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Autonomous Underwater Vehicle for Vision Based Tracking

G.Santhan Kumar*, Unnikrishnan V. Painumgal*, M.N.V.Chaitanya Kumar, K.H.V.Rajesh.

Vignan's Institute Of Information Technology, Besides VSEZ , Duvvada, Vadlapudi Post , Gajuwaka, Visakhapatnam, Andhra Pradesh, 530049, India

Abstract

This paper describes about the design, construction and control of an **"**Autonomous Underwater Vehicle for Vision Based Tracking**"**, built in Vignan**'**s Institute of Information Technology, Centre for Innovation Lab. The underwater vision robot is essentially an Autonomous Underwater Vehicle (AUV) for study of marine animals by automatically tracking and following them using computer vision. The AUV can also be used as a platform for Photo-mapping of the Seafloor using the onboard camera and light arrangement. The robot is proposed to have 5 thrusters configurations to achieve 4 degrees of freedom controlled by an Inertial Measurement Unit (IMU) interfaced with control unit and powered by commercial LiPo battery packs .The robot is equipped with roll, pitch, heading, and depth sensors which provide sufficient feedback signals to automatically control the vehicle to track a pre-planned trajectory. The centre of gravity and centre of buoyancy of the vehicle are positioned in such a way that it is self-stabilized. Along with this the combinations of sensors and speed control drivers provide more stability to the system using a closed loop control system, without the operator involvement.

The AUV also captures videos during its mission using the camera. It is planned to have a multi-core umbilical cable for video signal, water leakage alarm, feedback signals and battery charging lines. This will be only used for development and test purposes and will be removed during autonomous missions. Various control schemes can be applied for the vehicle to track different paths. The AUV is designed to the dimension of 575×210×175mm.TheAUV uses O-rings for the hulls for good water sealing effect as well as for faster assembly and disassembly.

We expect this AUV development to mature in to an advanced system can be used as a platform for study of the ocean by scientists, for environmental studies and for defense applications.

Keywords: Autonomous Underwater Vehicle; Vision Based Control System; Image Tracking and Processing.

1. Introduction

We know that more than 70% of the earth's surface is covered by the oceans and the ocean contain 97% of the earth water. However the knowledge we have about the oceans is limited and only less than 5% of the Oceans have been explored so far. Till now Ocean exploration and oceanographic surveys has been predominantly done by the use of ships and collecting samples from the sea by various methods [1]. However using ships is expensive and hence cannot be done in a larger scale. Therefore there is an increasing trend towards development and utilization of Autonomous Underwater Vehicles to lower the cost of ocean surveys and also reduce the risks of sending humans in to the hostile environments in the deep sea with unpredictable weather and the high pressure at greater depths. Therefore in this research we propose development of a low cost and reliable AUV which can make Ocean exploration affordable and enable greater data collection from the sea. The AUV can be also used as a platform to add various sensors for its missions including environmental studies and defense applications. The Australian Sea floor survey department [2] has developed an AUV which can do sea floor mapping of large areas.

* Corresponding authors. Tel.:+91-9493201623; +91-9940422310.
*E-mail address:*santhankumargsk374@gmail.com; pv.unnikrishnan@gmail.com

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However the AUV is not using the cameras for real time control of the vehicle. The camera images are captured and stored in memory for offline processing. The University of Tokyo a miniature AUV named Yebisura [3] is developed by the students to take part in student competitions. This AUV does line tracking based on real time images from forward looking and bottom looking camera. Hence the vision algorithm of the AUV is not capable of tracking moving marine animals whose shape and size can vary largely based on the distance of the animal (fish) or the pose of the animal. In the research proposed in this paper we take the challenging task of tracking a live fish and following the fish to study their behaviour and videograph them in fully autonomous manner. This will enable long-term unattended autonomous study of marine animals and also the same algorithm can be used for remote underwater surveillance for defense applications.

An Autonomous Underwater Vehicle (AUV) is an underwater vehicle capable of self-propulsion, also known as unmanned underwater vehicle. It is a robotic device that is driven through the water by a propulsion system, controlled by an on board computer and maneuverable in three dimension. Such vehicles come under the category of mobile robots that have actuators, sensors and on-board intelligence to successfully complete their task with little or no human efforts. The application of AUVs has increased in recent years, such as cable or pipeline tracking and deep ocean exploration. These AUVs are designed to be smaller and flexible so that it can go to smaller and constrained region easily. In order to reduce drag and in-turn to reduce energy consumption and improved dynamics, the AUVs are designed to have a streamlined body [4].

