AS Marine Autonomous Underwater Vehicles: Design and Implementation of an AUV

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***Abstract* – ASmarine is an Egyptian team formed of undergraduates and experienced graduates from Ihub Cairo, Egypt. Buffy is the team's first Autonomous Underwater Vehicle. The vehicle utilizes perception, localization, mapping, planning, and control modules to achieve fully autonomous behavior, with the aid of state-of-the art Computer Vision, Machine Learning, and AI technologies. The software system was designed to allow for a smooth flow of information across modules, entirely orchestrated by a single mission planner module. The AUV was successfully designed and manufactured in 9 months in accordance with Robosub rules. Throughout the process of designing and implementing the vehicle, team members were encouraged to think as entrepreneurs rather than just engineers.**

I. COMPETITION STRATEGY

ASmarine's approach towards the competition is to showcase the team's strengths and prove that it can push the limits and achieve satisfactory records despite it being its first time to join the competition. To achieve this, the team spent a period of two months studying previous competition events, going through old technical reports and making plans at the beginning of the season. The first target for the team was to observe and analyze as many design patterns and strategies as possible, and accordingly decide on the most suitable strategy to pick in each of the three different areas of design: software, electrical, and mechanical. Prior to the mission details being released, the team spent time working on their basic design aspects, which most teams usually pass on from one year to the next, such as thruster configuration and body design. On the other hand, software team members spent time working on mastering the required tools and frameworks. Moreover, team members worked their way into the final system architecture design by continuously implementing innovative ideas and testing their feasibility. To ensure the autonomous capability of the final system architecture, tests and simulations were run, results were observed and analyzed, and modifications were made accordingly. For executing the missions, the team's plan is to attempt to complete as many tasks as possible, and avoid trying out complex bonus tasks which would probably require moderate to advanced competition experience and would probably consume time without yielding an outcome that's worthwhile, only the style bonus task would be attempted, with our main focus on the first three missions, at least for the first stages of the competition. The main goal this year is to observe the vehicle's points of weaknesses and areas of improvement to work on, while also keeping track of areas of strengths to provide a solid foundation for upcoming years and make an investment for the team future. For this strategy to work, extra attention was paid to the LQR control and acoustic modules of the system, for it was believed that control performance and position feedback through acoustics would play a huge role in the vehicle's overall performance. Moreover, the team chose to pay extra attention to the less risky aspects of pointing, such as static judging and technical documentation. Finally, a thorough and detailed Debugging, Data Acquisition, Ground Control systems and pipelines were developed and utilized to allow for maximum utilization of training time, leaving room for further enhancements. Power monitoring and safety played a huge role in maximizing testing time. The aforementioned measures were taken to let the team be ready for any unplanned circumstances during the competition arising from lack of experience.

II. DESIGN STRATEGY

Despite this AUV being the first of its kind for this team, it is a team of engineers nonetheless, many of which are well-seasoned in the field of robot design. The team takes pride in the vehicle's design, in all its aspects: software, electrical, and mechanical.

A. Mechanical

The physical design of the vehicle began as a sketch on paper and evolved to a complete design using SolidWorks. The goal was to create a vehicle that could be easily expanded, modified or upgraded. The final rendering of the vehicle is shown in Fig 1. With the design and drawings completed, some parts of the vehicle were built in the manufacturing as shown in Fig 2, using a computer numerical control (CNC).

The team's experience served as a solid foundation for Buffy's design. The design process focused on making the sub rigid, relatively compact and ergonomic while at the same time facing the new challenges imposed by the change in vehicle size as compared to an ROV's weight and volume. The vehicle was built from scratch; and the team had to rely on relatively cheap but efficient technologies to manufacture the vehicle components since financial supplies were scarce and limited. AS Marine engineers turned the harsh conditions into an opportunity to learn how to work under pressure and achieve the best possible outcome. The design strategy was based on a sequence of decision-making meetings, each of which contributed to the final form of the vehicle and helped overcome both logistic and technical problems.

