Design and Implementation of BBAUV 3.5X

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Abstract - BBAUV 3.5X is the product of a team of undergraduates from the National University of Singapore (NUS). BBAUV 3.5X aims to complete the tasks by playing to the team's strengths: Acoustics Localization, Waypoint Navigation and Object Detection using Sensor Fusion. The vehicle was further improved over the previous version by redesigning the frame for better stability and protection, along with upgrades in the manipulator system, as well as increased focus on deep learning b ased computer vision. This paper discusses their integration and performances on the 3.5X.

1. Competition Strategy

BBAUV 3.5X has moved to a lighter aluminum frame for increased mobility. Moreover, the vision pipeline has improved to allow for external GPU nodes that can help perform deep learning inference for object detection. This allows the vehicle to easily and quickly identify objects of interest. Combined with the object detection capabilities using the Forward Looking Sonar (FLS), this results in a robust object detector and tracker that are essential to complete the "Slay Vampires" and "Stake Through Heart" Task.

In addition, the manipulator system has been upgraded to pick-up objects with a wider gripping range. This will allow the vehicle to move the lever for the "Drop Garlic" task and to pick-up the skeleton for the "Expose to Sunlight" task.

Regardless of how well each of these tasks can be done individually, an accurate acoustics localization and navigation module for movements between competition tasks and a well thought-out mission planner is crucial for the success of an autonomous run. Hence improvements were also done in these areas.

2. Vehicle Design (Novel Aspects)

Software Sub-System

<u>Addition of Separate Deep Learning Node</u>

As vision-based tasks in RoboSub are becoming more sophisticated with various complex images in tasks, the Single Board Computer (SBC) can no longer be relied upon to run Deep Learning inferences quickly. Without a dedicated graphics processing unit (GPU), the SBC was only capable of performing inference at 3 frames per second (fps) output, given its high computational load running other software submodules.

Hence, an Nvidia Jetson Nano GPU processing node was added to run the Deep Learning inference model and ease the SBC's computational load. The node is a ROS service used to provide the vision pipeline with information of objects identified by the Deep Learning Model based on the camera feed specified. This optimization has resulted in a significant speedup of up to 13 fps, from the previous 3 fps. (Refer to Appendix D)

With faster deep learning inferences, information from the deep learning models and information from traditional CV methods can be fused to achieve a more robust object detection and tracking module.

Despite the Deep Learning implementation, detection of the various objects at a distance visually by a camera is still a challenge, due to poor visibility underwater. However, such objects can be identified using the FLS. The FLS can provide range and azimuth of the objects relative to the vehicle, but not the depth, which is provided by the camera. To mitigate the shortcomings of the individual sensors, a particle filter was implemented to fuse the data from the front camera and FLS [1] to increase the accuracy of detection.

<u>Improvement of Annotation Pipeline</u>

The team improved the annotation pipeline to ensure that the entire process from data collection to annotation to model training was seamless and quick, even for large data sets. Building upon images_annotation_programme[1], it allowed easy multi-user annotation over LAN or internet to handle the increase in number of images used in tasks for RoboSub this year, without having to download custom programs.

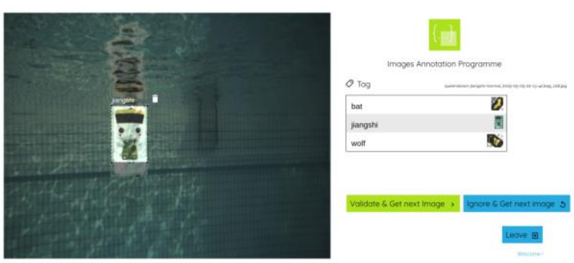

Fig 1. Web Annotation Tool

Further verification of annotations is also done via random repeated images assigned to users, allowing for a cross check of annotations.

A series of scripts will then convert the XML annotations (in PASCAL VOC format) and split them into training and test sets before producing a Tensorflow recognizable records format, which is then used to train the Deep Learning object detection model.

