SubjuGator 2010

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ABSTRACT

For the past fourteen years, students from the University of Florida's Machine Intelligence Laboratory (MIL) have brought their minds together to design and create autonomous robots with a focus on solving real-world problems for industry and military applications. Most of the team is currently enrolled in the Electrical and Computer Engineering or Mechanical and Aerospace Engineering departments. These graduate and undergraduate students are continuing the development of the sixth generation of their autonomous underwater vehicle, SubjuGator, for competition in the AUVSI and ONR's 13th International Autonomous Underwater Vehicle Competition. Currently, SubjuGator is designed to operate underwater at depths up to 100 feet. Two 3.5" x 5.75" Intel Core 2 Duo computers running Microsoft Windows Server 2008 provide processing power for monitoring and controlling all systems. The mission behavior of SubjuGator is being developed with the Joint Architecture for Unmanned Systems (JAUS) framework that communicates with a network of smart sensors and components. The smart sensor and component network provides vehicle and environmental state information by processing and integrating information provided by two cameras, hydrophone array, Doppler velocity log (DVL), inertial measurement unit (IMU), compass, depth sensor, imaging sonar, and altimeter. The submarine also makes use of custom-designed motor controllers with current sensing, four external actuators, and other peripherals necessary for completing the mission.

Keywords

Submarine, Autonomous, SubjuGator, AUVSI, Robot

1. INTRODUCTION

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) are sponsors of the 13th annual International Autonomous Underwater Vehicle Competition, to be held in San Diego, California at the SPAWAR facility July 13th through July 18th, 2010. A student team at the University of Florida's Machine Intelligence Lab is developing an autonomous underwater vehicle (AUV) to compete in the 2010 contest. The sixth generation SubjuGator (Figure 1) has evolved to not only meet the new challenges of the competition, but to engage in groundbreaking research projects.

Figure 1. CAD Rendered Model

2. MECHANICAL PLATFORM

As a sixth-generation vehicle, SubjuGator 6c (Figure 1), embodies the lessons learned in the previous thirteen years of AUV development at the University of Florida. We considered several key design criteria, including survivability in a chlorinated or salt-water environment, inherent stability of the platform while submerged, and expansion for future sensors and actuators.

2.1 COMPUTER AIDED DESIGN

To assist in the mechanical design we have developed a detailed computer model of our submarine (Figure 1). Nearly every component of the design was modeled to optimize placement and create an organized layout.

In a project that requires a great deal of planning before implementation, SolidWorks enables our mechanical development team to visualize potential problems and allows for open discussion of possible solutions.