The paper is organized as follows. At first we start with describing the specifications and features of the proposed AUV. Then we move on to the overall functional concept of the AUV. In section 1.3 the vehicle architecture is explained in detail along with a block diagram of the AUV. Then the vehicle control system is briefly presented. The section 1.5 explains about the Vision based tracking system proposed in the AUV. Then the vehicle external design and features are presented in section 2. Section 2.1 describes construction of the vehicle including the various hardware sections that form the essentials parts of the AUV. This includes thrusters, Camera and Controller Board. The section 2.2 explains the various tests conducted on the AUV and their results are presented. Finally the conclusion is discussed in detail in section 4.

1.1. Specifications

For the successful design of any complex systems, it is most important to start by clearly identifying the most critical requirements. In the case of underwater robotic vehicles, these are usually stated by the envisaged missions, such as depth rating, battery endurance, payload sensors, maneuverability, communications and user interference. The main design decisions are then determined by a combination of these specifications, together with possible constraints in fabrications, assembly and operational logistics. Hence we started the design of the AUV by defining the specifications as given in Table 1.

Table 1: Specifications of AUV

S.No	Features	Values
1.	Body dimensions (L x W x H)	575x210x175 mm
2.	Depth rating	10 meters
3.	Degrees of Freedom (surge, sway, heave & yaw)	4
4.	Hovering capability	Yes
5.	Image capturing feature	30 fps (max)
6.	Depth sensor, Leak detector	Yes
7.	Forward velocity	1 m/s (max)
8.	Endurance	2 hours
9.	Way point tracking	Yes
10.	Image tracking and vision based control	Yes

1.2. Concept

The main inbuilt feature of the proposed AUV is the vision based tracking and video recording of marine animal behaviour and photo mapping of the seafloor. The AUV is capable of diving to pre-programmed depth and follow waypoints to conduct the desired survey. During the survey the vehicle will capture images using two cameras, one is the forward looking camera and the other is the bottom looking camera. While following the waypoints, if the vehicle identifies any marine animals then it can enter in to the visual tracking mode and follow the animal such as fishes, then once the vehicle loses track of the animal then the vehicle follows to the next way point and continues its mission until reaching the last waypoint and then surfaces. During the entire mission the forward looking camera and bottom looking camera capture images and stores in the internal memory. The bottom camera images can be mosaicked using feature matching technique to create a large 2D photomap of the surveyed area through offline data processing.

1.3. Vehicle Architecture

The architecture of the proposed AUV is presented in the block diagram in Figure 1. The AUV is controlled by an onboard Raspberry PI CPU board which controls the mission as well as the processes the computer vision algorithms to enable the vision based tracking. The control system in the CPU controls the 5 thrusters based on the waypoints in the mission plan as well as based on the feedback from the vision based tracking algorithm. The Thrusters driver acts as an interface from the CPU to take the control signals and the deliver the proportional high-power current directly from the battery to drive the thrusters motor. The Depth Sensor, IMU and Leak detector are the sensor inputs to the CPU. The Forward and Bottom cameras and respective LED lights are also controlled by the CPU. The LED lights will be used for lighting the camera scene when sufficient natural ambient light is not present.

The images captured by the camera are stored in SD card memory by the CPU system. A 12Volt Lithium Polymer battery pack powers the entire system. The figure given below shows the block diagram of the proposed AUV.

