Computer Vision, Sonar and Sensor fusion for Autonomous Underwater Vehicle (AUV) Navigation

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Abstract

Even though a lot of research has been devoted towards AUVs in the West, the developing Eastern nations like India lack programs for development of AUV technologies that would better position them to understand their oceans. As such, the Indian Underwater Robotics Society started development of the first Indian AUV that would be portable and low cost while having widespread applications in academia, science, military, communication systems and public safety industries. The most important aspects of an AUV are its sensors, computer vision and sonar subsystems that assist its navigation. This paper presents some details on the sensor systems that were used in the AUV last year and also some of the developments that are in the pipeline for this year; including details on the patented computer vision system TOUCH and a passive sonar subsystem.

1. Introduction

AUVs have greatly improved the overall efficiency of marine research and also operations in the ocean related industries. By eliminating the operator from the chain of operation AUVs provide a much higher level of fault tolerance and are also able to perform much more complex tasks without being dependent on the limited capabilities and skill sets of their operator. Unlike Remotely Operated Vehicles, AUVs do not need to have a tether cable, thereby greatly extending the range of operation of the submersible vehicle. As such, AUVs can be effectively used for research, delivery and search and rescue operations in treacherous conditions and for complex tasks without endangering human lives. These robotic devices are also a great blessing for the scientific community as they simplify the research process by increasing accessibility to the oceans [1].

Autonomous robotic technologies are finding increasing commercial, scientific, defense and academic applications [2]; however, their high maintenance, development and manufacturing costs are the reasons that have kept AUVs out of developing nations [3]. In order to encourage adoption of these autonomous submersible vehicles the Indian Underwater Robotics Society (IURS) started work on a low-cost portable and modular task-adaptable AUV that could make these vehicles affordable.

The following sections of this paper will present some details on the computer vision, sonar and sensor systems along with an overview on the control system that integrates the input from all these sources to deduce an action or to compute navigational data. Some details on the sections ahead are provided below:

- Section 2 – BhAUV, The Indian AUV: This section provides insight into the design of the AUV that IURS has worked on and continues to develop. Some of the sensor systems and the physical design of the AUV are discussed along with the software as well.
- Section 3 – The sensor suite: All the major sensors being used to compute the navigational component and also the actions are covered.
- Section 4 – Computer Vision: TOUCH, the patented computer vision system that was developed by members of the society is presented.
- Section 5 – Passive Sonar Array: The details of the passive sonar array being used for acoustic target detection are discussed.
- Section 6 – Conclusions.

2. BhAUV, The Indian AUV

In order to be efficient and operational the design of an AUV needs to counteract the excessive drag created in water, have an appropriate buoyancy to allow the submersible to dive and surface without problems, and yaw/pitch/roll stability to maintain the suitable course without too many corrections [1, 2, 4].

The AUV being developed by the IURS named Bharat Autonomous Underwater Vehicle (BhAUV) has its components placed in a fashion that moves its centre of gravity below the submersible itself and also distribute the weight uniformly thereby creating yaw/pitch/roll stability. The issue of portability has also been successfully addressed with the design of BhAUV since the AUV only weighs approximately 10 Kg and is extremely small in size, about 3’ x 1.5’ x 1.5’ [1]. Figure 1 shows the first version of BhAUV that was successfully tested by the development team.

Figure 1. The AUV BhAUV

As seen in Figure 1, BhAUV has four screws that aid in its propulsion. The two screws on the outermost extremities of the starboard and port side assist in lateral propulsion whereas the two screws between the lateral propulsion screws and the main hull aid in diving and surfacing the vehicle.

The vehicle is designed with a primary and secondary hull. The primary hull houses the main electronics and battery power, whereas, the secondary hull was designed to house only the webcams for computer vision tasks. The primary hull of the vehicle has a total of eight bulkheads, four on the port side and the rest on the starboard side, to allow the electrical cables to pass through the hull and maintain the water tight nature of it. The electronics inside the primary hull are mounted as shown in Figures 2 and 3.

