Subjugator : A RECONFIGURABLE AUV

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Abstract

Graduate and undergraduate students at the University of Florida have developed an autonomous submarine, *Subjugator* , for subaqueous research and for entry in the annual ONR/AUVSI underwater vehicle competition. *Subjugator* was designed for operation down to 100 feet, and can be quickly configured to optimize for mobility or speed. *Subjugator* s body has mounts to support up to ten motors, each of which may be oriented in multiple directions. The vehicleis controlled through a single-board computer running the Linux operation system and custom software. The on-board sensor suite includes a digital compass, a fluidic inclinometer, a sonar altimeter, and a depth pressure sensor. In addition to the standard complement of navigational sensors, a computer vision system was developed for object recognition and tracking. In this paper the mechanical makeup of *Subjugator* will first be discussed. The electronics systems and processing hardware will follow with an analysis of vehicle control.

I Introduction

As one of the last unexplored regions of the Earth, the ocean is a fascinating environment for research and discovery. Vehicles which can sustain themselves and operate autonomously underwater are necessary to facilitate the exploration of this under utilized domain. Scenarios in which autonomous underwater vehicles have applications include, object recovery and delivery, identification, exploration, and mapping. Teleoperated machines exist which allow limited implementation of the above applications, but they require constant supervision and a human for control. It is the goal of this research to develop a system capable of navigation and environmental interaction without the requirement of human control.

The Autonomous Unmanned Vehicle Systems International (AUVSI)[1] and the Office of Naval Research (ONR) sponsor an annual autonomous underwater vehicle competition which was recently held in San Diego at the SPAWAR facility. The competition could best be described as task-based. Each year the platform and sensor suite are redesigned or reconfigured to suit the needs of the prescribed mission to be accomplished.

The submarine must be capable of navigating within the underwater environment while also performing tasks. In a past competition 18 targets bearing unique bar codes were placed in a know configuration. The submarine had to clear an initial gate leading to the competition arena and then attempt to identify and pair each targets height with the number encoded on its surface. A computer vision system was used to locate and identify the targets.

This paper will cover the design of the submarine in addition to the reconfigurable aspects of both the hardware and software.

II Mechanical System

As a third-generation vehicle, *Subjugator*[2] embodies the lessons learned in four years of autonomous underwater vehicle (AUV) development [3, 4, 5, 6]. Several key design criteria, including hydrodynamics, diverse mission adaptablity, deep water survivablity, and salt water survivability, were considered and refined over the years. *Subjugator* has evolved into a robust, reliable platform for underwater research.

Hull

The 36" long octagonal shape is composed of 0.25" thick aluminum plate and 0.5" thick square bar. A

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bulkhead on each end fastened with quick-release latches keeps the internals dry, while allowing access to the components from either end of the sub. Three hard-point rings are welded onto the frame (Figure 1) to strengthen the structure, provide mounting points for exterior sensors via blind-tapped holes, and carry all through-hull connections. The central hard-point ring also contains the cylindrical mounts for eight motors. The mount allows the motors thrust to be positioned in line with the body, or perpendicular to it. With a mount on each of the eight faces of the sub, a multitude of motor configurations are possible, allowing the vehicle to be quickly adapted and optimized for a particular situation or mission. Figure 2 shows one configuration (a) optimized for mobility while the other (b) is optimized for speed and power. For the 2002 competition, we have chosen configuration (b) to maximize our speed.

Farings

The fore and aft flooded 14" farings provide a more streamlined flow around the vertical motors and the frame. Additionally, the farings offer structural support and protection to any sensor mounted within them. Both farings are open on the top and bottom to provide for upward or downward looking sensors. Moreover, the for-ward section of the fore cone is open for any forward-looking sensors.

Motors

All six motors are Motorguide Power Plus electric trolling motors with 6.75" diameter propellers. At 12V these motors provide approximately 22 pounds of thrust, and are fitted with custom O-ring seals that allow for a salt-water depth of up to 100 feet. Each motor is shrouded to prevent incidental blade contact.