<u>Mission Planner Structure</u>

The mission planner is integrated with a new mission UI that allow users to easily scan through the mission path through the graphical user interface while allowing the user to select from many predetermined missions to be run on the fly. It is integrated with a mapper, with important FLS features overlaid, enabling waypoints to be easily identified and set. (Refer to Appendix E)

Electrical Sub-System

<u>Electrical and Power Architecture</u>

This electrical architecture adopted the backplane system. (Refer to Appendix F) There are two main communication channels used in this electrical architecture, namely Controller Area Network (CAN) and Ethernet. CAN is used for communication between embedded systems like the daughter boards while Ethernet is used for components that requires high bandwidth communication like SBC and FLS.

One of the unique features of the power architecture (Refer to Appendix F) is the load balancing system between the two batteries. This provides a hot swap feature that allows changing of batteries without shutting down the vehicle. Next, there is an isolation system between the internal electronics and inductive loads such as thrusters. The internal electronics peripherals draw their power through isolated DC-DC converters and any signal connected to these inductive loads are isolated as well.

[1]www.github.com/frederictost/images_annotation_programme

Backplane and Daughter Boards

The backplane system serves as the backbone of the electrical system where it contains three daughter boards as well as CAN bus channel. Among the three daughter boards, the sensor and telemetry board houses several sensors such as pressure sensor, depth sensor, humidity sensor and temperature sensor to monitor the internal conditions of the vehicle. The power control board controls the power that is being sent to the other daughter boards and sensors. As a result, the board can kill power to the thrusters as well as hard reset sensors such as the FLS remotely. The thruster board operates the thruster through an optoisolator because the thruster and its electronic speed controller is designed to be isolated from the other sensitive electrical system such as acoustics.

Manipulator Board

For this year's competition, all the pneumatic actuators are controlled via multiple solenoid valves. Due to them being high current inductive loads, the isolation system was changed slightly by adopting solid state relays as the primary method for controlling the solenoid valves. Compared to the Darlington arrays used last year, the new solid state relays have a higher current output rating and it is electrically isolated.

In addition, to protect against transient voltage due to the manipulator board being frequently plugged in and out, TVS diodes on both communication channels (CAN bus) and the power sources were added. In addition, the TVS diodes also serve as protection against inductive voltage spikes caused by the thrusters.

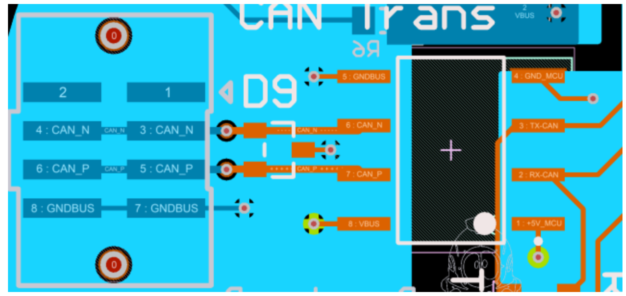

Fig 2. Protection system on manipulator board with TVS diodes (D9) on the CAN bus

Acoustic sub-system

The acoustics subsystem moved away from the sbRIO to a custom signal conditioning board, data acquisition (DAQ) board and raspberry pi 3B+ for localization of signals. This switch to a Linux based system allows for the usage of well-supported existing libraries and higher-level programming languages such as C++. This allows for the development of more complex and higher-level features.

The new custom DAQ board uses a Xilinx FPGA to align the data coming from the 4 ADC channels. By shifting the data alignment to the FPGA, the 4 channels can be processed in parallel which gives rise to lower latency and better performance. Furthermore, the DAQ board uses High-Speed USB to communicate with the SBC which enables interoperability with different SBCs and allows for the processors to be selected based on the computation power required.

The acoustics stack is also redesigned and optimized to utilize the multi-core ARM processor which allows for lower latency and a smaller error caused by the vehicle moving.
The principle of operation is similar to the previous system. The direct path signal of the desired frequency is identified using a dynamic thresholding method based on short-time Fourier transform. This reduces the false

positives due to multipath propagation and signals of other frequencies. The multiple signal classification (music) algorithm [2] is then used to calculate the direction of arrival (DOA) of the identified signal.