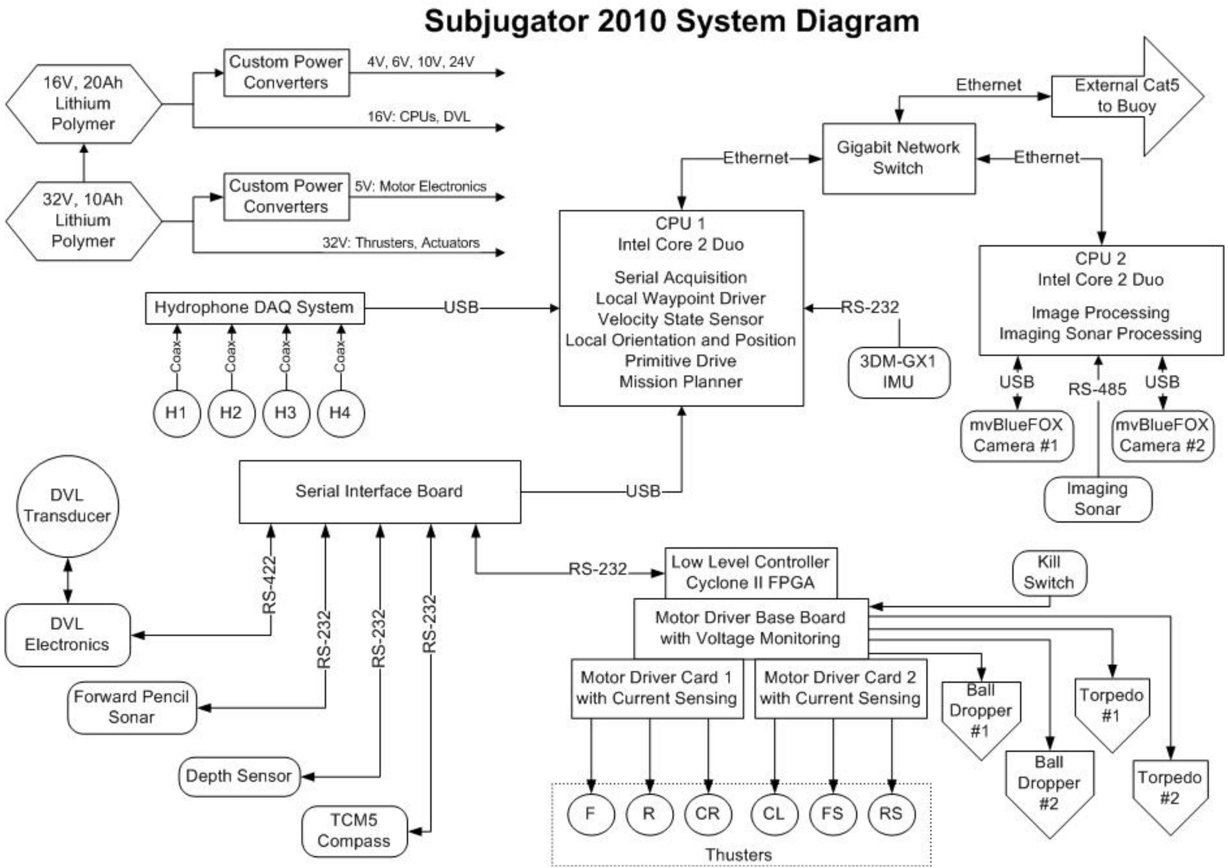

Figure 2. SubjuGator System Diagram

2.2 HULL

SubjuGator's central pressure vessel is built with a 24" long x 7" outer diameter (OD) aluminum tube with 1/8" wall thickness. Aluminum provides better machining characteristics [1] when compared to the polycarbonate of previous years, and permits more efficient heat transfer from the electronics into the water.

The end cap design was driven by the desire to implement a reliable, repeatable, and quickly deployable system. Both caps implement a double o-ring sealing system that is fault-resistant to the repeated opening and closing of the vehicle during development. The main hull is protected by a cage that is constructed from a hybrid carbon fiber and aluminum superstructure. This makes the AUV rigid, lightweight, and easy to handle. In addition, this exoskeleton protects the submarine from unintended collisions, eliminates the need for a stand, and provides a frame for the attachment of temporary or experimental sensors.

2.3 BATTERY PODS

Following the design intent of the hull, two battery pods are constructed of 20" long x 4.5" OD aluminum tubes that mount to either side of the vehicle. The tubes are symmetric so that the both sides and a spare can be freely interchanged. Stainless steel band clamps are utilized to allow for modular mounting with the existing aluminum superstructure. The positively buoyant pods are mounted near the top of the exoskeleton, adding inherent roll stability.

2.4 INTERNAL LAYOUT

SubjuGator implements a symmetric two-sided design to facilitate the easy assembly and removal of the internal electronics. This aspect of our AUV has proved very pertinent to our past success. The submarine is divided in half length-wise, with the DVL positioned directly in the center. The rear tray (Figure 3) holds the motor control system and 32V auxiliary actuator control, while the rear computer is located underneath. The front tray (Figure 4) houses a sensor interface hub, DVL electronics, hydrophone processing board, and the front computer. The two trays are guided by a pair of rails that reliably blind mate the trays to a backplane.

The DVL transducer head, compass/IMU sensor stack, and through-hull connectors are located between the two backplanes of the vehicle. This central hub allows efficient cabling between both sides of the platform, easy removal of electronics and acts as the pass-through to the external sensors and electronics via fourteen through-hull connectors.