Through-hull Connections

All through-hull connections use Burton 5500 series sealed and molded underwater connectors. The Burton connectors are a valuable piece of equipment for the submarine. Over the years, connectors have been shown to be one of the weakest links in submarine design. Poor connectors can mean leaks or bad sensor data. These connecters have never failed and allowed an enormous amount of flexibility in connecting external equipment to our computing hardware located inside the submarine. A kill switch is implemented with a Gianni hermetically sealed push-pull switch that disconnects power from the motors and initiates a software motor kill routine. A power switch is implemented with a Gianni hermetically sealed SPST switch.

Interior Layout

Two shelves guided on delrin rails provide support for all the internal electronics and power. Batteries and high-power electronics are stowed in the lower shelf to provide a metacentric righting-moment, while the upper shelf houses the remaining electronics. Electrical connections terminate at connectors at the front of the sub for expedient removal of both shelves.

The shelving system provides both quick and easy access for maintenance of the submarine, but also increases the modularity of the system. Different shelving combinations could be setup which would allow different sensor combinations to easily deployed depending on the type of mission.

Exterior Camera Enclosure

Subjugator uses a custom built underwater vision system. To contain the camera and its connecting electronics, we have constructed an ex-ternal forward mounted camera enclosure. This enclosure is mounted on the front nose of the submarine nominally pitched at 20 degrees forward, but is reconfigurable between zero and 40 degrees. It is constructed from a PVC compression fitting using a glass plate at one end, and a hose fitting at the other. The enclosure is connected to the internal cavity of the sub, and therefore of equal pressure.

For testing and extreme depths we are able to pressurize the internal cavity of the sub through the tubing connecting of the camera enclosure. This reduces the pressure gradient on the sub, and thus the chance of hull failure. Pressurizing the cavity has also assisted us in finding micro fractures in the outer casing of the submersible.

III Electrical System

The electrical system of the vehicle is composed of a power system (batteries and motor drivers), computing resources (x86 processor, microcontroller) and the sensors that provide information about the environment to the vehicle. The electronics, as previously mentioned, are fitted onto trays that are easily slid in and out of the submarine.

Power Supply

Subjugator uses four Powersonic 12 Amp-Hour 12V sealed lead-acid batteries, three to power the motors, and a one to power the electronics. A Keypower DX250H DC-DC ATX power supply provides for all of the electronics con-tained within the submarine. This

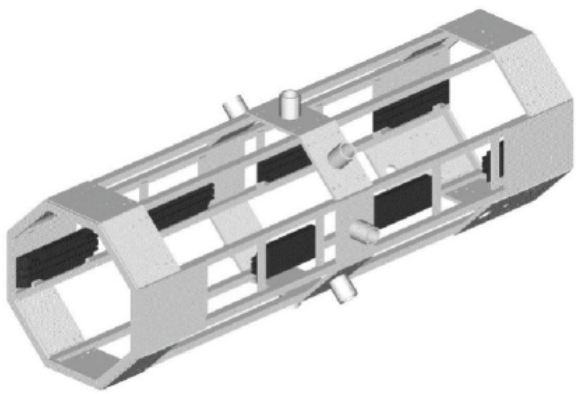

Figure 1: Hull Frame

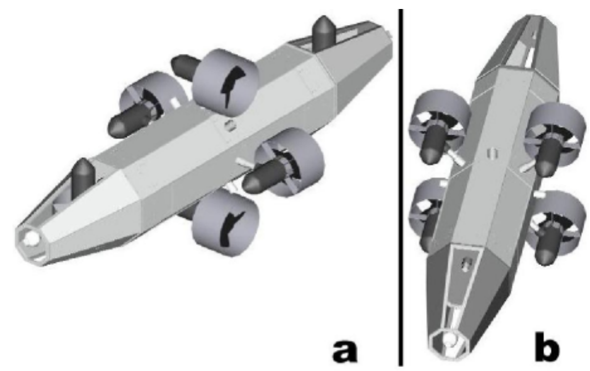

Figure 2: Example Configurations

configuration allows for 2.5 to 3 hours of operational runtime.

Computing

The various tasks of the computing system on *Subjugator* demand different approaches. First, the vision system and the main intelligence require a powerful processor to perform real-time decision making and analysis on the incoming sensor data. Second, the motor system requires a consistent and dependable output to control motor speed. To service these systems we chose the EEPD Pentium 3 700MHz Envader embedded single-board computer, and the Motorola 68HC11.

