Design and Implementation of Task-Oriented Autonomous Underwater Vehicle: Feryal

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Abstract—**This manuscript presents the design and implementation strategy of ASmarine's new AUV, Feryal. The Team will compete at RoboSub's 2020 event. The vehicle prototyping adopted a new philosphophy that best suits ASmarine's vision and competition targets with four cornerstones: physical simplicity, software originality, cost-efficiency and mission-oriented design. This philosophy reflects on how limitations imposed by lack of expensive hardware sets and satisfactory performance were turned into research and customized software development opportunities, thus combining rich contribution to academia and task-oriented competition planning in one scheme.**

This philosophy impacted the vehicle's design, putting time above complexity. The vehicle has an extremely simple, modular body suited for quick assembly and testing. The time saved in vehicle construction was heavily invested in the development of a fully customized software that makes the most use of available sensors/actuators and accounts for missing ones as well as smart selective mission planning that was validated by dozens of simulation trials. The final simulation and testing results show an autonomous performance that matches that of other vehicles equipped with much more expensive state of the art hardware in terms of clear perception, accurate localization and smooth trajectory tracking with minimal deviation from the desired mission run time and success rate.

I. Competition Strategy

A. Task Selection

The task selection process was a thorough combination of self-assessment and score sheets study. By careful examination of last year's results, it was obvious that attempting all tasks is a failing strategy. Over-complicating design would eventually embed redundancies and compromise reliability, therefore an objective function that assigns weights to both complexity and reliability based on the points of strength and weakness was formulated and optimized to maximize the score under given constraints of time and workforce.

The decision was made to drop all pick-up tasks from the plan and focus on tasks that require maneuvers and figure detection, since gripping tasks are tricky and often require time to master while maneuvering and detection require robust control development and skillful use of deep learning and/or conventional machine vision which happen to be among team strengths. The pinger localization requires further testing and refinement. Bonus tasks (except style) are to be dropped.

Based on the above, mission planners selected the following tasks:

- Gate: Pass through (No random flip - detect which image section was closer during penetration)
- Gate: Style (full yaw rotation-360 degrees)
- Buoys: select and hit the right shape (right in this context is affiliated to gate entrance image)
- Bin: Drop marker in the right bin (no bottle pick-up)
- Torpedo: fire through right shape (bigger size opening)
- Octagon: surface within area (no pick-ups or drops)

The sequence of task execution as well as task training (fig.1) was to follow standard order, since first tasks are usually the most guaranteed and fastest to execute and since the training period this year-due to external circumstances-was very insufficient to tell whether it's a good strategy to jump to a complicated task that may/may not be perfectly executed.

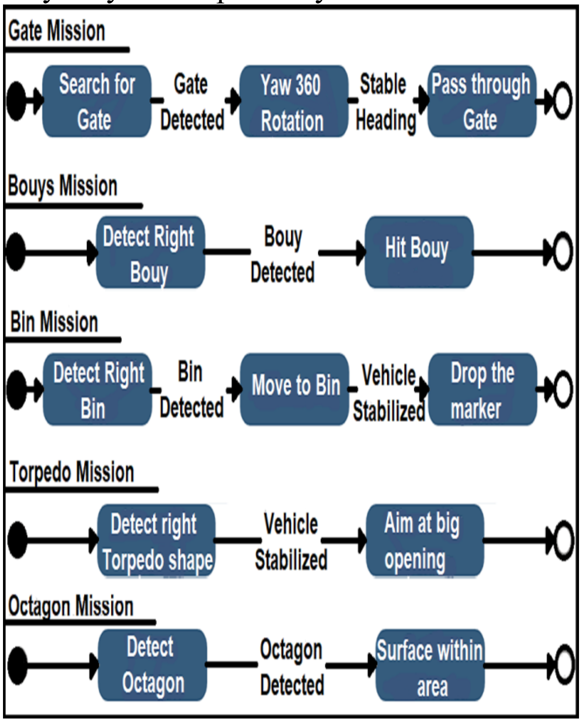

Fig.1 Execution/development sequence

B. Task Technical Requirements

Based on the above selection of tasks, two technical challenges need to be addressed. The first being the limited run-time. Accomplishing many tasks using one vehicle requires optimization of task handling time through real-time accurate detection and vehicle trajectory tracking. The assessment of time challenge success is made possible through manipulation of random variables in multiple simulations/experimental trials and measuring execution time mean and standard deviation. If the mean time happens to be within satisfactory limits and the standard deviation is sufficiently small, the strategy is deemed optimal. The second challenge is the absence of an accurate odometery measurement source for localization and velocity feedback (dvl, cvl, etc.) especially with the relatively long distance travelled and chances of getting lost. Addressing this challenge can be done by developing a very customized and efficient SLAM module that makes good use of available sensors (stereo vision camera, IMU, pressure sensor, Hydrophones and sonar) and fuses their data to provide compensative feedback.
A new vehicle is to be developed from scratch to be the perfect test subject in terms of assembly/disassembly speed and hardware accessibility in order to create the perfect environment for excessive software development and testing.