2.5 THRUSTERS

SubjuGator is a fully actuated platform with six thrusters. Four of the six thrusters are Seabotix BTD150 thrusters, oriented to provide control for heave, sway, pitch, and yaw. Roll control is also available; however, it is coupled with yaw actuation. The remaining two thrusters are VideoRay GTO thrusters which provide control for surge and yaw. Internally, both the GTO and the BTD150 thrusters employ the same 9200 series Pittman motor, albeit with different voltage windings. The GTO employs a 3:1 gearhead transmission and a unidirectional propeller.

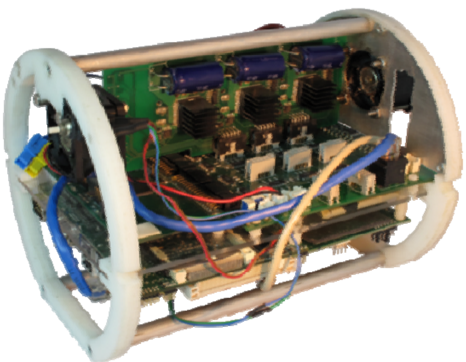

Figure 3. Rear Tray

2.6 THROUGH-HULL CONNECTIONS

All of SubjuGator's through-hull connections use Fischer Connectors' hermetic locking plugs and receptacles. The fourteen connectors can be used underwater to a depth of 260 feet. The connectors support four (of six) thrusters, power from two battery pods, four hydrophones, four external actuators, an imaging sonar, a external status display, Ethernet, and two cameras.

2.7 EXTERNAL CAMERAS

SubjuGator's external cameras utilize custom designed aluminum housings with Matrix Vision mvBlueFox-120a color USB cameras, Pentax 4mm f/1.2 CS-mount lenses, and LED arrays for illumination.

3. ELECTRONICS

3.1 BATTERIES

SubjuGator uses two separate, isolated battery systems. The electronics battery system consists of four 16V, 5Ah lithium polymer battery packs in parallel, providing approximately 300Wh at 16V. The motor battery system also consists of four 16V, 5Ah lithium polymer battery packs, providing approximately 300Wh at 32V. In typical applications SubjuGator is capable of running over four hours uninterrupted.

Lithium polymer batteries are susceptible to permanent damage from heat and excessive discharging. Hence, a custom battery protection and control system managed by an Atmel ATtiny microcontroller was implemented that provides protection functionality, independent of all internal electronics. Latching relays require a momentary pulse to turn the output power on or off. Each battery pod is signaled from outside the pod by a magnet waved over a Hall Effect switch. An under voltage monitoring network will cause an audible alarm if the voltage on any pack drops below 13.6V, and will interrupt all system power at 12.4V. Thermistors monitor temperature at three different points and will interrupt system power if the temperature exceeds 60°C.

3.2 COMPUTING

The wide variety of computing challenges posed by autonomous underwater robotics requires SubjuGator to use a diverse mix of processing systems to accomplish its goals.

3.2.1 EMBEDDED X86 COMPUTER

Major emphasis was placed on selecting an embedded computing solution that offers the highest performance available while being power efficient. Both computers run Microsoft Windows Server 2008 with the same hardware configuration: Intel T7600 Core 2 Duo 2.33GHz CPU, 2GB of 533MHz DDR2 RAM, and a 64GB SSD hard disk.

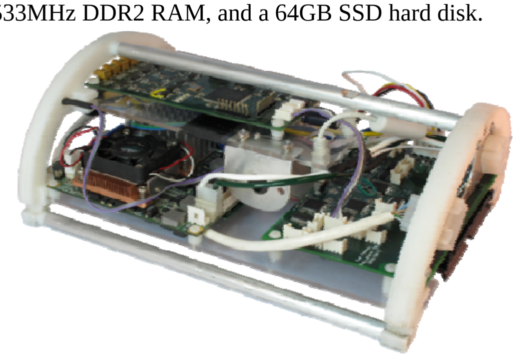

Figure 4. Front Tray

These computers are also the central point of our vehicle's sensor information and control system.

