Ben-Gurion University of the Negev Autonomous Underwater Vehicle: Design and Implementation of the Hydro-Camel HAUV

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Abstract – The Hydro-Camel team is composed of a group of 19 students from the departments of Computer Sciences, Electrical and Computer Eng., Mechanical Eng., Software Engineering. The group have designed and built a hovering autonomous underwater vehicle (HAUV). The platform has advanced capabilities of object and obstacle detection, navigation, motion and mission control. Among the unique features of the vehicle we might mention the use of carbon fiber for the frame and advanced modular robotic arm. ROS based architecture and GAZEBO simulator were used in this project.

I. INTRODUCTION

The Hydro-Camel team was established by a group of 19 students from different departments (Computer Science, Electrical and Computer, Mechanical and Software Engineering) at Ben Gurion University (BGU) of the Negev, Israel. The main objective was to design and build a HAUV which would be able to fulfill oceanographic research and provide underwater service. The AUVSI & ONR competition provided a suitable framework to fulfill both objectives.

As a first year team, our biggest challenge was starting from scratch. However, with a lot of hard work and the support of our mentors and sponsors, we managed to design and build the HAUV.

The work on the Hydro-Camel platform was mainly performed in the Laboratory for Autonomous Robotics, with the help from The Robotics Laboratory at the Department of Mechanical Eng.

II. DESIGN OVERVIEW

The Hydro-Camel structure is composed of five sections. The front or nose section contains the torpedoes and the stereo cameras. Two thrusters (z and y planes) and a battery are located in the following section. Two additional thrusters (z and y planes) and battery are located before the tail (back) section. The arm and a ninety degrees camera are housed in the aft. The above described sections are wet and have similar weight. The electronics hardware components (power supply, the main computer, the navigation system, etc.) are located in the central dry section. Two additional thrusters are attached to the middle section (Figure 1). The six thrusters allow the Hydro-Camel to have five degrees of freedom. The Hydro-Camel is cylindered shaped and its dimensions are 1.5m in length, 0.3m in diameter with a total air weigh of 45kg. It can operate at a maximum thrust velocity of 1m/s for an hour. An on-board Inertial Measurement Unit (IMU) provides the angles information to the attitude controller. The three cameras (two front stereo and one bottom view) provide the mission controller with information about the current position.

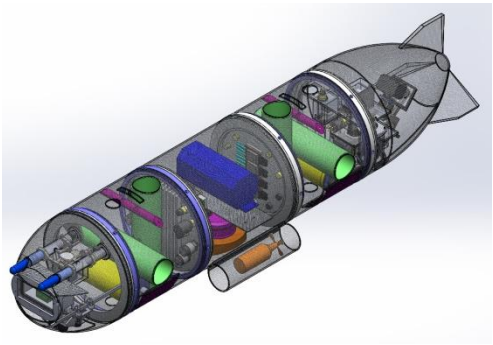

Figure 1: A SolidWorks model of the 2013 Hydro-Camel vehicle

III. MECHANICAL SYSTEMS

The mechanical team worked on the frame, torpedo, arm and hydrodynamics. They collaborated with the electrical and software teams in order to accomplish the design, build and integration of the platform in a short span of time.

During the summer of 2012 the team performed a comprehensive review of the different structural approaches used. The pros and cons of each configuration were analyzed. Finally, it was decided to design a missile-like vehicle able to move in 3 axis using 6 independent motors. The structure and its different components were modeled using CAD software (SolidWorks). The underwater behavior was studied using CFD software (SolidWorks Flow Simulation). The simulations allowed to ping-point the weak spots and correct the design before manufacturing. The body is made of carbon fibers and was manufactured by the mechanical team at one of the Hydro-Camel sponsor's workshop (Comparts).

A. Frame

The Hydro-Camel frame (Figure 2) is composed of 5 major parts, all made from Carbon Fibers. Those parts are connected by an aluminum ring into one solid body. The motor cells are identical. The remaining cells are the main or middle section, nose and tail. The submarine was built in a modular way so that it can be disassembled, allowing different sub-teams to work on it simultaneously. Only the main cell is dry cell (sealed), while the other cells are flooded with water and contain sealed boxes with internal components.

