Portable Low-cost Shallow Water Operation Modular Reactive Perceptive Autonomous Underwater Vehicle

Anuj Sehgal, Parth Shah, Kumar Garvit, Soumya Gayen

***Abstract*—This paper describes Jal, the new AUV designed by the student team of IURS for the purpose of shallow water survey, analysis and pipeline repair and monitoring operations. Propelled by two lateral and vertical propulsion thrusters, Jal weighs only about 7 Kg and measures close to 0.45 m in length and 0.36 m in width & height. Onboard sensor systems, custom passive sonar, real-time computer vision, sophisticated power system, a self designed IMU and a multi-agent action-oriented reactive perception software design is used for reliable operation of the submersible. The paper describes the architecture, components and software of the portable low cost AUV in detail.**

I. Introduction

WITH applications in the academic, defense, homeland security, fisheries, repair, rescue, telecommunications, power systems, geological survey and the oil and gas industries Autonomous Underwater Vehicles (AUVs) are extremely important. Carrying a plethora of sensors on board, these vehicles do not require any human control in order to perform the task at hand. The ability to collect, store, process and transmit data without the necessity of a communications or control tether to link it with any control unit increases efficiency and cost-effectiveness of these vehicles by enhancing their mission duration and range capabilities while also increasing their speeds compared to human divers and Remotely Operated Vehicles (ROVs).

High maintenance, manufacturing, development and research costs and systems complexity associated with AUVs have led to a slow adoption rate even though the industry has now begun to utilize them in comparatively simpler missions [1]. However, lightweight low-cost AUVs with relatively lower systems complexity that can be applied to a variety of missions have a very large developing market.

All IURS AUV's, LUV, BhAUV and Jal, including the currently under development AUV named *mi*LUV*u*, have been designed as low-cost lightweight submersible vehicles with an electronic and software system of relatively low complexity.

A *reactive*, or behavioral, *architecture* was used in order to coordinate and control the individual tasks performed by the AUV. While this architecture provides an overall control scheme, it lacks the insight into the actual design of the component behavior for a particular task [2]. To overcome this shortcoming of reactive architecture, *action-oriented perception* was used to obtain the appropriate response from components for a particular task. This action-oriented reactive perception architecture coupled with a multi-agent control system (MACS) form the software architecture for the AUV; combined with a layered modular electronics and hardware structure, the overall control scheme for Jal ensures low complexity with high mission adaptability.

II. Mission Capabilities

An extremely important application of unmanned underwater vehicles (UUVs) is pipeline inspection, maintenance and repair; a task that is currently extensively performed by ROVs. However, AUVs are better suited to this task because of their longer operational range and higher maneuverability [1].

Figure 1. BhAUV: IURS' First AUV; It Became the First Indian and Non-North American Entry to the US Navy Competition

A. Autonomous Navigational and Heading Control

The AUV is capable of navigating under location uncertainty by fusion of sensor data. Equipped with navigational sensors and a sophisticated heading control system the AUV is capable of tracking it's own inertial motion, correcting it's relative position with complete 6-degrees of freedom and also maintaining appropriate navigational headings suitable to the mission.

The research scholars & students of the Indian Underwater Robotics Society (IURS, now Intelligent Unmanned Robotics Society) performed this work in entirety. IURS, the funding and sponsoring agency, is a not-for-profit non-government-organization formed in order to facilitate practical applications of skills learnt in the classroom by students.

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B. Autonomous Docking

Utilizing a visual beacon the AUV is able to dock autonomously with a submerged docking station in order to enable recovery and in-mission rapid reprogramming of the AUV.

An omnidirectional light located on the docking station provides homing and navigational guidance to the AUV. The light is modulated at two different rates; a 3 kHz flash rate (square-wave, 50% duty cycle) gated on and off at 3 Hz in order to best enable detection from the farthest possible distance.