Mechanical Sub-system

Replacement of Aluminum Frame

In light of the under-specification of the previous vehicle's structural integrity, each individual component of the vehicle's frame was replaced with a more rugged design. The replacement of aluminum frame resolves the unstable vehicle behavior observed last year due to the lower position of the yaw thruster. Additionally, the new aluminum frame protects all of the vehicle's components, especially the thrusters, from collision against external objects.

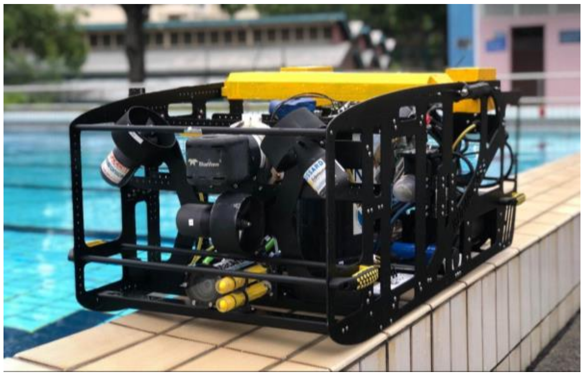

Fig 3.1. Frame of AUV

Modification of Claw Grabber

The pneumatic claw grabber was redesigned from Robosub 2017 to have a wider gripping range. The claws were designed to have larger gripping curvatures and extended arm lengths as compared to the previous iteration. This provided the vehicle with a greater aiming tolerance when grabbing the pipes of various diameters. Another consideration taken was to enable the arms to retract higher than the lowest point of the grabber. This allowed the grabber to be installed at a lower height without exceeding the base level of the vehicle frame. The grabber was positioned directly behind the front-facing camera and very near the bottom-facing camera for better vision-and-grip coordination.

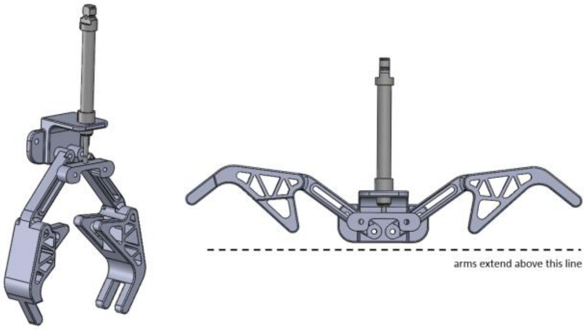

Fig 3.2. Claw Grabber Design

Upgraded Cooling System

The liquid cooling system for the SBC was upgraded with a pump-block combo, modified from an all-in-one liquid cooler.

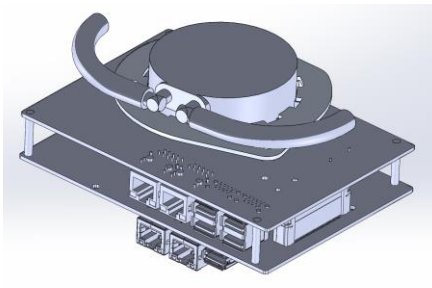

Fig 3.3. Water block on SBC

This allowed for direct contact between the CPU and the cooling block, which along with a better thermal interface material, lowered the temperature of the CPU to about 50°C under full load and 37°C while idle, approximately 20°C decrease from the previous design. The new cooling solution is half the size of the previous design, which freed up space in the vehicle to include a Jetson Nano, and an inline power filter for the FLS. A small fan was used to provide some airflow over the radiator fins on the Jetson Nano. (Refer to Appendix H)

3. Experimental Results

Deep Learning Performance

The MobileNetV2 with SSDLite [3] was chosen from the list of pre-trained models of the Tensorflow models zoo [4] and was used as a base for training deep learning models. A total of 4800 training images, 600 validation images, and 800 test images were collected. Images were collected in various lighting conditions in the testing pool to minimize overfitting. Training was performed using the NUS HPC (High Performance Computing) GPU server and exported as a frozen graph before optimizing the model via TensorRT for optimal performance on the Jetson Nano.

Object to Detect	Slay Vampires (Jiangshi, Aswang, Vetalas, Draugr)	Bin (Bat,Wolf, Checkboard)	Stake Through Heart (Vampire)
mAP	0.892	0.937	0.894

Table 1.1. Object Detection and mAP (mean average precision)

The results indicate a high level of accuracy of the deep learning trained object detection model. Moreover, this model runs at 13fps on the Jetson Nano, resulting in a fast and reliable object detection module. More image collection and training will be performed at the competition venue to prevent overfitting.