68HC11. The Motorola 68HC11 is an eight-bit microcontroller unit with flexible and powerful on-chip peripheral capabilities. These include an eight-channel analog-to-digital (A/D) converter with eight bits of resolution, an asynchronous serial communications interface (SCI), and five output-compare timing output lines. The A/D converter, together with the SCI system, interfaces analog sensors to the digital main processor. The SCI system also receives motor output specifications, which are fed to the output-compare lines to generate precise speed control for the motors. These signals are then fed into motor driver boards we designed to provide accurate high-current motor control.

Main Processor. Top-level control is handled by an EEPD Envader single board computer. This Pentium 3 based 700MHz board has 256MB of RAM, IEEE1394 (Firewire), USB, PC/104+, and runs Red Hat Linux 7.3 [7]. We are using a PCMCIA adapter to interface our wireless ethernet card. All sensor information, gathered on one system, is evaluated, and consequent instructions are then issued to all subsystems.

Wireless Access

A communications interface between a base station and the vehicle utilizes a wireless ethernet (802.11b) connection with an 11Mb/s datapath using ZoomAir 4105 cards. This allows secure shell, ftp, and simultaneous programmer access for parallel code development and debugging.

Testing of the sub is performed by remote operation through software running across the wireless link. By viewing the real-time sensor data, we can tune most aspects of the subs intelligence and control.

IV Navigation and Control

Subjugator relies on a host of sensors coupled with a sophisticated control system that allows the submarine perform during submarine competitions. This section will provide an overview of the makeup and coupling of these systems.

Navigational Sensors

An AUV must be able to maintain a heading, a depth and attitude for even the most basic operation. The performance of the submarine is directly related to the quality of the sensors at its disposal. These sensor are the eyes, ears, and sense of feeling for the submarine which attach directly to an arbitor which is the brain of *Subjugator* .

Digital Compass.*Subjugator* uses a TCM2-50 compass from Precision Navigation which contains a triaxial magnetometer, a fluidic inclinometer, and a micro-

Figure 3: Burton Connectors

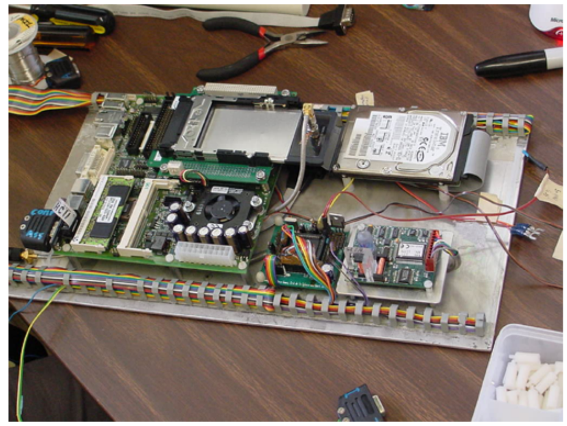

Figure 4: Electronics Tray

processor. This compass generates heading, tilt and roll information throughout its operational range.

Depth Sensor. Depth measurements are gathered with a Measurement Specialties MSP-320 series pressure sensor which is rated to 25 PSI with a rated accuracy of .25 PSI. The sensor outputs an analog voltage between 1-5 V, which translates to a depth resolution of 2 inches.

Sonar Altimeter. Height above the bottom of the pool, lake, etc. is acquired by the Datasonics PSA-916 sonar altimeter. This model is modified to measure distances from 30cm to 100m with a resolution of 1cm over an RS-232 connection.

Control Software

The control software is a layered mesh of simple system that from the outside, due to the sheer volume of code, looks complex.

Modular Software Design. The design of the submarine's software is rather simple. Each sensor has an individual process assigned to it. This architecture has several advantages. First, since each sensor runs in it's own process, development and debugging of the code is simplified. The entire submarine does not have to be running to get data from the sensor and development and debugging can occur on a workstation rather than the submarine itself. Also, since each sensor has it's own process to gather data and place it into shared memory, adding new sensors to the code base is simple and does not induce new bugs. Thus lengthy testing is not required when new sensors are added to the system.

All of the different sensor processes are handled by a process manager which has the capability to start, stop, and restart a sensor's process. Thus as the submarine moves along the competition course, systems can be turned on or off as needed. However this higher level of control is not actually handled by the process manager, but rather another process called the arbiter which will be discussed next.

