittingly check for any simple errors or hazards that may potentially damage any equipment or injure any team members. In addition, we always take caution before making any decisions while constructing and maintaining our ROV to minimize the possibility of creating a dangerous situation. This attitude, held by all the members of Fox Enterprises, makes our workspace an ideal environment for productivity.

Electronic Safety

To maximize safety and prevent our onboard electronics from short-circuiting, our team has made sure that all of the electronics on board are sealed in a watertight container. The wires are fed through M10 penetrators and potted using marine epoxy to ensure that the container remains waterproof. Within the watertight container, we also made sure that there was plenty of air between electronics and insulation to prevent overheating. Additionally, we heat-shrank and electrical taped all connections to prevent short circuits.

Mechanical Safety

In past years, members simply referred to JSAs to ensure safety, but we had to revise the JSA and install new safety protocols this year because we began using a 3D printer. Only two members were allowed to do prints on the 3D printer to ensure safety. Lawrence and Luke were the two members with prior 3D printing experience, so they were in charge of fabrication. This way, no one without the proper knowledge of the 3D printer and how to use it would be exposed to hazards in which they could burn themselves on the extruder or heat-bed or otherwise damage the printer. In having two members dedicated to the printer, we were able to avert possible issues by having them always on standby to stop prints. For example, on one failed print, the printer began spewing hot filament all over the floor of our lab. An occurrence like this could have become a possible safety hazard, but Lawrence was able to promptly stop the print before any harm was done to team members or equipment.

The second aspect of our safety protocol is used when we are operating the ROV. Before even turning on the power, we appoint a safety supervisor to oversee the upcoming test. First, they go through our Pre-ROV test safety checklist (pictured below). After this, they complete another series of checks to make sure that everyone around the ROV is prepared and aware of the upcoming test. Before connecting power, the safety supervisor checks the entire ROV and control area to make sure that nobody is working with exposed wire. After this, they give the all clear to connect to power. Before the ROV is placed in the water, the safety coordinator makes sure that the ROV is safe. This entails checking for sharp edges, making sure that the electronics capsule is completely sealed, and checking the thruster sheaths to make sure that all possible hazards are avoided. Next, they make sure that there is a tether operator to make sure that nothing gets tangled and nobody trips over the tether. Finally, after confirming that the pilot is ready to begin, the safety operator shouts a warning to the surrounding area and gives an all clear to the crew. Only then can the ROV be operated. During the ROV test and after, we follow the Fox Enterprises JSA to make sure that everybody is staying safe, and in case of an emergency, we always have a copy of the JSA and a first aid kit on hand. Ian, certified in CPR and Wilderness First Aid, also has experience with treating injury, so he was on hand to be consulted if the need arose.

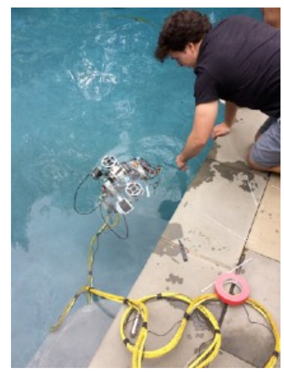


Figure 4: CSO Ian Palk '20 safely retrieves Sienna from the water at a pool practice. *(Picture Credit: Isabel Laguarda '21)*

Safety Features

Sienna contains a multitude of safety features, including but not limited to, fuses, the use of non-corrosive materials, 3d-printed propeller protection sheaths, a lack of sharp edges, the exclusive use of GFCI outlets, and an internal leak sensor. Sienna is equipped with a 25-amp fuse to protect both our electronics and divers in the event of a malfunction. In addition, our power supply is used exclusively with GFCI outlets that will cease power if electronics fall in the water. Because we use onboard electronics, ensuring that the ROV remains free of water is a major concern. To that end, we have installed a leak sensor that will alert us if a leak is detected so that we can cut power to the ROV immediately. The leak sensor also absorbs a small amount of water in the event of a small leak to prevent short-circuiting before we can cut power to the ROV. Because Sienna's frame is mostly 3d-printed, it contains no sharp edges. Also, we constructed propellor sheaths using 3d-printing as well as wire mesh to ensure that the propellers do not come in contact with people's fingers.

Safety Checklist

Fox Enterprises uses these checklists prior to any testing of Sienna:

Checking Sienna:

- ☑ **Examine all equipment before it is used**
- ☑ **Ensure all materials are securely attached to the ROV**
- ☑ **Untangle tether wires**
- ☑ **Appoint tether manager to adjust length and protect tether during testing**
- ☑ **Check electrical connections in the subsurface electronics enclosure**
- ☑ **Seal waterproof electronics enclosure**
- ☑ **Leak test: decrease the pressure inside using the vacuum pump to determine whether the enclosure will be waterproof**

Self check:

- ☑ **All members must be wearing lab-appropriate clothing (i.e no baggy clothing and durable, close-toed shoes)**
- ☑ **All must behave appropriately during construction**
- ☑ **Make sure workspace is clean and there are no parts on the ground**
- ☑ **Clear an adequate amount of space to safely construct and use tools**
- ☑ **Members must learn to use tools correctly**
- ☑ **Put on safety glasses when soldering, sawing, or drilling**
- ☑ **Power tools that are not being used must be unplugged**

Design Rationale

Frame

After deciding that we wanted to build an ROV using onboard electronics, we decided that the strongest and most efficient materials to be the base of our ROV were 3D prints and acrylic. We printed rings to be fastened around the electronics capsule that had "standard connections" branching off of the rings. Acrylic pieces fit snugly into these connections and can be used to connect to any prints, specifically camera mounts, and motor mounts. This design allowed us to perfectly determine and accurately adjust the angle and position of all of the aspects of our ROV by specifically designing our own 3D printed parts. Additionally, the 3d-printed structure allowed us to quickly make changes to the design should the need arise, making our design modular. In fact, we can even create multiple components and swap them out as needed during the ROV's use. Sienna's body is also relatively simple, and with no central frame, broken parts can be easily be replaced without damaging the structural integrity of the ROV.

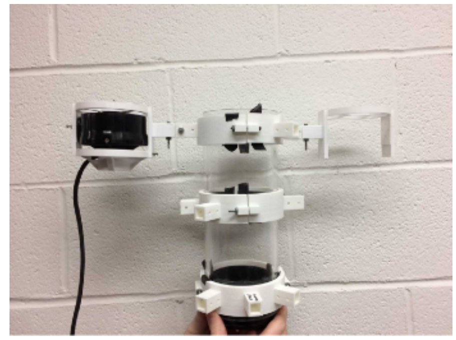


Figure 5: Demonstration of Sienna's 3D printed frame. *(Picture Credit: Isabel Laguarda '21)*

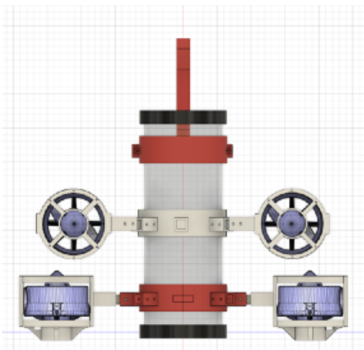


Figure 6: Top view of Sienna's frame. (*CAD Credits: Luke Primis '20)*

We decided to make our prints out of Polyactic Acid (PLA). PLA is non-toxic, cost-effective, and easy to print, all three of which were very important in our decision-making process because we wanted to minimize expenses. The frame pieces are printed at a relatively low infill density of about 30% to help reduce the weight of the ROV. Acrylic is also a cheap and widely accessible product. The use of Acrylic and 3D prints throughout our ROV allows it to be easily and cheaply reproduced. Sienna's frame is not only strong and precise but also simple and cost-effective. Its efficient and modular design means that it can be easily adapted to tackle missions outside of Boone Lake.