C. Timeline Planning

A full timeline for 2020 season was made that carefully considered the innovations required and providing sufficient training time. The timeline included:

- A proper recruitment plan to hire personnel of high caliber especially in vision and control fields **(1 month)**
- Rich literature review **(1 month)**
- Full design cycle (fig.2) based on VDI model [1] **(5 months)**
- Testing and training **(4 months)**

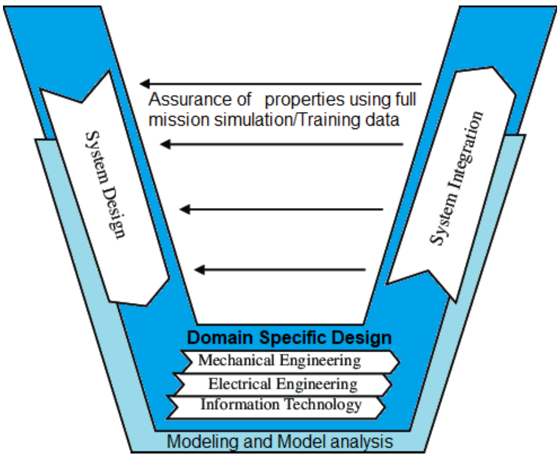

Fig.2 Applying V-model in AUV development

The covid-19 outbreak emerged by the end of the vehicle assembly phase and eliminated the chance for pool testing and hence modifications were made to the plan. The design cycle validation step was achieved through dry test-rigs (for software-hardware interfacing), simulation scenarios (for autonomous performance assessment), stereo-camera shallow underwater testing (for depth estimation), previous years' video footage and image synthesis (for detection).

II. Vehicle design

The vehicle design process was mission-oriented in nature adopting a philosophy that interprets the team's tendency towards problem solving using academic research methods and implementing solutions using professional industry-level procedures. Major weight was assigned to software development in terms of time and workforce while minor weight was assigned to vehicle mechanical/electrical complexity. The design carefully considered cost-optimization to account for lack of financial aid this year while maintaining high-level autonomous performance through dedicated algorithm development.

A. Mechanical

The mechanical design target was to develop a vehicle that is cost-efficient, fast to manufacture/assemble and most importantly, highly modular (fig.3).

Fig.3 Feryal's compact frame with plug and play sealed modules

One of the novel aspects of design this year was the new sealing method for electronics. The team decided to give up on the standard pressure hull design and create a number of modular electronics' boxes. Each box contains a functional element in the vehicle hardware (fig.4). The new design offers a lego-like mechanical structure that speeds up the assembly/disassembly process and facilitates quick troubleshooting. Each box provides feedback regarding its status using both LEDs and standard communication protocols with the main computer. Last year, no electrical member was available on site due to travelling complexities. This incident made it extremely difficult for software members to handle troubleshooting issues. The new design offers a very user friendly plug and play hardware interface that enables any regular user to replace damaged electronics swiftly. A user is even encouraged to add or remove any hardware feature in seconds without having to unlock any sealing enclosures, which makes Feryal the optimal test subject for software endeavors.

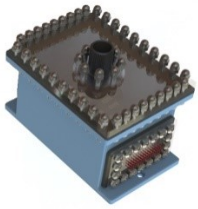

Fig.4 Thruster control unit box

Another novel aspect is the frame design which could be best described as rigid and cheap. HDPE was used as frame material since its density is close to fresh water which helped achieving almost neutral buoyancy. The vehicle weight was successfully reduced to 26 kg this year making it compact and easy to transport unlike last year.

The vehicle is equipped with an innovative torpedo firing kit (fig.5) that uses only one sealed servo motor (optimizing both space and wiring density) and a sequential let-go rack and pinion mechanism to sequentially fire torpedoes through servo motor angular command. The vehicle also has a very simple marker dropper mechanism that uses two solenoids to block the marker's path when extended and let it fall freely when retracted.