Improved acoustics performance

By switching to the Linux based system with custom DAQ board, the data acquisition latency and DOA estimation time is reduced significantly with minimal impact to the accuracy of the system. The reduction in latency also allowed for a higher sampling rate of the pinger signal as compared to the sbRIO based system.

	sbRIO	**Raspberry pi**
DAQ Latency (125ksps for 75k samples) /ms	200	0.2
DAQ Latency (250ksps for 125k samples) / ms	700	4
DOA estimation time / ms	120	60
Accuracy (azimuth)/degree	±3	±3
Accuracy (elevation)/degree	±6	±6

Table 1.2. Improvements in Acoustics System

Robosub preparations

During the summer break, pool tests were conducted daily, roughly 7 hours a day on weekdays and 3 hours on the weekends. The vast majority of the electrical and hardware systems were done before the summer and the team has been working on the competition tasks.

4. Acknowledgements

Team BumbleBee’s development and achievement would not be possible without the help from various organizations and people. The team would like to express their deepest gratitude to the sponsors (Refer to Appendix I), including Title Sponsors - National University of Singapore (NUS), and the Platinum Sponsors - DSO National Laboratories, Future Systems and Technology Directorate, DEME Group. In addition, the team would also like to thank the Sport Singapore, Republic of Singapore Yacht Club, and the US National and Oceanic and Atmospheric Administration (NOAA) for allowing us to test at their facilities.

References

[1] Y. Raaj, A. John and T. Jin, "3D Object Localization using Forward Looking Sonar (FLS) and Optical Camera via particle filter based calibration and fusion," OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, 2016, pp. 1-10. doi: 10.1109/OCEANS.2016.7761077, Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7761077&isnumber=7760990

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[4] Howard, A. G., Zhu, M., Chen, B., Kalenichenko, D., Wang, W., Weyand, T., ... & Adam, H. (2017). Mobilenets: Efficient convolutional neural networks for mobile vision applications.

Appendix A: Expectations

Below is the scoring table showing the points associated with each task. Enter the points you expect to score with the vehicle(s) that you have designed and engineered. At the end of the competition, enter the points you actually scored in the last column.

Subjective Measures			
	Maximum Points	**Expected Points**	**Points Scored**
Utility of team website	50	45	
Technical Merit (from journal paper)	150	140	
Written Style (from journal paper)	50	45	
Capability for Autonomous Behavior (static judging)	100	95	
Creativity in System Design (static judging)	100	95	
Team Uniform (static judging)	10	9	
Team Video	50	48	
Pre-Qualifying Video	100	100	
Discretionary points (static judging)	40	35	
Total	650	612	
Performance Measures			
	Maximum Points	**Expected Points**	**Points Scored**
Weight	See Table 1 / Vehicle	-250	
Marker/Torpedo over weight or size by <10%	minus 500 / marker	0	

Gate: Pass through	100	100	
Gate: Maintain fixed heading	150	150	
Gate: Coin Flip	300	300	
Gate: Pass through 60% section	200	0	
Gate: Pass through 40% section	400	400	
Gate: Style	+100(8x max)	0	
Collect Pickup: Crucifix, Garlic	400/object	0	
Follow the “Path” (2 total)	100/segment	200	
Slay Vampires: Any, Called	300,600	600	
Drop Garlic: Open, Closed	700,1000/Marker (2 + pickup)	2000	
Drop Garlic: Move Arm	400	400	
Stake through Heart: Open Oval, Cover Oval, Sm Heart	800, 1000, 1200 / torpedo (max 2)	2200	
Stake through Heart: Move lever	400	400	
Stake through Heart: Bonus - Cover Oval, Sm Heart	500	500	
Expose to Sunlight: Surface in Area	1000	1000	
Expose to Sunlight: Surface with object	400/object	800	
Expose to Sunlight: Open coffin	400	400	