C. Pipeline inspection

A sophisticated computer vision system based on a modified 4-connectivity approach and a self-designed convolution filter for edge detection enable the AUV to track an underwater pipeline and identify cracks and fissures using texture changes for identification.

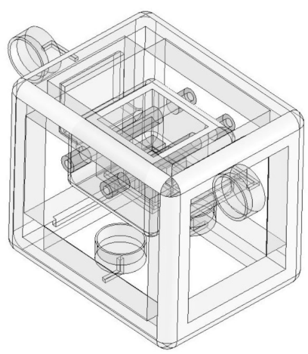

Figure 3. A 3-D Wire Mesh CAD Drawing of Jal's Development Model Mechanical Structure

D. Acoustic Tracking

Passive sonar completely designed by the IURS team is used in order to provide target identification and tracking utilizing acoustic data. This data is collected using a pair of hydrophones and enhancing the audio quality through a preamplifying variable band pass filter. The processing is done using a novel analog-digital system that encodes the first point of arrival and enables computation of the azimuth and distance basted on inter-aural time differentiation (ITD).

III. AUV DESIGN

Every component of Jal, from mechanical to software, has been designed to be modular following the lessons learnt from BhAUV's design. The aim was to construct a lightweight AUV while retaining its low-cost and mission adaptability goals. In designing, manufacturing and constructing most of the components in-house members of the IURS development team were able to meet these goals without jeopardizing the technical aspects of the AUV.

A. Mechanical Design

Jal is designed to be a modular system from the ground up. The ability to add or remove components quickly enables easy debugging, replacement of faulty parts and also provides the ability add new components easily. The frame, motor mounts, propellers, motor shrouds, the primary hull and the cooling system constitute the mechanical components of the AUV.

The AUV has been equipped with two vertical thrusters and two lateral thrusters as shown in Fig. 3. In order to keep the overall cost of thrusters' construction low 12V 2A Rule 1100 GPH bilge pump motors [4] were used to power Jal's locomotion. These motors are mounted within custom-designed thrusters housing, also containing motor shrouds for operational safety, to better control the flow direction and thrust provided by the motors. Brass propeller blades were used in order to replace the impellers that the bilge pumps ship with. An example of these self-created thrusters can be seen in Fig. 4.

Figure 4. Bilge pump based thruster design.

The primary hull, designed from 10 cm PVC pipe, is the waterproof compartment that houses all the electronics. Furthermore, a frame of 1.25 cm PVC has been constructed around the primary hull in order to allow quick and easy placement and removal of additional external components. Furthermore, this PVC frame provides trim control for the AUV as well by selectively flooding specific quantities into specific pipes.

In order to provide good heat dissipation to the electronics housed inside the primary hull two tubes run through it as well. When these tubes fill up with water they help in radiating the heat generated by the electronics inside the primary hull.

The frame of the entire AUV measures 0.45m in length and 0.36m in width and height and the total weight of the AUV, including all electronics, is only about 7 Kg. The relatively small size and low weight make it extremely portable and highly manoeuvrable.

B. Electrical Systems

The AUV is equipped with some highly complex electronics like the drive system, computing backbone and sensors; as such the electronics needed a triple voltage configuration in order to have appropriate voltages supplied to the individual components. Completely isolated power supply systems were used to separate the drive motors and the electronic subsystems in order to avoid damaging feedbacks and draws. Furthermore, each subsystem has its own power supply regulators and has also been protected by using fuses to avoid any unexpected failure or current draw while maintaining a steady voltage.

For emergencies, a main kill switch controls the power supply to the motors. The switch also controls a digital circuit monitored by the power monitor agent to put the system in a standby mode or in software shutdown mode after saving mission data.

