Sir Watson

RoboSub Club of the Palouse

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The creation of an autonomous underwater vehicle (AUV) for the International RoboSub Competition poses mechanical, electrical, and software engineering challenges. This year, the RoboSub Club of the Palouse redesigned the entire system from scratch. Compared to previous years, the AUV is improved in all aspects. All systems are implemented using a highly modular design intended to facilitate collaboration between a large number of club members. The AUV is more mechanically stable and was designed for improved water movement stability and easy access to internals. The final weight is fifty-one pounds. The electrical systems, PCBs, and wiring layouts are more organized and thoroughly tested. The software driving the sub is flexible to modification and includes extremely reliable image segmentation algorithms. The AUV, due to its dashing mustache, has appropriately been named Sir Watson. Sir Watson is ready to compete and challenge last year's RoboSub finalists.

1 Software

ImplementationSir Watson's software is written entirely in Python using ∅MQ for module communication, OpenCV for vision processing, and numpy/scipy for interprocess computation.

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1.1 Inter-process communication

Communication through the GrapevineSoftware module communication is achieved with the ØMQ socket library. Using Sir Watson's Grapevine interface, all modules communicate through ØMQ via a publisher/subscriber paradigm. Messages are passed as JSON objects and can be read by debugging software without changing Sir Watson's runtime settings. The Grapevine keeps the impact of crashed modules localized and allows a maintenance daemon to detect and restart non-responsive processes. Additionally, modules using the Grapevine can be transparently distributed across multiple networked devices and can interact with any programming language should the need arise.

There are three main communication pipelines: sensors, movement, and vision. At the intersection of all three pipelines is the AI task module. At the opposite side of the sensor and movement pipelines from the AI task module is the microcontroller.

1.2 Sensors

The sensor data is fed through five parallel pipelines; one for each of the gyroscope, accelerometer, compass, battery voltmeter, and depth sensors. This pipeline starts as the microcontroller sends its raw sensor readings over a USB serial port to the main computer. Once the data is on the computer, it is passed through the sensor pipeline. When the sensor values are read from the serial interface, the signals are converted into human readable values. Since these values are still noisy, pipeline uses uses exponential smoothing to filter the noisy measurements.

1.3 Movement

The AI module produced directives that are in the format, "Relative to my present location, the submarine should be at a specific location with a specific orientation." The movement pipeline is arranged around the three portions of a fuzzy logic controller: an input "fuzzification" stage, a processing stage, and an output "defuzzification" stage.

The fuzzification stage of the pipeline receives the directive that the submarine should be at a specific location and must determine what should happen at the present moment to begin moving to that location. The output from the fuzzification movement phase is a collection of fuzzy set membership values. The processing stage is responsible for reading the fuzzy set memberships for Sir Watson and producing new fuzzy set membership values for each of the six motors. Finally, these values are defuzzified into motor magnitudes before they are sent over the USB serial port to the microcontroller. At this point, the motors will be activated.

1.4 Vision processing

The vision software design relies on extremely accurate image segmentation to eliminate artifacts and jagged edges that may confuse line and shape detection algorithms. Image segmentation begins with a filter that ignores pixels that are extremely unlikely to be part of an object of interest.

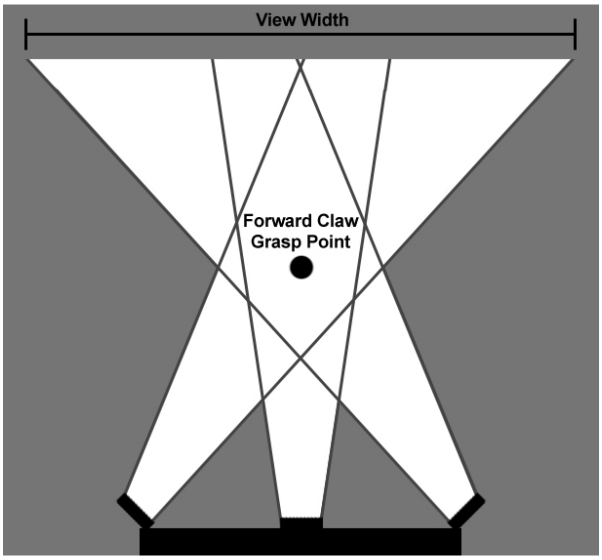
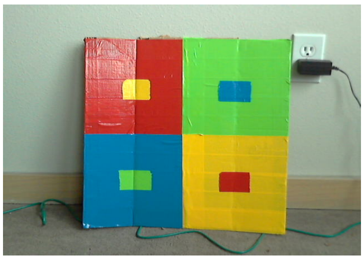
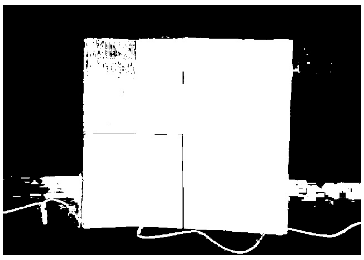