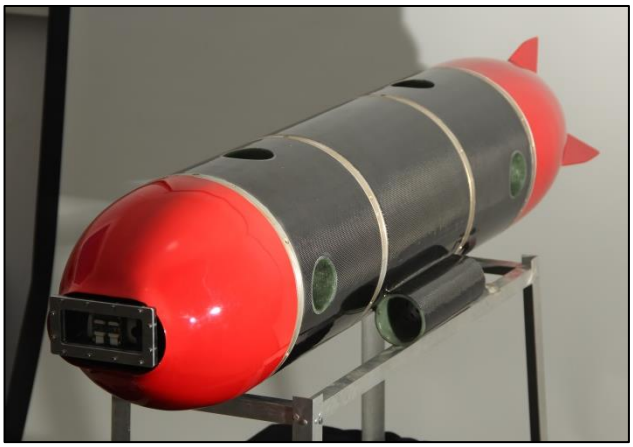

Figure 2: Hydro-Camel Frame

B. Modular robotic arm

This system consists of 3 sealed boxes: 2 DC motors and "Robotis CM-700" controller. It is designed to be sealed underwater for at least 3 meters depth.

The arm grabber (Figure 3) is responsible for grabbing objects. The grabber motor is connected to a strip gear that allows the movement of the pair of jaws. The design allows manipulating objects of up to 3 kg.

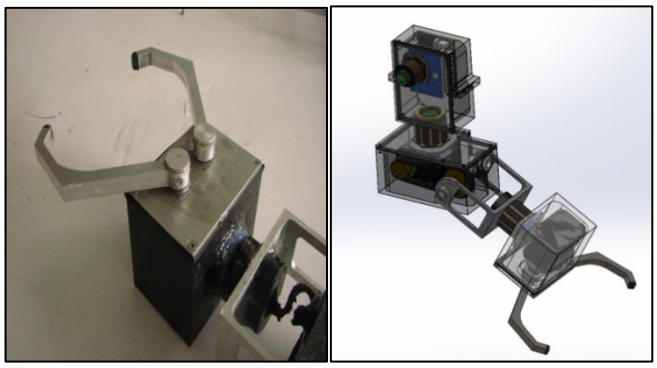

Figure 3: Grabber and Modular Robotic arm

C. Torpedo launcher and droppers

The torpedo system (Figure 4) consists of a motor, a video camera and a launcher mechanism that allows shooting two torpedoes separately. Each torpedo is made of ABS polymer, printed with a 3D printing machine. This material gives the torpedo the strength and buoyancy needed. The torpedoes are propelled by freeing springs and have a range of approximately 2 meters in water environment.

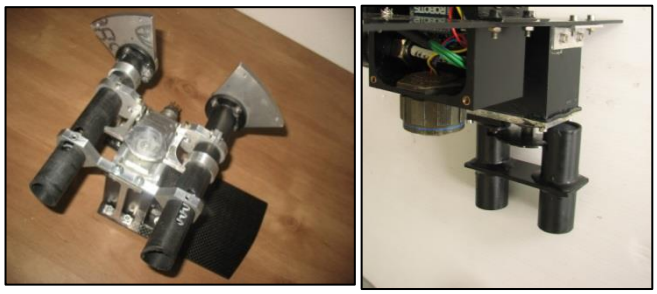

Figure 4: Torpedo launcher system and Droppers

D. Hydrodynamics

The hydrodynamics team had three main goals: 1) Estimation of the submarine center of mass, center of buoyancy and the forces acting on it during movement and in steady state. 2) Characterization of the flow regime developed by the submarine during its movement and 3) Computational Fluid Dynamics (CFD) analysis on the submarine in order to investigate the flow regime, improvement and streamlining of the submarine design. During the research, the team found that at full speed the drag force that will act on the submarine will result in about 8N, which means that the engines will be able to propel the submarine easily. The CFD simulations indicate that some boundary layers separations will develop on the tail. Those

separations result in loss of efficiency and will be dealt with in the future.

Although most of the work was done in the design phase, there was still a need for some corrections due to differences between the CAD model and the fabricated real life submarine.

IV. ELECTRICAL SYSTEMS

A. *Power management*

The power supply system was designed to ensure the robustness and safety of the Hydro Camel. The main modules of the power management approach are shown in Figure 5.

