Kasetsart University Underwater Vehicle: Design, Strategy, and Implementation of SEAPUP AUV 2022

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***Abstract*—The purpose of this paper is to describe the design of the PUP-01 as well as the competing strategy of our team. Since our aim this year is to attain as many tasks as possible, the competition strategy is to decompose the complexities in each tasks for some common aspects. Then, those features will be grouped and a solution will be proposed. In design creativity, the overall system is briefly explained. The topics were categorized by the sub-teams which consists of mechanics, electronics, and software. Lastly, the experimental result shows the outcomes of each aspects described in the design section.**

I. Competition Strategy

This year, our team intends to complete as many tasks as possible. Overall, the computer vision is responsible for object detection and localization. The target object position is sent to the mission planner to perform a reference goal calculation. Then, the goal is given to the guidance system in order to maneuver the AUV.

- Gate: Firstly, the computer vision would return the positions of both of the sides of the gate. The mission planner then decides a side and send the desired goal to the GNC. Finally, the AUV will pass through the gate while performing style.
- Torpedoes and Buoys: In these tasks, the computer vision uses neural network along with the stereo cameras for locating the obstacles and returning the position to the mission planner. Then, the decision will be made by the mission planner whether the AUV should do.
- Octagon and Bins: The hydrophones are responsible for determining the position of the pingers. The positions were passed to the mission planner, as the same manner as the returned position from the computer vision. The system was designed in this fashion to reduce the complexities while possessing reliabilities. After the AUV moves to a pinger location, the computer vision will identify whether the task is Octagon or Bins. The object such as bottle or bin cover would be identify using the neural network, and determine the position using the stereo cameras.

For the best practice of performing each tasks, a milestone will be set. After each milestone, the result of the test-run will be evaluated and discussed further in order to improve any imperfections. All the algorithms were tested in the simulation before launching in the pool-test. The shared or any open-source data from other competing teams that were available in the Robosub data sharing was also used for developing algorithms. Finally, our former members' past experiences and our previous mistakes were considered as suggestions for our progress for working on our AUV.

II. Design Creativity

A. Mechanical Design

Our AUV, PUP-01, was designed, developed and manufactured to be able to operate at the competition. There are five different hulls including the front hull, hydrophone hull, rear hull and two battery hulls assembled to the structural frame of PUP-01. The frame was covered with the buoyancy foam which could provide addition buoyancy to the AUV. Moreover, the thrusters were allocated symmetrically along the frame as shown in figure 1.

- Hulls: The aluminium 6061 was used as the material of the hulls which the front hull has a rectangular shape with face seal, while the rest of the hulls are in cylindrical shape with bore seal. Devices such as cameras, thruster controller boards, and other electrical devices were installed in the front hull which could provide an adequate space for visibility and accessibility. Meanwhile, other sensors that rarely require maintenance were placed in the rear hull. The hydrophones were located in a separated single hull for the ease of isolate testing. Lastly, the battery hulls were designed to be capable of disassembling for swapping charged battery hulls, each hull contains one pack of battery.