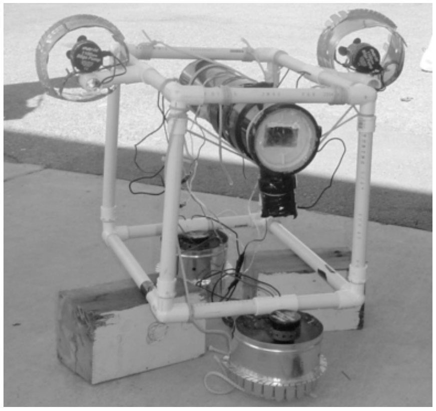

Figure 5. Jal – IURS' 2006 Competition AUV

Three 6000mAh 11.1V lithium poly pack batteries power the drive system of Jal. Connecting all of these in series provides 18Ah of current; an additional lithium poly pack also provides us power for the x86 CPU that draws peak current of 5A, thereby providing the AUV a minimum operational capacity of 1 hour. 5V batteries power other electronics; and a 9V dual power supply is used for the acoustic filters.

Lithium polymer batteries explode when the batteries are overcharged, or, if a single cell in the battery is discharged below 3V; the capability of the battery is annihilated [5]. To overcome this volatility of lithium polymer batteries, Jal also has power monitoring capabilities in the form of a battery protection circuit that can cut off power supply in case the battery voltage falls below a threshold voltage set experimentally using a comparator. Furthermore, to ensure reliable and safe operation of the electronic equipment each motor's power supply is also isolated from each other.

C. Processing & Computing Units

In order to retain the modular design of the system and also isolate each high processing requirement electronic system as best possible from the other, Jal makes use of multiple processing units that are organized in a Master-Slave relationship. Each of these processing systems was chosen since they are best suited to the task that they perform. Currently, the AUV utilizes a VIA EPIA Mini-ITX form factor x86 system as the primary processing unit (PPU) along with two slave processing unit (SPU) microcontrollers, the Atmel AVR ATMega16 and Savage Innovations OOPic-C.

The VIA Mini-ITX, used as the PPU, is an x86 architecture based single board computer motherboard supporting low power consumption with a small footprint. Equipped with a 1GHz processor the Mini-ITX in Jal provides the ability to install IDE drives for data logging, an Ethernet port for easy LAN access, RS-232 and USB 2.0 ports for I/O systems, thereby amounting to a highly formidable computing platform; all of which fit into a small form factor. Equipped with ample hard drive storage and memory the Mini-ITX provides the fastest and most flexible possible operation environment.

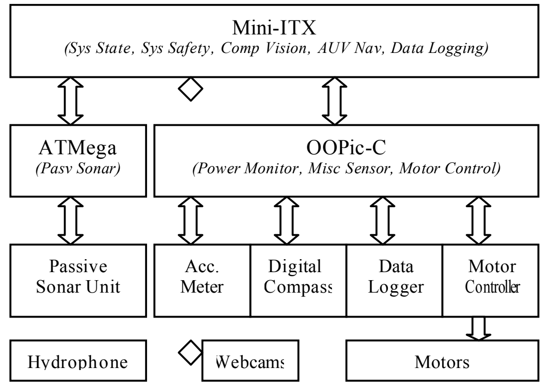

Figure 6. PPU & SPU Control System Architecture – Software Agents in Parenthesis

Utilizing this platform as the PPU allows us to rapidly program software in a familiar development environment and utilize the benefits of easily available components for the system. Furthermore, the Ethernet link to the vehicle is used to control, develop and test the vehicle before it is placed into operation mode. Data can be collected in real-time over this link; it also allows the vehicle to be remotely operated like a ROV and for in place programming and debugging utilizing tools already placed on the AUV. All the high-level software agents work on this PPU; an overview of all agents along with their host processing units and system control architecture is provided in Fig. 6.

The ATMega16 microcontroller board onboard Jal was designed by the team itself for use as an SPU in order to run the middleware software agents. This processor uses an 8 MHz crystal to provide a relatively high clock speed necessary for high-speed timing between the interrupts raised by the passive sonar system. The custom designed development board provides 32 available I/O points and an RS-232 port for communication with the PPU. It's built in real time clock along with the 16-bit counter and low power requirements make it a suitable microcontroller for the passive sonar subsystem of the AUV. The passive sonar system interfaces to an interrupt on the ATMega16, which runs the passive sonar agent as well.