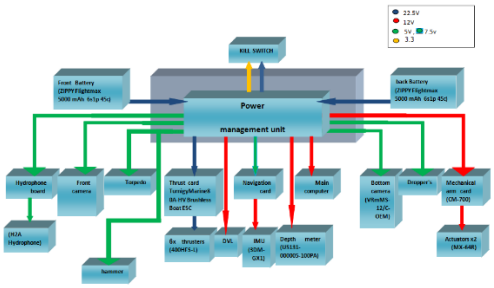

Figure 5: Power management chart

In order to ensure the fulfillment of the desired requirements power supply boards were designed (Figure 6).

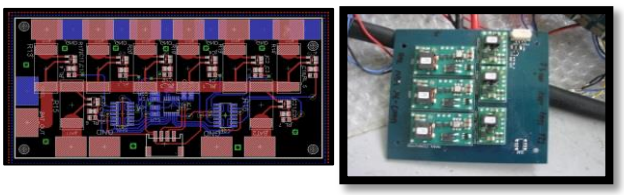

Figure 6: Layout of the two power supply cards

A switch (**Error! Reference source not found.**) based on Hall sensor was designed to allow easy power on/off of the platform. The switch integrates emergency push down and status led lights (Figure 7).

Figure 7: A power kill switch

B. *Motion Control*

Motion is performed by 3 pairs of thrusters (Figure 8).

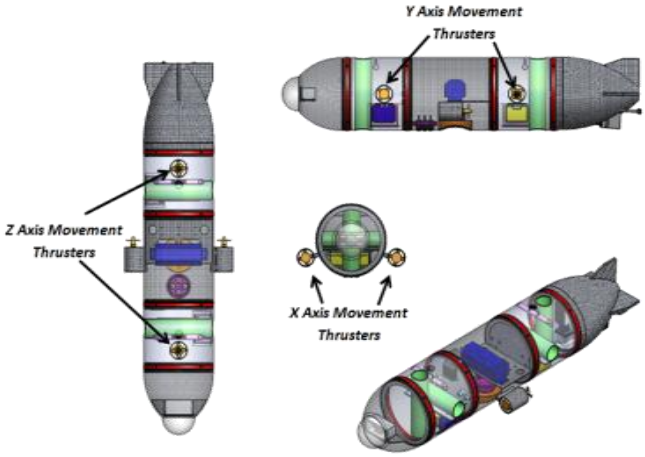

Figure 8: Thrusters' locations

The location of the thrusters allows control on five degrees of freedom x, y, z, yaw, pitch. The CrustCrawler "High Flow 400HFS-L" Series Thrusters were employed (Figure 9).

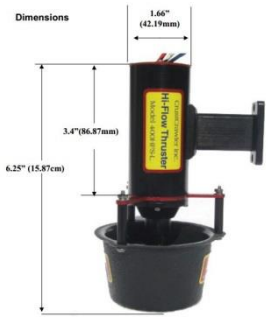

Figure 9: CrustCrawler "High Flow 400HFS-L" Series thruster

The control system sends PWM signals to six speed controllers (TURNIGY Marine 80A-HV Brushless Boat ESC, Figure 10).

Figure 10: TURNIGY Marine 80A-HV Brushless Boat ESC

Each degree of freedom is controlled by a linear PID controller algorithm. The control system is implemented (in C code) on a STM32F4 controller (Figure 11).

Figure 11: STM32F4 controller

V. SENSORS

A. Cameras

Two Front Cameras (Figure 12) are used for 3D measuring and front view. The cameras are VRmMS-12/C-OEM

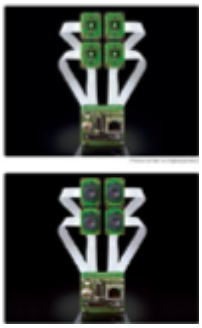

Figure 12: Front Cameras

An additional camera (Bottom Camera) is used for path and obstacle detection (PointGrey USB3.0, 1.3 MP).

B. Hydrophone Array

The hydrophone array is a system of passive hydrophones that is used to locate an underwater platform/object by receiving, processing and analyzing the signal and the time delay received by each hydrophone. The localization of the pinger relatively to the HAUV moving direction is performed by a set of four H2a hydrophones (Figure 13) located on the front section.