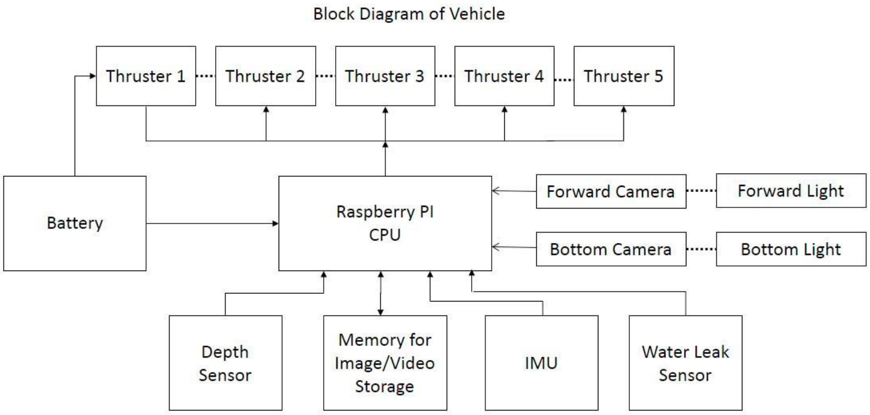

Figure 1: Block diagram of the proposed AUV

1.4. Vehicle Control

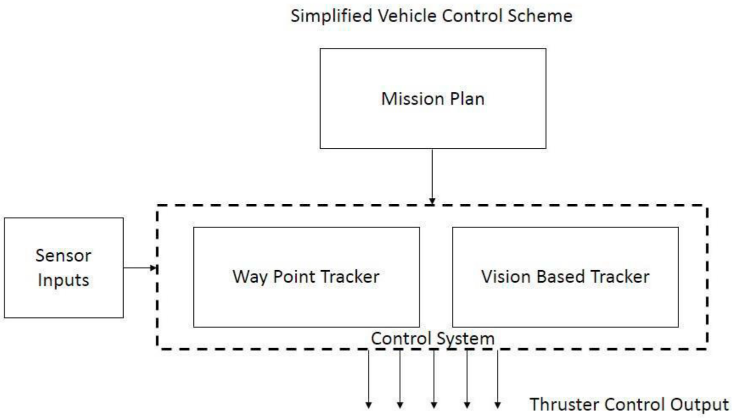

Figure 2: Simplified control scheme

The Figure 2 shows a simplified vehicle control scheme. The mission plan will contain the details of the depth of operation, the cruise altitude from sea floor and way points of the mission including surfacing location. In the absence of the vision based tracker the waypoint tracker takes care of the control system and generates control signals to control the thrusters based on feedback from the sensors like depth sensor and IMU. The vision based tracker system continuously looks for marine animals of interested mentioned in the mission plan for the particular mission. When a marine animal such as a fish matching the shape/colour features mentioned in the mission plan and internal feature data base is found then the control system keep the last passed way point in its memory and starts tracking the fish and capturing videos. Once the vision tracker loses track of the object of interest, the vehicle continues to its next waypoint as per mission plan and completes the mission. The low-level control is done using a simple PID controller to send control signals to thrusters in real-time.

1.5. Vision based tracking

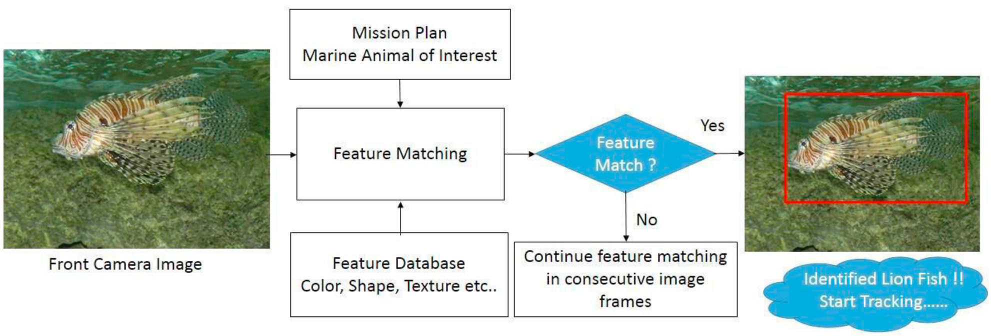

Figure 3: Schematic of vision based tracking system

A schematic of the vision based tracking system is shown in Figure 3. The vision based tracking system proposed in the AUV will use image feature matching technique to identify the species of marine animal of interest which is specified in the mission plan. Instantaneous images captured by the vehicles front camera will be scanned for matching features by the feature matching computer vision algorithm. The features are compared with the features in a feature database pre indexed with the marine animal features of the common animals commonly found in the geographic area of survey. Until a match is found each acquire image frame is scanned for matching features. Once a marine animal with matching features is found as per mission plan input, then the identified animal is tracked by the standard vision tracker algorithm and the vehicle thrusters are also controlled to follow the animal and keep the animal in the scene of the camera as closely as possible to capture its behaviour in the images. Once tracking is lost i.e. the marine animal is not visible in the camera image then feature matching again starts and the process continues.

2. Vehicle design

The design of the AUV is show in the Figure 4. The vehicle will have one waterproof central main cylinder with a transparent dome faced front section as seen in the figure. The dome portion in the front will be made from acrylic material to enable transparency for the front camera to the see the front area of the vehicle. The remaining section of the cylinder will be made from aluminum or other opaque materials. There will be two small auxiliary cylinders in either side which can be used to carry additional batteries to extend the endurance of the vehicle in a single diving mission. There will be 5 thrusters to provide 4 degrees of freedom namely Surge, Sway, Heave and Yaw for change of heading. The central cylinder will contain all the electronics systems and main battery required for operation of the vehicle. There will be a skid below the vehicle for proper placement and transportations of the vehicle on land and also to prevent hitting or damaging the bottom camera when moving close to the seafloor.