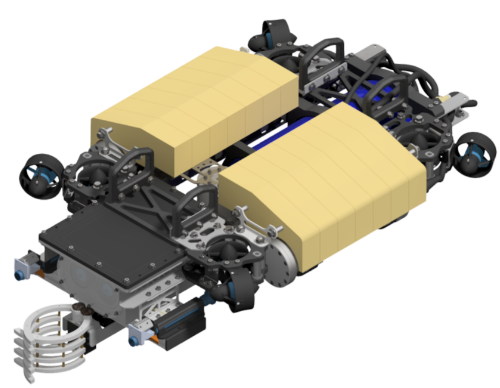

Fig. 1: PUP-01 AUV

- Frame and Buoyancy material: Main objectives of the frame are positioning all the hulls. The frame were attached to the cowling providing strength rigidly. The stainless 316 C-beams were arranged in longitudinal direction by the Polyoxymethylene (POM) structures in lateral direction. Considering the buoyancy material, a high-performance PVC for sub-sea was applied to provide an additional buoyancy force to the AUV. The PVC were assembled as in a number of sections for tuning buoyancy of the AUV to float on water in inoperative state.
- Torpedo Launcher: The torpedo launcher mechanism utilized the potential energy of the spring to launch a torpedo. The spring coil was chosen based on desired distance of two meters. The solenoid was used to hold compressed position of the spring whereby a torpedo located. The chosen actuator was not a waterproof grade; therefore, enclosing within a piston in which is sealed by double-acting piston seals were used to operate underwater.
- Gripper: The gripper is composed of underwater servos and claws. It is located below the frontal hull so that it could operates within a sight of bottom cameras. To grasp a bottle, the servo controls both left and right claws to tighten alike interlocked fingers. Another servo moves the gripper arm in lateral axis to pitch up and down the arm.

B. Software System Design

The PUP-01 software system consists of 3 major subsystems: mission planner, guidance-navigation-and-control (GNC), and computer vision as shown in figure 2. The mission planner is the conductor of the AUV operations. It receives the positions of the AUV and mission targets; then, decides the appropriate AUV movement to complete each task. The GNC focuses on the navigation and control algorithms to commute the AUV and to keep the stability of overall system. Finally, the computer vision takes care of underwater image processing and object detection. Moreover, there are several minor subsystems used to integrate sensors and controllable components with the software systems such as the sub-system for gripper and hydrophone. Detail of these minor sub-system will be described separately within their section.

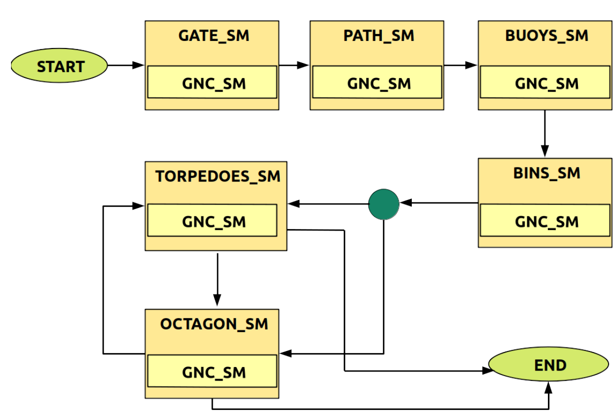

Fig. 3: Mission Planner Flow-chart Diagram

1) Mission Planner: Mission planner (MP) is at the top of the system hierarchy. It orchestrates the AUV according to sensor inputs as well as the input from computer vision. MP operation was designed on the principle of state machine. Tasks are break-down into states. Each state represents a status of the AUV such as its position and target. The machine transits from a state to another by a trigger event or condition. Some states may not require any trigger to move to another state. In this case, the system base-line event, which is a periodic timer, is used as the trigger.

Mission planner was implemented using Transitions library [1], a part of Pytransitions. package. The library provides a formal way to describe states, transition, and machine. However, it is a standalone generic library. Though, the library can be used within ROS platform, it cannot utilize ROS message-based architecture to run its machine. Therefore, events in ROS platform, communicated through call-back and message-passing mechanism, cannot initiate any transition. To overcome this problem, we use a time-based task to periodically trig the state machine. When trigged, the machine polls the required conditions and events and chooses an appropriate transition or staying at the current state. The state-machine structure is hierarchical. The main state stays at the top level and other states for controlling each task are in the lower levels as shown in Fig.3. We designed the state machine in top-down manner. A state performs only a specific task which may have some sub-tasks inside. For example, an object-targeting task has guidance tasks as its sub-tasks. Another object-targeting task might have the same sub-tasks. Same sub-tasks inside two separated tasks are created from a common template to suppress redundant declaration.

