The University of Maryland, College Park

robotics @ MARYLAND

Chris Carlsen Nicholas Limparis Stephen Christian
Katherine McBryan Justin Kanga Donald Gregorich Eliot Rudnick-Cohen
Joshua Pugh Nicholas Arnold-Medabalimi Johnny Xian Yi Mao
Faculty advisor: Dr. Nuno Martins, Ph.D.

Abstract

Designed by students from the University of Maryland, Tortuga is a fully autonomous underwater vehicle designed to compete in AUVSI and ONR's 16th RoboSub International Autonomous Underwater Vehicle Competition. The fourth generation in the Tortuga series of AUV's, Tortuga IV returns this year with some key upgrades including reworked vehicle AI, advanced rotation control and a more robust vision system to tackle this year's more complex objectives.

1 Introduction

Tortuga IV is an autonomous underwater vehicle designed and built by Robotics@Maryland (R@M). R@M is a registered undergraduate student organization based at the University of Maryland. The first iteration of Tortuga was built in 2006 to compete in the 10th annual international RoboSub competition. Over the years Tortuga has been upgraded and retrofitted. Currently Tortuga is running its 4th generation hardware for the third year to compete in the 2013 RoboSub completion. To fulfill the mission parameters of the competition, the AUV is capable of controlled aquatic motion, manipulation of objects, detection of sonar, and machine vision, all working toward the completion of objectives within a specified time limit.

2 Mechanical

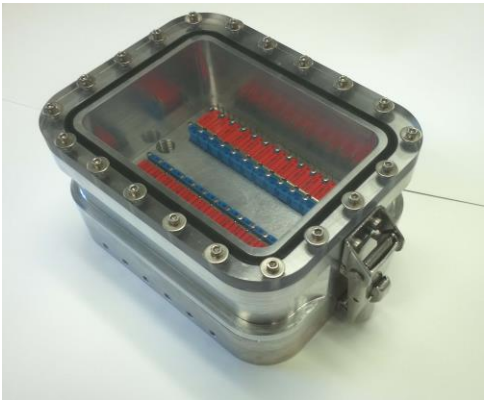
The mechanical design of Tortuga's frame values modularity and ease of access. Constructed out of 80/20® Inc. T-slot aluminum beams the relatively simple design allows for a variety of actuators and hulls to be added and removed as required for mission completion. In addition the accessibility of the design allows easy access to all of the major components.

2.1 Main Hull

The main hull houses the processor and power supply for the robot. It consists of an acrylic tube sealed with 2 aluminum end caps. The acrylic tubing allows for visual inspection of the o-ring seals and debug displays on the electronics. One of the aluminum end caps acts as the mounting surface for the various SubConn® wet-mate electrical connectors. The other end cap has been machined to give the maximum exposed surface area for heat dissipation. The heat dissipating end cap is mounted on 80/20 frame where it is latched onto the robot. These latches allow us to quickly remove the hull from the robot if necessary. Finally, to allow activation of the robot when sealed there are a number of magnetically activated switches positioned close to the inside surface of the hull for easy activation and deactivation of the robot.

2.2 Camera Hulls

For completion of visual tasks our robot uses two cameras; one downward facing and one forward facing. These 2 cameras are in individual custom hulls designed by the team which allow them to be adjusted independently.



Tortuga's pneumatics manifold assembly

2.3 Pneumatics

For the actuation of manipulators Tortuga utilizes a CO_2 pneumatic system. The core of this system is the pneumatics hull. This hull can support up to twelve dual action pistons. The system is very robust and reliable. In addition, the CO_2 cartridges are easily accessible allowing the gas supply to be quickly refreshed.

2.4 Downward Manipulator

The bottom manipulator consists of piston actuated tines. When the robot descends onto the "pizza box," the tines passively capture the pizza box. When the robot needs to release the pizza box the piston extends flexing the tines causing them to release the pizza box. The passive grabbing system has high reliability due to its simplicity.

Tortuga's camera hull assembly

2.5 Bin Droppers

The markers consist of illuminated cylinders with ferromagnetic bases. These are suspended against Delrin® stoppers with magnets actuated by pistons. When the robot needs to release a marker a pneumatic piston pulls the magnet away allowing the marker to fall straight down. The actuators are adjacent to the downward facing camera. This allows increased accuracy with the droppers when the camera is centered over the bins.