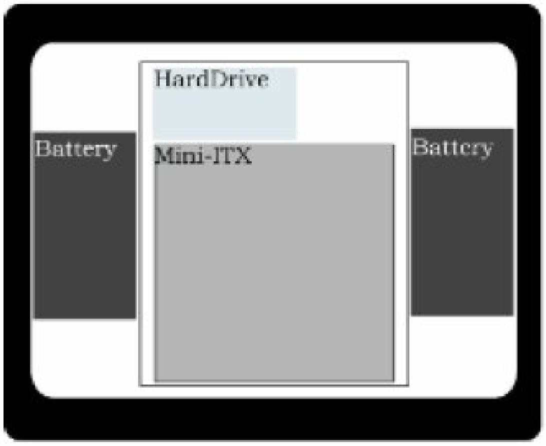


Figure 2. Top view of the primary hull

The secondary hull of the AUV is designed only to house the vision processing subsystem that consists of two webcams, one facing forward and one downward to provide a large field of view.

Figure 3. Side view of the primary hull

BhAUV is equipped with two webcams for effective computer vision, an extensive sensor suite consisting of depth and leak sensors, digital compass, accelerometers to counter the yaw, pitch and roll and also a passive sonar subsystem for acoustic target location. In addition to the sensing system, the submersible has two high current dual H-bridge drivers that control the four propulsion screws.

This design of the AUV is however being modified now to be more modularized and efficient. As part of this goal, the twin hull design is being replaced with a single frame that will house independent hulls for the critical subsystems. This will allow quick removal and addition of components into the submersible. Also, the size of the AUV is being reduced to only 2’ x 1.5’ x 1.5’. Due to previous experiences [1, 2] with the dual H-bridges, these are being replaced with dedicated high-current H-bridges for each screw. These revisions in the design are sure to improve the performance of BhAUV while maintaining its low-cost and portable aspects.

3. The Sensor Suite

Coupled with the high capacity hard drive, the extensive sensor suite makes BhAUV an excellent marine data gathering platform that is capable of recording not only sensor information but also time stamped videos or still pictures of the environment that it is deployed in. The first version of BhAUV was equipped with only a digital compass, leak sensor, accelerometer and pressure sensor [1]. However, the new revision of BhAUV will also contain an additional accelerometer and a temperature sensor.

The digital compass is used in order to obtain the current heading information of the submersible while also ensuring that the submersible remains on course. Additionally, any new heading information calculated is correlated with information provided by the digital compass to calculate the appropriate new heading.

The accelerometer being used is a dual-axis accelerometer; thus, the use of two accelerometers allows us to obtain acceleration vectors for all three dimensions of movement. As such, not only is it possible to use the accelerometers to control the descent, ascent and lateral motion [1] of the robot but also to use them as bump sensors to detect the direction in which the AUV bumped an object. The data obtained from the temperature sensor is used for data logging purposes and also to monitor the ambient operation environment and determine when it is unsafe for the AUV to continue operating. This data is also stamped on the video frames that are captured by the computer vision system along with the data acquired from the pressure sensor.

The pressure sensor mounted externally is used to calculate the depth of the AUV and also control the pressure release hatch in order to release pressure in case it nears critical. Additionally, the information from the pressure sensor is used to determine the amount of thrust that would be required in order to surface the submersible as well. The analog data received from the pressure sensor and the temperature sensor is converted to digital using the inbuilt ADC lines on the microprocessor.

4. Computer Vision

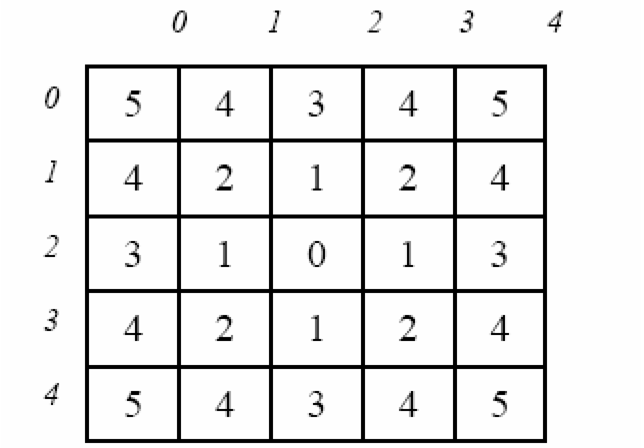
Most of the existing terrestrial computer vision algorithms are insufficient for underwater computer vision for many reasons such as limited visibility, poor light conditions, variability of image quality, visual artifacts induced by moving artificial sources, objects lacking regular structure and form due to refraction, etc [4]. A combination of mentioned and other factors leads to unfavorable conditions for usage of computer vision as a tool for underwater object recognition and tracking in this environment features that are generally extracted from an image in terrestrial vision systems tend to disappear rather quickly [5].