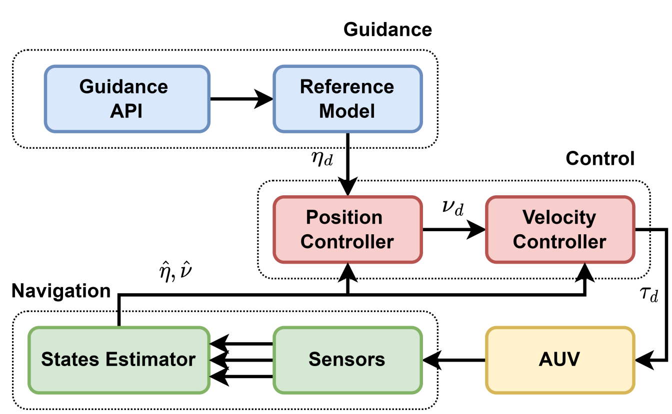

Fig. 4: GNC System Diagram

2) Guidance, Navigation, and Control: The GNC system can be disintegrated into 3 sections: guidance, control, and navigation as illustrated in figure 4.

- Guidance: The guidance system can be separated into 2 sections: the API and the reference model. The command such as desired position or the waypoints was sent to the guidance API through the mission planner via ROS action. Thus, the trajectory for the AUV to reach the desired destination was generated. On the other hand, the reference model, which is the second-order system with

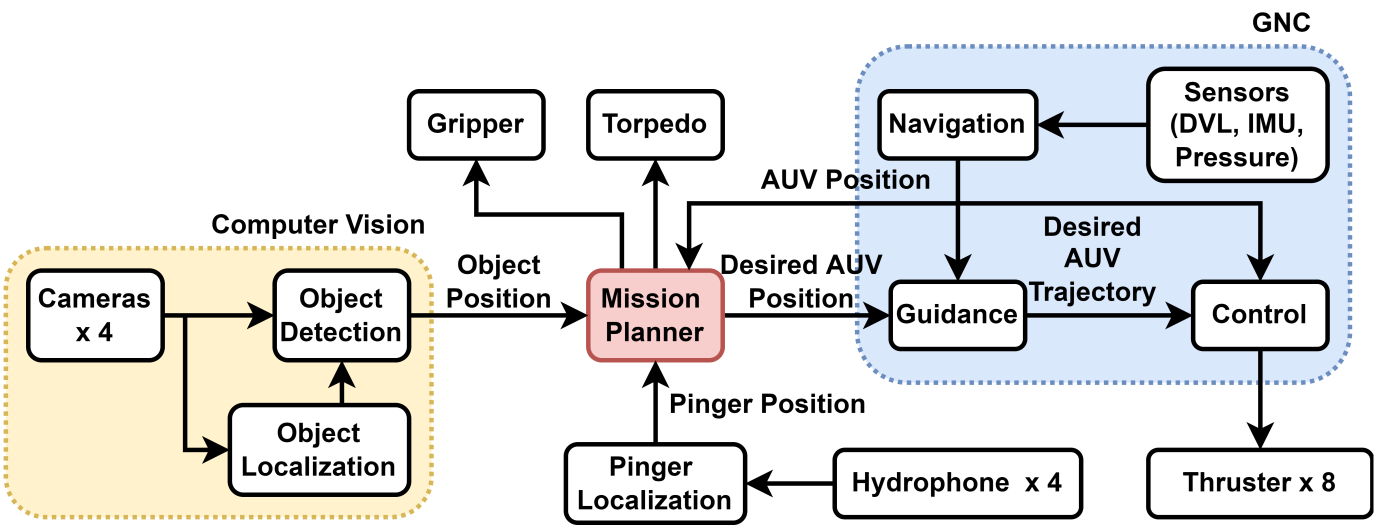

Fig. 2: Software System Diagram.

the acceleration and velocity bound [2], was also used to determine the behavior of the AUV.