Payload Tools

In developing our ROV we thought carefully about which tasks we wanted to prioritize. After careful consideration, we decided that in order to best achieve the given tasks (maximize public safety, ensure healthy waterways, and preserve history) we needed payload tools to lift and carry items and release them. In prior years we tried using claws to secure items, but they failed to work reliably. Due to our struggles in the past, we decided to try a different approach. In this year's competition, we found that every item that needs to be carried has a #310 U-bolt, except for one rubber tire and the water sample, which is easily hooked by its floating string. The items with a U-bolt only require a hook to carry them, rather than a more complicated claw, so we decided on using a static hook for carrying items.

We spent a considerable portion of time considering how to build the static hook for our ROV by analyzing different approaches and prototyping different hooks. The process began with us bending an iron hook into a shape that we could use. Although iron provided considerable strength and stability for lifting items, especially the

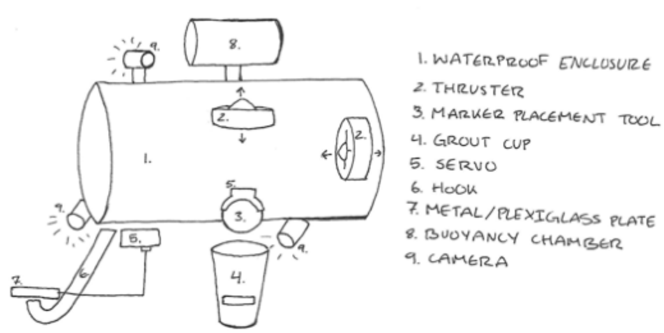


Figure 7: Diagram of ROV from side view. Drawing is not to scale. (*Credit: Golpari Abari '20*)

heavy cannon, we struggled with how to attach the hook to the frame of the ROV. We decided that any potential connection like drilling the hook into the frame's acrylic or screwing the hook into the frame's 3D print would create a weak connection that could be easily damaged or broken by excess force. We next considered 3D printing the hook because we could make a secure attachment to the ROV. We were worried about it potentially snapping from strain, so we decided we could print the hook with a thick and reinforced body. The hook could also be printed with an attachment point for the frame and its dimensions could be measured to jut out without exceeding sizing requirements. Assuming a 3D printed hook was strong enough, it was clearly the best option because it could be easily adjusted to fit our exact needs. Having decided how to make our hook, we printed it between meetings and securely attached it to the mainframe via acrylic. After stress testing it with heavier loads than it needed to carry we deemed that it was strong enough and kept it on the ROV.

Building off of our static hook, we looked to lower items from the surface: fish and grout. We decided that we needed a closed container that could be opened on the bottom, utilizing gravity to release the items. But we also needed a method that was accurate and consistent enough to release the grout into a small area. While we initially thought of using scrap metal, this would have resulted in possibly sharp, hazardous edges. In addition, we felt that using a plastic solo cup would have been more sensible because it was cost effective and easily replaceable. However, the plastic cup proved too weak to stand for the task, and broke too frequently, causing us to seek another solution. In the end, we developed a modular container that we could easily screw on to a new threaded jut-out on the underside of the static hook. This container had no bottom but provides a good base for our dropping mechanism. It offers modularity, allowing us to leave it off of the ROV for tasks where it would be too bulky, and accommodating a quick swap for the dropping tasks.

While planning out how to cover the bottom of the container, we also decided that we needed a method to cover the hook so that when we were lowering the new screen for the trash rack to the bottom of the surface it did not float off of the hook. The cover would keep it pinned in place. Available to us were only two waterproof servos, and we needed one for the panel at the bottom of our grout/trout container and we were using the other servo for our marker dropping mechanism. We were limited in resources and did not want to spend money and buy another servo or spend time unreliably making our own waterproof servo (which has been inconsistent in the past). Therefore, we designed our driving plan such that we never would need both the hook and container covered at the same time. Thus, we decided it would be optimal to combine these two covering methods into one. Basically, we could use the same servo arm to close the container or cover the hook, and it would only need one servo. Since the container was a modular attachment under the static hook, we decided to make another screw on attachment on the hook coverer. Thus we could screw on a piece that would go down from the hook coverer and then act as the base for the container.

We calculated that the grout needed to accomplish the task (roughly 300 ml) would weight approximately 0.374 kg, so we knew that that cover would need to be able to support roughly 4 Newtons above water. With this in mind, we were able to proceed with our 3D printing plan, considering our the strength of our prints would be more than enough to support the grout. We then attached the servo and arm to the ROV precisely so that it lined up with the static hook as well as the container when both modular pieces were attached.

We also decided to complete the cannon shell testing task, which is what we used our second servo for. In order to quickly test whether the cannon shells were metallic, we chose to use an inductive proximity sensor. This sensor detects metallic objects in a 20mm range, allowing us to quickly distinguish metal cannon shells. Next, we considered how to mark whether we had identified it as a cannon shell or not. In order to maximize time efficiency, we decided that we wanted to bring all 8 markers down to the lake bottom at once so that we could avoid unnecessary and time-consuming trips to the surface to pick up more markers. Using a waterproof servo, we decided to keep the design simple. We would have a vertical gear carrying all the markers in its notches, and it would twist to drop a marker, turning the gear clockwise to drop one type of marker, and counter-clockwise for the other marker. Finally, we chose to attach this servo at an angle to the bottom of the ROV so that it would not conflict with our other mechanisms.

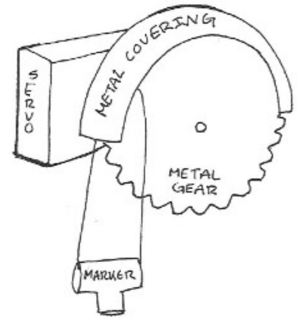


Figure 8: Diagram of marker dropping mechanism. Drawing is not to scale. (*Credit: Golpari Abari '20*)

Tether

The tether on Sienna was designed to prevent tangling and to be neutrally buoyant in order to maximize maneuverability and ease of driving for Nicholas Spasojevic, our pilot, when he repairs trash racks, takes water samples, or transports trout and grout. A yellow tether cover protects our two most important cables: our positive and negative power cables. Our data wire is protected in its own waterproof sheath via the Fathom-x tether, which we purchased. Camera wires and an air tube for Sienna's adjustable buoyancy run on the outside of the cover, bound in place. Spaced out on the entire tether are positively buoyant foam pieces to ensure neutral buoyancy along the tether, thus preventing the tether from affecting the buoyancy of the ROV. We make the tether neutrally buoyant by testing different quantities and spacings of foam. Foam allows the tether's buoyancy to be easily adapted to the differences in buoyancy it may experienced in different bodies of water. The tether contains few wires in order to ensure low weight for easy maneuverability and handling. This is attainable due to Sienna's onboard electronics, without which the tether would have to carry data wires for each thruster and application on the ROV.