Figure 1: Sir Watson's vision system consists of three forward-facing cameras and one downward-facing camera. The forward-facing cameras are arranged with the middle camera facing straight forward and the two outside cameras angled inward. All three fields of vision overlap at the point where the forward-facing claw grasps.

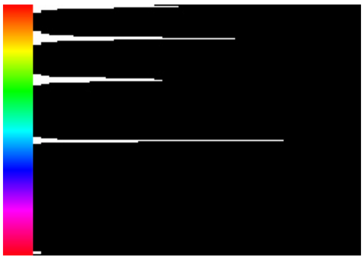


(a) Unmodified video frame of a test object.

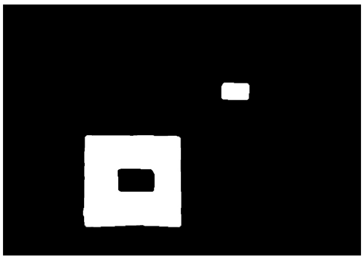


(b) Mask after discarding low saturation pixels.

Figure 2: Saturation filtering



(a) Histogram of observed hue in unmasked regions of image.



(b) Flood fill on hue channel using blue relative extrema as seed.

Figure 3: Color histogram

Building a histogram of the pixel values in the unmasked regions reveals colors that are likely produced by uniform objects. Using these extrema to determine light values for objects of interest works well with cheap cameras and in dynamic lighting conditions.

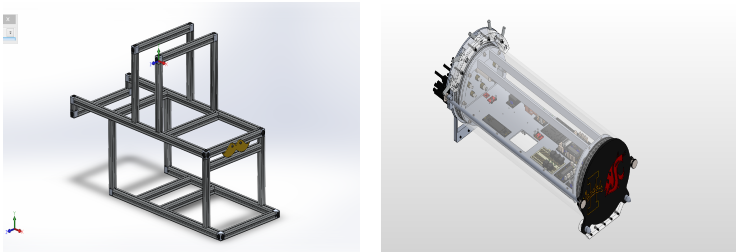
Pixels matching each relative extrema are used as seed values to flood fill the image with flood tolerance set very low, leaving only the object of interest. After smoothing the edges, a mask is left over that is used with standard computer vision shape and line detection algorithms with a high chance of success. This method of object detection does not require fine tuning.

1.5 Artificial Intelligence

In order to simplify the individual tasks, most components were designed to be stateless. The only place that breaks this guideline is the AI state machine controller. This module is responsible for tracking which tasks have been accomplished, which task to pursue next, and when to give up on a task. Once this state machine decides what task to execute, it promotes an AI task module to control the submarine. The AI task modules are stateless. The modules have well-defined input sources, and after evaluating these input sources, it produces a single output directive. While each AI task module is stateless, one of the inputs is the AI state machine controller. The AI task modules respond in different ways due to the inputs from the AI state machine.

2 Mechanical Design

Sir Watson's physical systems were separated into the frame, hull, battery tube, pneumatics, claws, and cameras. Each system was designed to be simple, rust proof, and as lightweight as possible, within reason. All of the components were machined in-house, except for the cameras, motors, and wires.



(a) Frame (b) Main Hull

Figure 4: Principle body components

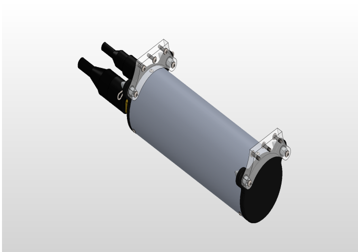
2.1 Frame

Sir Watson's frame is made from aluminum Bosch framing. This was chosen both for the slots on the framing that allow for easy attachment and moving of parts, and because aluminum is rust-proof. Though a different material and attachment style could have been chosen to save weight, without the slotted aluminum it would lack the indispensable versatility of allowing for unplanned changes on the fly. All fasteners are metric sized to keep everything standard, and are stainless steel when needed.