- Control: The cascade PID controller structure was utilized in the system. The cascade controller was designed based on the model-based control, in which the hydrodynamic parameters were obtained from the computational fluid dynamics. The position controller uses the desired position ($\boldsymbol{\eta}_d$) as the reference signal to calculate the desired velocity ($\boldsymbol{\nu}_d$). Then, the desired velocity ($\boldsymbol{\nu}_d$) was used to calculate the desired forces ($\boldsymbol{\tau}_d$) through the velocity controller. The forces were then mapped to each thruster via the thruster manager. The position and velocity controller was used as the outer and inner loop controller, respectively.
- Navigation: The DVL, IMU, and pressure sensor were utilized to determine the position and velocity of the AUV. Consequently, the sensors data received were fused using the Unscented Kalman Filter as the state estimator. In addition, the parameters such as the process and measurement noise covariances were selected based on the characteristics of the sensors and the behavior of the AUV.

3) Computer Vision: The computer vision system is an essential part of AUV. It allows AUV to understand the visual data acquired from the cameras. Computer vision can be separated into 2 main parts, i.e., Object Detection and Object Localization.

- Object Detection: With the complexity of the tasks and light conditions, the general image processing approach is too difficult to perform the tasks. This year, we use more advanced algorithms, which are better performance and more robustness, running along with YOLOv5 [3], a deep learning-based approach.
- Object Localization: To accomplish the task, the object position is needed to identify after object detection. We employ the stereo vision technique to locate its 3D position. We have decided to use 4 cameras that the two cameras are acquired forward-looking images while the others are received downward-looking images. To obtain the camera parameters, the underwater image data set of the chessboard calibration pattern is utilized for stereo camera calibration. We use the calibration results for the rectification and reprojection process based on OpenCV. The VPI [4] is provided to compute the disparity map with semi-global Matching algorithm for fast and accurate performance running on NVIDIA's embedded GPUs. To get the depth information, the detected object on the image is converted pixel coordinates along with the disparity value into real-world 3D points.

C. Electrical System Design

The electrical system can be considered into 4 sections, a power management section, a processing section, a communication section, and an underwater acoustic section. The power management section is relating to the power conversion and distribution from the batteries to all on-board electronic hardware. The processing section is a pair of computers handles most of the software contributing to the AUV. The communication section is a medium between all the hardware and the computers, provides the computers an access to the underlay hardware. Finally, the underwater acoustic section detects the signal of the pinger and estimates its bearing relatively to the AUV.

1) Power Management System: The power management system provides 4 different rails of voltage for the AUV, a battery rail, which supplies the voltage equals to the battery voltage, a 12 VDC rail, an isolated 12 VDC rail, and an isolated 5 VDC rail. Each of the rail supplies the power to the corresponding hardware with the isolated rails are intended to provide a protection against the ground loop. The thruster kill-switch is also a part of this system and was designed to directly cut the power off from the thrusters. The system is capable of sharing the load between 2 battery packs. However, operation with a single battery pack is also possible without any performance degradation. This allows the AUV to be swapped with a fresh battery without powering it down.

2) Processing System: The processing system consists of 2 NVIDIA Jetson Xavier NX, both are intended for different purposes. One unit dedicate for the computer vision and another unit for the the mission planner and the GNC. The Jetson also provides the NVIDIA CUDA cores which can significantly accelerate software that require intensive calculations, particularly in the computer vision software. Additionally, it can directly interface with various communication protocols which allows us to considerably reduce our communication system comparing to the previous system.

3) Communication System: The communication system can be seen as an extension to the processing system. It enables the Jetson to communicate with the hardware using the protocol that the Jetson do not supported. Currently, 2 hardwares are under the communication system, the communication hub and the Embedded Thruster Control And Monitor (ETCAM). The communication hub enables the Jetson with RS-232 protocol which is used to communicate with the DVL. The ETCAM provides DSHOT protocol [5] which is used to command the thruster drivers to drive each thruster to desire point of operation.