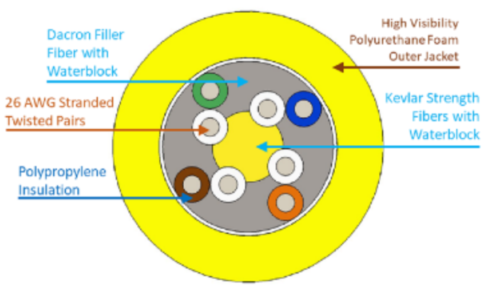


Figure 9: Sienna's Fathom-x cable. Drawing is not to scale. (*Credit: Zachary Roberts-Weigert '20*)

Command and Control

For our subsurface control system, we opted to have onboard electronics on the ROV. Inside of the Blue Robotics watertight enclosure, there is an Arduino Uno microprocessor as well as four electronic speed controllers (ESCs). Each ESC controls a thruster and is connected to the Arduino, which also controls two servos, an induction sensor, and a temperature sensor. The decision to use onboard electronics was mostly driven by a need for convenience. In our current control system, we are able to take advantage of powerful Blue T100 thrusters as well as servos and both the temperature and induction sensors. If we had chosen to keep our controls completely surface-side, we would not have been able to accommodate them in our ROV. In addition, our tether would be much larger, increasing drag and reducing our ability to finish tasks efficiently.

The surface-side controls were simplified since most of the wiring is actually done within the ROV's waterproof enclosure. Our Arduino plugs into our USB to Cat5 extender which plugs into our computer. The computer uses a Processing program to connect to the Arduino over serial and send the controller data. For cameras, all of them plug into a single multiplexer, which passes through a capture card (for image recognition applications) to a single monitor which allows us to view all of our cameras at once.

Buoyancy

Our adjustable buoyancy tank consists of a 4-inch PVC pipe with rubber caps. The tank works on the same principle as a diving bell, using only a hand pump. We opted to use this system instead of a pressurized air system to reduce costs. It is sealed on all sides except for several holes on the bottom of the tank. A tube that connects to the top of the tank runs along the tether and to the surface, where we can either add air or remove it using a two-way pump. Even by adding only a small amount of air, we can drastically change the buoyancy of the ROV. When full, the adjustable buoyancy tank provides a vertical thrust of about 3 Newtons. The adjustable buoyancy allows us to lift objects that would normally be too heavy for our thrusters alone, and it also allows the ROV to ascend to the surface quickly. The addition of the adjustable buoyancy helps the ROV lift items such as the broken trash rack quickly and easily. We decided to include adjustable buoyancy because Fox Enterprise's ROVs in previous years have had problems operating effectively at depth, and adjustable buoyancy allows us to have more control over our ROV. All of the pieces of the adjustable buoyancy tank are reused from previous years and the pump was lent by a team member. See Appendix A: SID of Pneumatic System (page 22).

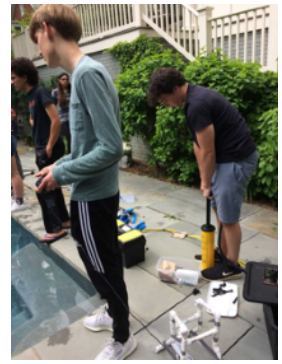


Figure 10: Ian Palk '20 (right) inflates Sienna's adjustable buoyancy container. (*Picture Credit: Isabel Laguarda '21*)

Cameras

Sienna uses a total of three cameras. We tried to use as few cameras as possible in order to minimize costs, so we had to make each camera serve multiple functions. The ROV utilizes a sideways-facing camera, a camera facing at the claw, and a camera at the back pointing downward. All three cameras are held in place using 3d-printed camera mounts. We excluded thrusters that would allow sideways movement for cost-effectiveness and reliability, so the sideways camera takes advantage of our greater forward/backward and vertical maneuverability when mapping cracks on the dam.

Our second camera points at the hook in order to allow us to pick up and drop items such as the water sample, cannon, screen for the trash rack, and reef ball accurately. This camera is also used to view our trout/grout dropping mechanism. Our final camera is mounted down and to the side from the middle of our ROV. This final camera is used to watch the cannon shell marker dropper as well as being used for the benthic species recognition.

In the past, Fox Enterprises has had issues with blurry camera feeds, so on the surface side, the camera power is fed through a SeaMATE Camera Power Filter to provide a better image by regulating the voltage. The data from the cameras is fed through a multiplexer which combines the three camera feeds. This data is then sent through a capture card to allow us to use our benthic species recognition program and finally to a display monitor.

Thrusters

Sienna uses four Blue Robotics T100 Thrusters. They are some of the parts that we were able to reuse from previous years. We chose these thrusters over other thrusters we have in the lab because these are optimized for onboard electronics, and they are much stronger and more reliable than our other thrusters, such as the bilge pump motors Fox Enterprises has used in the past. Their short power and data wires make the ROV significantly less cluttered, reducing the risk of a wire getting caught or tangled. In addition, the wire sheath, when acetone is applied to it, adheres readily to marine epoxy, making it convenient to pot. They provide sufficient thrust for Sienna to move quickly, even with an object on the hook.

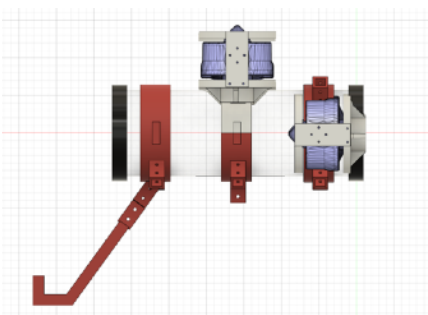


Figure 11: Side view of Sienna and thruster placement. The Y axis is the vertical axis, the Z axis is parallel to Sienna lengthwise (the red line shown), and the X axis is perpendicular to Sienna and the Y axis. (*CAD Credit: Luke Primis '20*)

After we decided on the 3D printed frame design, we had to decide where to put the thrusters. We wanted the ROV to be able to move in the Y and Z dimensions, but we were not sure whether we wanted to prioritize lateral movement. We considered both an orthogonal design in which we would use only Y-dimension and Z-dimension thrusters as well as a vectored design in which we would use four horizontal thrusters at 90-degree increments in addition to the two vertical ones. Although the vectored design would have allowed our ROV to move laterally, although at the cost of almost an additional $300. We would have to limit the speed of each thruster even further to prevent the ROV from drawing over 25 amps for the vectored design. Also, the use of thrusters 45 degrees off of the Z-dimension of our ROV would reduce the total forward thrust to about 70.7% of what it would be with the orthogonal design. Because of these factors, we decided to use an orthogonal design with two Y-dimension thrusters and two Z-dimension thrusters. The Y-dimension thrusters are slightly above center because we decided that as long as they are centered along the X and Z axes of the ROV, they will provide equal thrust. With this in mind, we chose to raise them to prevent interference with the Z-dimension thrusters. Similarly, the Z-dimension thrusters are slightly behind the center to prevent obstruction of the Y-dimension thrusters.