Expose to Sunlight: Drop Pickup	200/object (crucifix only)	0	
Random Pinger first task	500	500	
Random Pinger second task	1500	1500	
Inter-vehicle Communication	1000	0	
Finish the mission with T minutes (whole + factional)	Tx100	200	

Appendix B: Component Specifications

Components	Vendor	Model/Type	Specifications	Cost (if new)
Buoyancy Control	**BlueRobotics**	**R3312**	**Density: 192 kg/m^3**	**USD 94**
Frame	**Cititech Industrial Engineering**	**Custom aluminium laser cut**	**Custom**	**Sponsored**
Waterproof Housing	**Achieve Engineering Feimus Engineering**	**Custom CNC end caps and enclosure**	**Custom**	**SGD 1,500**
Waterproof Connectors	**SubConn Inc. - MacArtney**	**Assorted Micro and Low-Profile Series**	**Depth rating PEEK: 300 bar**	**Sponsored**
Thrusters	**Sterling Comms**	**Pro 4 Videoray**	**10 kgf fwd thrust**	**Legacy**
	Aquila Nova	**Rovee Brushless Thruster**	**3.6 kgf fwd thrust**	**Legacy**
Motor Control	**Tekin**	**RX8**	**Input Voltage: 6S LiPo**	**Legacy**
High Level Control	**ATMEGA**	**ATmega2560 & ATmega328P**	**16 MHz, 8-bit microcontroller**	**SGD 50**
	Raspberry Pi	**Model 3B+**	**1.4GHz 64-bit quad-core processor**	**SGD 52**
	Odroid	**XU-4**	**• Samsung Exynos5422 • 2Gbyte LPDDR3 RAM • eMMC5.0 HS400 Flash Storage**	**USD 49**

Actuators	**Festo**	**MHE2-MS1H-5/2-QS-4K** **DSNU-8-10-P-A**	**5/2 Way Solenoid Valve** **Linear Pneumatics Piston**	**Sponsored**
	ImperiaX	**Ninja Gas Tank** **PalmersPursuit Regulator**	**3000 PSI, 13 Cubic Inch** **0-250 PSI Output**	**SGD 100**
Propellers	**N/A**	**N/A**	**N/A**	**N/A**
Battery	**Tattu**	**Custom-made 6-cell battery**	**12000 mAh**	**USD 160**
Battery Monitoring System	**In-house**	**Custom-made circuit board**	**Custom**	**N/A**
Converter	**Murata**	**UWQ-12/17-Q48PB-C** **UVQ-24/4.5-D24P-C**	**204W Isolated 24V-12V** **108W Isolated 24V-12V**	**Legacy**
Regulator	**OPUS**	**DCX1.250 ATX PSU**	**250W**	**Legacy**
CPU	**AAEON**	**GENE-KBU6 BIO-ST03-P2U1**	**Intel Core i7-7600U Intel® i210**	**Legacy**
GPU	**Nvidia**	**Jetson Nano**	**128-core Maxwell,** **4 GB LPDDR4**	**USD 109**
Internal Comm Network	**In-house**	**CAN / Ethernet**	**1000kbps / 1000Mbps**	**N/A**
External Comm Interface	**In-house**	**Ethernet**	**1000Mbps**	**N/A**

Programming Language 1	**C++ Foundation**	**C++**	**Compiled**	**N/A**
Programming Language 2	**Python Software Foundation**	**Python 3**	**Duck-typed**	**N/A**
Compass	**Sparton**	**AHRS-8**	**±1.2 Gauss**	**Legacy**
Inertial Measurement Unit	**Sensonor**	**STIM300**	**±10g acceleration, RS422**	**Legacy**
Doppler Velocity Log	**Teledyne Marine**	**Pathfinder DVL**	**600kHz Phased Array**	**Legacy**
Camera(s)	**BlackFly S PoE Gigabit Camera**	**BFS-PGE-31S4C-C**	**2448 x 2048 at 22 FPS**	**Legacy**
Hydrophones	**Teledyne Reson**	**TC4013**	**Acoustic transducers**	**Legacy**
Manipulator	**In-house**	**FDM 3D Printed**	**ABS**	**Sponsored**
Algorithm: vision			● **Thresholding Particle filter** ● **Machine learning**	**NA**
Algorithm: acoustics			● **Multiple Signal Classification (MUSIC)** ● **Localization with Short- Time Fourier Transform (STFT) based Ping Extraction**	**NA**
Algorithm: localization & mapping			**Error State Kalman Filter**	**NA**