The vehicle form was primarily based on a tradeoff between size and weight, the electrical system demands space, but a larger volume would create a higher buoyant force, and the sub would need to counteract the effect by either increasing the thruster effort which would drain the battery faster, or increasing the sub weight which might lead to disqualification. Such decision required a variety of conceptual designs and sketches till the final form was approved. The final form (fig.1) suggested the presence of a central hull with four inlets (one from the back, two from the sides and one from above) to easily access the vehicle electronics without the need to pull the electric kit out of the vehicle. In case pulling the kit out was necessary to handle some serious issue, a mechanical release mechanism for the hull end caps would facilitate the process. The central hull inner diameter (190 mm) was picked to satisfy the electric kit volumetric needs while at the same time maintain an acceptable buoyant force. The next step in the process was the frame design, our previous ROV frame designs were compact and small, and the weight was very little compared to a fully functioning AUV, hence there were no strict constraints on frame material which was mostly acrylic or HDPE, an AUV imposed a technical challenge since it weight was significantly larger and the frame links would certainly buckle under static loads, get damaged due to fatigue introduced by the dynamic thrust force cycles, or break under shock loads during loading and unloading. There was an obvious tradeoff between material cost and rigidity; a problem that was solved by introducing the "sandwich" idea, each link is composed of a 4mm HDPE layer sandwiched between two 2mm Aluminum 6061 layers, thus combining the rigidity of aluminum and the ductility of HDPE, while-simultaneously- reducing the overall cost and vehicle weight.

Fig. 1: AUV Final design featuring a rigid "sandwich" frame and hull inlets

The vehicle sealing strategy was studied and the engineers found it best to rely on mechanical sealing. For this purpose, parker static O-Rings [1] were used instead of chemical sealing as the engineering standard assures a functioning sealing till 1000m beneath water surface without leaving any weak or exposed points. Two O-Rings were installed in sequence in each location to reduce the probability of leakage due to O-Ring deformation and external pressure changes. Mechanical design considerations were all considered. ASmarine engineers validated their designs through multiple stress analysis simulations including static, impact and fatigue simulations. The mechanical team members spared no effort in CFD analysis of the vehicle, carefully analyzing the forces of drag and lift and their effects on vehicle motion and thruster effort, and thus the vehicle thrusters were properly sized to obtain reasonable vehicle speeds up to 0.8 m/s. Finally, safety was addressed by removing all sharp edges, shrouding the vehicle thrusters and sticking safety labels on both the vehicle and the workshop walls.

B. Electrical

Buffy features a highly modular electrical system (fig.2); this helps increase reliability and ease of system integration, while at the same time reduces troubleshooting and testing times. Each module was carefully designed, simulated, prototyped, tested and installed by the electrical sub-team members. Despite the team's little experience, the members managed to follow a very systematic system design approach, which yielded high quality custom-made boards and helped members enhance their technical and self-learning skills. The vehicle designers' top priority this year was safety and power monitoring, as unfortunate incidents are almost inevitable for an inexperienced team. The rest of the designers' focus was directed towards the hydrophone signal processing board which was entirely built up from scratch using off-the-shelf basic electronic components and a Tiva C board as well as the actuator controller, manipulation kit controller and data acquisition boards. Structural integrity and efficient wiring mark the vehicle's electrical system. All wire lengths were chosen with optimization in mind, and special tracks were included in the electric kit to allow for wire routing in an organized fashion to ensure wire relief and avoid the unpleasant "macaroni" wiring. This was achieved through a very detailed and thorough CAD modeling process of the electric kit, which included every detail and every wire in the kit.

The boards can be accessed easily as the entire kit can be pulled out via a user-friendly mechanical release mechanism. Furthermore, troubleshooting is made easy through indicator LEDs and feedback communication protocols with the Jetson TX2 main board.

