MSOE Underwater Robotics: The Mosquito[1]

Allison Ahern

Milwaukee School of Engineering, Milwaukee, WI

Abstract

The MSOE ROV team is a fourth year student organization at the Milwaukee School of Engineering that competed at an international ROV competition that took place at the NASA Neutral Buoyancy Lab. The goal was to create an ROV that could complete tasks that simulate bringing the ROV into space and exploring one of Jupiter's moons, Europa. Named Mosquito for its appearance, the ROV was designed specifically to be compact and light to allow for easy transportation to remote parts of the world. The system is broken down into subsystems that could easily interface and synergize with each other to accomplish all of the needed tasks related to the mission to Europa. Tasks include collecting CubeSat and oil samples, studying coral, and converting oil rigs to reefs, all while diving deep.

[1] Funding provided by WSGC, Midwest ROV, and Yaskawa

Background

Remotely operated vehicles (ROV) are being used by many organizations, including the National Aeronautics and Space Administration (NASA). On Earth, they can recover equipment and take oil samples from the Gulf of Mexico, collect samples of corals to check their health after an oil spill, and create new reefs from unused oil platforms. In the near future, underwater ROVs may also have a use in outer space. Scientists recently found that one of Jupiter’s moons, Europa, could contain life in its ice-covered ocean. A manned mission is not practical for multiple reasons including the temperature, which is about -160°C, but an unmanned vehicle could make the trip. There are many technical aspects to consider, including size and weight of the ROV, as sending equipment into space is extremely costly. The smaller and lighter the equipment and tools, the easier they are to transport and store. Another aspect to consider is the frigid temperature. The system will have to operate under extreme conditions.

Methods

Google docs was used to track progress, goals, to-do lists, and ideas which also allowed for easy collaboration and document storage. The team began meeting with the actual robot and parts weekly beginning the first weekend before school started to increase team motivation. Such a team setup and environment is only possible with the egoless team structure that was present, where everyone on the team had a similar knowledge level and equal say in the ROV’s design.

Design Rationale

Frame. Since design and planning of the ROV started well before the mission release, the original frame was too large and needed to be optimized. Once the mission details were out, the design was adjusted so that the size requirements were met. Compacting the design into a frame that only incorporated the necessities, kept the weight down and increased utility. Polycarbonate was used to print the first rendition of the frame; however, the frame began to crack after a month of testing and usage. The final frame was printed in acrylonitrile butadiene styrene (ABS), a plastic, which has a lower density of 1.05 g/cm^3, compared to polycarbonate density of 1.22 g/cm^3, thus saving weight while gaining performance. ABS is more elastic than polycarbonate therefore, the frame is able to better hold up to the rough handling that the ROV experiences on a regular basis. The final improvement made to the design was for it to be printed with a sparse filled honeycomb pattern, which kept the frame rigid while saving 0.8 kg of mass.

Thrusters. For the past 3 years the team used a brushless system, but many difficulties were encountered. Therefore, a more reliable brushed bilge pump solution was chosen. Opening a bilge pump showed a quality shaft seal that increased sealing performance under pressure and a motor that filled the entire space given. This allowed for an excellent power-to-size ratio and a reliable seal.

Thruster guards. For the design of the thruster guards, the team had to balance safety concerns with efficiency. The original design was made to cover the thruster props and provide an efficiency boost using a Kort nozzle design to aid in thrust performance. The guard was then attached to the bottom of the modified bilge pump with a compression zip-tie on extruded arms. These arms were designed to flow with the basic shape of the guard while providing the least amount of resistance to water flow possible. The guard originally had a honeycombed mesh to prevent unwanted objects, such as fingers, to be sucked into the prop; however, this was removed due to a major drop in efficiency because of the decreased water flow. This problem was fixed with the finalized design by increasing the clearance between the prop and the guard and moving towards a modified Kort nozzle design to improve thrust. This modified Kort nozzle was engineered to act similar to how airfoils work for aircraft wings and incorporated the design into a safe but efficient model for improved thrust. The final design was tested and verified to provide a 60% increase in thrust, for a measured thrust of 3.15 N.