Algorithm: autonomy			**ROS SMACH**	**NA**
Open source software			**OpenCV, ROS, Tensorflow Object Detection API**	**NA**
Team size	**28**			
HW/SW expertise ratio	**3:1**			
Testing time: simulation	**0**			
Testing time: in-water	**279 hours**			

Appendix C: Outreach Activities

Team Bumblebee strongly believes in publicity and reached out to various communities and organisations to create awareness of the team's vision and mission. Therefore, Team Bumblebee has actively participated in various exhibitions and showcases in school and locally to provide people a better understanding of Bumblebee's technology and initiatives.

<u>Public Showcase and Exchange</u>

Bumblebee has participated in the University Innovation Design Programme (iDP) Showcase, Engineering Open House and at the Innovfest Unbound 2019, which aims to showcase the latest developments in the technologies and engineering sector to the delegates and public. Through these events, the team is able to interact and engage effectively with the general public.

Fig 4.1. Innovfest Unbound 2019

<u>Lab Tour and Sharing Sessions</u>

As part of Bumblebee's public relations campaign, the team invited various international teams for lab visit to Bumblebee's lab, to exchange knowledge and build lasting friendships. Earlier this year during the Singapore Autonomous Underwater Vehicle Competition (SAUVC), Team Bumblebee has hosted National Chiao Tung University (NCTU) from Taiwan for a week in Bumblebee's lab where members of both teams engaged with one another.

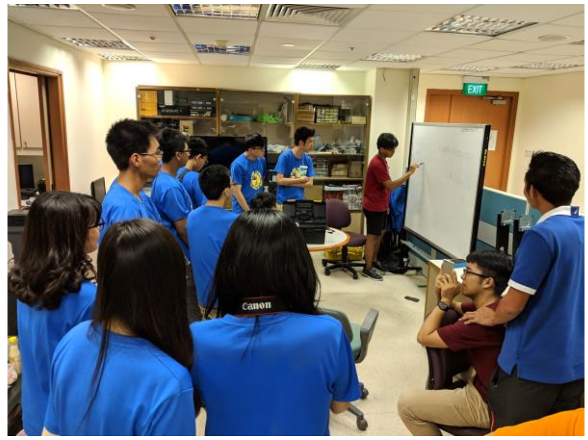

Fig 4.2. Bumblebee's member sharing with National Chiao Tung University from Taiwan

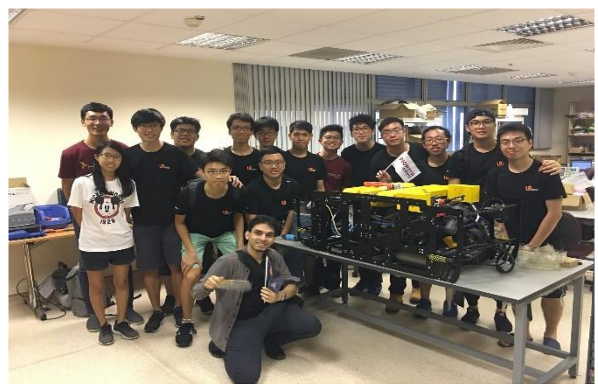

Fig 4.3 Team Bumblebee with City University of Hong Kong Underwater Robotics Team

Industrial Partnership and Appreciation

Industrial Partners are essential for the sustainability of Team Bumblebee. Without their advice and support, the team will not be able to achieve excellence. Therefore, industrial visits are organized with the partners to gain first-hand exposure to the real-world challenges and to gain experience. The team also organizes Sponsor’s Appreciation Day bi-annually to recognize these important individuals and presented them with a token of appreciation for their continuous support and guidance. This is extremely crucial to maintain strong industrial public relations.