(a) (b) (c) (d)

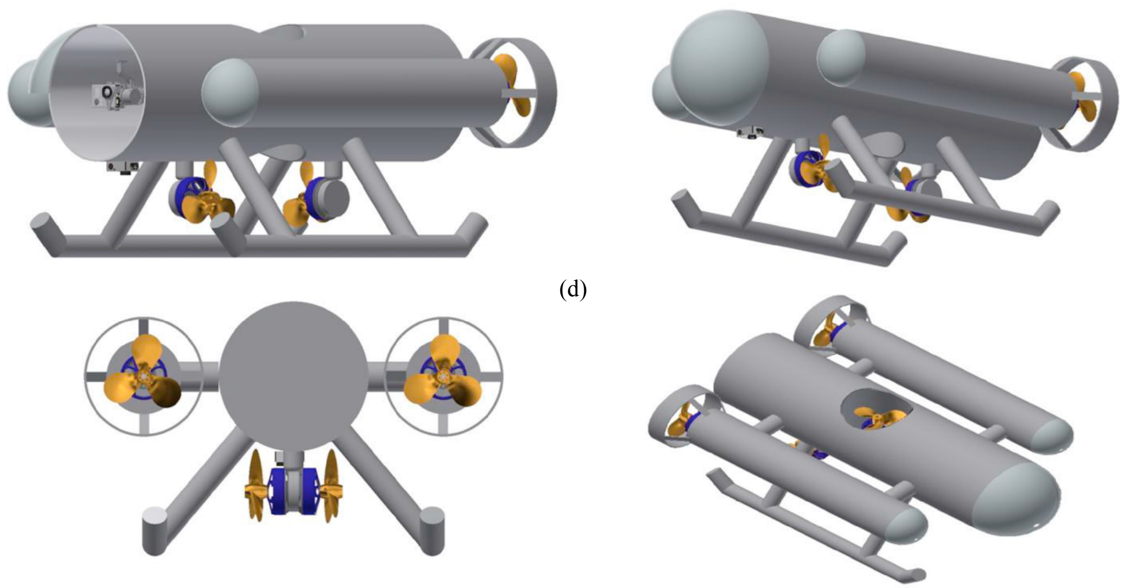

Figure 4: Different views of AUV

2.1. Construction

2.1.1. Building materials

The AUVs dome portion in the front will be made from acrylic material to enable transparency for the front camera to the see the front area of the vehicle. The remaining section of the cylinder will be made from aluminum material. The bottom camera casing will be made from acrylic material.

2.1.2. Propulsion

The AUV uses brushless DC motor along with customized and 3D printed propellers to act as it thrusters. Thrusters take the electrical energy from the battery and transform it into mechanical energy or motion.

Thrusters have a cowling on them and specially shaped blades to conform to the inside of the cowling called Nozzles or **"**Kortz Nozzles**"**. The Kortz Nozzles help to generate higher net thrust as compared to thruster without the nozzle [5]. We used standard Quadcopter BLDC motors available in our lab to reduce the development cost and also to speed up the overall project development time.

- *Motors*

  Here we are using brushless DC (BLDC) motors of 1000kv and 12volts rating.

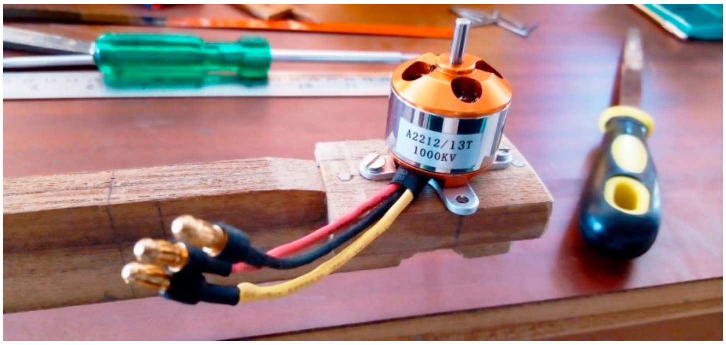

Figure 5: Brushless DC motor

- *Propellers*

We used propellers which are made on 3D printing machine using PLA material of 1.75 mm thickness. Figure 6 shows the different models of propellers which are made and tested.

Figure 6: 3-D printed propeller models

2.1.3. Electronic speed controllers

The motors can spin in both directions i.e. clockwise and counter clock wise by using bi-directional ESC**'**s connected with Arduino board.

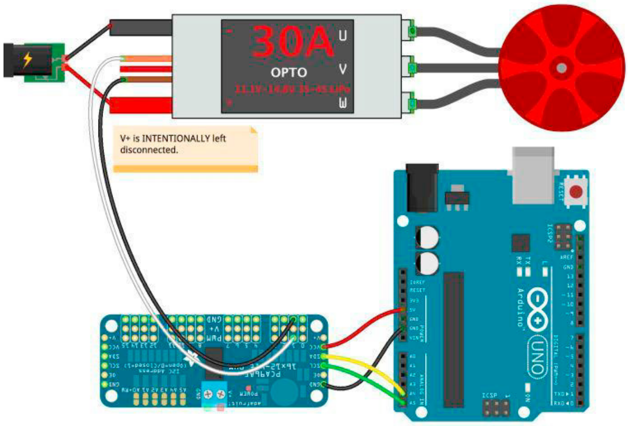

Figure 7: Controlling bidirectional ESC using arduino

2.1.4. Battery (LiPo)

The AUV use electrical power from an on-board battery as the source of energy to drive its various components. The power source we used is a 12V DC Lithium Polymer battery. The actual voltage produced by a fully charged LiPo battery is about 13VDC which directly fed to thruster motors through ESC. The low voltage supply required for the controller board is obtained by using a step down DC-DC converter. The vehicle is designed to operate for about 2 hours when operating autonomously in untethered mode [5].