Dry housing. On past ROVs, the team had previously used rectangular boxes with success, but did have minor issues with the box compressing at a depth greater than 3 meters and changing ROV buoyancy. With having to go deeper this year, it was necessary to move to a stronger enclosure capable of withstanding greater pressures. The team decided to use a cylindrical dry housing because cylinders are much more capable of withstanding pressure and the circular seals work better due to the lack of corners. Cylinders also have much better hydrodynamic properties with their lower drag coefficients compared to a rectangular prism. This allows for faster acceleration while also reducing the effects of undesired currents pushing the ROV around. The only downside is that they require more focus on organization and planning in order for all the electronics to fit.

The team decided to go with 2 customized 10 cm acrylic tube enclosures from Blue Robotics that had been tested to depths of 100 meters. The electronics were split among both tubes to reduce total ROV size. The 2 tubes displace 3.5 liters of water (20 Newtons) compared to the 12 liters (120 Newtons) of the old dry housing. That change allowed for a great reduction in added weight to the ROV, and much less surface area, which greatly increased acceleration. The clearness of the tubes allows for verifying that no water has entered the enclosure and that the system is running with the status LEDs. The enclosure has a vent to hold the two caps in place with pressure differential, and uses a dual o-ring system for sealing. Two straps were added to prevent the caps from coming off in the event of a bulkhead getting caught on something. The straps also double as a way to secure the tubes to the frame.

Gripper. Upon initial review of the mission requirements, the ability to grip cylinders of 90mm and 25mm diameters was identified as a crucial design goal. Additionally, it was agreed upon that one well-designed gripper would allow for a high mobility ROV to complete all of the missions. Use of 3D-printed parts was also identified as a priority, as gripper parts were expected to undergo repetitive and stressful motions, and would likely need to be replaced as testing and practice occurred. The first method of achieving these gripping abilities was to use two arc-shaped claw pieces with interlocking “finger” extensions. These claws would rotate about a shared pin, causing them to grab and release in a wide arc pattern. The motion of the claw pieces was to be controlled with a waterproof servo motor, which was deemed ideal due to the need for less than 180° of motion, allowing the motor to directly drive the claw piece. This first claw design was abandoned prior to 3D printing due to a desire for a more conventional claw design, which relied on parallel beam linkages for claw piece motion.

The parallel beam linkage concept drove the gripper design revisions once the first version had been rejected. This concept involved using two pairs of identical beams to connect each claw piece to a common base. The length of these beams was optimized to allow for the original 90mm and 25mm gripping requirements to be met while also allowing the claw pieces to remain parallel throughout their entire motion pattern. The use of parallel beam linkages also allowed for a section of the claw pieces to achieve full contact gripping, greatly improving the ROV's ability to grip smaller objects.