3.2.2 SUPER SERIAL BOARD

SubjuGator's custom designed Super Serial board merges all of the serial devices into two USB connections to the front computer. Containing a 4-port USB hub and four quad serial-to-USB translators, the board can provide power and connections for up to 10 RS-232 and 4 RS-422/485 serial devices.

3.2.3 ALTERA FPGA

Two Altera Cyclone II EP2C8 Field Programmable Gate Arrays (FPGAs) are utilized, one in the hydrophone data acquisition system and one in the motor control system. FPGAs are extremely versatile and allow a tremendous amount of customization to these systems.

The motor control system uses the FPGA to generate the Pulse Width Modulated (PWM) signals for motors, the actuation control signals, and thruster current measurements. This FPGA is the interface between the computer and the drive system's electronics.

The FPGA in the hydrophone data acquisition system is used for parallel data acquisition of all four passive sonar channels. After acquisition, the data is processed in real time using the rear computer.

3.2.4 *WIRELESS SYSTEM ACCESS*

A communications interface between a base station and a floating buoy utilizes a wireless Ethernet (802.11n) connection with up to a 300Mbps data path. The buoy is tethered to SubjuGator with Category 5e (CAT5e) Ethernet cable that connects to a gigabit switch inside the vehicle. The tether allows for easy viewing of real time system information, as well as access to the tunable parameters. When the tether is removed, the AUV is a completely isolated, independent autonomous entity.

3.3 NAVIGATIONAL SENSORS

For even the most basic operation, an AUV must be able to maintain a heading, depth, and attitude. Regardless of mission specific operations these sensors provide position and orientation information for basic AUV control.

3.3.1 *EXPLORER DVL*

Teledyne's Explorer Doppler Velocity Log (DVL transducer head in Figure 5) is a sensor that directly measures it's velocity in three dimensions with respect to a stationary plane (the seabed). To measure this, the piston head emits a 600 kHz acoustic pulse called a ping from four ceramic transducers. The seabed reflects this energy and the returning signals are measured by each transducer. By performing an autocorrelation of the four signals, the information results in a precise velocity vector, with accuracy on the order of ±0.5 inch per second. Additionally, on each ping, the sensor outputs an estimation of the error, and height over the average bottom. This completed packet is sent to the front computer over RS-422 at variable rates from 5 to 8 Hz.

Figure 5. DVL Transducer Head

3.3.2 *TCM5 COMPASS*

The primary orientation reference is the Precision Navigation TCM5 compass. This compass is rigidly mounted near the geometric center of our vehicle. While the compass contains accelerometers, magnetometer, and a microcontroller to perform hard-iron calibration and filtering, SubjuGator only use unfiltered magnetometer data. Since SubjuGator's platform produces a dynamic magnetic field due to close proximity of thrusters and high current power buses to the compass, a dynamic field compensation and hard iron calibration are preformed in real-time on the front computer.

3.3.3 *3DM-GX1 INERTIAL MEASUREMENT UNIT (IMU)*

The Microstrain 3DM-GX1 contains triaxial magnetometers, gyroscopes, and accelerometers, which output internally filtered data at approximately 80 Hz and unfiltered data at 300 Hz. SubjuGator utilizes the IMU's unfiltered gyroscope and accelerometer data to estimate position and orientation between updates from the DVL, or for short period of time when the DVL no longer outputs valid data.

3.3.4 *DEPTH SENSOR*

SubjuGator utilizes a Measurement Specialties Model 85 Ultrastable 30 psia pressure transducer. The transducer is a small profile, piezoresistive silicon pressure sensor in a stainless steel housing. A ceramic substrate is attached to the package that contains laser-trimmed resistors for temperature compensation and offset correction. This transducer ensures non-linearity of ±0.1%, pressure hysteresis of ±0.02%, and repeatability of ±0.02%. The piezoresistive element forms an internal Wheatstone bridge. Figure 6 shows how the transducer is utilized in our custom depth sensor system.