Fig 4.4. Sponsors’ Appreciation Day 2019

Fig 4.5 Mechanical Sub-team visit to Bossard

Hornet Training Program

Since its inception 4 years ago, the Hornet Training Program has evolved to a staple element of training for our freshmen. Through this program, we provide new members a platform to build an AUV to compete in SAUVC. The main aim of this programme is to challenge the freshman to explore and implement bold designs instead of replicating what others and predecessors have done.

Fig 4.6.Team Hornet in SAUVC 2019

Appendix D: Vision Pipeline Architecture including new Deep Learning Node

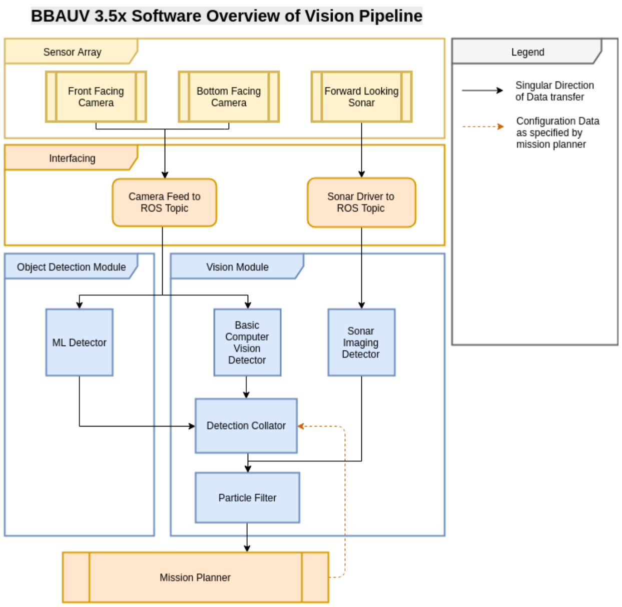

Fig 5.1: Vision Pipeline Architecture

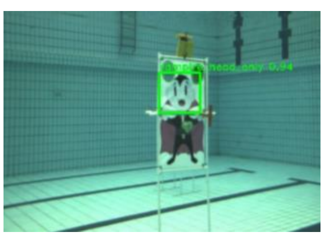

Fig 5.2: Jetson Nano Deep Learning Inference

Appendix E: Mission Planner User Interface

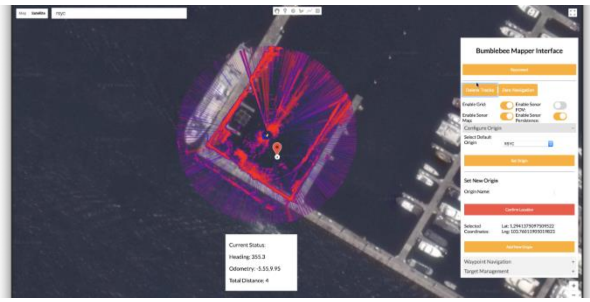

Fig 5.3 Mission Planner User Interface

Appendix F: Hardware and Power Architecture

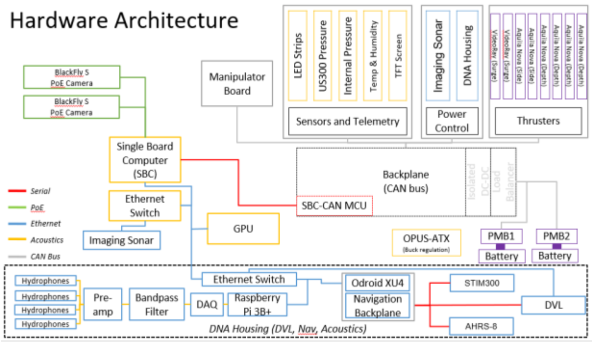

Fig 6.1. Hardware Architecture

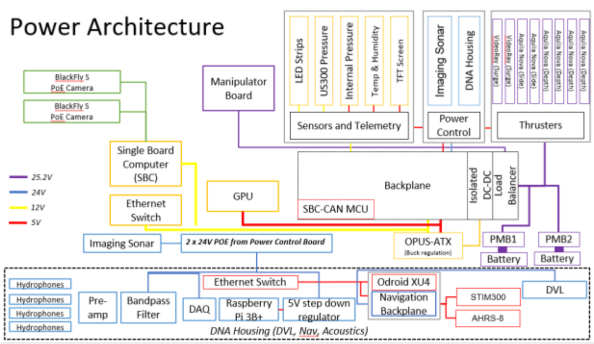

Fig 6.2. Power Architecture

Appendix G: Changes in acoustics architecture

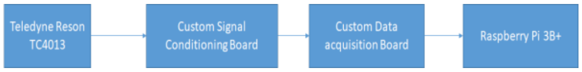

Fig 6.3. New Acoustic Architecture

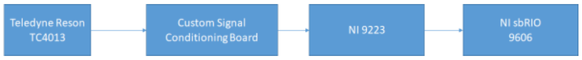

Fig 6.4. Old Acoustic Architecture

Appendix H: Design and benchmark of cooling system

Bottleneck of cooling performance of the previous cooling design was thought to be due to the small and possibly insufficient radiator dissipating the heat from the cooling setup. A new radiator block was thus design with a better thermal conductor (Copper) and greater surface area.

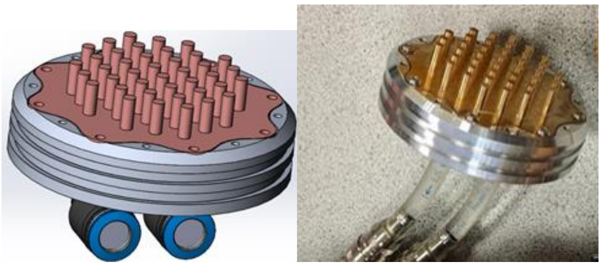

Fig 7.1. Radiator Block

Simulation performed on SolidWorks Fluids estimated heat dissipation properties of ~200W at 35°C of internal liquid temperature, and ~350W at 45°C of internal liquid temperature, to an external ambient water temperature of 25°C.