3 Electronics

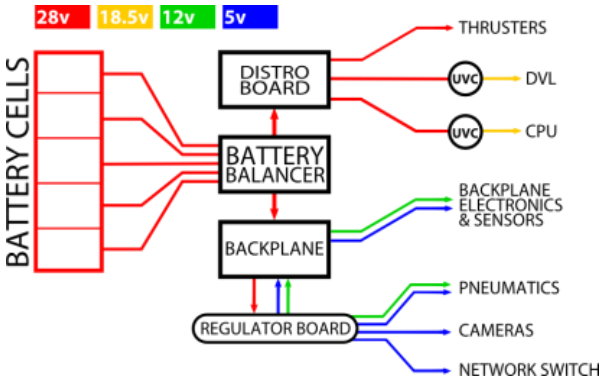
As in previous years, the electrical system on this update to Tortuga IV is a modular system with a radial control structure chosen for its logical separation of functions, expandability, and ease of servicing. In this design, a central board links plug-in cards, each card with a specific set of functions. Our electronics stack consists of a backplane board which holds six other modules: the power regulator (DC/DC), battery load balancing, power distribution, actuator control, sensor, and sonar processing boards.

3.1 Power

Power within Tortuga IV is handled primarily by three of the main six boards, namely the DC/DC, Battery Balancing, and Distribution boards, with additional device-specific regulation by two peripheral UVQ boards. Power for the system is drawn from a 5-pack block of 25.9 volt, lithium-ion batteries. In order to supply sufficient current for the robot, these packs must be connected in parallel, which necessitates battery balancing to keep the draw as even as possible from each pack. The even draw mechanism disconnects batteries which have a lower nominal voltage, preventing the batteries from wasting power, and ensuring a long operational period.

Next, the power is distributed throughout the robot. This task is handled primarily by the dedicated distribution board, which serves the various devices requiring high currents, such as the motors, the Doppler Velocity Log (DVL), and the computer, while controlling which devices receive power. The remaining distribution is handled by the backplane itself, which shares power between all of the plug-in boards. The distribution board gives Tortuga control over which devices are currently receiving power. This manner of power distribution does not require all devices to be active, which allows for quick diagnosis of problems and power conservation when the robot is not in the water. There is also a safety mechanism which can terminate power to any device if the software detects unsafe conditions.

The final step in the power subsystem is to regulate the voltage from the input batteries to useful, common voltages for the lower power devices. This is handled by three separate boards. The first is the regulator board, which handles power to the backplane, hydrophones, inertial measurement units, and the router. The voltages produced by this board are 20 volts, 12 volts, 9 volts, and 5 volts.



Tortuga IV power distribution

The remaining regulation is performed by a pair of UVQ boards, so named for manufactures designation for isolating DC-DC converters. The UVQ boards provide the power needed for the DVL and the computer (2009 Mac Mini). Currently, power into and out of the UVQ boards requires filtering to prevent excessive electrical and magnetic interference (EMI) from interfering with other systems. This is accomplished using an inductor/capacitor pair on the input and output wires.

3.2 Software, Firmware, and Sensor Communication

Communication between the main computer and the various actuators and sensors happens through a serial communications bus to a single integrated circuit (IC). This Microchip dsPIC (the master IC), distributes commands to all of the other microcontrollers, and allows any microcontroller with enough pins to interface with the current electrical system. Any microcontroller capable of a few simple protocols (I^2C, rs-232, and SPI) could easily replace the current PIC architecture, but Microchip dsPICs were chosen over Atmel or ARM microcontrollers because the electrical team was already familiar with their use.

Certain high-bandwidth sensors, such as the Doppler velocity log (DVL), inertial measurement units (IMU), and cameras, are interfaced directly to the computer rather than through the master IC interface. The DVL and IMUs are connected directly through USB to serial converters, while the cameras connect via firewire. This allows the computer to more quickly pull data from the sensors, rather than relaying request commands through the IC network.