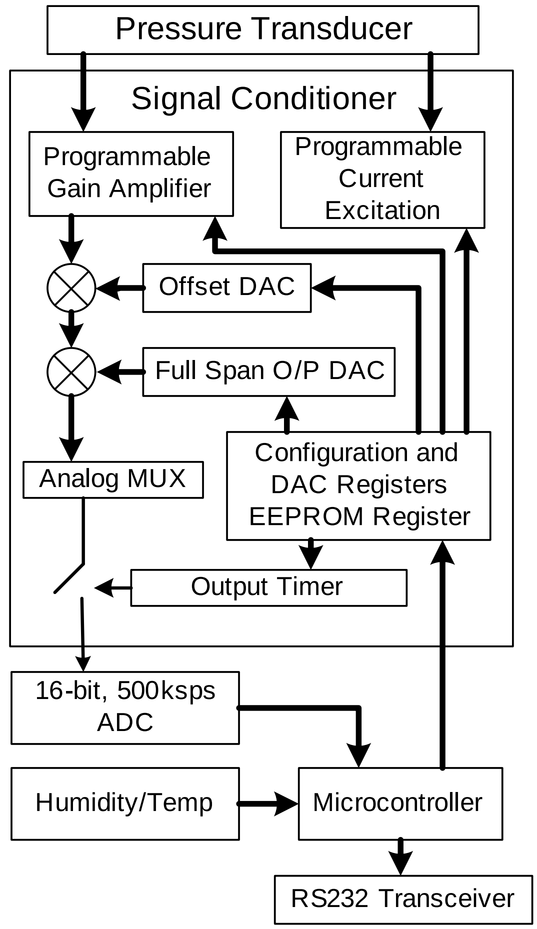

Figure 6. Custom Depth Sensor

A Maxim MAX1452 analog-sensor signal conditioner was chosen to provide the desired current excitation, offset correction, and gain. The MAX1452 architecture includes a programmable current excitation, 16-step programmable-gain amplifier, 768 bytes internal EEPROM, four 16-bit DACs for offset, span, and temperature compensation, uncommitted op-amp and on-chip temperature sensor. The fully analog signal path introduces no quantization noise in the output signal while enabling digitally controlled trimming with the integrated 16-bit DACs. It has a single serial digital I/O pin used for setting the configuration and DAC registers and reading their status. It automatically detects the baud rate of the host computer when the host transmits the initialization sequence. The analog output pin is also multiplexed to output various internal analog voltages.

The Frequency response was adjusted to 150Hz bandwidth using the on-chip uncommitted op-amp.

The analog output is digitized to a 16-bit value by an Analog AD7686 ADC, at 500ksps and transmitted over Serial Peripheral Interface (SPI). A PIC 16 microcontroller controls the internal registers of the MAX1452, reads SPI data from the ADC, processes the pressure data, scales it appropriately and then outputs the information over RS-232 to the front computer.

3.3.5 HYDROPHONE SYSTEM

The hydrophone system detects acoustic vibrations in the water, and is specifically tuned to an acoustic pinger. The system's four stages are:

1. Hydrophone Receiver
2. Analog Filter and Amplifier
3. Data Acquisition
4. Digital Signal Processing

SubjuGator utilizes four hydrophones mounted in a planar configuration resembling the letter T (Figure 7) to create the geometry needed to identify the direction from which the received signals originate [3].

Figure 7. Hydrophone Array

Reson's TC4013 hydro-phone transforms the acoustic pinger's pressure wave to a voltage signal, where the amplitude represents the magnitude of the wave. A 2nd order analog bandpass filter is used to remove frequencies outside the 19 to 31 kHz band, followed by an instrumentation amplifier to linearly increase the voltage (Figure 8). Each signal is discretized by its own analog-to-digital converter at a throughput rate of 250 kHz. The FPGA transfers the sample to local memory, and transfers a complete packet to the computer over RS-232. The digital signal processing is done with MATLAB to determine the three time-of-arrival differences between the center hydrophone and the surrounding three. Knowing the speed of sound in water, the three distance differences can be converted to azimuth angles from the array to the pinger.