Software

Control of the ROV involves two programs: a surface side program written in Processing/Java running on a laptop and an Arduino language program running on the onboard Arduino. The surface side program reads input from the driver's controller, packs the inputs into a byte array, and sends the data over serial to the Arduino. The surface program will print any data it receives over serial from the

Arduino. The Arduino program then reads the serial data and signals the ESCs to change thruster speeds and the servos to change positions.

Forward and backward movement is controlled with Y-axis of the left control stick, turning is controlled by the X-axis of the right control stick, and up and down movement is controlled with the left and right triggers respectively. The bumpers control the "dropper" servo (which drops markers) and the "A" button toggles the position of the servo connected to our hook/container cover. If the "B" button is pressed, the Arduino will poll for a reading from the temperature sensor and sends the result to the surface program. Similarly, if the "X" button is pressed, thee Arduino will poll for a reading from the inductive proximity sensor. If the leak sensors are triggered the Arduino sends "LEAK DETECTED" to the surface program.

Figure 12: The game controllers we use to control Sienna

In addition to the Processing program, Sienna utilizes two other programs, written in java, that run on the laptop and use the video feed from the capture card. The first program is for Benthic species recognition, and information for that program is in the Image Recognition Documentation document. The second program is used for all of Sienna's length measurements. The key idea behind this program is using known lengths to adjust for any scaling due to distance from the measured object. The program user can pause the video feed at each of the measurement perspectives and select the points of the reference lines or rectangle and the points of the length to measure. The longest crack in the dam foundation uses the known dimensions of the grid rectangles. The program finds the perspective transformation from the drawn quadrilateral to the actual rectangle dimensions, and then applies that transformation to the drawn line giving the actual crack length. All other measurements use a simple ratio instead of a perspective transformation. The length of the cannon is determined using the cannon's U-bolt and its radii are measured with a ruler mounted on Sienna for reference. The user can choose the composition, and the program will calculate the volume of the cannon and its weight.

Testing and Troubleshooting

Over the course of this year, Fox Enterprises was able to minimize the amount of issues we had by considering what issues could arise from a specific design before putting it on the ROV and then further testing the design before putting in the water. When an issue did appear during our testing procedures, we were able to isolate the problem and find a solution. Fox Enterprises put a large amount of time into building and perfecting each system and piece of the ROV. We first started by designing our 3D printed joints and connections to the frame of the ROV. It took many iterations to develop the perfect connection piece for our frame which both minimized our 3D print time and PLA usage, but still stayed strong and served its purpose.

Another part of Sienna which underwent many prototypes was our hook. At first, we designed a hook made out of a curved metal rod. This didn't give us the precision we needed, so we decided to design and 3D print our own hook that could be custom-fitted to the tasks we wanted to accomplish. At our regional competition, Sienna had a hook with a curved end to prevent props from falling off. However, it was very difficult to place the reef ball and the screen for the trash rack, so we decided that we needed to remodel it. Our new hook has a flat end to fix this problem, but it also has a piece connected to a servo that moves over the edge of the hook to keep trash racks, cannons, and other items from falling off.

Another essential part of the ROV that underwent many prototypes and changes was the frame. As we developed our ROV, the placement and number of connection points on the frame changed, so we needed to update and replace our frame multiple times. When we did this, we also re-engineered parts of the frame, for example, strengthening the joints that link the two half-rings together. Eventually, we realized that it was inefficient to replace parts of the frame every time we added a new mechanism to Sienna, so, to ensure wiggle room for prototyping in the later stages of creating our ROV, we designed our 3D-printed frame with extra prongs for additional acrylic attachments later on should the need arise. These extra prongs allowed us to attach a third, rear-facing camera to view our marker placement tool and complete our benthic species analysis.

Before the ROV entered the water, we used a vacuum pump to make sure the electronics enclosure could hold 300 psi of pressure for 15 minutes and tested each motor to ensure that they ran according to our driver signals to ensure productive practice. Two years ago and for a large part of this year, we had many issues with leakage in the electronics enclosure that prevented the ROV from entering the pool. We were having trouble figuring out exactly where the problem was originating. To find the source of the leakage, when the pressure dropped below 300 psi in the 15-minute period when pressure-testing the chamber, we isolated individual penetrators by installing all blank penetrators around the one being tested to verify that it was not the one leaking. We would also remove the caps and O-rings on the enclosure, clean them with alcohol and grease them with silicone grease, and do the same for each penetrator when issues proved persistent. Usually, a thorough cleaning would make for an airtight seal and allow us to continue testing. When this did not work, we inspected the entire length of the power, ethernet and camera wires and applied Flex Seal where we noticed any possible breach.

Challenges

Throughout the design and build process, Fox Enterprises faced many challenges in building Sienna. One of our largest technical challenges came when we first decided to build an ROV using onboard electronics. Because of the high prices associated with this, we immediately knew that we had to reuse the electronics chamber and thrusters from previous years. Unfortunately, some of the thruster cables had been scored, compromising their waterproofing. Because the thrusters needed repairs, we had to devote a lot of time at the beginning of the season to fix the thrusters and other damaged equipment instead of building a quick prototype to test our build design and frame layout. This was a large setback and made it very difficult to achieve our goal of making a water-ready ROV by early April. We solved this problem by coming in during the week to put extra time into fixing the thrusters, and we managed to get back on track. Another technical issue that we faced came when we tried to waterproof our electronics enclosure. To ensure the safety of our electronics, the capsule needed to be completely watertight. As previously mentioned, we tested this by removing air from the enclosure with a vacuum pump and making sure that it could hold a partial vacuum. For weeks, we were unable to maintain a perfect seal, and after cleaning and greasing our O-rings multiple times, we decided to isolate every cable or penetrator that entered our ROV. We discovered that the issue was in our Cat5 cable, and after researching the issue, we discovered that our cable was not actually waterproof. We weighed our options and looked at possible cables that we could buy, and we determined that it was more cost and time effective to buy a new, pre-waterproofed Cat5 cable than it was to fix our old one. Next, we needed to decide which cable to buy. After weighing the options, we decided to buy the Blue Robotics fathom tether because it is purpose-built for ROVs. This issue challenged both our time and resource management skills, and it tested our problem solving and technological abilities.