New additions this year include a relay circuit to better stabilize the connection to the camera hulls, as well as an improved status lighting array for in-dive diagnostics.

3.3 Actuator Control and Communication

Our current actuation system is comprised of six thrusters and various pneumatic pistons. The thrusters are controlled through a simple I^2C interface. Although the I^2C protocol allows for all the thrusters to communicate on the same 2-wire bus, we have isolated each thruster so that a failure or power outage in any individual thruster does not affect our ability to communicate with any other thruster. The pneumatic system is run by a single dsPIC connected through serial lines to the main hull. To actuate the pneumatic system, the small pneumatic relays are opened and closed to control the flow of pressure to and from the piston chambers.

4 Control

Designing an effective control system requires the careful consideration of nearly every aspect of the AUV's design. Starting with the careful attention to vehicle dynamics, the selection of accurate sensors and actuators, and the design of communication hardware to allow low-latency transmission of measurements and thruster commands, the foundation for a well-behaved vehicle is laid before any control algorithms are written.

Tortuga IV is designed with preference of maneuverability over speed, having control over all six degrees of freedom. In order to control all six degrees of freedom, we have chosen to incorporate six

thrusters into the design rather than dynamically vectoring the thrust. Having six thrusters greatly simplifies the code to control all six degrees of freedom and additionally allows us to control all six degrees of freedom simultaneously. SeaBotix SBT153 thrusters were selected because they fit well with the dimensions of the robot while providing enough thrust to move at a reasonable speed. Additionally, these thrusters include integrated motor controllers and encoders which allow precise control over the thruster output.

The control subsystem software architecture has been designed with the primary goal of creating a modular object-oriented system which can accommodate multiple control algorithms, allowing for quick switching between algorithms without recompilation. An object-oriented design significantly reduces the amount of logic required, converting semantic errors to syntax errors, which are much easier to identify. This makes development and testing of new control algorithms significantly easier and less error prone. This design also separates code into reasonably sized components, drastically improving the readability and making the understanding of logic flow much easier.

4.1 Depth Control

Tortuga IV primarily holds a fixed depth, so depth control has been implemented as a regulator as opposed to a tracking controller. The possible non-linearity that stems from the vehicle being positively buoyant can be treated as a constant disturbance due to the buoyancy design. Thus, any linear controller can be used as long as it is augmented with an integrator for constant disturbance rejection. Several depth controllers have been implemented on the vehicle. PID, LQG, and model based observer controllers [2] are currently available to be selected at run time. Since the vehicle's buoyancy and trim characteristics are often altered for new actuators or adjustment of ballast, the robustness of the control algorithms is as important as controller performance. After comparing the various depth-control algorithms on the vehicle, a PID implementation was chosen.

4.2 Rotational Control

The rotational control algorithm is based off [3], a full three axis non-linear PD controller. The controller uses quaternions, making it singularity free (i.e. immune to "gimbal lock" problems). This rotational controller is a tracking controller and subsequently can be commanded to rotate the vehicle in any direction by either specifying a desired orientation or specifying a desired angular rate and integrating the desired orientation. A more advanced rotational control algorithm based on Egeland and Godhavn's adaptive attitude control algorithm [4] has also been implemented. As an adaptive controller, it can "learn" Tortuga IV's inertia, drag, and buoyant moment properties while running to provide a significant improvement to the vehicle's attitude control.

4.3 Motions

The ultimate goal of the control system is to allow the execution of complex motions. To achieve this we have chosen a design where the artificial intelligence / planning subsystem generates a trajectory for the controller to follow, which allows the controller to reach our desired state more quickly. This also allows the artificial intelligence / planning subsystem to keep track of when the controller has finished motions.

4.4 Visual Servoing

A visual servoing controller has also been implemented for use in aligning with various vision objectives in the competition. The controller sets the Cartesian velocities of the robot based off a proportional control scheme. The velocities are then maintained using a PID controller. This controller allows the vehicle to quickly and accurately position itself around the objectives for the course.