Figure 13: H2a hydrophone

An electrical circuit (Figure 14) filters and amplifies the signal. The difference time of arrival is estimated by a timer of the STM32F4 processor.

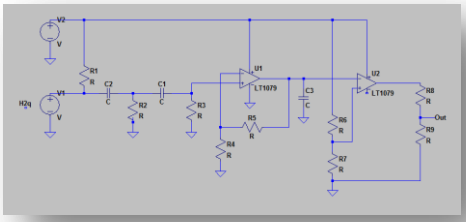

Figure 14: Amplifying filtering and processing signal circuit

The angle of the pinger relative to the HAUV is estimated by using the difference time of arrival to the hydrophones (Figure 15).

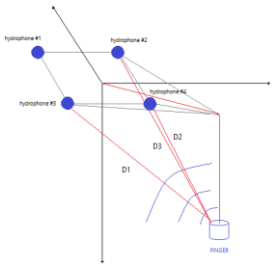

Figure 15: Pinger position localization

C. Inertial Measurement Unit (IMU)

An IMU is a basic component in Dead Reckoning Navigation systems. It provides inertial measurements of the vehicle's linear acceleration and angular velocity. The Epson Tyocom's AH-6120LR was chosen as IMU, mainly due to its high precision and low power requirements. This MEMS based analog sensor provides 3 axial readings of acceleration and angular velocity.

D. Magnetometer

To improve orientation estimation, a 3 axial magnetometer is integrated into the AUV's navigation system. The Honeywell HMC5843 digital compass that was selected for this task provides magnetic force measurements within 7 mili-Gauss resolution.

E. Depth sensor

An analog underwater pressure sensor (U5100) is installed on the AUV's navigation board. By measuring the pressure

as the AUV submerges, it is possible to accurately estimate the vehicle's depth, i.e. vertical distance from sea level.

VI. Control and Navigation system

In an underwater environment, no GPS signal is available. Additionally, the Robosub competition rules explicitly prohibit any communication of the AUV with the ground or surface. However, the AUV must know its location and orientation at all times.

To overcome the above challenge, a dead-reckoning based navigation system was designed. This navigation combines reading from a wide range of sensors (such as pressure, altitude, IMU, etc.) to form a complete picture of the AUV's dynamics and kinematics.

By integrating these readings over time, together with odometric inputs from the AUV's control system it is possible to correctly estimate location and attitude.

Even with high precision measuring equipment, the integration leads to a substantial error drift. In order to reduce the error a set of dedicated software based real time adaptive filters were developed. These filters prove to dramatically improve the system's performance.

The developed navigation system relies highly on the DVL, whose shipment is still delayed due to export regulations. As such, there is a high chance that this system won't be used during the 2013 Robosub run. In this case, we shall use a back-up auxiliary navigation system instead.

A collaborative effort of the Hydro Camel team and the Laboratory for Autonomous Robotics lead to the development of a state of the art hardware/software solution for AUV control and navigation. The board (Figure 16) is designed to be generic, flexible and independent of other boards making it a perfect standalone solution for any type of Autonomous Vehicle.

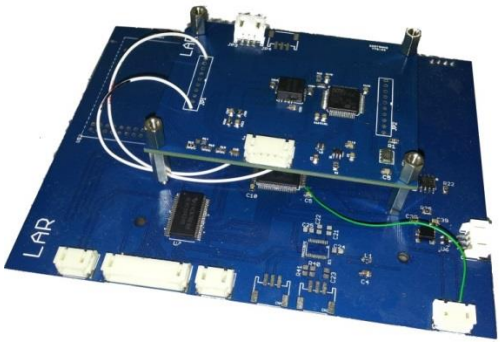

Figure 16: Revision 1 of the Control and Navigation board

The solution consists of two separate sub-systems: a control and I/O board and an optional navigation "Piggy Back". Both systems are equipped with ST electronics' STM32F4 MCUs with ARM4 cortex that serves as powerful CPUs and DSP processors.

The ARM4 CPUs are fully capable of providing all of the AUV's power control, motion control, actuators and navigation algorithms offloading these tasks from the AUV's mission control unit.