There are at present many algorithms that present ways to generate three dimensional images based on acoustic imaging [6]. With all their advantages these algorithms fail to represent the visual light spectrum and as such do not depict extremely valuable information for analysis by the robotic vehicle. It was towards countering this shortcoming of the popular methods that TOUCH was designed to use digital video and provide target guidance for underwater vehicles efficiently in real-time [5].

Unlike the traditional 4-connectivity algorithm which is relatively slow for a real-time implementation on non-specialized hardware [7], the TOUCH algorithm is based on a modified 4-connectivity algorithm that is based on native digital video processing that allows for real-time video decoding to take place.

The modified 4-connectivity algorithm obtains the image as a matrix; 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). The neighborhood of this coordinate, (0, 1), has not already been analyzed 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. Also, the iterative version uses fewer resources than a recursive search. A sample of the matrix that would be retrieved by TOUCH is provided below:



	0	1	2	3	4
0	5	4	3	4	5
1	4	2	1	2	4
2	3	1	0	1	3
3	4	2	1	2	4
4	5	4	3	4	5

This modified 4-connectivity method is very efficient in its performance for analyzing the connectivity of pixels. Pseudocode for the modified 4-connectivity algorithm follows [5]:

```
Get Image[x][y]; //x, y is the resolution
For r from 0 to y
    For c from 0 to x
        If Image[r+1][c] = Image[r][c] Then
            Image[r+1][c] is connected;
        Else
            Image[r+1][c] is not connected;
        End If
        If Image[r-1][c] = Image[r][c] Then
            Image[r-1][c] is connected;
        Else
            Image[r-1][c] is not connected;
        End If
        If Image[r][c+1] = Image[r][c] Then
            Image[r][c+1] is connected;
        Else
```

```
            Image[r][c+1] is not connected;
        End If
        If Image[r][c-1] = Image[r][c] Then
            Image[r][c-1] is connected;
        Else
            Image[r][c-1] is not connected;
        End If
    Loop
Loop
```

TOUCH works by scanning the frames for a target hue that is decided by the user. Hue is a property that is dependent on the dominant wavelength of light reflected from a particular surface and as a result does not change when reflected off of a particular surface [7]. Moreover, hue also is a relative representation of the red, green and blue colors in one value itself [8], thereby, greatly improving the response times of the system since only one value needs to be acquired and processed.

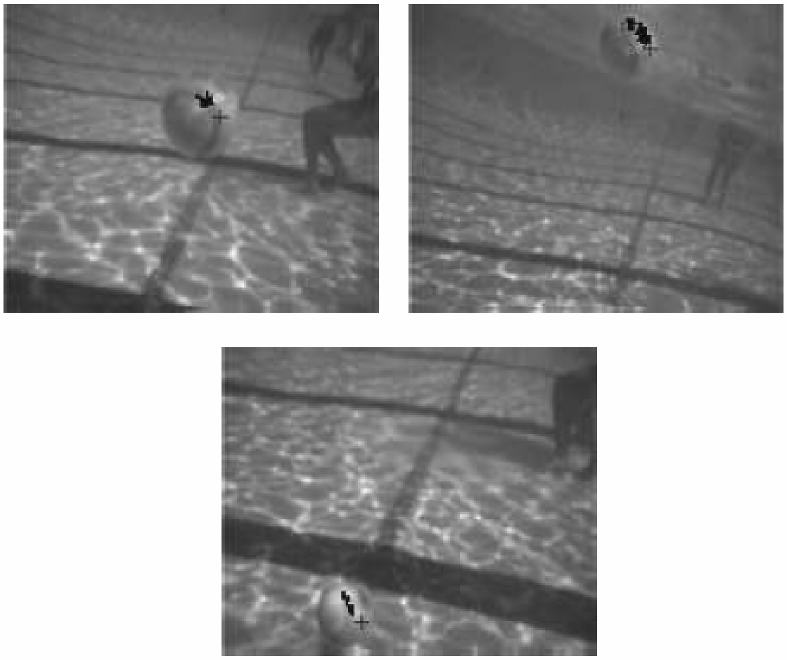


Figure 4. Tracking results from TOUCH

Since refraction and turbulence in the water can cause changes in wavelength of the light being intercepted by the camera, TOUCH uses target range for the hue, instead of one value itself. This range is such that, if the hue is represented by H, then,

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

such that H_{min} is the lowest acceptable weight for the hue and H_{max} is the highest acceptable weight for the hue.