5 Software

The software architecture on Tortuga IV is designed around a few core concepts: modularity, extensibility, and configurability. Focusing on these tenets has helped reduce development and testing time while improving software quality. We have selected C++ as the core language because of its object-oriented facilities, good performance, and easy integration with other languages. All performance sensitive code is written in C++, aside from the drivers, all of which are written in ANSI C. Code that is not performance-sensitive is written in Python because it is more expressive than C++, leading to shorter development times, and does not require compilation after modifications are made.

5.1 Modularity

Modularity comes about naturally from the use of object-oriented design. The software is divided into subsystems, each of which represents an abstraction around a particular task. Each subsystem makes use of abstract classes, each of which serves as an interface to a different physical device or algorithm, reducing both the amount of code that must be written and the number of locations where modifications must take place to integrate new devices or algorithms.

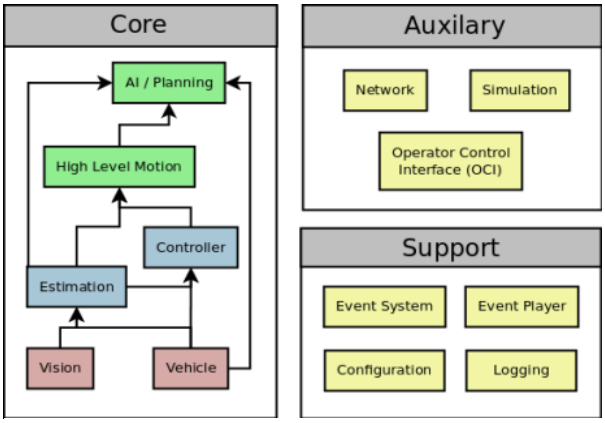
5.2 Extensibility

Extensibility is essentially a measure of the amount of work required to implement enhancements. Even a modular system is not necessarily extensible. Extensibility requires foresight of what future enhancements will need to be implemented. Since the software on Tortuga IV is under continuous development and new algorithms are frequently being added, careful attention has been paid to make the design general enough to incorporate algorithms that require slightly different input. This extensibility is partly attained through our event-driven architecture.

We have implemented a custom publisher/subscriber system using the Boost C++ libraries as a backend. Event-driven architecture reduces the coupling between subsystems as the location in the code where an event is published can be changed without requiring changes to the code of the subscriber.

5.3 Configurability

Configurability is an extremely important design aspect. Our configuration system allows us to select different algorithms and



A diagram of Tortuga IV 's software system

tune the parameters of our algorithms without the need for recompilation. Being able to change the behavior of compiled code without the need for recompilation is most important when testing and tuning our algorithms. Compilation is one of the most processing intensive operations and consequently requires a significant amount of battery power. By reducing or eliminating the need for compilation while testing and tuning, we greatly extend the amount of time that Tortuga can be operating in the water without the need to change or recharge batteries. We have selected YAML as a configuration language because it is human readable and writable. It also integrates very well into Python and C++.

5.4 Development Practices

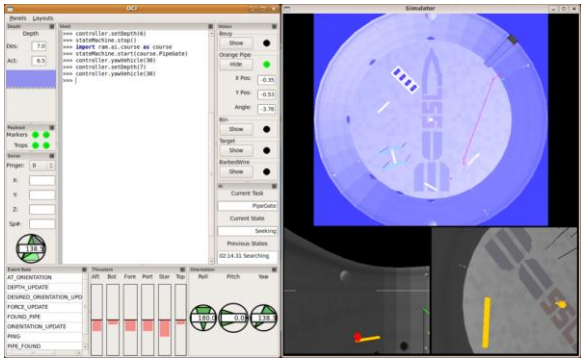
In order to facilitate development in a team environment, we use Github to host all of our code, and CMake as a build system. These tools reduce development times, allow multiple developers to work simultaneously on the same code, and provide a system in which to solve bugs systematically while providing documentation of the solution. The build system generator allows different environments to easily build the code with minimal work required from the developer.

5.5 Debugging Tools

There are several debugging and tuning tools which help speed development and analysis of the software. The rst is the event player which reads logs of received events during a dive operation and can replay them so developers can more closely examine what occurred during a dive. This system enables developers to more easily debug errors received during a dive. Another tool is the real-time state visualizer, which enables any networked computer to plot time series of any aspect of Tortuga's sensor suite. This immediate feedback is invaluable for tuning estimation algorithms and controllers.

