Launch and Recovery of Autonomous Underwater Vehicle

Submitted by

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Abstract

In this thesis, the launch and recovery system of an Autonomous Underwater Vehicle (AUV) from an Autonomous Surface Vehicle (ASV) is presented. The primary objective is to determine the feasibility of launching an AUV from an autonomous surface vehicle (ASV) and implement it on the system. The LARS is primarily designed to cater for the Maritime RobotX Challenge but deployable for low sea state use. The AUV used in this system is the Bumblebee 3.0 which was used to participate in International Robosub Competition 2016.

To meet this objective, industry LARS are examined closely with engineers, reading from paper works, and multiple digital sources. The most feasible method is determined to be using load-bearing tether coupled with the use of a telescopic arm to reduce the effect of splash zone transition. The concept was tested with series of prototype tests and proven to be useful in developing subsequent product. The literature review of LARS, designs, experimental results, and recommendations for future work are presented in this thesis.

Acknowledgement

Firstly, I would like to thank the whole team for providing me the opportunity to develop a challenging project. I would also like to thank Prof. Marcelo Ang for supervising the team since its founding in 2012 and Prof Mandar Chitre for giving valuable advice and guidance on unforeseen issues with the help of his deep experience in underwater systems.

This project is only possible because of the multiple support from various parties.

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List of Symbols and Abbreviations

LARS	Launch and Recovery Systems
MAR	Marine Advanced Research
WAM-V	Wave Adaptive Modular Vessel
ASV	Autonomous Surface Vessel
ONR	Office of Naval Research
AUVSI	Association of Unmanned Vehicles System International
AUV	Autonomous Underwater Vehicle
TMS	Tether Management System
HPU	Hydraulic Power Unit
fpm	Feet per minute
mpm	Meters per minute
PHC	Passive Heave Compensation
EMI	Electromagnetic interference
RFI	Radio frequency interference
FORJ	Fiber optic rotary joint
GRIN	Graded Index Lens
FGE	Fiber glass epoxy
COTS	Commercial off the shelf
AOD	Argon Oxygen Decarburisation
F_{me}	Mechanical Force, N
F_{cable}	Force acting on cable, N
T_{me}	Mechanical torque by winch, Nm^{-1}
T_{cable}	Torque caused by cable, Nm^{-1}
r	Radius of spool, m
σ	Density of seawater, kg/m^3
A	Characteristics area, m^2
V	Velocity of ROV in water, ms^{-1}
C_d	Non-dimensional drag coefficient
f_n	Vibration natural frequency of isolation system, Hz
f_d	Disturbing frequency, Hz
K_v	Average spring rate, kg/m
δ_{st}	Static displacement, m
W	Equipment weight, kg
f_s	Shock natural frequency of isolation system, Hz
f_p	Natural frequency of shock pulse, Hz
K_s	Average shock rate, kg/m
δ_d	Dynamic deflection, m
T_p	Half sine shock pulse duration

1. Introduction

1.1 Purpose

The purpose of this project is to build a reliable launch and recovery system for an AUV that can be used in the Maritime RobotX competition and to provide the basis of developing a more integrated LARS with recharging capability in the future. This system will be a feasibility study to understand the effectiveness of multiple platform integration to execute a maritime mission.

1.2 Motivation

The drive to develop this system focuses on the need to extend system's capability and to eliminate human involvement in maritime mission. Usually a surface vessel can only perform survey from the water surface and is not capable of performing detailed analysis of the ocean floor, for example. On the other hand, an AUV can perform underwater missions such as close-up scanning and manipulation such as object retrieval and sampling. If both platforms are combined, the range and types of mission the system can conduct is significantly magnified.

There is also a need to eliminate human operations in sea missions. The reasons are clear because the ocean is a harsh and unpredictable place. A man-operated system cannot perform as consistent as these autonomous vehicles because of physiological factors such as fatigue and stress. The unpredictability of the sea makes it dangerous to conduct long duration surveys. It is very often that a mission is delayed or canceled because of weather factor. In manned vessel operations, most of the cost is channeled to the means of sustaining the people day-to-day; the wages, food, and facilities to live.

At least 90% of the ocean remains unexplored, the success of this integrated system will open the frontier of ocean exploration.