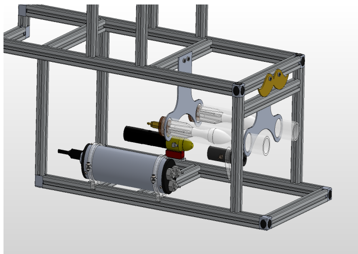
The total size and framing is kept to a minimum while still providing the room needed to easily work on the components. The tail on the back is there to let the large mass of wires to run out of the back of the bulkhead without hitting the rear thruster. The bars on the top are for the mounting of the top thruster, which enables a thruster configuration that has 6 D.O.F. control of movement.

2.2 Main Hull

The main hull houses most all of Sir Watson's electronics. The tube is made from transparent lexan which is light and allows for visual inspection for leaks. The front and back face are removable and seal with a double axial o-ring seal. The front face was machined from lexan to save weight, and the rear from aluminum for extra strength. The faces are connected with two tie rods, preventing them from accidentally falling off. The front face uses guide pins to ease mounting. A pressure release valve in the rear face prevents the buildup of internal pressure during the hull's reattachment. All electrical connections into the bulkhead use waterproof seacon connectors. The external on/off and kill switches use a rotating embedded a magnet to activate reed switch in the inside of the hull. This setup requires no extra wire waterproofing. A cantilever rack attached to the rear face holds the electronics, allowing for easy removal of the front face. Electronics are attached to both the top and bottom of the rack. The rack has two large gaps in it to allow wires to pass from the bottom to the top of the rack.



(a) Battery tube



(b) Pneumatics

2.3 Battery Tube

The body of the tube was machined out of aluminum for durability and to provide good thermal conduction for the battery. The two end caps are made from Delrin for its high strength, good wear properties, and light weight. Each end cap features dual radial O-ring seals to reduce the chance of leaks. The rear end cap has a pressure relief valve to balance the pressure between the inside and outside of the housing by releasing excess internal pressure, which would otherwise push the caps off. There are also two waterproof SEA CON connectors. The first connector sends electrical power to the main hull and the second is for sensor data such as pressure and battery temperature.

The tube is secured to the Sir Watson's frame using a quick pin release system. The system uses tapered aluminum support pins that slide into lexan mounts. They are held in place using two hairpin cotter pins which slide through the rear set of support pins.

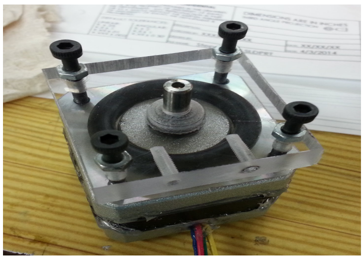
2.4 Pneumatics and torpedo launcher

The pneumatic system consists of two torpedo launchers powered by a canister of CO2 . The system is housed externally from the main hull for easy maintenance and CO2 replacement. The CO2 is regulated from 800 psig to a safe 100 psig. The regulated gas is released by the two solenoid valves, which fire the two torpedoes independently.

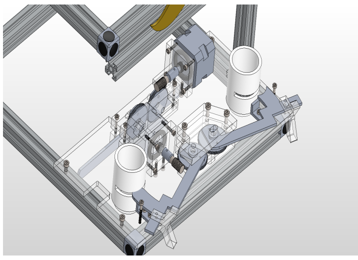
The torpedo tubes are made from lexan which makes it easy to see if one is loaded. The torpedoes are 3D printed and held in place by small magnets to prevent them from falling out prematurely. Each tube has a one-way valve to keep water from traveling into the pneumatic system.

2.5 Stepper Motors

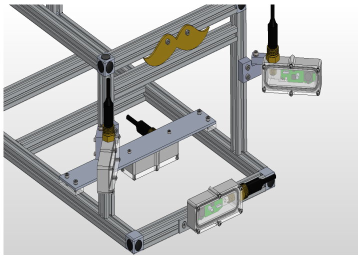
Sir Watson uses two waterproofed stepper motors as its actuators. Stepper motors natively work under water, but were made waterproof to prevent rusting of the internal wires. Creating a secondary housing would be excessive, so instead the original housing was made waterproof. All cracks and screw holes were sealed using a double layer of window sealant. This sealant was chosen because it remains soft and can be taken apart in the event of a leak. The shaft seal consists of a lexan front plate with an exit hole for the shaft, made watertight with a double axial o-ring seal. The transparent lexan lets the user see any water in the motor in the event of a leak.