Another SPU being used on the AUV is the OOPic-C microcontroller manufactured by Savage Innovations. The greatest advantage of using the OOPic-C is that its serial control protocol (SCP) allows for rapid development of communications between the OOPic-C and the PPU; SCP also provides the ability for the OOPic-C to be reprogrammed on the fly during an active mission, thereby reconfiguring the SPU to better suit its operating environment and parameters.

Additionally, SCP allows the OOPic-C's active application to be stopped, single stepped, resumed or branched to while being controlled by the PPU. SCP also provides direct access to the RAM, EEMPROM and I2C port without the need for developing interface software. This SPU's role is to communicate with the navigational sensor systems while also providing a data logging and motor control interface to the PPU. The OOPic-C board resides on a custom fabricated PCB that contains other sensors and devices it interfaces with over I2C and analog signals and also an RS-232 port for communication with the PPU.

D. Navigational Sensors

Jal's navigational sensor suite consists of digital compass sensor, pressure sensor and an accelerometer. These low cost sensor devices were chosen over complex high-level sensors like IMUs in order to keep the system complexity and overall cost as low as possible; while not as advanced as IMUs these sensors provide all the capabilities that such an AUV requires. Even though the acoustic and vision subsystems are navigational devices, due to their relative complexity these are treated as separate systems and discussed in following sections.

A digital compass sensor operating over the I2C protocol and interfaced with the OOPic-C SPU is being used to assist the AUV in following a particular heading without deviation. This compass works on a nominal voltage of 5V and provides a resolution of 0.1 degrees with accuracy between 3-4 degrees.

Horizontally mounted on the custom sensor board PCB inside the primary hull, readings provided by the CMPS03 over the I2C protocol are in uniform robotic control protocol (URCP) values [6]. As such, a particular heading is represented not in degrees or radians but rather in brads. Unlike analogue signals that need to be converted to digital and then calibrated with respect to the environment, URCP values are pre-calibrated to suit multiple environments [6]. The high resolution and URCP capabilities of the digital compass ensure accurate heading information and control for the AUV.

To further aid the navigation capabilities of the AUV two dual-axis accelerometers are mounted horizontally inside the primary hull of the AUV and provide a PWM signal corresponding to the tilt on a particular axis. Mounted perpendicular to each other these accelerometers are able to provide tilt and acceleration information on every axis; pitch, roll and yaw are covered accurately owing to the accelerometer's resolution of 1 mg with the ability to measure acceleration up to ±2g.

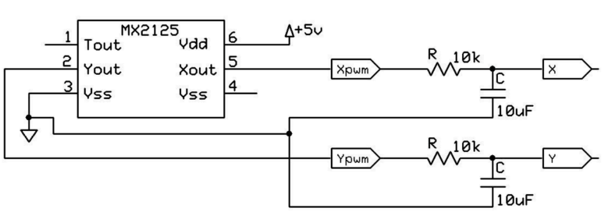

Figure 7. Accelerometer PWM signal to Analog Signal R-C Converter

The PWM signals for both X & Y axis are then passed through an R-C filter (shown in Fig. 7) in order to convert the PWM into a continuous analog signal that can be read by the OOPic SPU into its 10-bit ADC. The calibrated output provided by the sensor is used to provide roll, pitch and yaw stability while also sensing any object collisions. This accelerometer is also equipped with a temperature sensor that is used for data logging and systems safety purposes.

Additionally the OOPic also interfaces with a Motorola pressure sensor that acts like a depth meter in order to maintain a steady altitude during an operational mission. This differential pressure sensor can take measurements up to 36 PSI and provides a linear analogue voltage output proportional to the pressure. This sensor is connected to the OOPic-C's A/D converter as well in order to monitor the depth that the AUV attains.