This method of using the hue range with modified 4-connectivity is used to identify objects underwater and track them effectively at high speeds. Figure 4 shows some typical frames outputted from TOUCH. These images were recorded while a tennis ball was thrown into a pool at high speeds and a + marks the ball in those images.

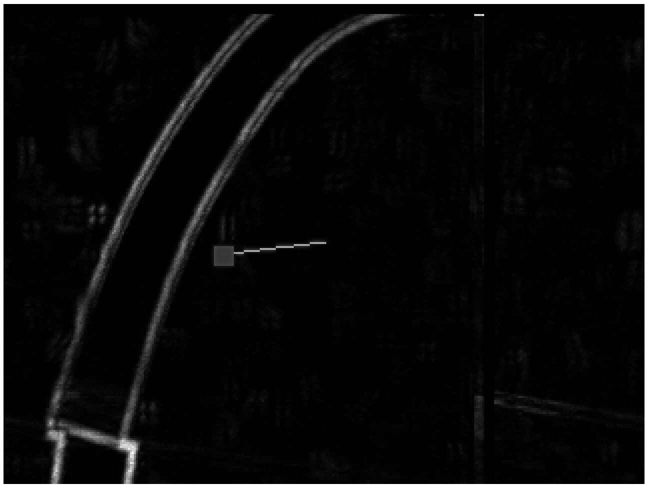


Figure 5. Resultant image from edge detection

Further work on TOUCH has now also equipped it with edge detection features and image normalization. Before applying edge detection to image frames, TOUCH normalizes the video stream in real-time by running a histogram on this image frames and eliminating the highest occurring values from the frame since these mostly constitute of the background and not the actual target. Following this procedure a simple convolution filter is applied to the image. Since edge detection is most useful to AUVs in case of pipeline following, the following convolution filter was adopted:

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

In order to apply this 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 if 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 this 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. Figure 5 shows an example of how this filter is able to filter out only the edges of an underwater pipeline.

5. Passive Sonar Array

Since sound travels in water much greater ease than light, acoustic target tracking is much better suited for applications in AUVs. The design of BhAUV would also be incomplete without an acoustic array. The sonar array on BhAUV enhances the basic concepts of sonar navigation.

One of the most important aspects of a sonar array is the Hydrophone, an instrument that converts underwater acoustic energy into electrical energy and is used in passive sonar systems [8].

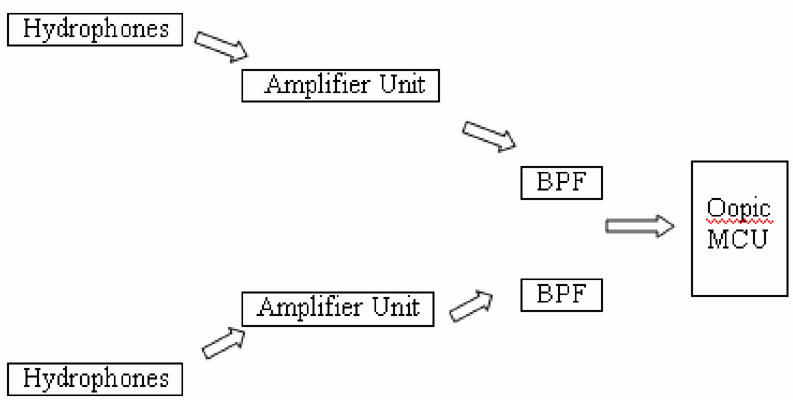


Figure 6. An overview of the passive sonar design

BhAUV uses an acoustic array positioning system that consists of two hydrophones sensors in an Ultra Short Baseline System (USBL). A UBSL system comprised of two or more hydrophones spaced a maximum of ½ wavelengths apart to the center frequency of the incoming signal [9], mounted on the starboard and port sides of the AUV. Also, the passive sonar system on BhAUV uses a Biomimetic Interaural Time Differentiation (ITD) system that triangulates the position of the sound source by computing the time delay of arrival (TDOA) [8, 9] of the sound wave at the hydrophones.

The raw signal obtained from a hydrophone contains all the ambient noise and undesired frequencies and additionally the voltage is also not high enough for further processing of the signal. As such, the preamplifier assists in amplifying the voltage to a suitable level for filtering, rejects common noise and provides a wide bandwidth for effective processing of the signal.