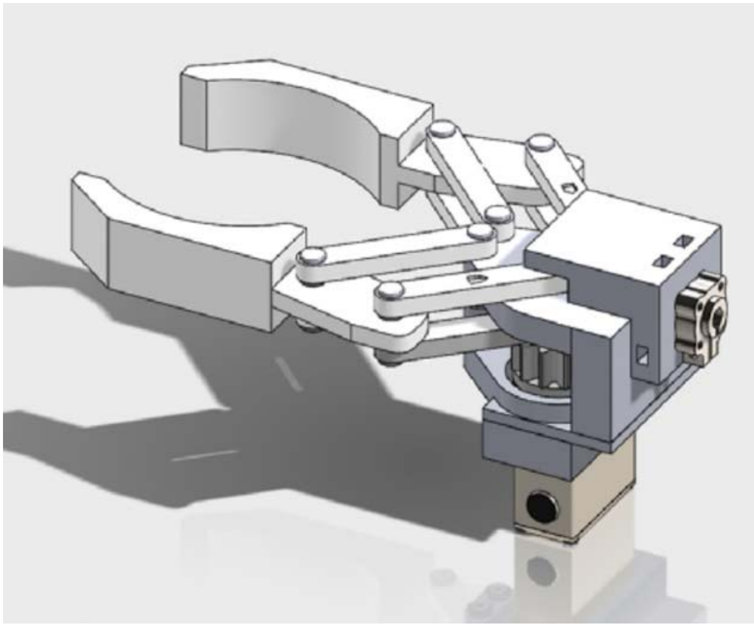

Figure 1: Early design of the gripper

The gripper designs which employed the parallel beam linkage were revised mainly to accommodate different methods of position and torque control. Using the waterproof servo from the first design, a 2:1 torque gear chain was designed in order to allow for higher torque application to the claw pieces across their entire motion. The claw piece that was driven by this gear chain also had a 1:1 gear connection with the other claw piece, allowing for symmetry of motion. Both gear chains were contained within a single piece base platform. The gears in both gear chains were created using gear generating software and some manual SolidWorks editing.

The first major edit to the parallel beam linkage concept was the removal of the 2:1 torque gear chain between the servo motor and the driven claw piece. Instead, a direct drive and magnetic clutch system was designed and constructed. The clutch consisted of two cylindrical pieces, each containing four (later increased to six) neodymium magnets arranged in a circular pattern and oriented to attract the other cylinder piece. This clutch helped protect the servo motor from excessive stress on its internal gears while still smoothly transferring torque. This required a change to the common base platform, which was redesigned to employ four-piece construction and a different servo motor location. This design was the first to be 3D-printed and performed adequately to complete select missions.

A shift away from coplanar rotational control of the claw pieces and the waterproof servo motor prompted a final redesign. It was decided that a bilge pump motor (same type used for propulsion) would be a more suitable gripper operator due to its increased torque potential. The bilge pump motor was implemented with a threaded rod and threaded nut setup which allowed for stronger gripping strength.

Power system.

Regulation. For any load greater than a few watts, a switching regulator was used since they are much more efficient than an alternative linear regulator. The switching regulators used are two TDK-Lambda PAF700s operating at an efficiency of 90%, and an input voltage range of 36-72 V allowing for spikes and drops on tether voltage. The PAF700 also has electrically isolated outputs which provide additional safety and help to reduce the possibility of external noise from interfering with the ROV. PAF700 regulators have been with the team for several years (hand delivered by engineers of TDK-Lambda) and are still one of the best performing regulators on the market. They were found to have no water damage, and have new PCBs made to fully utilize all of their features that have been discovered over the past few years. The PAF700 regulator is turned to 13.8 V, from its nominal 12.0 V, allowing for the electrical system to get 15% more power out of the Tsunami 1200 GPH bilge pumps. Slightly boosted voltage also helps to account for voltage drops through wiring, motor controllers, and LC filters. It provides a steady voltage as long as the input voltage is within operating range. The small overvoltage applied to the “12 V” rail is still within specifications for all devices connected to it. Using a regulated source on the ROV allowed for more predictable operation under varying surface power supplies and power conditions. It also gave the onboard electronics and motors a close, low impedance power source that didn’t suffer from the somewhat large tether resistance and inductance.

Electrical Filtering. The 12 V rail has over 150 mF of electrolytic capacitors to account for large spikes in the current when several motors switch directions quickly. That induces a large back EMF to the system followed by a very large current draw (over 60A from 4 motors). This problem could have alternatively been solved by adding acceleration/deceleration ramps for slower starts and direction switches, but this would have impacted ROV performance negatively.

All power supply outputs were sized with bleeder resistors, so the system is non-functional in 3 seconds. LEDs indicate that voltage is present and the system is unsafe to work on. While all motors stop moving after 3 seconds, power supply

LEDs are dimly lit for slightly longer than the 3 seconds. They take up extra space and add some cost, but overall increase system performance and reliability.