For maximal integration flexibility, the control and navigation board supports a wide range of communication protocols: I^2C, SPI, Ethernet, UART and RS-232. The relevant drivers for the ARM environment, running under a RT operating system, were also developed.

As the control and navigation HW solution is still under tests at the moment, it is highly unlikely that it will be integrated in Team Hydro Camel's AUV for the 2013 Robosub competition.

However, the extent of work done now will allow incorporating this solution in future versions of the AUV.

VII. SOFTWARE

A. ROS framework

The robot's system was developed using ROS (Robots Operating System) .

ROS provide advanced data handling and object serialization, thus allowing a development of a very modular code. Furthermore, using the ROS master server saved time in integrating the drivers for controllers.

B. System design

Each mechanical feature is controlled by a specifically designated program that acts as communication node with a master server that manages all the data flow (Figure 17). The actual features of the mission control modules are developed separately and communicate with the Comm nodes through the server.

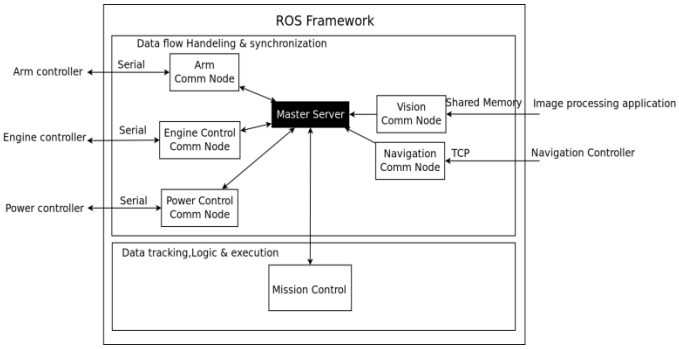

Figure 17: Data flow Handeling & synchroniztation

C. Mission Control

The mission planning was separated into two main section, data mapping and decision making.

The data handler constantly maps the data received from the sensors and searches for a mission (task) that is yet to be completed, missions found are added to the “missions’ pool” (Figure 18).

The decision making program works a part-utility part-reflex agent and constantly evaluates its course of action.

If the missions’ pool is empty, that means that the data mapped so far is insufficient for discovering new missions. The appropriate course of action would be to advance towards an uncharted part of the map and acquire more data.

If the pool is not empty, the missions in the pool will be executed best missions first. The rating of how good a mission is would be determined by a ratio of points/estimated completion time.

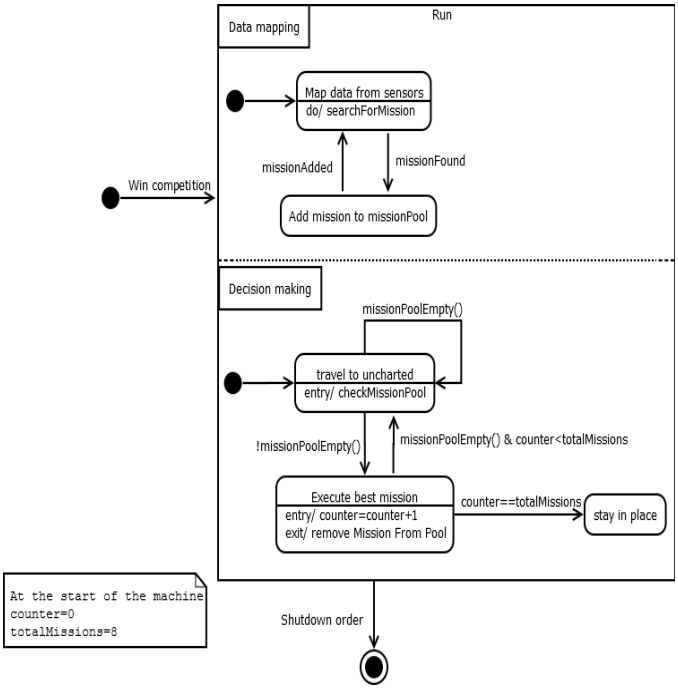

Figure 18: Mission Control's state chart

In order to make quick changes during real-time testing, most of the decision making code is written in python. We found that using a script language allows better configuration flexibility since it doesn't require compiling in order to run.