Figure 8: LiPo Battery used for the AUV

2.1.5. Forward Camera

A camera with frame rate of 30fps is used for image capturing and also for image tracking and processing. Two servo motors are used to form a gimbals mechanism to provide pan and tilt motion for the camera. The entire pan, tilt mechanism and camera arrangement is placed inside the hemispherical acrylic dome of the vehicles main cylinder. This fully enclosed design allows 180 degrees of camera view maintaining a waterproof seal. The pan and tilt feature provides a wider field of view of the camera. Light emitting diodes (LEDs) on the board are used to illuminate the underwater environment. The end cap has two grooves for the O-rings to keep the enclosure watertight [6].

2.1.6. Bottom Camera

The bottom looking camera is used to capture the images of the sea bottom directly below the AUV. These images can be stitched together during offline data processing to form a photo mosaic image map of the seafloor. The bottom camera is also useful for taking part in AUV competitions where line tracking of a line marked in a tank or pool floor is necessary. The secondary camera is placed in a waterproof housing similar to the image shown in Figure 9.

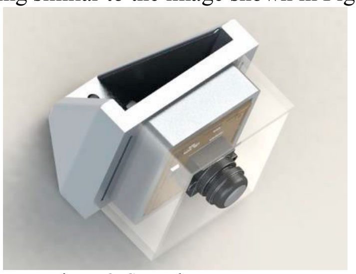

Figure 9: Secondary camera

2.1.7. Control Board (Raspberry Pi)

A Raspberry Pi Controller was chosen to be used because of its more complex design for a full processor and its established software drivers and libraries. The Ethernet port on the R-Pi board enables remote communication with the AUV through a Ethernet cable during debugging process. In addition to this the R-Pi board has 4 USB ports which can be used to interface standard low-cost USB cameras to the board for the vision based tracking. Additionally the USB cameras as less expensive as and littler than Ethernet port based camera’s [7].

The Raspberry Pi software management is easier and can be easily kept up-to-date. The board can run a standard Linux OS on the board which gives way to several additional features and standard programming libraries that are available. The programming of the board is done in Python, which allows for quicker unit testing and easier management of a large code base rather than lower level C programs. Using the Ethernet port on Raspberry Pi board, the AUV is able to have its code updated while in the water using remote login capability. This allows for rapid fixes and iterative improvements while testing the AUV in the water [8].

2.2 Tests and Results

2.2.1. Thrust measurement

The thrust measurement was done in a water tank (size 650 x 470 x 360mm) to calculate the thrust values in grams that can be produced by each BLDC motor according to the respective thrust input give in percentage. To carry out thrust measurement in the lab we made a custom setup of thrust measuring equipment as show in Figure 10. The thruster is attached to one end a wooden pole as seen in figure. The wooden pole is fixed on to a wooden sheet using a circular metal rod which acts like a pivot and double leaver arrangement. At the other end of the pole at the same distance from motor to pivot point a digital balance gauge is attached as seen in the figure. The thruster power was increased in percentage from 10% until 100% to measure the corresponding force by using the digital gauge. Out test showed that the thrust generated is directionally proportional to the percentage thrust control. The measured thrust values during the experiment are shown in Table 2. Figure 11 shows a graph representing the thrust generated by the thruster for the various thrust input in percentage.