4) Underwater Acoustic System: The underwater acoustic system converts surrounding sound wave into digital information. The system inputs are 4 hydrophones (i.e.,underwater microphones). Analog signals from the hydrophones are synchronously converted into pulse-coded-modulation (PCM) form. As the sound frequencies used in the Robosub are in ultrasonic range, the Nyquist frequency of the signal sampling should be more than 100kHz. Further signal processing in digital domain requires even higher conversion frequency. To achieve such a high conversion frequency, we combine a high-speed analog-to-digital converter (ADC) with a high-performance Field-Programmable Gate Array (FPGA), Xilinx Artix7™, to perform acoustic processing and timing synchronization. The output of this system, having the effective sampling frequency at 1MHz, is transferred to the AUV main computer via a high-speed USB connection. The 1MHz sampling frequency is far higher than the minimum requirement. It gives room for further processing, which usually further reduces the effective sampling frequency.

III. Experimental Result

The experiment was carried out through the university swimming pool. Since the facility is an outdoor swimming pool, the lightning cannot be controlled; therefore, each pool-test needed to be planned thoroughly. Overall, the AUV structure linked all the sensors as a whole. The buoyancy of the vehicle can also be easily adjusted due to the buoyancy foams. Contrary, the torpedo and gripper mechanisms are in the developing progress. The power manager and the communication system of the AUV supports the system to operate smoothly. On the other hand, the processing system needed an optimization of the program to reduce the computation cost. In addition, there are some issues on the underwater acoustics hardware; however, can be solved and would be ready for this year competition.

The usage of the hierarchical state machine enable us to test the program handily. The program can be adjusted without affecting other parts of the system due to the modularity of the hierarchical state machine.

The guidance system allows the vehicle to track the command from the mission planner; moreover, the behavior of the AUV was changed by the reference model. Likewise, the control algorithm is capable of the vehicle tracking the desired trajectory with minimum error.

For object detection, we collect the dataset of images in underwater conditions to train the YOLOv5 model. The average runtime per frame was around 5.8 miliseconds. The performance of YOLOv5 of the example objects is illustrated in figure 5. An example of detections is shown in figure 6.

Object	Precision	Recall	mAP
Badge	0.99	0.982	0.934
Bootlegger	0.981	0.972	0.869
G-Man	0.939	0.977	0.805
Gun	0.988	0.992	0.913

Fig. 5: The Precision, Recall, and mAP of YOLOv5 of the example objects

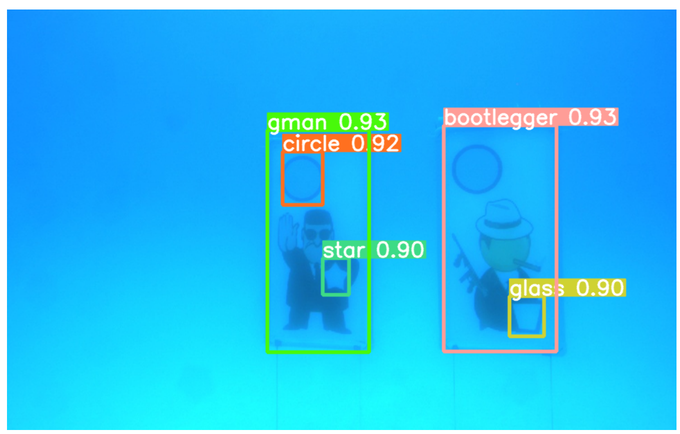

Fig. 6: Underwater object detection using YOLOv5

To calibrate the stereo camera, we use the stereo camera calibrator application on Matlab R2021b and evaluate the calibration accuracy of forward cameras. The accurate calibration results in undistorted and row-aligned of pairwise images in the stereo rectification shown on left and middle of figure 7, respectively. An example disparity of rectified images using VPI is shown on the left of figure 7. The inaccurate disparity occurs due to the similar intensity and noisy image in underwater. We use median and gaussian filter for image denosing before the rectification process. For object localization, we consider the ROI of object detection to get the disparity value and convert it into real-world coordinate to obtain the 3D position.

Fig. 7: The rectified images of forward cameras (left and middle) and the disparity map (right)

ACKNOWLEDGMENT

SEAPUP AUV team has to thank many sponsors. Our highly respected main sponsors are Faculty of Engineering, Kasetsart University and PTTEP, which provides us financial supports. Finally, we thank Kasetsart University for providing us time and space to use a university diving pool.

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