As such, in order to obtain a good sample the output from the hydrophone is sent to a preamplifier circuit which in turn feeds the amplified wave to a band pass filter that filters the signal. This filtered signal is then supplied to a MCU to pre-process the signal and supply the results to the main onboard computer that computes a bearing for the robot towards the target source. An overview of this system is provided in Figure 6. To calculate the actual heading that the AUV needs, this signal is supplied to the MCU for pre-processing.

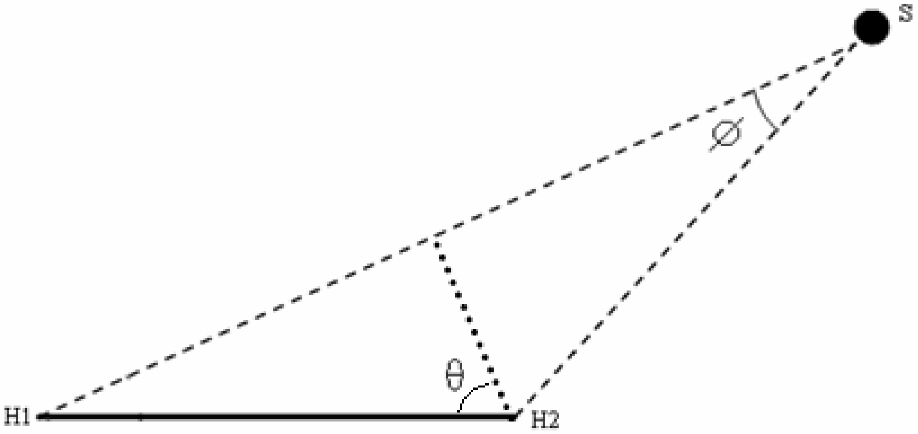


Figure 7. Sonar Object Tracking

Referencing to Figure 7 and assuming that the target to be tracked in this case is a sonar pinger located at point S 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 is the angle *theta.*

The angle *theta* is computed by calculating the TDOA of the sound pulses from S at H1 and H2. In order to calculate 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; furthermore, let T_1 be the time difference between the time of arrival of the first pulse and the subsequent second pulse on the hydrophone H1. Similarly, T_2 can also be calculated for the hydrophone H2.

If $T_1 > T_2$ then the robot turns towards H2 or vice-versa. If the distance between S-H1 is a, H1-H2 is b and S-H2 is c then these values can be computed easily using the formula $v = s / t$. As such, the angle *theta* will be the angle at which $a = c$.

In addition to using this ITD method, the team is also working on implementing a phase shift method to calculate the new heading for the AUV. To implement this functionality the team intends to use a DSP chip and a specialized timer for accurate timings [10]. For this scenario, the hydrophones can be placed in a baseline configuration as well. The distance between the hydrophones d would be less than one full wavelength of the measured signal. Due to fixed distances of the hydrophones on the same axis, it would allow us to create relationships for the time delays between hydrophones on the same axis. This phase difference between the hydrophone outputs is used in the bearing calculation.

To measure the phase difference between two signals, a common point is chosen so that the time delay measurements will be accurate; in case of sinusoid waves, the zero-crossing [10]. Special zero-cross detectors take care of extracting the exact zero-crossing time for each signal and the data from the hydrophone is amplified before the phase difference information is extracted. This wide band signal now passes through a higher order of band pass filter to eliminate out of band noise and frequency. A zero-cross detector rejects all the noise that is not sufficiently attenuated by the filter and the output is then fed into the DSP.

6. Conclusions

The AUV BhAUV has been developed with a sound technical base. Combination of the data obtained from the sensors, webcams and passive sonar system is processed by the central onboard computer that has multiple agents monitoring the dataflow from each component. This allows for only the relevant information to be shared between the sub-agents of the software and the master agent that computes the navigational heading and controls the motors of the AUV. The information provided by each sensory device is classified according to its own hierarchical importance order, which assists in prioritizing responses according to predefined constraints. Moreover, an individual software agent approach at processing the data ensures that any component failure doest not effect the other operations of the AUV.

Being light weight and low-cost, BhAUV is turning into an excellent platform for research and development tasks. Using novel systems like TOUCH that have proven themselves in two previous International AUV Competitions ensures successful operation of the AUV.

The IURS team is now looking forward to completing development on this year's AUV and competing against the world's best minds in the 9th International Autonomous Underwater Vehicle Competition being organized by the U.S. Navy. and AUVSI.

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