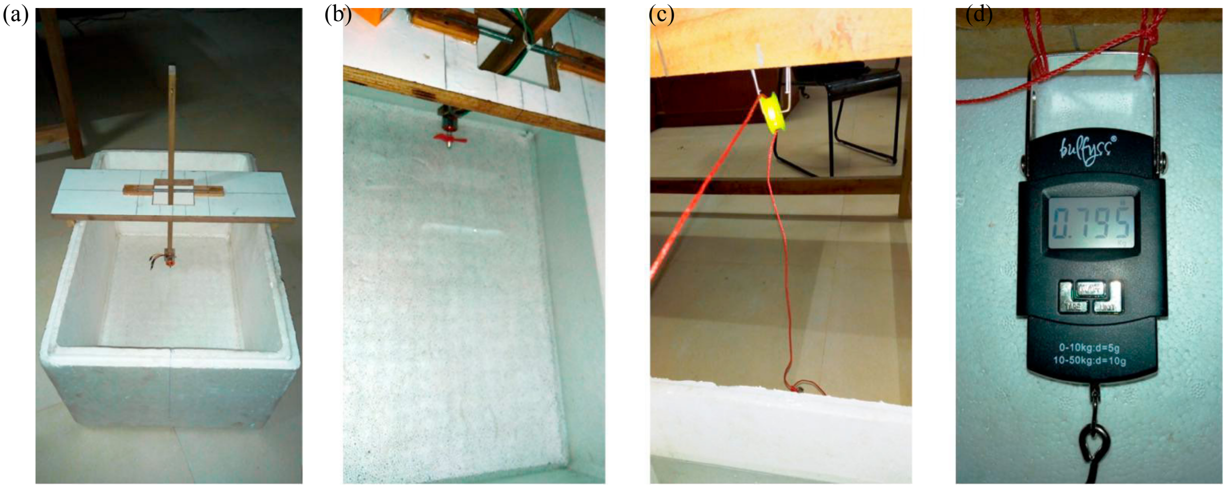

Figure 10: (a) Thrust measurement setup; (b) Measuring thrust in water; (c) Rope connected to weighing machine hook over a pulley and (d) Digital weighing machine.

2.2.2. Results

Table 2: Thrust measurements values

S.No	Thrusters Input (%)	Thrust Value (Grams)
1	0	0
2	10	220
3	20	350
4	30	540
5	40	760
6	50	820
7	60	910
8	70	1050
9	80	1120
10	90	1200
11	100	1280

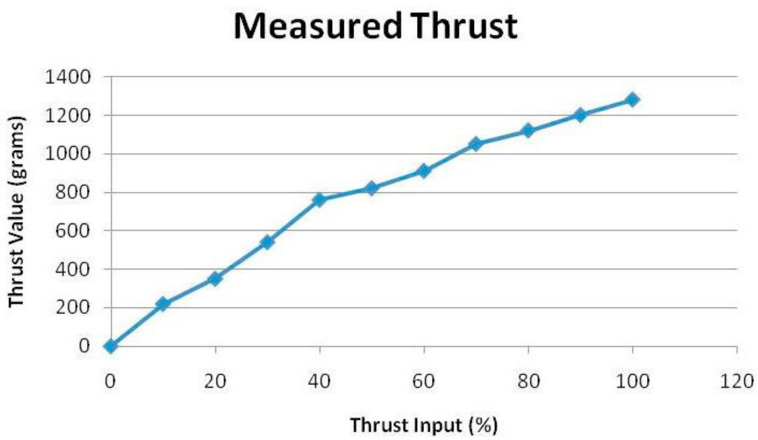

Figure 11: Thrust generated by the thruster during the lab test

Following are the some important tests which are conducted on the AUV

- Non-diving test to check functionality.
- Testing vision based tracking.
- Diving test of test heave, surge, sway, yaw, and automatic depth control using feedback from pressure sensor.
- Testing automated wave point tracking.

3.1 Development and test of the vision based tracking Algorithm:

The past few decades have witnessed rapid increase in automated robots taking tedious or dangerous tasks such as surveillance, rescuing, and geological exploration etc. Among these tasks, target tracking by using unmanned aerial vehicles (UAVs) and autonomous underwater vehicles (AUVs) has found many applications in engineering practice with both research and commercial background [9].

Traditional approach to target tracking by an AUV involves image detection of the shape, size and velocity of the moving target. On the other hand, processing the uploaded images of the moving object provides the global coordinates of the tracker to facilitate navigation. In particular, with the help of the image processing technology, image trajectory of a moving target can be obtained by the use of a surveillance camera. Moreover, real-time tracker positions are estimated by an algorithm. These two sets of information can be considered substitutes for the detecting data of the target and the global coordinates of the tracker. They jointly provide sufficient feedback for the tracker to achieve a tracking task.

Vision-based tracking by an AUV basically consists of three consecutive steps. They are (i) Image processing, (ii) Coordinate transformation/estimation and (iii) Trajectory following. By applying an image processing algorithm to a sequence of image frames taken by the surveillance camera on the tracker, visual tracking of the target on these image frames can be achieved. Coordinate transformation between the image frame and the real world frame then generates the desired trajectory for the tracker in the real world frame such that the projection of the desired trajectory on the ground plane imitates the original target movement. Based on the real-time estimation of the current tracker position obtained from the algorithm. A trajectory following law propels the AUV to follow the desired trajectory so that target tracking can be accomplished.

Tracking is achieved by collecting the information of the approximated horizontal distance between the target and the tracker from an image frame as feedback to navigation law that keeps the distance within a reasonable range in the real world frame. The centroid of the moving target in an image frame is then guaranteed to be inside a given area, and the navigation law guides the AUV to move in a path to follow the target.

3.1.1 Components of the Testing Platform for vision based tracking test

The testing setup comprises of an aquarium with a live gold fish. The fish is the objective point for following, so we conduct feature matching test on every single image frame data of the red gold fish which has been captured for the visual tracking. A Logitech webcam is utilized as surveillance or observation camera to track the fish. Image frames generated by the camera have 640 pixels in width and 480 pixels in height.