Another issue came when we were preparing to have pool meetings and we realized that we did not have access to a pool. In previous years, we have used a pool near the school owned by an alum of the Sidwell Friends robotics program, but they had recently sold the house, so we needed to find a replacement. Members of the company spent the next week calling public pools and reaching out to members of the Sidwell community to find a space where we could test our ROV. After a long search, we found two Sidwell families, the Passmores and the Baos, who were willing to let us use their pools to test Sienna. We are very grateful for their decisions to help our company and give us the tools to succeed.

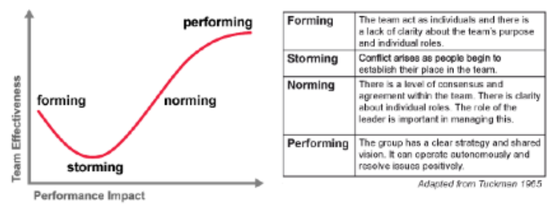


Figure 13: The Tuckman Team Development Cycle. (*Diagram Credit: Lumen Learning*)

Another challenge we faced as a company is one most teams face; the process of finding our stride. The Tuckman Team Development Cycle, pictured to the right, predicts that all newly formed teams will go through four stages - forming, storming, norming, performing. Our goal as a team was to move as quickly through the "storming" phase as possible and hopefully reduce the time lost to disagreement and conflict. When we formed, we immediately assigned jobs and designated each person's role in the company based on their specific skill set and so that there was as little overlap as possible. We also took time to lay out almost every detail of our ROV and made sure everyone agreed with and understood the design before we commenced construction. By doing this, we streamlined our company's efficiency and kept the "storming" phase to a minimum. This also allowed us to reach the "performing" phase more quickly, so we were able to work more efficiently and effectively for longer, allowing us to create the best product possible.

Finances

This year, Fox Enterprises received a grant of $1000 from Sidwell Friends School (out of which the company is based). This grant was the base estimate for the maximum expenses of our ROV. Fox Enterprises alway intends to spend less than what is available, but in the event that extra money is needed, fundraisers are organized. Thankfully, resources besides the Sidwell Friends School grant are rarely required to fund the creation of new ROVs, and due to preemptive budgeting, Fox Enterprises did not have to rely on any other resources to fund the production of Sienna. Fox Enterprises always relies primarily on recycled materials for the production of its ROVs rather than newly purchased materials, which saves the company as much money as possible and keep its expenses within reach. Our company's aim is to build new ROVs with as many materials as can be acquired out of disassembling old ROVs, so only single-use items like zip-ties, electrical tape, or specialty items must be purchased for each new creation. Sienna is built with its thrusters, buoyancy chamber, underwater electronics enclosure, penetrators, power cables, and Arduinos all repurposed out of old ROVs. Recycling old parts is financially sustainable, eco-friendly, allows Fox Enterprises to prevent the waste of useful parts, and promotes economic and ecological sustainability.

To build the ROV and test Sienna, Fox Enterprises spends no money and graciously uses donated lab space and pools. Along with the grant, Sidwell Friends School provides a small basement for the production of the company ROVs, free of charge. For pool-time, the company reaches out to friends, family, and nearby pools (both public and private) and asks to use their pools. Paying for pool-time was not necessary to test Sienna, because we were able to find willing hosts, for whom we are very thankful. The company recognizes and thanks the families of Brooke Bao and James Passmore, members of the Sidwell Friends School graduating class of 2022, as the hosts who graciously invited us to test Sienna at their home pools.

Finally, transportation to and from the MATE Regional Competition in Pennsylvania is funded by each company member attending. The cost is subsidized by Sidwell Friends School, which pays for food for the members on the trip, but each company member is expected to pay an estimated $100.00 for the cost of transportation and lodging for one night before the competition. Since we are driving to the International Competition each attendee is only expected to pay $500.00 out of pocket to cover the hotel, food, and gas money. If a company member cannot afford the cost of the trip, they may choose not to go, but more likely, their fee will be paid by the rest of the company and they will only pay what they are capable. Fox Enterprises worked as a team to create Sienna and wants all members to be able to attend the competition, so company members make sure to provide the necessary resources for each other. See Appendix C: Finances (page 23.)

Build vs. Buy

Throughout the process of building Sienna, our company focused on minimizing costs. However, vital items were still purchased. Before purchasing a new item, we considered how quickly and reliably we could build it ourselves, and whether it would be cost and time effective to do so. One important item that we bought was the Fathom-x tether from Blue Robotics. Before buying this item, we tried to use a regular Cat 5 cable to carry the data to our ROV. Unfortunately, this cable was not waterproof and we quickly realized our mistake. We had the option to either find a way to waterproof the cable or to buy a replacement. Seeing as our regional competition was only a few weeks away, we also wanted to spend our time preparing or for the competition, rather than waterproofing a 15 meter cable. Due to time restraints and the amount of waterproofing required for an entire cable, we decided to buy the Blue Robotics Fathom-x cable.

New vs. Reused

At Fox Enterprises, we pride ourselves on reusing the majority of the components of our ROV from prior years. Although many of the parts required maintenance and took significant time to prepare for Sienna, we were able to reuse many of the important and expensive systems and elements. For example, we were able to reuse all four of our thrusters and the waterproof enclosure for our electronics. This greatly decreased our costs allowing us to spend more time building Sienna rather than fundraising to purchase new items. See Appendix C: Finances, subsection Re-used vs. Purchased.

Lessons Learned

One of the most important lessons we learned is that we should always thoroughly test every part of our waterproofing. Throughout the design process, Fox Enterprises encountered many issues with waterproofing. Our ability to test buoyancy and practice our driving was often hindered by the fact that our ROV was not waterproof, as we learned from vacuum pump testing. We were often hesitant to individually test each individual penetrator and would stop after we found one that either appeared to be leaking. However, that never solved all of our problems. It was not until we painstakingly inspected, cleaned, and tested all the individual penetrators did we locate the issues and were able to remedy them. While this took longer at the time than guessing where there was a leak, in the long run, it would have saved us time and allowed us to practice more in the pool if we had done it sooner.

Team management was one of the most important lessons that we learned as a company. Fox Enterprises was fortunate to start out with talented team members, but failure to share ideas, cooperate with one another, and delegate tasks would have prevented our success. We learned how to work with one another and to each use our strengths to accomplish a mutual goal. For example, Lawrence Rhoads had prior experience with 3D printing but was unfamiliar with how to utilize CAD software. Luke Primis had prior CAD experience on the other hand but had never once used a 3D printer. The team recognized that while neither individual member had the required knowledge to 3D print a frame for the ROV, each had skills that would complement the other's. As a team, we delegated Lawrence and Luke to work together on the frame, with Luke leading the design and Lawrence taking charge of the fabrication. Additionally, later into the design process, Isabel Laguarda was able to help with the design of components. In delegating the task in this manner, we were able to bring a unique, versatile, and durable frame to our ROV that is indicative of our successful collaboration. No one team member could have done this by themselves. This is only one example of the group management required in the design of this ROV; tasks were delegated in almost every area of Sienna including the manipulators, tether, waterproofing, wiring, programming, and more.