Control system.

Microcontroller. The Tiva C is the connected microcontroller used on the ROV. It's low cost and high performance, with a 120MHz ARM processor (with 150 million instructions per second), 90 GPIO, and a built in Ethernet port. The processor has a floating point unit that is useful for performing kinematic calculations and running control loops. That eliminates the need and extra development time to transfer calculations to fixed point integer math. It also contains a high precision, integrated 12-bit ADC that provides a precise way of monitoring current and voltage currents without needing to add additional components. There is a team-designed and built breakout board that adds buffering to all outside connections, reducing the chance of the Tiva C from getting damaged. Output buffers also improve signal quality with the increased current capacity, and provides the necessary logic level shifting to bring the signals to 5 V over the Tiva C's 3.3 V logic. Signal degradation to servos and sensors has been an issue that has been faced by the team in the past, and the output buffers fix that.

Motor controllers. Polulu simple motor controllers provide a reliable brushed motor controller with a lot of features for adjusting PWM frequency, acceleration/deceleration, under and over voltage cutoffs, temperature monitoring, thermal shutoff, and motor braking and regeneration. They also provide a large variety of input possibilities (e.g. UART, RC PWM, analog, USB). The team uses a 115200 baud UART connection to each driver. It's more reliable and more precise than an RC PWM signal (the UART has CRC error checking and then receives exact numerical values instead of depending on reading pulse lengths to sub-microsecond precision). UART data gives an integer motor control range of -3200 to 3200. Extra precision allowed for enhanced precision modes that restrict the range. Each motor controller receives its own UART signal instead of chaining the controllers together on one daisy chained UART bus. It's a more reliable design that allows the ROV to partially function in the case of a single point of failure. Each UART command utilizes an 8-bit cyclic redundancy check (CRC-7) to verify the integrity of the transmitted command and data. That eliminates any erratic behavior that can occur from signal noise and failed transmissions. There is also a built in watchdog functionality that disables the motor if a command hasn't been received in the past second. The motor controllers themselves are physically compact, and thoroughly tested. The team was also able to retrofit a connector to plug into a power breakout board to reduce the wiring needed.

Human machine interface. Java code running on a laptop provides feedback from the sensors of the ROV and sets thruster values. Whenever possible, a PlayStation 4 controller is used to provide input to the system. The PS4 controller was chosen for its ideal joystick placement, large amount of buttons available for input, and its widespread use. It’s comfortable to hold and familiar to the team members. It’s able to be read over USB, providing enhanced stability in noisy environments, or Bluetooth, allowing the pilot to move around, which was especially handy in testing. The HMI connects to the ROV via a user data protocol (UDP) stream that is updated at 50Hz. UDP allows for efficient data transfer with minimal overhead, though some packets might be dropped occasionally.

Conclusion

Competition Results. The MSOE ROV team took 5th place in the 2016 Marine Advanced Technology Education (MATE) international ROV competition. The robot was able to operate at 40 feet consistently and accomplished a majority of the tasks, time being the only constraint. The team also submitted a 22-page technical report and gave a 15-minute engineering presentation at the competition.

Future improvements. Switching to a brushless thruster system would allow for weight and size to be reduced, while increasing thruster force and reducing electrical consumption. The Past three years of the team have tried using brushless motors without much success, but it is still a possibility for the future. Having a professionally built tether that is neutrally buoyant, or slightly positively buoyant would greatly add to the value of the ROV. While the team’s current tether is more than adequate for most ROV operations, it would still be improved by a thoroughly researched and designed special purpose tether.

References

MATE. (2012). Marine Advanced Technology Education. Retrieved from http://www.marinetech.org/

Stackpole, E. (2013). OpenROV. Retrieved from http://openrov.com/

Steven, M., Bohm, H., & Jensen, V. (2010). Underwater Robotics: Science,Design & Fabrication. MATE.