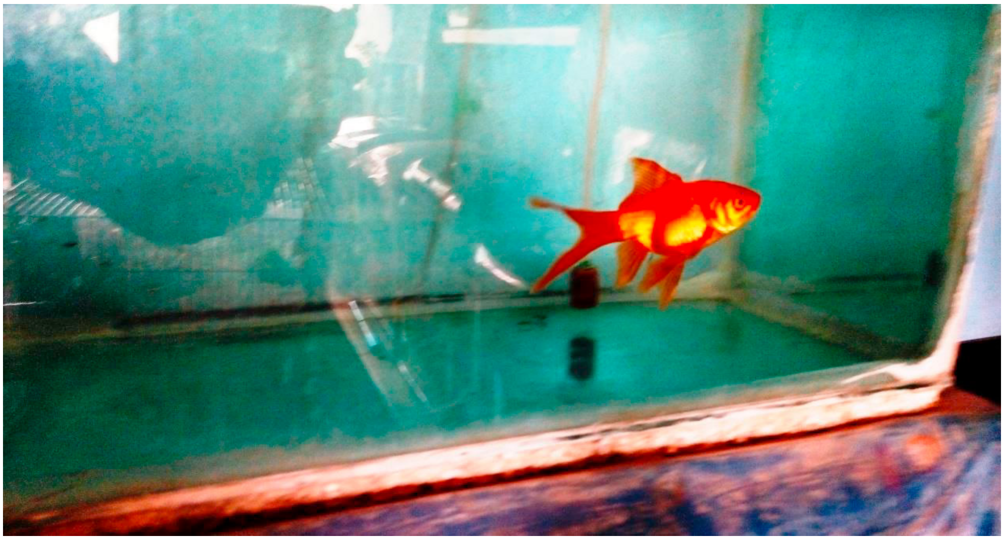

Figure 12: Live gold fish for image tracking

3.2. Image Processing Algorithm:

The Image processing algorithm captures the real-time image frames from the camera and compares it with the template image already fed in to the feature matching algorithm. Once the match is found then image tracker tracks the object of interest. We have used ORB based feature matching and tracking. The underwater environment is fairly clutter free and so the features of the target (fish) like color and shape can be identified and tracked.

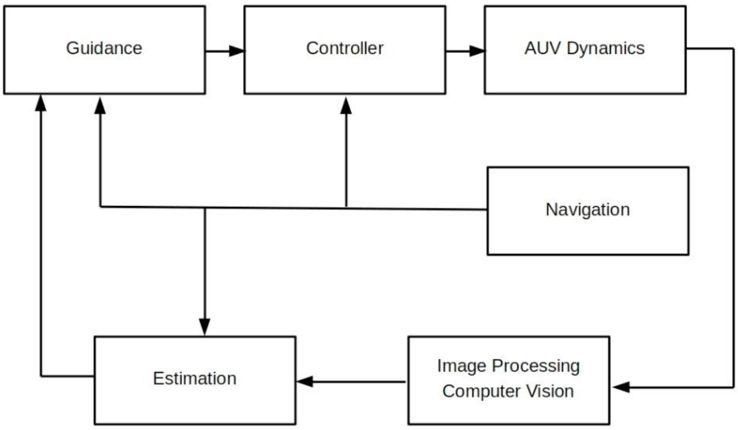

Figure 13: System overview

3.2.1. Feature based object tracking

Accurate tracking of feature points over image sequences is a critical and essential process for vision systems algorithm based on target recognition to achieve visual tracking .We will load the template of query image or training image at a rate of 4 frames per sec. Here tracking is done by ORB (Oriented FAST and Rotated BRIEF) with open CV library. This is an efficient good alternative to SIFT or SURF due to the computational cost and feature matching speed. Moreover ORB is an open source code and can be used freely without any patent restrictions [10].

ORB is basically a fusion of FAST key point detector and BRIEF descriptor with several modifications to enhance the performance. First it uses FAST to find key points, and then apply Harris corner measure to find top N points among them. It also use pyramid to produce multi scale-features. But one problem is that, FAST doesn't compute the orientation ORB is much faster than SURF and SIFT and ORB descriptor works better than SURF. ORB is a good choice in low-power devices like the Raspberry PI board.