Company members also learned many individual skills. Nate Aurbach, Isabel Laguarda, and Lawrence Rhoads, all new members of Fox Enterprises, learned basic skills such as soldering connections and waterproofing with marine epoxy. Lawrence Rhoads learned to maintain and repair a 3D printer in the process of creating our 3D-printed parts, and Isabel Laguarda learned to use Autodesk Fusion software to design some components of Sienna, such as the adjustable buoyancy holder. Individual skills were learned as a matter of necessity because Sienna was entirely company created.

Future Improvements

One future improvement we could make to Sienna is the addition of a micro ROV. Originally, we aimed to include a Micro ROV on Sienna. We knew that if we could not only map cracks on the surface of the dam but enter a drain pipe with a micro ROV to inspect for what might be causing dam failure, it would be a huge step in ensuring public safety on the Boone Lake. Fox Enterprises owns several older thrusters that do not provide enough power for use on Sienna but would be powerful enough to propel a micro ROV through a drain pipe. In preliminary sketches of the micro ROV, we determined we could fasten four PVC pipes around the thruster as guidance down the pipe and create a 3D-printed mount for a camera for inspection. This design would be as simple as possible, cheap, and effective. We could attach a waterproofed motor on Sienna to then spool the tether on the micro-ROV back to Sienna to preserve safety and vision for the other tasks.

The reason we did not attempt the micro ROV came down to time; waterproofing Sienna simply took too long for us to consider this fairly complicated task. Therein lies another future improvement, this time to our company process as a whole: more efficient waterproofing. When we waterproofed Sienna, we were inefficient at isolating different penetrators. We would test several at a time, which rarely led us to the root cause of the leak. Next time we encounter persistent leaks, we should make more of an effort, isolating each penetrator individually for testing. This effort early on will save us more time later. It will give us more practice driving, more time to test in the water, and more time for projects such as the micro ROV.

Reflections

Golpari Abari '20: "The season was not perfect and we had plenty of challenges, but I have learned a lot and grown close with my team. I think our team works well together, and we all have our skill sets, but we need to think things through more carefully. We have yet to reach peak efficiency."

Isabel Laguarda '21: "Younger company members learned a lot of new skills, which was great. For example, I learned how to do computer-aided 3D design using Autodesk 360 Fusion software. I ended up designing the buoyancy tank holder, something I would have had no idea how to do at the start of the season. I also learned basic soldering, how to heat-shrink, how to use epoxy for waterproofing, and began to learn to operate the 3D printer."

Nate Aurbach '20: "In hindsight, we should have started testing and waterproofing our onboard electronics earlier in the year, but I am very proud of how Sienna came together."

Luke Primis '20: "The decision to go with a 3D printed frame allowed greater customization than a PVC alternative, but as the only team member with prior CAD experience I put a large burden on myself to lead the design process. I think the 3D printed frame was our biggest collaboration on the ROV and I am extremely proud of how our team came together."

Ian Palk '20: "Being a member of Fox Enterprises has taught me how to work as a part of a team. Building Sienna was a complex project over an extended period of time. While there was a learning curve, Fox Enterprises quickly adapted and began to flourish."

Lawrence Rhoads '21: "The biggest challenge for me throughout the season was learning about the 3D printer. At the beginning of the season, I had to assemble our printer, a Prusa i3 mk3 (a kit-based 3D printer). Assembling the printer and learning how to use it took many hours of work, but in the end, I am extremely proud of what I have accomplished."

Arjun Thillairajah'20: If we had spent more time at the beginning fixing our leakage issues in our electronics enclosure, which turned out to be one of our largest problems later on, we could have spent a lot more of our pool time practicing driving and testing other issues. As the season progressed Fox Enterprise, grew learned how to work more efficiently together as a team and were able to delegate tasks to make sure the company was always being productive.

Zachary Roberts-Weigert '20: "Our benthic species image recognition system was a great opportunity to learn something new. It was my first time using OpenCV and I had very limited experience with computer vision. Although, as head software engineer, I wrote most of the code for controlling our ROV and image recognition, collaboration was crucial. Luke got serial communication working and Nicholas made suggestions for our benthic species recognition system that improved it massively."

Nicholas Spasojevic '20: "Working with 3D prints was a new and exciting learning experience for me. However, working with a new medium presented its share of challenges. It was truly rewarding, albeit difficult, taking an active role in ensuring that the different mechanisms of the ROV functioned as a unit. As the Pilot I also had to thoroughly consider different driving plans and how our ROV could quickly complete as many tasks as possible."

Acknowledgments

Fox Enterprises would like to acknowledge the following:

- Brooke Bao and family for providing pool-time
- James Passmore and family for providing pool-time
- Sidwell Friends School for providing funding and laboratory space
- Darby Thompson and Martin Suresh for mentoring
- All donors and families of team members for providing financial support and dinners for meetings