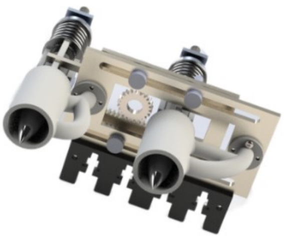

Fig.5 Torpedo firing kit

B. Electrical

The electrical team targeted a simple efficient design with no complications. The most notable novel aspect this year was the development of a new ultra-low noise hydrophone signal conditioning circuit that was simulated using proteus and was verified through lab testing. The board was manufactured as a custom board and drastically improved the pinger localization performance.
The electrical team focused on safety because testing trials require a perfectly secure AUV. Safety features include: battery management system, circuit breakers, DC-DC converters over-current protection circuits and more.

C. Software

Software design aimed at creating an architecture perfectly customized for both Transdec's missions and the available sensors. ASmarine engineers developed a state of the art visual perception module. One of the novel aspects of this module is its ability to eliminate the effects of light scattering and energy absorption that pose a threat for the vision system due to poor lighting conditions at transdec lake and the team's inability to create datasets that take lighting variation into consideration due to quarantine restrictions and pool lockdown. The pre-processing technique used for image enhancement [2] was validated using old transdec lake footage (fig.6).

Fig.6 Image enhancement

The detection pipeline relies on two techniques. The first technique uses conventional vision to detect simple objects and shapes like bin/torpedo openings and path markers. The second technique uses a deep learning model named "Yolo V.3" which yielded satisfactory results and proved to be capable of detecting sophisticated shapes as bootleggers/g-men characters. Training the model was a major challenge due to the absence of props data and quarantine. To face this issue, perception engineers used three different techniques to synthesize dataset images namely: image blending, image scraping and image augmentation. Implementing this whole pipeline helped the team continue the software development process despite external interruptions (fig.7).

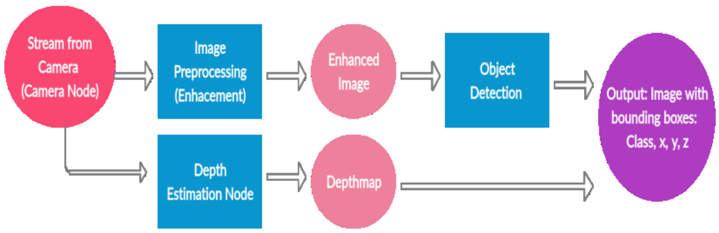

Fig.7 Perception pipeline

ASmarine engineers developed an EKF SLAM module from scratch that predicts vehicle states and mission coordinates based on available odometery data and updates its belief using visual perception feedback and stereo vision depth estimation. This approach helped obtain accurate feedback without using expensive hardware sets. The simplicity of EKF SLAM and its computational efficiency (due to small number of landmarks) made it extremely efficient and practical. Despite the simplicity of the idea, it had physical limitations due to light refraction while travelling through different media which highly affected the depth estimation capability of the stereo camera. However, a solution was developed and implemented based on a complete analytical refraction model using snell's law to correct the depth estimation data and endorse the

physical applicability of the EKF SLAM concept.
In order to obtain a robust trajectory tracking and stabilizing controller for proper mission execution, the vehicle dynamics analysts developed and simulated a full non-linear state space model of the sub which was later used to validate the efficiency of proposed controllers. A novel trajectory tracking controller based on model predictive control was developed. This new algorithm proved to be very efficient for intricate path following since MPC adjusts its control action based on evaluation of an objective function that takes into account both current and future set-points unlike last year's LQR based control [3]. MPC is, however, not robust to un-modeled dynamics and system noise. In order to overcome this deficiency a PID based trajectory correction controller was added (fig.8).

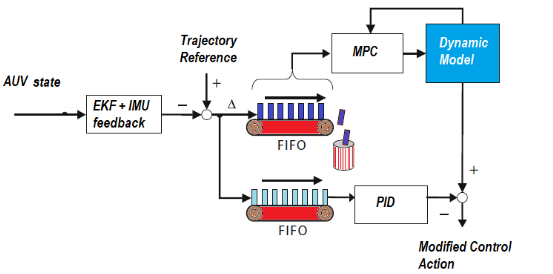

Fig. 8 A novel trajectory control algorithm

Each of the newly developed algorithms was verified using simulations and converted to well-written ROS nodes that were properly linked together and integrated to build the entire AUV software structure.