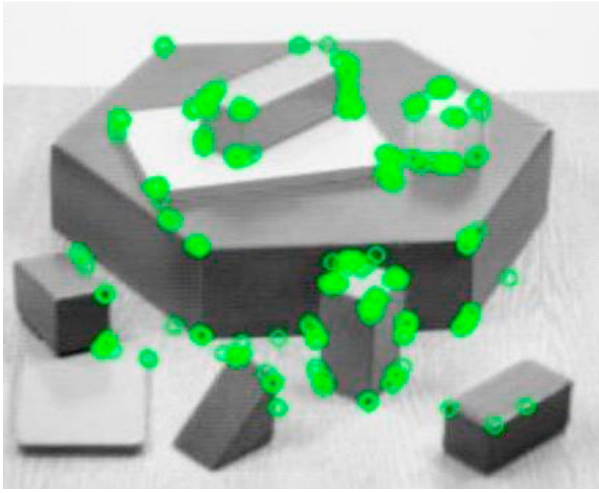

Figure 14: ORB feature matching

- *SIFT*

Scale Invariant Feature Transform (SIFT) is a feature detector developed by Lowe in 2004. Although SIFT has proven to be very efficient in object recognition applications, it requires a large computational complexity which is a major drawback especially for real-time applications.

- *ORB*

ORB is a fusion of the FAST key point detector and BRIEF descriptor with some modifications. Initially to determine the key points, it uses FAST. Then a Harris corner measure is applied to find top N points. FAST does not compute the orientation and is rotation variant. It computes the intensity weighted centroid of the patch with located corner at center. The direction of the vector from this corner point to centroid gives the orientation. Moments are computed to improve the rotation invariance.

Table 3. Results of matching object in real time

Object detection method	Time taken for each frame	Accuracy in matching %
SIFT	4.2 sec	76
ORB	0.22 sec	63

The SIFT requires greater computational power and it is also a patented algorithm. We adopted for ORB method because it is open source and it requires less computational power which is best suitable for Raspberry PI. Due to its fastness in matching it can work in real time tracking of object while SIFT cannot be applied for real time tracking. The Table 3 shows the comparisons of object tracking performance between SIFT and ORB algorithms. The speed of SIFT is 4.2 seconds for each frame whereas ORB is much and can process 4.5 frames per second and takes only 0.22 seconds for each frame. However looking at the object detection accuracy SIFT performs better than the ORB algorithm. We tested for 100 frames with a printed image of a fish (shown in figure 3) moving it manually in front of the camera and the camera was kept static. Although the accuracy of the ORB algorithm is lesser than the SIFT algorithm, we chose to use the ORB due to its enhanced computational speed. A more detailed and consistent accuracy test can be conducted. However the focus of our work was to use a faster algorithm for our target application on Raspberry PI, a detailed comparative study was not essential for our study.

3.3. Testing of Image based Tracking

We tested the image based tracking algorithm on live fish in an aquarium tank as shown in the figure 12. As explained in the previous section, the ORB tracking algorithm was used for the tests. The python coding was made in a way that if the target is found then the program draws a box around the target then prints a text as "fish found" and if no target is found then the text "fish not found" is printed on the image.

As you see in Figure 15 (b) the images with other fishes and with no fish is automatically marked as "fish not found" by the program. Whereas in images where the gold fish is present (Figure 15 (a)) are marked as "fish found" and also the bounding box and centroid of the bounding box (green color) is marked by the program. In the figure 15 (a) we can also notice the red color cross line marking the center of the image frame and is marked as 0,0 by the algorithm. The distance from center of the object of interest from the center of the image frame is also calculated and marked in green as (48, 49). This represents the pixel number in-terms of rows and columns. Similarly the position of the tracked object (85, 45) is marked in the figure 15 (c). The values of distance of the centroid of the tracking object from the center of the image frame will be used as control values to control the thrusters with a control goal of bringing the target object exactly to the middle of the image frame. This will ensure that the vehicle follows the fish and captures the images of the fish during the entire tracking period until the object is lost completely from the field of view of the camera or moves relatively far away that tracking algorithm is not able to detect the fish.

Presently the USB camera was placed outside the aquarium and the tests were carried out. However in the actual application the Raspberry PI board and USB camera will be placed in the water proof enclosure inside the body of the AUV. Presently the fabrication of the AUV structure is in progress and soon we will be able to assemble the entire AUV and test the tracking Algorithm to do automatic real-time control of the AUV to track the fish and capture the images.

a) Object/fish found

b) Object/fish not found

Figure 15: Results of fish tracking test

4. Conclusion

This research presents the design and development of a compact and low-cost AUV which is capable of performing autonomous image based tracking and photo mosaicking. The detailed design and features of the vehicle has been presented. A custom designed thrusters using brushless DC motor and 3D printed propeller blades are used to propel the AUV. The AUV is also capable of tracking marine animals using the onboard camera and vision based tracking algorithm. The AUV is developed for a depth rating of 10 meters which is suitable only for test tank operations. However once we demonstrate this vehicles capability to the probable end users of the vehicle such as CIFT (Central Institute of Fisheries Technology), DRDO etc. We plan to apply for further research funding for developing the vehicle in to a full ocean going vehicle and utilize for real field applications. In future the AUV also can be used as a platform for testing and learning conventional and advanced control algorithms and techniques. Using neural networks and artificial intelligence the AUVs autonomy can be further enhanced in the future.

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