E. Vision System

Most existing terrestrial computer vision algorithms are insufficient for underwater use for many reasons such as limited visibility, poor light conditions, variability of image quality, visual artifacts induced by moving artificial sources, objects lacking regular structure and form due to refraction, etc [7].

It was towards countering some of these shortcomings that the team designed our hue-based image processing system, called TOUCH [8], to use digital video and provide target guidance for underwater vehicles efficiently in real-time. The advantage of using hue in an underwater system is that hue is a property dependent on the dominant wavelength of light reflected from a particular surface and as a result does not change when reflected off a particular surface across various illumination conditions [9]. Moreover, hue also is a relative representation of the red, green and blue colors in one value itself [9,10,11], thereby, greatly improving the response time of the system since only one value needs to be acquired and processed.

Jal is equipped with two webcams mounted within the primary hull, one facing forward while the other is bottom facing. This configuration of the webcams allows for the software to dedicate one webcam towards locating the docking station, target tracking or other mission defined purposes while the other is used to track the pipeline and identify the abnormalities.

A blob-tracking mechanism is used by the AUV's vision system in order to locate the docking station and pipeline. Unlike the traditional 4-connectivity algorithm that is relatively slow for a real-time implementation on non-specialized hardware [9], TOUCH is based on a modified 4-connectivity algorithm that is based on native digital video processing that allows for real-time video decoding. The modified 4-connectivity algorithm obtains the image as a matrix of pixels; then starting at coordinates (0,0) the 4-neighborhood is analyzed for connectivity and then it proceeds to the next coordinate horizontally, which is (0,1) and only analyzes it if it has not already been tested for connectivity. By doing so, the modified 4-connectivity does not analyze every cell for connectivity, but only the ones that have not been already checked, thus improving the running time of 4-connectivity greatly.

Instead of one value itself TOUCH uses a range for the target hue of the object such that if the hue is represented by H, then,

$$H_{min} < H < H_{max}$$

where H_{min} is the lowest acceptable weight and H_{max} is the highest acceptable weight for the hue. This method of operation overcomes problems like refraction and turbulence in the water that can cause changes in wavelength of the light being intercepted by the cameras.

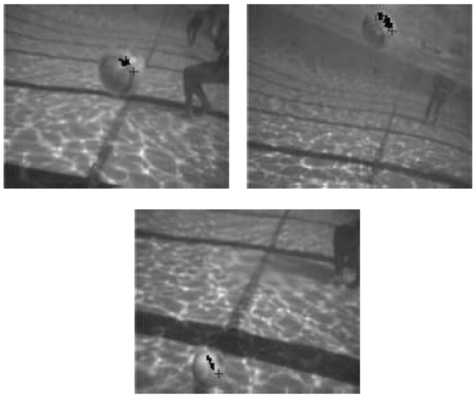

Figure 8. Underwater blob tracking results from TOUCH; The '+' sign marks the target, in this case a tennis ball

Additionally, the video stream is also normalized in real time by running a histogram on the image frames and eliminating the highest occurring values from the frame since these mostly constitute of the background and not the actual target.

-1	-1	-1
-1	8	-1
-1	-1	-1

Figure 9. Convolution Filter for Edge Detection

TOUCH is currently used in order to locate the blinking light beacon of the docking station and is also applied towards locating the pipeline. Furthermore, TOUCH is also utilized to initially locate the pipeline and then control is passed to the edge detection system to follow it. The target hue range values used by TOUCH are determined experimentally in order to provide the maximum accuracy.

Edge detection techniques are extremely useful in tracking an acquired target; this very method is utilized by the AUV to track the pipeline once TOUCH acquires it. To find the edges of the pipeline a simple convolution filter, shown in Fig. 9, is applied to the image.