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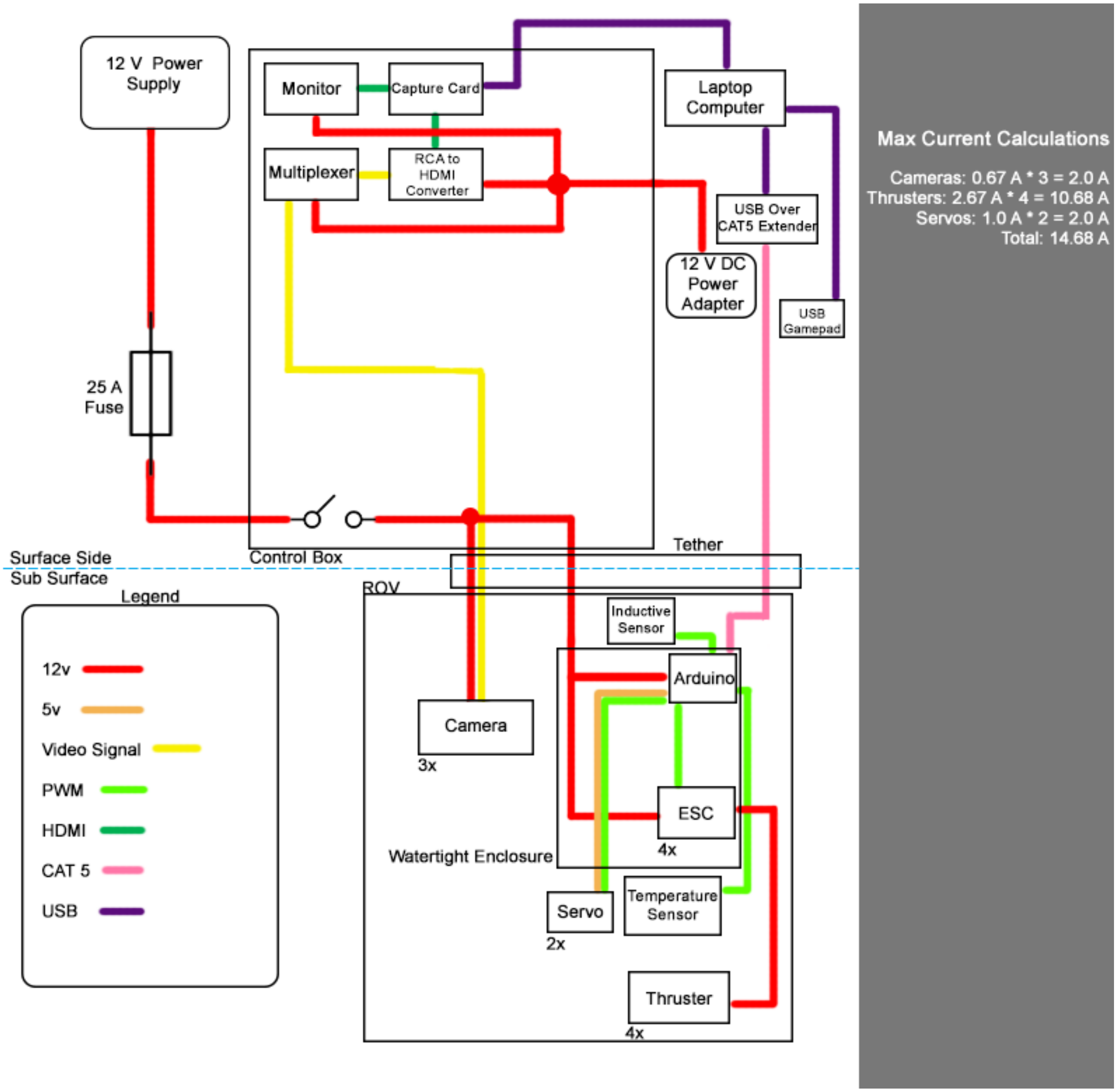
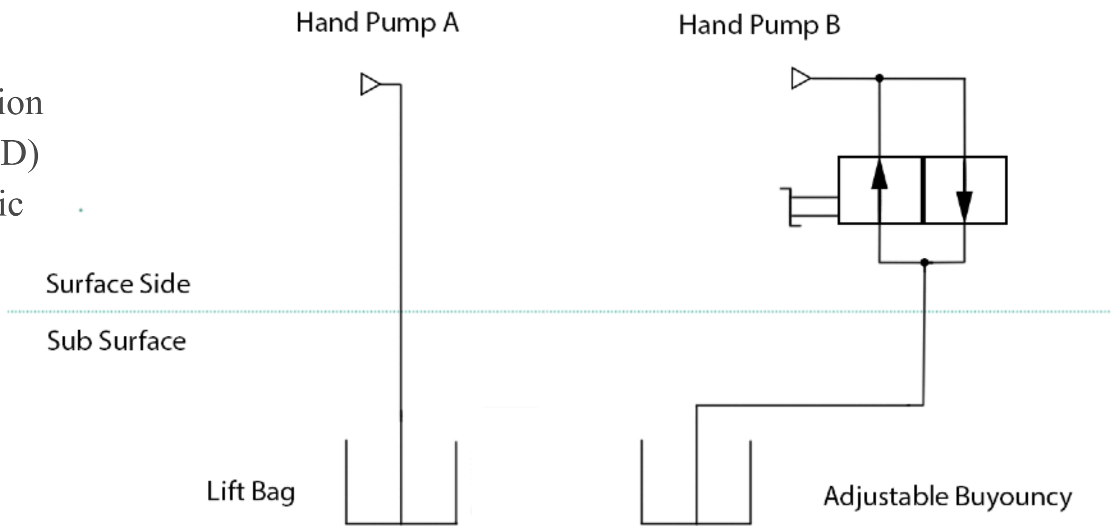
Appendix A: Systems Interconnection Diagram (SID)

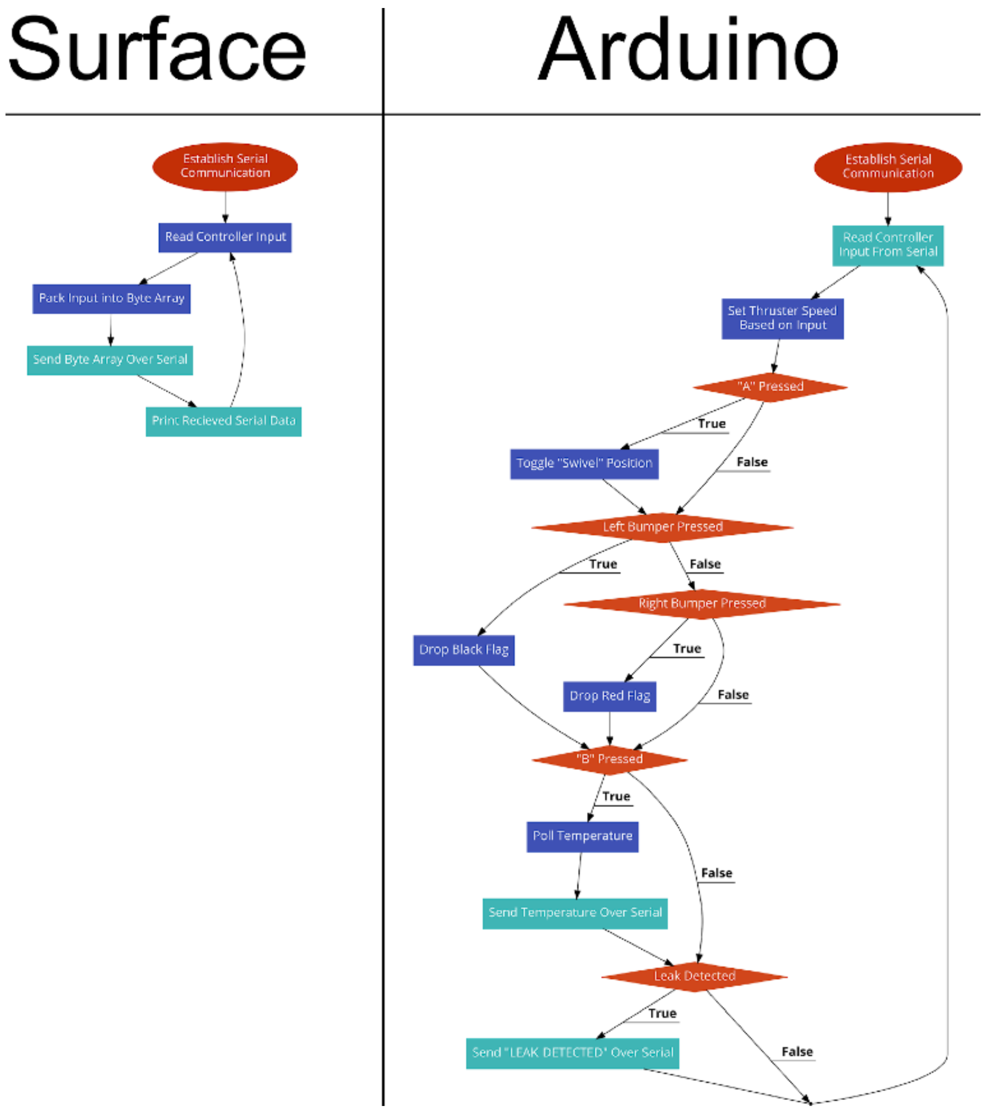


Max current from each thruster running at 1900 µs is 13.26 A, but our ROV programming runs at a maximum 1700 µs, which according to the thruster's documentation has a current of 2.67 A. Thus, even with all 4 thrusters running simultaneously, our total current will never exceed 14.68 A, falling well within the 25 A fuse.