5.6 Operator Control Interface

Tortuga IV's dive operations are supplemented by an Operator Control Interface (OCI) program designed to allow simple interaction with all of the subsystems while displaying telemetry data in a modular fashion. The OCI is composed of multiple panels, each displaying one category of



A screenshot of our OCI and Simulator

telemetry, such as orientation or artificial intelligence state. The layout of these panels can be reconfigured during runtime to display as much or as little information as the user desires. Individual panels also reconfigure themselves based upon the number and types of devices present on the vehicle. Interaction with the subsystems is accomplished via an integrated Python interpreter.

5.7 Simulation

The OCI can also be run concurrently with our Simulator. This program simulates Tortuga IV's hardware as well as the competition environment, completely replicating a testing environment. Additionally, the simulator is able to display the view of the on-board cameras, thus

enabling integration testing of almost all of the software systems without time-consuming physical dive operations. The simulator, through the use of these mock subsystems, enables concurrent development of the AI and subsystems it is dependent on.

5.8 Modifications for 2013

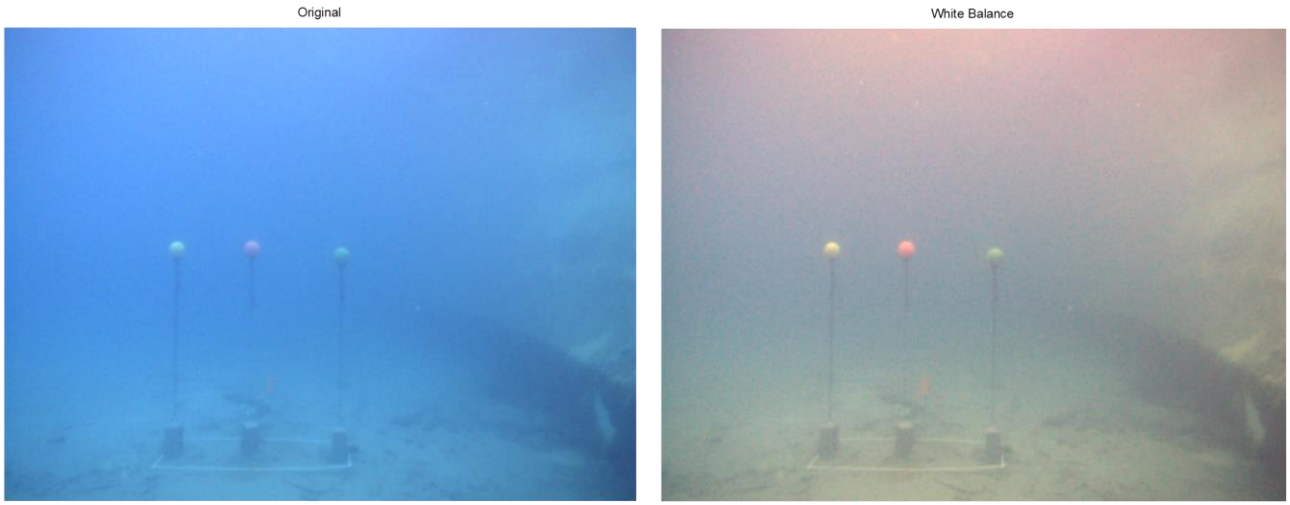
During the past year, we have made many improvements to our vision; specifically, we have focused on being able to track objects using the AI in order to bump them, like with the buoys, or perform numerous other tasks. Using these improvements, we have adapted much of our AI to be more accurate and more robust. We are hoping that these modifications will enable us to complete more of the competition tasks successfully.

6 Vision

The vision system serves to give Tortuga IV's software information about the locations of visual objectives in the view of the forward and downward facing cameras. The vision system input consists of two Toshiba Teli FireDragon cameras which stream video over FireWire to the Mac Mini. The two cameras are stored in housings separate from the rest of the vehicle's electronics. One camera faces downward while the other faces forward. The external housing provides a flat optical viewing surface for the cameras.