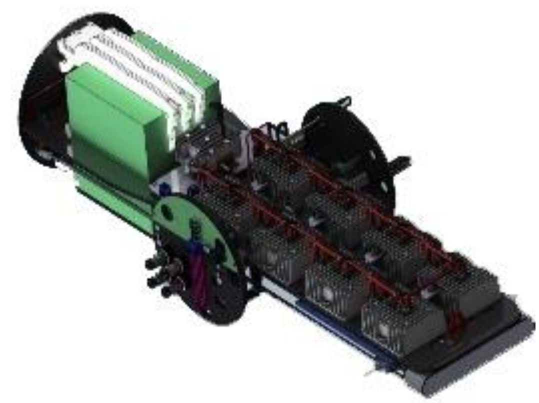

Fig. 2: rendered image for the electric kit

The power module was designed to ensure safety and a smooth power flow. The module comprises a soft start mechanism to prevent electrical sparks while starting the vehicle. Several safety aspects were considered in the design of the module. Both component built-in and external safety features are incorporated in the system. The battery has a built in BMS that manages cell balancing and offers over-voltage, over-current and over-heating protection. The battery is also equipped with a 35 A fuse to offer extra-protection against persistent high loading conditions. Additionally, a 20 A fuse was also added to each thruster's power line. The power module also comprises a current sensor attached to a custom-made monitoring board that computes the voltage, current and state of charge data and feeds them to the main Jetson TX2 board. The hydrophone signal processing board represented a real challenge, as the signal is very susceptible to noise and requires a very high sampling rate to be adequately analyzed. The custom-made board comprises a very efficient preamplifier, followed by a 4-stage band pass filter. A Tiva C board is being used to analyze the signal using FFT algorithm to compute the phase difference between hydrophones and deduce the bearing and heading. PCB design considerations were applied strictly to prevent EMI. The board was further shielded using an aluminum foil cover to reduce signal susceptibility to noise.

As the vehicle manufacturing process was significantly hindered by logistic delays, we managed to work around this complexity by developing our own sealed test rig for testing and troubleshooting purposes. This helped the members enhance their hands-on skills as well as verify-and even-improve their designs. The test rig was equipped with sealed cables that were wired to a surface station that 4included voltage and current monitors as well as RS485 communication channels.

C. Vehicle Dynamics

System dynamics were studied thoroughly, and a comparison was made between different controllers. The team saw it fit to use a MIMO controller instead of conventional SISO controllers like PID, since the vehicle dynamics are highly coupled and non-linear, making the control of several vehicle states simultaneously using multiple SISO controllers a very tiresome task. The optimal control theory offers a very practical solution to this case. This solution is the LQR controller, which the team engineers decided to develop and use to simultaneously control the linear and angular speeds of the vehicle as well as the depth [2]. All physical parameters related to the vehicle mass properties and geometry as well as acting hydrostatic/hydrodynamic forces and the control action produced by a particular thruster configuration were extracted using CAD models, CFD (fig.3) and finite element analysis tools. This data was fed to the non-linear state space dynamic model which was developed from scratch using MATLAB/SIMULINK. The simulation results showed an accurate convergence to the desired set points and acceptable response times.

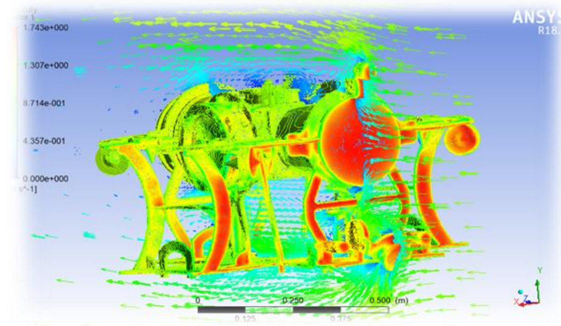

Fig. 3: CFD analysis of the vehicle using Ansys workbench

The LQR controller key matrices (state matrix and input matrix) were deduced by linearizing the model and used to compute the required gains for thruster actuation to stabilize and control the vehicle smoothly and accurately (fig.4). The controller runs via a python script, receives feedback from the sensor fusion and localization modules and sends the required thrust values to the actuation controller board which interprets thrust in terms of PWM values and feeds the PWM signals to the electronic speed controllers (ESC).