Systems Interconnection Diagram (SID) of pneumatic system



Appendix B: Software Flowchart



Appendix C: Finances

Budget

Income				
Source				Amount
Sidwell Friends School Grant				$1000.00
Expenses				
Category	Type	Descriptions/Examples	Projected Cost	Budgeted Value
Hardware	Re-used	4 Blue Robotics T100 Thrusters	$476.00	$476.00
Hardware	Re-used	Electronics enclosure	$288.00	$288.00
Hardware	Purchased	General mechanical parts and waterproofing materials	$150.00	$150.00
Electronics	Re-used	Tether Cover	$175.00	$175.00
Electronics	Re-used	Arduino and breadboard	$26.50	$26.50
Electronics	Purchased	Cameras	$200.00	$200.00
Electronics	Purchased	Monitor	$75.00	$75.00
Travel	Purchased	Travel to and accommodation at Villanova University	$600.00	$600.00
Sensors	Purchased	Task specific sensors	$50.00	$50.00
Total Income				$1000.00
Total Expenses				$2040.50
Total Expenses-Re-used/Donations				$1250.00
Total Fundraising Needed				-$250.00

Project Costing

Date	Type	Category	Expense	Description	Sources/Notes	Amount	Running Balance
08/2016	Re-used	Electronics	Capture Card		Benthic Species Analysis	-$165.00	-$165.00
01/2017	Re-used	Hardware	4 T100 thrusters		From Blue Robotics	-$476.00	-$641.00
01/2017	Re-used	Hardware	Electronics enclosure	Waterproof enclosure	Houses electronics on ROV	-$288.00	-$929.00
01/2017	Re-used	Hardware	4 M10 penetrators		Waterproofing	-$20.00	-$949.00
1/2017	Re-used	Electronics	Arduino Uno			-$20.50	-$969.50

01/2017	Re-used	Electronics	Breadboard			-$6.00	-$975.50
02/2017	Re-used	Hardware	2 servos	Waterproof servos	For two payload tools	-$19.80	-$995.30
02/2017	Re-used	Hardware	6 Cable penetrators		Waterproofing	-$17.34	-$1012.64
04/2017	Re-used	Hardware	Power wires			-$15.00	-$1027.64
01/2018	Re-used	Hardware	PVC		Adjustable buoyancy	-$18.90	-$1046.54
01/2018	Re-used	Hardware	Acrylic	3.9 cm by 3.9 cm solid acrylic	Connects 3D printed parts	-$2.28	-$1048.82
03/2018	Re-used	Hardware	Tether cover		Contains our tether	-$175.00	-$1223.82
01/2019	Cash Donated	Funds		Funds from Sidwell Friends School	Used for vehicle construction	$1000	-$223.82
01/2019	Purchased	Hardware	Vacuum pump		Testing waterproof enclosure	-$21.00	-$244.82
01/2019	Purchased	Hardware	Misc.	zip ties, electrical tape, etc.	From local hardware store	-$30.00	-$274.82
02/2019	Purchased	Hardware	Marine epoxy		Waterproofing	-$34.36	-$309.18
02/2019	Purchased	Hardware	Flex Seal		Waterproofing	-$13.99	-$323.17
02/2019	Purchased	Hardware	PLA	3D print filament	Used for printing much of our ROV	-$30.00	-$353.17
04/2019	Purchased	Electronics	USB-Cat5 extender		Replaced broken one	-$10.00	-$363.17
04/2019	Purchased	Hardware	Fathom-x tether (25m)	Waterproof Data Cable		-$162.50	-$525.67
04/2019	Purchased	Hardware	3 cameras	Waterproof cameras		-$150.00	-$675.67
04/2019	Purchased	Sensors	Temperature sensor	Sensor which connects to arduino	Measuring water temperature	-$15.93	-$691.60
05/2019	Purchased	Electronics	Monitor		Main display	-$70.00	-$761.60
05/2019	Purchased	Hardware	Waterproof Box		Used as control box	-$50.00	-$811.60
05/2019	Purchased	Travel	Travel to and accommodation at Villanova University	Gas, food, and hotel costs for six team members and two chaperones	For regional competition	-$600.00	-$1411.60
05/2019		Travel	Travel to and accommodation at Kingsport Aquatics Center	Gas, food and hotel costs for eight team members and three chaperones	For international competition	-$4000.00	-$5411.60
05/2019	Cash Donated	Funds		Funds from parents	Used to fund travel costs for regional and international competitions	$4600.00	-$811.60
05/2019	Purchased	Sensors	Induction sensor	Sensor which connects to arduino	Cannon shell analysis	-$8.99	-$820.59
05/2019	Purchased	Hardware	Hiking dry bag	Waterproof bag	Lift Bag	-$12.95	-$833.54
Total raised							$5600.00
Total spent							-$6433.54
Final balance							-$833.54

Re-used vs. Purchased

Item name	Re-used/Purchased	Reasoning for reuse / purchase
USB-Cat5 extender	Re-used	Readily available
Fathom-x tether (25m)	Purchased	Necessary for waterproofing
Electronics enclosure	Re-used	In good condition, readily available, and expensive
PVC for buoyancy chamber	Re-used	Readily available
PLA 3D print filament	Purchased	Unable to 3D print without it
Acrylic	Re-used	Readily available
2 servos	Re-used	Readily available
2 underwater cameras	Re-used	Readily available
1 fish camera	Re-used	Readily available
4 M10 penetrators	Re-used	Readily available
Marine epoxy	Purchased	Required for waterproofing
Flex Seal	Purchased	Required for waterproofing
Tether cover	Re-used	Readily available
4 Blue Robotics T100 thrusters	Re-used	Readily available and only required light restoration
Arduino Uno	Re-used	Readily available
Breadboard	Re-used	Readily available
Capture Card	Re-used	Readily available and expensive
Power wires	Re-used	Readily available
6 Cable penetrator blanks	Re-used	Readily available
Vacuum pump	Purchased	Necessary to test waterproofing
Solo cup	Purchased	Not readily available
Misc. (zip ties, electrical tape, etc.)	Purchased	Not readily available / are single-use items