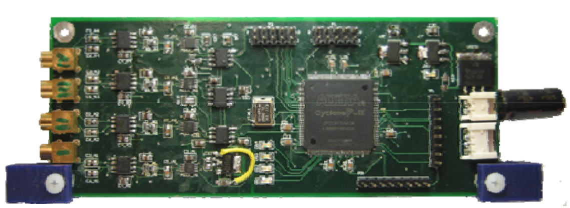

Figure 8. Hydrophone Signal Processor

4. SOFTWARE AND CONTROLS

4.1 SOFTWARE ARCHITECTURE

The SubjuGator Team is currently developing a Joint Architecture for Unmanned Systems (JAUS) software framework for SubjuGator. JAUS is an unmanned systems framework that provides an open and common communication protocol [4]. SubjuGator's implementation is designed to separate the vehicle's software into components (Figure 9). Inside of the JAUS topology, the vehicle is defined as a subsystem. Within that subsystem are nodes with defined processing capabilities. In the case of SubjuGator, the front, rear and external computer (which houses the vehicle's real-time graphical user interface) are defined as nodes.

The JAUS standard includes many predefined components that are common to most unmanned platforms. SubjuGator utilizes four predefined platform components which include the Local Waypoint Driver, Local Orientation and Position Sensor (LPOS), Velocity State Sensor (VSS), and Primitive Driver (PD). SubjuGator developed an array of custom smart sensors that capture, process, and package relevant information from four environmental sensors which include two cameras, imaging sonar, and hydrophone array.

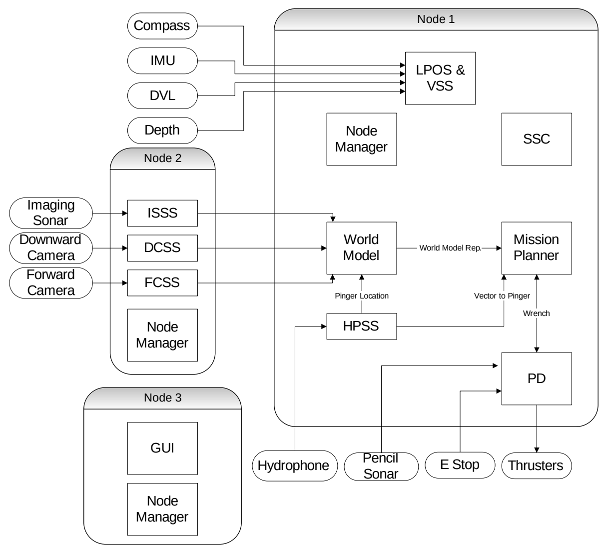

Figure 9. Software Architecture

All communication between components is directed though the node's Node Manager and is made available to all the connecting nodes and their components. At any time these components can be seamlessly moved to different nodes or can be replaced while maintaining communication over a LAN/WAN, via TCP/IP. This allows for flawless integration of the software into an evolving hardware platform.

The Mission Planner component acts as the software's central processing unit. It uses all of the information in the Local World Model, coupled with an a priori mission plan to determine the next course of action.

4.2 CONTROL SYSTEMS

Control of the vehicle is implemented in the Local Waypoint Driver (LWD) component. This service is responsible for feedback control of position and orientation using a nonlinear multilayer neural network feedforward and RISE feedback control structure [14]. Feedback is obtained through a depth sensor, DVL, IMU, motor current sensors, and compass. These sensors allow the SubjuGator to measure many of the states needed to effectively control its pose in the water. The measured states are the three translational velocities, yaw position, pitch position, roll position, approximate motor thrust, and the depth. Control inputs to the Primitive Driver service are sent from the LWD service in the form of a wrench which can be decomposed into a desired force and moment acting on the submarine.

The generated wench is then passed to the PD. The PD maps the incoming wrench to the vehicle's six thrusters through a force mapping algorithm [5]. The requested force is then produced using a unique voltage to force curve.