(a) Stepper motor



(b) Claws



(c) Camera housing

2.6 Claws and Marker Droppers

Sir Watson has two claws run by stepper motors that worm gears. The first claw faces downward and uses plastic teeth to grab the k'nex pieces of the recovery challenge. It has a grabbing zone that's 2 inches long, allowing for some error. The second claw faces forwards and uses a padded V-shaped claw to grab the PVC tube of the reroute power task. It has a grabbing zone that's 1.5 inches long. Attached to this claw are the two release pins for Sir Watson's steel ball marker droppers, which are contained in the two white PVC tubes. The release pins pull out as the claw closes, and are different lengths so the balls are released separately. Combining the marker dropper with the forward facing claw like this allowed us to remove an extra actuator and simplified the system. The marker droppers are used first, so they won't be accidentally released while trying to use the front claw.

Stepper motors were chosen for their ability to keep track of position and relative ease to waterproof. Worm gears were chosen because they are not back-drivable, preventing losing the position of the claws. Each claw has a magnet and reed switch to detect if they are fully open and zero the claws, or allow the microcontroller to put itself in a known state.

2.7 Camera Housing

Sir Watson features four waterproof camera housings. Each housing consists of: a Delrin base, a polycarbonate face, an O-ring, and a SEA CON waterproof connector. The housings are sealed using an face seal with the O-ring compressed between the delrin base and polycarbonate face. The original cases were removed from the webcams to make them more compact. Each side facing webcam is secured to the frame using adjustable 3D printed mounts while the bottom-facing and forward facing camera are supported using aluminum plates.

3 Electrical

3.1 Power system

Sir Watson is powered by a single 18.5V, 8 AH Li-Po battery. Main power is switched with a high-current automotive relay which controls power to all other components.

Last year's team ran into problems where their batteries would become damaged and unusable from being over-discharged. To prevent this, a cutoff circuit was implemented which cuts power off from the entire system by opening the relay if the battery voltage falls below a threshold of 16.2V. This voltage can be fine tuned to the desired level using a potentiometer. The electrical systems on Sir Watson run on four different voltage levels. Unregulated voltage direct from the battery is used by the Stealth computer and the H-bridges that power the thrusters. 5V and 12V regulators are fed by raw battery voltage as well. The stepper motors and pneumatics run on 12V power, while an LED array is powered by the 5V line. A 3.3V regulator also draws its power from the 5V supply. The sensors and all microcontrollers use the 3.3V power. Anderson PowerPoles were chosen for all power connections because of their high current capacity and because they are easy to connect and disconnect. To protect against electrical shorts, the battery tube houses a fuse. A set of switches also provide power control, thruster kill, and mission start capability. These switches are the reed-based switches described in the mechanical section.

3.2 Low level I/O

The low level systems such as sensors, pneumatics, stepper motors, and debugging interfaces are managed by microcontrollers. Last year's design used MPIDE (a variation of Arduino) as the programming language, and utilized the built-in libraries for communication. These libraries used blocking functions which were slow and inefficient, ultimately crippling the submarine. This year The team decided to use C to program the microcontrollers, and decided early on that efficiency and speed were the driving factors when designing the code. Last year's microcontroller system was comprised of a dev board made by Digilent which used a PIC32MX460F512L and a custom shield that sat on top of it to further break out pins. Our first course of action was to bring last year's sub to an operational state so that it could be used to test and debug high level AI code. It was during this time that we developed our code base for our vital functions such as the timer, ADC, UART, and I2C into stable, self-contained modules.

3.3 PCBs

As the new sub's design began, the goal was to design the microcontroller system to be modular and easy to expand. To accomplish this, different functions were separated onto different boards/microcontrollers, with a total of 4 microcontroller boards. The primary board contains a 3.3V regulator and a 4-channel FTDI-chip, and also a microcontroller that handles sensors. The first UART channel goes to the sensor microcontroller, which communicates with all sensors and reports the data to the computer. The second UART channel is passed to the H-bridges. This allows the computer to directly control the thrusters. The third channel is connected to the LED board, which displays patterns to an LED array at the direction of the computer for debugging purposes. The fourth channel is connected to the actuation microcontroller, which controls the pneumatics and stepper motors. Functional components are separated onto different boards so