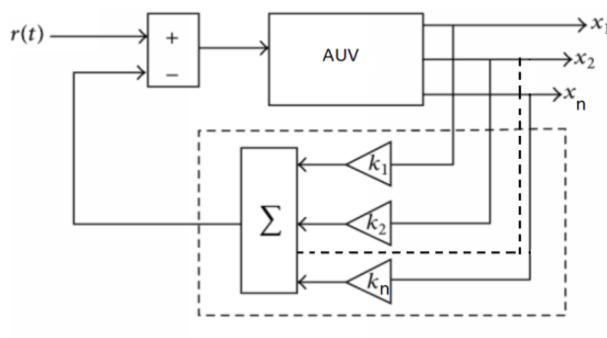

Fig. 4: LQR control diagram

D. Software

The software architecture was developed in a most detailed and organized fashion, to meet the task requirements and provide a reliable platform that would form a solid base for future enhancements in upcoming years, Software ROS Architecture was designed to best utilize all components, while maintaining design modularity and upgradability. The system cleverly has a place for every component, with a well-defined job description and list of responsibilities for each module. For the vehicle to be able perform autonomous navigation, local information from its sensors have to be transformed into global information. To achieve that task, SLAM was used to better enhance our vehicle localization.

Data flow starts at the perception module, which reads feed from a ZED camera and two monocular cameras at the bottom of the vehicle, to provide a full view of the mission scene. The frames go through an object detection module, which includes all the Computer Vision algorithms for many different scenarios and objects of interest. Our state of the art computer vision module includes both conventional and machine learning vision algorithms, maximizing the visual system's efficiency and working around hardware limitations. In addition to visual perception, extra hardware was used to obtain further data including a ping sonar to better enhance the vehicle's depth estimation for objects and overcome visual deficiencies. Another set of hardware utilizing two IMU's fused together using EKF is also used to obtain orientation and acceleration feedbacks.

The team possesses no DVL device due to financial difficulties. However, the team managed to develop an innovative alternative. By fusing the data coming from the IMU hardware set with the position data coming from the hydrophone module, it was feasible to obtain a relatively accurate vehicle velocity estimation required for the LQR control algorithm to operate. This was a breakthrough in the vehicle's performance since IMU's alone will always drift due to noise and hydrophone data is obtained after relatively long pinger idle time intervals, each of which not capable of providing sufficient odometry information, a problem that was solved via fusion. The data coming from the perception module, the hydrophone-IMU odometry module and the sonar module are all fed to a state of the art SLAM module.

A Mission Planner module instructs the vehicle on how to handle the tasks according to the current state of the mission planner state machine. Finally the vehicle path is fed to the LQR controller.

III. EXPERIMENTAL RESULTS

The team was founded in October. The literature review period started and lasted for almost 2 months. The vehicle design process started around December and ended in March. The system manufacturing followed and was met by countless logistic troubles that the team managed to cross. Most logistic troubles were related to the mechanical team, which would've endangered other teams since no physical system was available to test the electric and software modules, but the team managed to work around this complexity by implementing hardware test rigs. That left almost a month for vehicle deployment and training. But thanks to the team's systematic design strategy, it didn't take much time to tune the vehicle parameters, since the real results were very close to computer simulations, the LQR control module took zero time to tune, the cameras however required some calibration adjustments to work efficiently underwater [3][4], since image distortion highly affected depth estimation, but the error was resolved after some adjustments. The mechanical design was both rigid and ductile, and the links could handle the dynamic stresses induced by thruster loads. The electric kit worked fine with no problems, since extensive testing was already carried out during the manufacturing period. ASmarine keeps testing its vehicle daily till the competition time. The manipulation mechanisms are continuously improved to eliminate any mechanical limitations.

IV. ACKNOWLEDGEMENTS

4 **The** authors wish to acknowledge the support of ASRT (Academy of Scientific Research & Technology in Egypt) for their endorsement of this research.