In order to apply the shown 3x3 convolution filter to the image, its values are multiplied with the values of a data block within the image; following this, the resultant values of the multiplication are summed up. If this sum of the resultant values is S, then the $v=(S/d)+B$, where d is the divisor and B the bias, i.e., 1 and 0 respectively for our filter.

If the value $S > 255$ then we set $S = 255$ and if $S < 0$ it is set to $S = 0$. As such, S becomes the new pixel value for the central pixel in the data block just examined. This same method is then repeated for the other 3x3 data blocks in the image and all edges of the image stream are ignored. Fig. 10 shows an example of how this filter is able to filter out only the edges of an underwater pipeline. It is fairly simple to track the pipeline once this image is obtained by calculating the centroid of the image that causes the coordinates to always lie on the edge of the pipeline.

Figure 10. Resultant image of underwater pipeline after application of the convolution filter

F. *Passive Sonar Array*

Sonar navigation is a technique used by submersibles to detect various underwater bodies. Sound travels in water with much greater ease than light thereby making acoustic systems the primary source for localization systems below the water's surface [12].

Passive sonar systems, like the one that Jal is equipped with, listen without emitting any sound waves. They play a very vital role in detection and tracking of acoustic sources underwater. Jal utilizes an onboard passive sonar array configuration with individual transceivers placed in an Ultra-short, or Super-short, Baseline System (USBL or SSBL) in order to continuously detect and localize the acoustic sources.

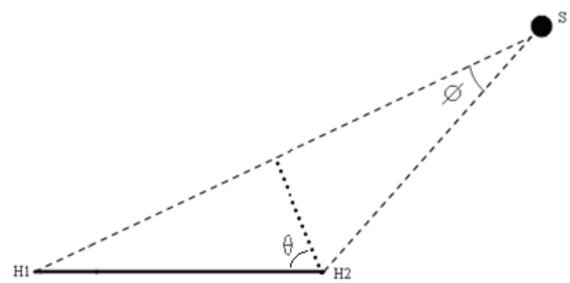

Figure 11. Conceptual representation of hydrophones in a USBL configuration on and AUV and an acoustic source.

A USBL system measures phase comparison on an arriving "ping", from the acoustic source, between individual elements within the hydrophone array. This coupled with a time of flight interrogation technique provides a range to the beacon as well. Low system complexity and good range accuracy with time of flight systems [12] makes a USBL arrangement of the hydrophones an appropriate configuration. Furthermore, being a shallow to medium depth water solution [12], USBL is also an excellent choice because the accuracy of USBL acoustic systems is quoted as a percentage of slant range [13]; in other words, USBL is appropriate for medium to shallow waters.

Hydrophones with frequency response in the range of 10 Hz to 50 KHz and an omni-directional polar response are used on the AUV. A pair of these hydrophones spaced a maximum of ½ wavelengths apart to the center frequency of the incoming signal is mounted on the starboard and port sides of the AUV in order to provide the most efficient configuration. The only disadvantage of using two hydrophones is the ambiguity in the direction of the acoustic source, i.e. whether it is located towards the bow of the vehicle or the stern. This ambiguity can be overcome by spinning at a particular point to take multiple samples of the sound generated by the acoustic source.

The raw signal obtained through the hydrophones contains all the undesired ambient noise and frequencies while the voltage is also not high enough for further effective processing of the signal. To maintain a low cost point for the acoustic system as well, the hydrophones used are not equipped with built-in preamplifiers. As such, an external preamplifier that assists in amplifying the voltage to a level suitable for processing rejects and provides a wide bandwidth for effective processing of the signal was also designed by IURS.

This preamplified signal is passed through an active band pass filter with calculated variable resistors and capacitor values enabling us to choose any frequency between 20 kHz to 30 kHz with a bandwidth which can go as low as 1 kHz to a maximum of 10 kHz, in order to rapidly adapt the acoustic system to function with the greatest accuracy against the frequency of the acoustic source. Comparators are used to compare the amplitude voltage with an experimentally determined threshold.