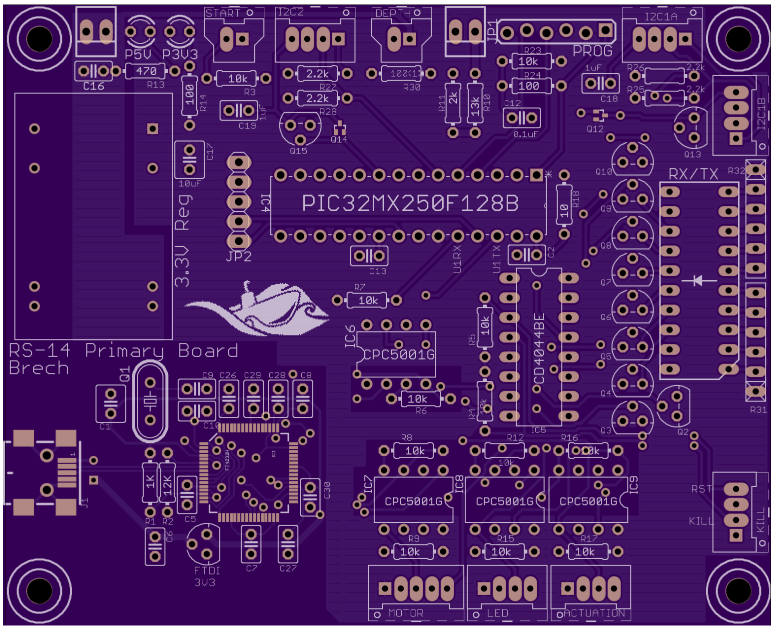


Figure 7: Primary board

that if a board needs to be modified by future teams due to changing requirements (or an opportunity for improvement), only one small board would need to be ordered and constructed. Multiple microcontrollers were chosen for several reasons. First, this separates code of different criticality levels. For example, if a bug in the code for the LED microcontroller were to cause the microcontroller to hang, it cannot affect the sensor microcontroller. Second, this improves efficiency by parallelizing different processes on separate CPUs. Finally, this also makes the system more modular. Small, special-purpose boards can be replaced if test requirements change, instead of revising a large all-encompassing board. This separation also is helpful on the computer side. Each microcontroller has its own UART channel, which also means it has its own serial port on the computer. The computer in turn has a separate module for each serial port. Therefore, threads of execution are separated at both the microcontroller and computer level. The microcontrollers being used this year are PIC32MX250F128B from Microchip which come in 28 pin DIP packages and are configured to operate at 30 MHz. While their speed is less than half of the previous year's 80 MHz microcontroller, it was easy to maintain functionality due to efficient module design and the breakout of different functions.

3.4 Microcontroller software architecture

The software architecture for the microcontrollers was designed for expandability, modularity, and speed. It supports interrupt-driven processes for most microcontroller functions, including the timer, ADC, UART, SPI, and I2C hardware devices. Seeking to avoid a recurring problem of the microcontroller system failure due to blocking functions, it was decided to create our own interrupt-driven functions. This allows for asynchronous functionality which enables us to quickly respond to hardware events instead of the synchronous polling system used previously. Another advantage of this asynchronous system is that it was able to free up a significant portion of the microcontroller's processing time to allow it to processes data faster and even help reduce the workload of the computer. This new architecture is expandable and easy to manage. The same code base is used for all four microcontrollers, one only needs to set a flag at compile time to enable/disable the desired features and configure the code for the particular microcontroller board. The unified code base allows the team to share common features between microcontrollers without cut-and-pasting code, reducing the chance for bugs to occur.

3.5 Debugging

The submarine contains an LED array composed of 96 high-power LEDs along the top half of the hull. The array was designed to allow Sir Watson to easily communicate with divers in the water and operators on the shore. The thruster debugging microcontroller listens on the second uart channel(from the PC to the H-bridges), interpreting the H-bridge commands and lighting LEDs to indicate the current speed and direction the thrusters should be moving. This allows the team to test code without actually running the thrusters (the thrusters can overheat and burn out if run out of water).

3.6 Signal processing

Three hydrophones are used to detect a pinger. A custom built board powers the hydrophones and combines the received data into two stereo channels. Each hydrophone outputs data on a single channel, but the computer only has two audio ports, so the board combines the three channels into stereo channels, with one channel being shared between the two. From here it gets recorded and processed on the computer. An angle of arrival is determined by performing a cross-correlation on the received signals and the resulting time delay is used in calculating an angle using trigonometry.