D. Vision Processing

All algorithms were developed using the OpenCV library. For color detection a real time fast and robust color detection algorithm for the AUV vision systems was developed.

This algorithm produces a gray level intensity map (Figure 19) for each specific Hue. Meaning, the closer the pixel's color is to the color we search for, the brighter this pixel will be on the intensity map. The algorithm works directly on the RGB color plane and is highly computationally efficient, because it has only computational operations such as addition and scalar multiplication .

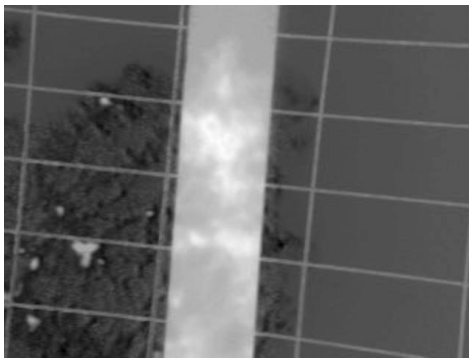

Figure 19: Intensity map

After color detection, different kinds of segmentations were used in order to get a binary image. The main segmentation we used is OTSU's segmentation and some thresholding based on standard deviation. Then the extracted contours are filtered by employing measurements such as area and shape in order to specify if this contour is the sought object. After segmentation the attained information is stored as a new object representing the searched object. For example, for the path the angle, height, width, and center point are stored.

The developed algorithms operate at 15-30 fps. The vision application runs the algorithms as multithreading in order to allow the mission control to receive information with minimum delay.

Due to the ROS framework messages can be sent easily and receive the input from the cameras and the proceeded output in real time.

A test application that allows easily configuring and testing of different algorithms has been developed. It provides the ability to see the data that each algorithm produces besides the final result, making it easier to test the algorithm (Figure 20 and Figure 21). In addition, several images can be tested in a single batch.

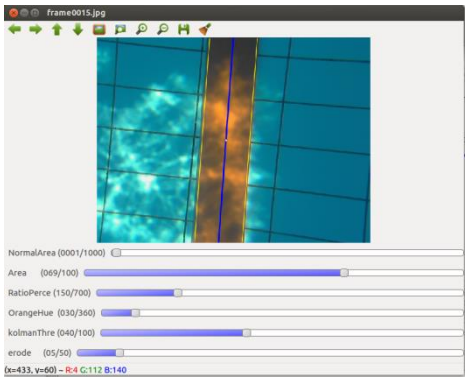

Figure 20: Configuration window

Figure 21: Process image - Thresh

E. Vehicle Simulation

Testing is performed alongside the development on the Gazebo simulator. The simulator allows creating multiple scenarios and analyzes the different outcomes (Figure 22 and Figure 23). Using the scenarios provided from the previous Robosub competition, a model of the pool environment and the various tasks was made. The simulation was used to develop the mission control data hander and some of the engine control algorithms.

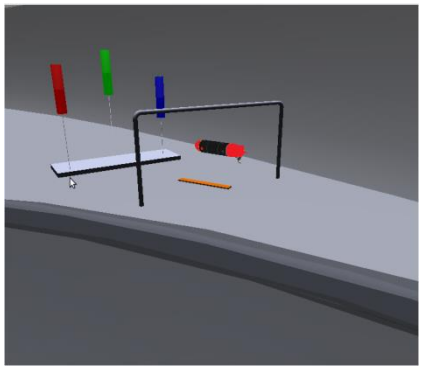

Figure 22: Gate mission simulation

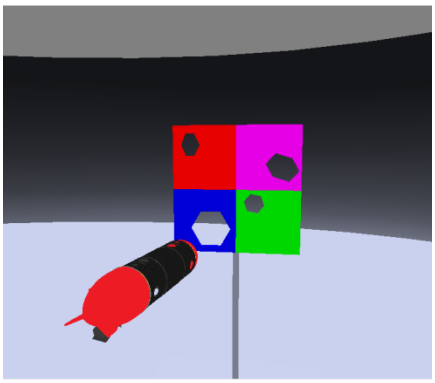

Figure 23: Torpedo mission simulation

VIII. ACKNOWLEDGMENT

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