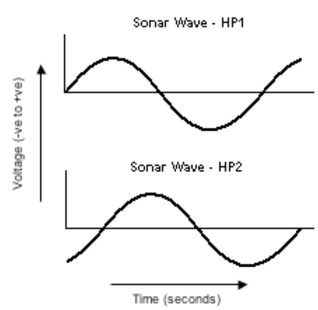

Figure 12. Analog Sonar AC waves as received on the hydrophones.

To surface exactly at the source of the acoustic signals the bearing angle, azimuth, with respect to the AUV needs to be calculated [13]. Jal achieves this by calculating the time difference of arrival (TDOA) of the wave front at the two hydrophones. This is an analogy to the Interaural Time Difference (ITD) cue used in the auditory cortex of the mammalian brain [14, 15]. ITD in Sonar Localization is the time taken by sound to arrive at the contralateral hydrophone once the ipsilateral hydrophone has detected the sound. When the first hydrophone detects the ping, the TDOA needs to be calculated from the same point along the waveform in order to get the accurate measure of the ITD.

The signal processing method used to calculate the TDOA based on ITD and the first point of arrival (FPA) calculates the phase difference of the waves received at two hydrophones, H1 and H2. A conceptual representation of this hydrophone configuration is shown in Fig. 11.

The waves received at the two hydrophones, H1 and H2, are phase shifted because the distance the wave generated by the acoustic source, S in Fig. 11, has to travel in order to reach the two hydrophones will not be exactly the same while the AUV is acquiring headings. As such, the waves received from the acoustic source at the two hydrophones resemble the AC waves depicted in Fig. 12.

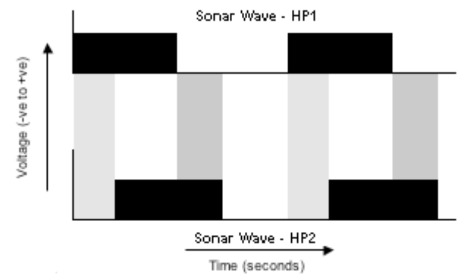

Figure 13. AC Sonar waves converted to equivalent TTL.

In order to calculate the TDOA and FPA these waves are converted to their corresponding square waves using a Schmidt Trigger based circuit. This transformation of the AC waves is depicted in Fig. 13; the dark black shaded areas on the two axes are the crests of the square waves, while the light grey shaded area depicts the time difference of arrival, or TDOA, of the sonar pings between the two hydrophones; the dark grey area on the other hand depicts the time it takes for the ping to complete on the second hydrophone after the signal has already subsided on the first hydrophone.

By subtracting the two square waves in Fig. 13 a third wave, shown in Fig. 14, which corresponds to the light and dark grey shaded areas, is obtained. This newly obtained wave contains all the information necessary to deduce the FPA, calculate the TDOA and also the distance to the sonar beacon in the recovery zone.

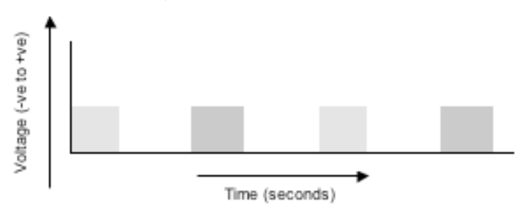

Figure 14. Square wave resultant from subtraction of AC Wave TTL Equivalents; contains FPA and TDOA information.

As such, if the resultant square wave in Fig. 14 is in the negative spectrum, the FPA is computed to be H2, whereas if the vice-versa were the case then the FPA would be H1. The length of time the light grey crest from Fig. 14 stays high provides the TDOA as well.

Since the obtained wave also provides the ability to calculate the total time of flight between the first and second pings, the distance to the acoustic source is easily calculable by the formula,

$$s = v * t.$$

In order to obtain this value, it can further be assumed that the time difference between each pulse emitted by S is X seconds and that the pulse lasts for Y seconds. Now, if T_X is the time when the first dark grey pulse starts and T_Y represents the time when the second light grey pulse starts, then

$$t = (T_Y - T_X) - (X + Y)$$

while v is the velocity of sound in water.