This year's main goal for the vision system is to keep it simple. Rather than moving to more complex algorithms, methods to make the simpler algorithms work more effectively are implemented. In this vein, simpler algorithms, such as blob detection instead of shape recognition, are implemented. These simpler methods have many benefits: they are implemented in open source software (e.g. OpenCV), they are fast to run, and are easy to understand. The simpler methods are being improved by the use of white balancing, color filtering in HSV space, and comparing results over multiple frames.

Detecting the blobs is heavily dependent on having an accurate color filter. A good color filter is able to have a small enough range that it only detects the desired color but also a large enough range that it can handle changes in lighting. Lighting changes are particularly important when operating outdoors where clouds, weather, and time of day all affect what the camera sees.



An example of white balancing performed on imagery from TRANSDEC

Two methods are used to improve the color filter: the first is the use of HSV color space rather than RGB. HSV (Hue, Saturation, and Value) is a color space which separates the color hue and the 'brightness' of the color. In this sense it is less susceptible to lighting changes. A second benefit of using HSV space it that only one channel, the hue channel, requires filtering. This reduces the computational complexity by 2/3 compared to RGB.

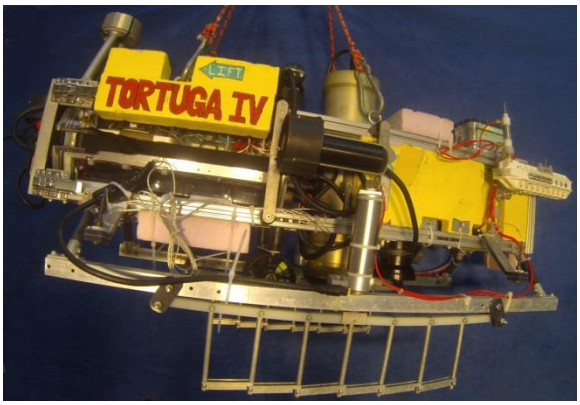
The second method to improve the color filter is the use of a white balance. Images taken underwater have a green or blue tint to them. This greatly increases the difficulty in differentiating some colors, such as green and yellow. A white balance corrects this tint and allows the ranges for the different colors to be increased without resulting in false positives.

Blob detection is done on the filtered image using SimpleBlobDetection, an OpenCV algorithm. Open source algorithms allow for quicker implementation time and therefore more testing. In addition, open source algorithms are well documented and easy to understand. This greatly decreases the learning curve for new users. The SimpleBlobDetection method uses a number of different parameters to identify a blob. These parameters include: area, circularity, convexity, circularity and inertia.

No vision algorithm is perfect, particularly if it needs to run fast. False positives are an issue, as they can confuse the estimator more so than losing the object for a frame. In order to reduce false positives, multiple frames are used. The center of the object should be relatively close between the frames. If it cannot find a match between the previous two frames, or even one frame, it is declared a false positive. This helps reduce the effect of noise in the image.

7 Acknowledgements

Robotics@Maryland would like to thank its sponsors, without whom Tortuga IV would have never left the drawing board. Within the University of Maryland we would like to thank the Institute for Systems Research, the A. James Clark School of Engineering, the Space Systems Laboratory, the Student Government Association, the Maryland Robotics Center, and the Departments of Computer & Electrical Engineering, Aerospace Engineering, and Computer Science. We would also like to thank SAIC, MEMSense, Sidus Solutions, TC technologies, SubConn, Advanced Circuits, Teledyne RD Instruments, the NSF ECCS division, Northrop Grumman, PTC, USBFireWire, BAE Systems, L3 Communications, and Lockheed Martin.



Tortuga IV

References

[1] M.D. Shuster and S.D. Oh. Three-axis attitude determination from vector observations. Journal of Guidance, Control, and Dynamics (ISSN 0731-5090), 4(1):70{77, 1981.

[2] S. Skogestad and I. Postlethwaite. Multivariable feedback control: analysis and design. Wiley, Chichester, 1996.

[3] B. Wie and P.M. Barba. Quaternion feedback for spacecraft large angle maneuvers. Journal of Guidance, Control, and Dynamics, 8(3):360{365, 1985.

[4] O. Egeland and J.M. Godhavn. Passivity-based adaptive attitude control of a rigid spacecraft. IEEE Transactions on Automatic Control, 39(4):842{846, 1994.