III. EXPERIMENTAL RESULTS

Design was finished by mid-February and the manufacturing activities proceeded reaching a partial assembly phase for the frame by the beginning of March. The initial plan was to use a sealed vision-SLAM test rig to validate perception and SLAM modules in parallel with vehicle assembly to save time, and then install the vehicle's electric kit to deploy it in water and test the control module before testing the integrated performance of perception, SLAM and control by the beginning of May. However, the plan was stalled due to the covid-19 and the enforcement of a total lockdown that lasted several months. The plan was altered to continue development in light of present circumstances. The process was to rely on the use of hardware test-rigs for software-hardware interfacing (mostly communication protocol and thruster testing) and the exchange of components between electrical and software members using local shipping services. The validation of perception module relied on old footage by old teams and image synthesis techniques. Results were discussed in online meetings till a satisfactory performance of 0.59 mean average training precision and 0.35 mean average testing precision was reached. SLAM and control were entirely validated through Matlab/Simulink simulations as shown in fig.9. Finally, the entire autonomous performance was validated through full mission simulations on Matlab/Simulink.

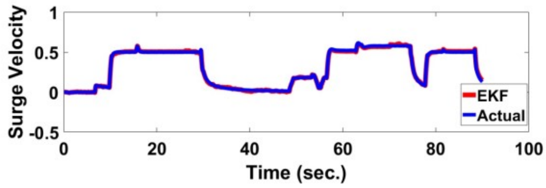

Fig.9 EKF estimation vs. Actual velocity

Each mission was assigned a confidence rating based on simulation success rate, mean execution time and execution time standard deviation. These metrics highlighted the importance of simulations and thorough investigation before attempting physical trials to save time and enhance system efficiency.

IV. ACKNOWLEDGEMENTS

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APPENDIX

A. Component Specifications

component	vendor			
Buoyancy control	n/a	n/a	n/a	n/a
frame	El Akkad	Routing	commercial	117.5$
housing	In-house manufactured	3d Printing	Custom	295$
connectors	Bluerobotics	M10 cable penetrator for 10mm wires	Dry connectors	n/a
thrusters	Bluerobotics	T200	Brushless thrusters	n/a
Motor control	Bluerobotics	Basic ESC	Speed control	n/a
High level control	ASmarine	Optimal control	MPC/PID	n/a
actuators	Future electronics	Servo motors	Position control	50$
propellers	n/a	n/a	n/a	n/a
battery	Hercules	13S6P battery	Lithium ion	500$
Converter	szwenagoa	Dc-Dc converter	48v to 12v waterproof dc-dc converter	n/a
CPU	NVIDIA	Jetson TX2	Six 2Ghz ARM8 Core	n/a
Microcontrollers	ARM	Tivac	microcontrollers	50$
Internal comm network	n/a	I2C	Serial	free
External comm interface	Bluerobotics	M10 cable penetrator for 10mm wires	Dry connectors	n/a
Programming language 1	Python Software Foundation	Python	interpreted	free
Programming language 2	WG21/FSF	C++	compiled	free
Inertial Measurement Unit (IMU)	Adafruit	Bn05	I2C communication	n/a
Algorithm: vision	Pytorch	Yolo V.3	vision	free
Algorithms: acoustics	Implemented by members	FFT	Discrete fourier transform	free
Algorithms: localization and mapping	ASmarine	Custom EKF SLAM	EKF	free
Algorithms: autonomy	Implemented by members	State machine	State machine	free
Team Size (Number of People)		26		
Hardware/Software expertise ratio		12:7		
Testing time:simulation		100		
Testing time:in-water		0		

B. Outreach activities

Media Outreach: As a technical team, we believe that we have a responsibility is to add value and purpose, so ASmarine participates in many events such as Makerfaire, YLF (youth leadership foundation) and Traverse to share our ideas and passion towards what we do. Social media platforms are used to promote our team and stay updated with the latest trends.

Corporate Social Responsibility: Because of our commitment to both our community and our work environment, corporate social responsibility (CSR) plays a fundamental role in our operations at ASMarine. Our business impacts our local environment and touches the lives of a lot of people across Egypt. Education Supporting Initiatives This year, ASMarine participated in the ASU Academy where free sessions were provided for college students. Community Engagement Initiatives The profit that comes from selling our branded merchandise like team shirts, mugs and even custom-made pcbs is given fully to charity, with special focus on Dar Al Mowasa Orphan Center and The Children’s Cancer Hospital 57357.