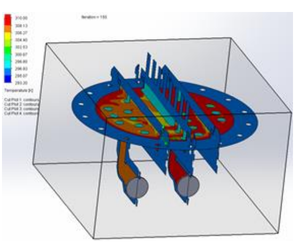

Fig 7.2. Temperature result from SOLIDWORKS Thermal Analysis

However, during actual deployment of the new radiator design, there were negligible differences in temperature of the CPU despite the better heat dissipation of the radiator. This was likely due to the low thermal output of the CPU being cooled (25W). Due to the drawback of the heavier new design with the use of denser copper material, but little benefits provided, we have decided to reuse the old radiator design.

Each component of the cooling system was also isolated and bench tested with different options to benchmark their impact on cooling performance.

Variable	Testing setup	Tested option	Result
CPU block	i7-7600U CPU stress test	Pump-block combo	60°C
		Individual direct contact plates	70°C
Thermal interface	Heat gun, 60°C	Thermal compound	40°C
		Graphite thermal pad	41°C
Coolant	i7-7600U CPU stress test	Water	64°C
		Coolant	61°C
External radiator	i7-7600U CPU stress test	External fin radiator	60°C
		External convection radiator	50°C
		Copper radiator	61°C

Table 2.1. Comparison of Thermals with different Cooling Components

Solutions for the Jetson Nano to be included to the liquid cooling loop were also explored with a small cooling plated but were rejected due to the very low thermal output (10W) of the component. Actual deployment of the Jetson Nano with the small fan saw temperatures of around 45°C under load.

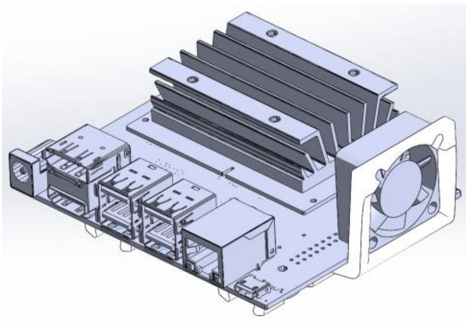

Fig 7.3. Fan for Jetson Nano

Appendix I: Our Sponsors

Title Sponsor
NUS (Faculty of Engineering, School of Computing, Advanced Robotics Centre, Engineering Design and Innovation Centre, Department of Mechanical Engineering, Department of Electrical and Computer Engineering): For their cash support, equipment procurement, and academic support in our project.

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