Assuming that the sonar source is located at point S, as in Fig. 11, and the robot is between points H1 and H2, with H1 and H2 being the two hydrophones that are placed in a baseline configuration, then the angle that the AUV needs to modify its heading by, in order to be directly facing the acoustic source, is the angle *theta*. Using the method described, since the TDOA is known, *theta* may now be calculated in order to obtain the angle by which the AUV must modify its angle to have an accurate heading towards the retrieval zone and the distance to the acoustic source may also be calculated using the method provided above.

G. Software System

A reactive architecture was used for the development of the software in order to eliminate the need for constructing explicit course models [16] and avoiding the need to dead-reckon the course in advance. [17]. Since this model lacked the necessary insight on individual component behaviour it was coupled with the action-oriented perception [18] approach forming the action-oriented reactive perception software model for the AUV.

This allowed the team to approach each task as its own mission and develop software suited for it by following action-oriented perception method of sensing the environment and performing a task based on the sensory input. Using the reactive approach the beginning and end of a particular task were easily identified.

The action-oriented reactive perception approach made it necessary to maintain modularity of the software and isolation of each task's software from the other. Towards this goal each system was designed with its own agents that communicated indirectly through a central system agent. Using multiple agents provided the advantage of performing the software development for the AUV in languages suitable for an individual task. VB .NET, MATLAB, C and Perl on WinXPe were used.

The control software was also divided into multiple agents in order to simplify the development cycle and retain software modularity. At the highest level runs the state agent that changes states of the system to development, mission or standby. In the development state the software executes in ROV mode allowing for testing, development and debugging; this mode is automatically activated upon detecting a LAN connection. The mission state, activated by pushing the start button, executes the programmed mission tasks and the standby state, activated by flipping the kill switch, puts Jal into a ready state to execute the mission. A relationship diagram of all the software agents in Jal is provided in Fig. 15.

The AUV navigation agent gathers data from navigational devices and controls the motors according to the task it needs to perform; the system safety agent monitors system parameters and power levels and in case of a value exceeding thresholds it shuts down the system, faulty agent or the motor depending on the severity of the failure. The computer vision, misc. sensors and passive sonar agents are responsible for their own self-describable tasks. The motor control agent is dedicated to controlling the direction of the motors. All the data flowing between these agents is also intercepted by the data-logging agent and recorded along with time stamps in order to assist with debugging the system and further improve the AUV during development.

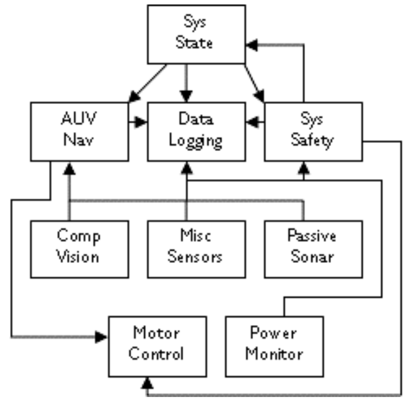

Figure 15. Software Agents Relationship Chart

IV. Conclusions

Good performance of the AUV during the test runs and encouraging feedback from expert AUV developers and industry at the AUVSI competition has reinforced the belief that the team is accurately developing an effective system. Having one of the lightest and the cheapest AUV's across the globe it is clear that the low-cost methodologies used by the development team are also useful. The team is now focussing on enhancing the efficiency and accuracy of the individual systems since there were no major breakdowns or failures in the software and other systems; other than unpredictable electronic hardware failures, which were within tolerable norms. The low-cost lightweight mission adaptable design of this AUV makes it an excellent platform for academic and hobbyist research and also for other teams interested in developing low-cost underwater vehicles.

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