4.2.1 ACQUISITION AND STATE ESTIMATION

The Subjugator's data acquisition system gathers data from four multirate sensors; the TCM5 Digital Compass, the 3DM-GX1 IMU, the Teledyne Explorer DVL and our custom depth sensor. These sensor measurements are used to update and estimate the position, velocity, and orientation states of the system.

The IMU generates translational accelerations and angular velocities in the vehicle's frame at a maximum 330 Hz. The accelerations and angular velocities are integrated and transformed to a fixed coordinated frame attached to the local north, east, down tangent plane to give an estimated position, velocity, and orientation in the Internal Navigation System (INS) [6]. The estimated position, velocity, and orientation from the INS are corrected using an Indirect Unscented Kalman Filter (UKF) [7]. The indirect filter uses state error measurements to converge on a best estimate of error, which is subtracted from the INS's estimated state (Figure 10). The error measurements are generated by subtracting low order sensor measurements from the INS estimated state.

The DVL provides readings at approximately 6 Hz for translational velocities in the vehicle's frame. The velocities are transformed to the fixed frame and used as the low order sensor to generate velocity error.

The compass generates yaw, pitch and roll readings at approximately 20 Hz from magnetometers and a gravity vector estimate using the QEUST Algorithm [8]. The attitude is represented as a quaternion which relates the body frame to the fixed frame. The angular positions are used as the low order sensor to generate orientation error.

The depth sensor provides depth measurements in the fixed frame at 20 Hz and is used to generate the position error in the downward direction.

The UKF will update its error estimate upon receipt of a new reference sensor measurement. This is achieved through multiple update loops inside the UFK. In between reference sensors inputs, the INS is used to dead reckon position, velocity, and orientation.

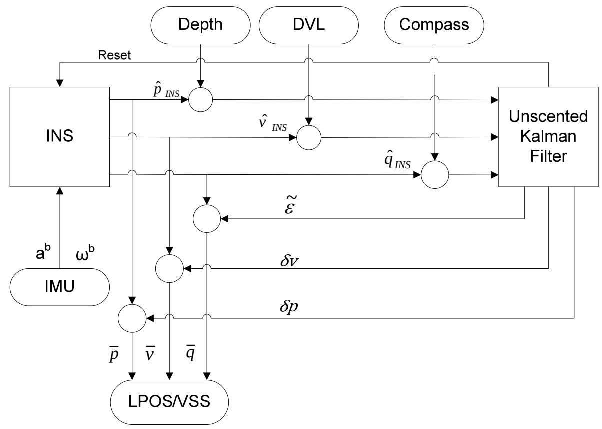

Figure 10. State Estimator Design

5. COMPUTER VISION SYSTEM

The rear onboard computer captures real-time video feeds from two USB industrial machine vision cameras. One camera faces forward to detect objects ahead of Subjugator in the water column; the second camera faces downward to detect objects lying below the vehicle.

Objects are identified by first thresholding the raw image frames received from the cameras. Adaptive thresholding techniques are used to segment objects of interest from the rest of the image [9] [10]. A Gaussian model is used to accurately segment objects with high variances. The main benefit of adaptive thresholding is the ability to segment a single object that may have different color space values at different locations on the object due to lighting variations or noise.

The major objects which must be detected using the vision system include rectangular-shaped path segments, rectangular-shaped horizontal targets, square-shaped vertical targets, circular-shaped buoys, and rectangular-shaped obstacles. Due to the similarities in object shapes, contour-based search algorithms help to identify the thresholded objects in each frame. Each object contour allows the vision system to bound the contours with geometric shapes, which can be used to provide feedback for visual servo control.

In addition to two-dimensional visual servo control, the vision system incorporates the ability to sample real-time geometric pose information using coplanar feature points on the objects. A homography based approach presented in [11] [12] allows for the determination of relative distance and orientation to objects within the field of view of the camera. Euclidean homography relationships are used to recover the pose of an object with respect to a camera frame. The Euclidean pose information obtained by the vision system can be used as additional feedback to the controller. Internal camera calibration and distortion parameters are obtained using [13].

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