Arbiter. Each of the sensor processes place their data into shared memory. Some processes make heading, speed and depth requests to improve the position of the sub in relation to the targets or to avoid collisions with objects in the water. Due to the various strengths and weaknesses of particular sensors, and the occasional sensor anomaly, these requests may sometimes conflict. Therefore an arbiter, a rule-based algorithm specifically tuned for the competition environment, is tasked with deciding on the next action for the sub, given the various, possibly erroneous, sensor inputs.

Kalman Filter. The Kalman filter is an alternative way to calculate the minimum mean-squared error (MMSE) using state-space techniques. R. E. Kalman, a former graduate research professor in the Electrical Engineering Department of University of Florida, first developed the filter in 1960. An advantage of the Kalman filter estimator is that it is computationally efficient by recursively processing noisy data. It functions as a real-time estimator based on models of the systems, and the noise under test. [8]

The Kalman filter estimates a process by using a form of feedback control. The filter estimates the process state at some point in time and then obtains feedback in the form of noisy measurements. The filter equations fall into two groups: time update equations and measurement update equations. The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the a priori estimates for the next time step. The measurement update equations are responsible for incorporating a new measurement into the a priori estimate to obtain an improved a posteriori estimate. The time update equations can also be thought of as predictor equations, while the measurement update equations can be thought of as corrector equations.

A Kalman filter is used to filter noise and disturbances out of some of the sensor data before it is put into shared memory to be accessed by the arbitor.

PID. The PID controllers assigned to each motor are the last link in the control system. They implement the final commands from the arbitor.

As the submarine moves through the water, errors between the desired and current values of heading, pitch, and depth are controlled through a standard PID controller [9]. The determination of the motor actuation values is based on the submarines position and orientation divergence according to, where m(t) is the motor value and e(t) represents the error at time step t. The continuous equation is converted to its discrete-time equivalent and the errors are calculated from the difference between the current and desired heading, pitch and depth.

The individual gains (Ki) are tuned through repetitive testing, at various depths and operating conditions. For each of the possible speed and depth range configurations, the sub maintains a separate set of control parameters. These parameters are determined through experimentation and simulation.

$$m(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d e(\dot{t}) \quad (1)$$

Underwater Vision System. The recent competition in San Diego required the locating and reading bar-coded targets. Also the heights of the targets must be determined along with the decoded bar-code number. A sonar altimeter is attached as a supplement to the vision system both for confidence and collaborative height detection.

To accomplish underwater computer vision we have developed and constructed both hardware and software capable of capturing images and processing them completely onboard the submarine. The sub is using a Unibrain Fire-i400 progressive-scan camera, capable of 640x480 resolution at 15fps. The camera has an interchangeable lens and interfaces to the embedded computer through IEEE1394 (Firewire).

The latest Linux kernels have built in support for plug-and-play Firewire devices. Using the digital camera libraries available for Linux, custom software for both frame grabbing and acquiring video were written.

The detection, localization, and classification of the underwater targets is accomplished using the camera and the computer vision algorithms. Once a barcode has been detected, that part of the image is isolated and a variant of linear regression is used to classify and decode the data. The scaling and the many possible orientations of the targets are also taken into account.

V Conclusion

This paper has discussed the designed of the submarine *Subjugator* to highlight it's reconfigurable aspects. *Subjugator* has evolved throughout the years in mechanical and software design to meet new challenges. Soon the submarine will under go another transformation and the lessons learned here will be carried forward.

Much thought went into the current mechanical design, which has several years of experience in submarine design behind it. The burton connectors used to run wires in and out of the submarine were waterproof and minimized the number of holes in the hull. Over the years, as the competition evolved, the burton connectors were adapted to connect different equipment. The mounting points on the hull have been used to mount motors and other equipment as missions changed from year to year. The electronics trays allowed the internal equipment of the submarine to be easily accessed for maintenance and repair.

The software was equally as reconfigurable. The design of process manager made adding and removing sensors year after year easy and bug free. The arbiter was the brain of the operation and the only code that had to be changed each year. Since there is a well defined interface between the arbiter and shared memory (where the data is located), modifications here did not effect the stability of the overall code base.

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