I. REFERENCES

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APPENDIX

A. *Expectations*

Subjective measures			
	Maximum Points	Expected Points	Points Scored
Utility of team website	50	45	
Technical Merit	150	145	
Written Style	50	44	
Capability for Autonomous Behaviour (static judging)	100	90	
Creativity in System Design (static judging)	100	89	
Team Uniform (static judging)	10	8	
Team Video	50	48	
Pre-Qualifying Video	100	100	
Discretionary points (static judging)	40	0	
Total	650	569	
Performance Measures			
	Maximum Points	Expected Points	Points Scored
Weight	See Table 1/ Vehicle	-187.3 penalty	
Marker/Torpedo over weight or size by <10%	Minus 500/ marker	0 penalty	
Gate: Pass Through	100	100	
Gate: Maintain fixed heading	150	150	
Gate: Coin Flip	300	0	
Gate: Pass through 60% section	200	0	
Gate: Pass through 40% section	400	400	
Gate: Style	+100 (8x max)	400	
Collect Pickup: Crucifix, Garlic	400 / object	0	
Follow the “path”	100 / segment	200	
Slay Vampires: Any, Called	300,600	300	
Drop Garlic: Open, Closed	700, 1000/marker (2+pickup)	700	
Drop Garlic: Move Arm	400	0	

Stake through heart: Open Oval, Cover Oval, Sm Heart	800,1000,1200 / torpedo (max 2)	800	
Stake through heart: Move Lever	400	400	
Stake through heart: Bonus – Cover Oval, Sm Heart	500	0	
Expose to Sunlight: Surface in Area	1000	1000	
Expose to Sunlight: Surface with Object	400 / object	0	
Expose to Sunlight: Open coffin	400	0	
Expose to Sunlight: Drop Pickup	200 / object (crucifix only)	0	
Random Pinger first task	500	500	
Random Pinger second task	1500	0	
Inter-Vehicle Communication	1000	0	
Finish the mission with T minutes (Whole + fractional)	Tx100	0	

B. *Component Specifications*

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy control	n/a	n/a	n/a	n/a
frame	El radwan	Aluminum laser cut	commercial	117.5$
Waterproof housing	In-house manufactured	Conventional machining	Custom	295$
Waterproof connectors	Bluerobotics	M10 cable penetrator for 10mm wires	Dry connectors	150$
thrusters	Bluerobotics	T200	Brushless thrusters	169$
Motor control	Bluerobotics	Basic ESC	Speed control	200$
High level control	ASmarine	Optimal control	LQR	n/a
actuators	Future electronics	Servo motors	Position control	50$
propellers	n/a	n/a	n/a	n/a
battery	OSN power	13S6P battery	Lithium ion	488$

Converter	szwenagoa	Dc-Dc converter	48v to 12v waterproof dc-dc converter	118$
regulator	Manufactured in-house	n/a	custom	2$
CPU	NVIDIA	Jetson TX2	Six 2Ghz ARM8 Core	470.5$
Microcontrollers	Arduino	Arduino nano, Arduino Mega	microcontrollers	$22.00 ,$38.50
Internal comm network	n/a	I2C, RS-232 RS485	Serial	free
External comm interface	Bluerobotics	M10 cable penetrator for 10mm wires	Dry connectors	150$
Programming language 1 Programming language 1	Python Software Foundation	Python	interpreted	Free
Programming language 2	WG21/FSF	C++	compiled	Free
compass	n/a	Inside each IMU	n/a	n/a
Inertial Measurement Unit (IMU)	Adafruit	BNO055	I2C communication	$34.95
Inertial measurement unit (IMU)	PX4	Pixhawk’s IMU	USB communication	$120
Doppler velocity log (DVL)	n/a	n/a	n/a	n/a
camera(s)	Stereolabs, GoPro	ZED, GoPro Hero 5	Machine vision cameras	sponsored
hydrophones	teledyne	AS1	Acoustic receivers	1200$
manipulators	In-house manufacturing	Laser cut	Gripper	30$
Algorithms: vision	Transfer learning using tensorflow	Mobilenet +SSD	vision	free
Algorithms: acoustics	Implemented by	FFT	Discrete fourier	free

	members		transform	
Algorithms: localization and mapping	Robot Lab- Université de Sherbrooke	RTAB-Map	lidar and visual SLAM	open-source
Algorithms: autonomy	Implemented by members	State machine	State machine	n/a
Open Source Software	ROS-Industrial	ROS	Autonomous	free
Team Size (Number of People)		26		
Hardware/Software expertise ratio		12:7		
Testing time:simulation		20		
Testing time:in-water		100		

C. *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 (fig.5).

Fig. 5: ASmarine's participation in the Egyptian makerfaire'19 to teach youngsters the value of underwater vehicles and display our team's vehicles for illustration

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.