1.3 Scope

This thesis includes the in-depth analysis of existing launch and recovery system (LARS) in the market. It also includes the design and fabrication of a telescopic arm specific to the moonpool feature of the ASV. The physical limits of the design must be within competition rules since this system will be used in RobotX 2018.

1.4 Design Methodology

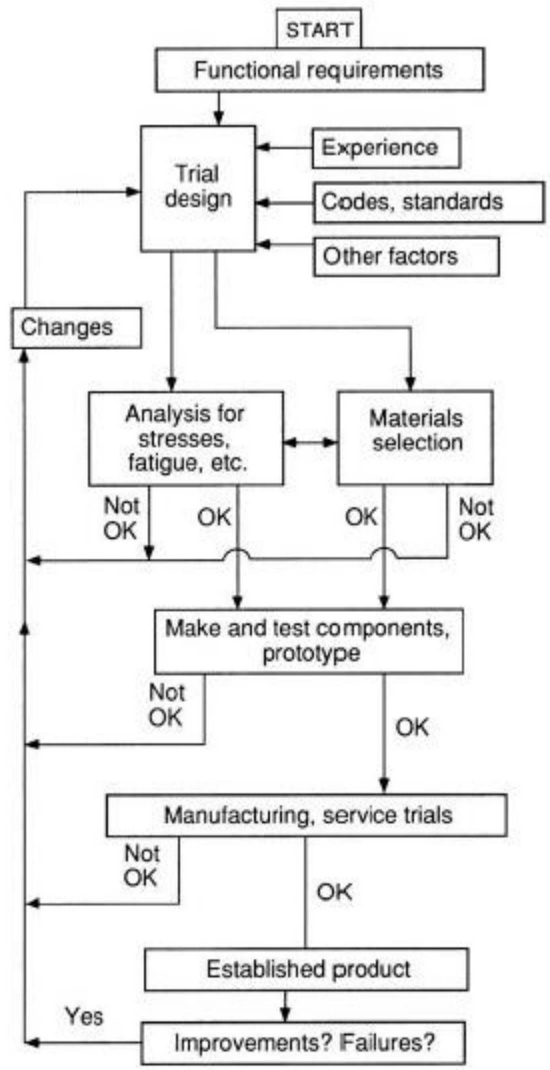

Figure 1 Design Flow

In all design of a product, the first step always begins with the functional requirement. For this project, the primary requirement is to participate in the RobotX 2018 competition. The nature of the competition obstacles is such that an underwater vehicle must be deployed to execute missions on obstacle V, VI, and VII as mentioned the section: Competitions. Factored in the requirements are the nature of the obstacles course which includes the depth of water, size of course, wave height, wind speed etc.

The trial design can then be conceptualized in paper drawings. For this project, all the designs are first conceptualized in a A4-size note book for clear documentation purposes. Experience from previous handling of AUV and ASV aids a lot in the trial design of this project scope. Codes and standards from the industry are taken as reference but has limited influence on this project because of its nature.

After a design has been conceptualized, materials are selected and put in design analysis work to determine its strength, working life and cost. Like any other project, saving cost is of utmost importance but some expenses are unavoidable especially in the concept proving stage.

Finally, prototypes undergo fabrication and testing to produce important data and observations that will aid in development of better prototypes. After a suitable number of prototypes and when reliability is established in design, the product undergoes full scale manufacturing so that it can be deployed in actual scenario. Further design improvement should do only minor part changes and shall not affect the basic established design.

2. Competitions

The system designed is to be used in the Maritime RobotX Challenge. The primary goal of this competition is to foster interest in autonomous technology with an emphasis on the science and engineering of cooperative autonomy. This emphasis on autonomous technology can be seen with the compulsory use of WAM-V surface craft manufactured by Marine Advanced Research (MAR), allowing teams to save time and focus more on developing the algorithms.

This competition is organized by the Association of Unmanned Vehicle Systems International (AUVSI) and heavily invested by Office of Naval Research (ONR). Held biannually, this competition started its inaugural launch in Singapore in 2014. The first competition saw teams from five countries: Singapore, United States, Japan, Korea and Australia. But it has since then opened to more participating countries such as China and India.

The full details of competition tasks are stated as follows:

2.1 Demonstrate Navigation and Control

All teams must be able to show that their ASV has the capability to detect channel markers and navigate through it. This is a compulsory task which failure to do so will result in not being able to proceed in the competition.

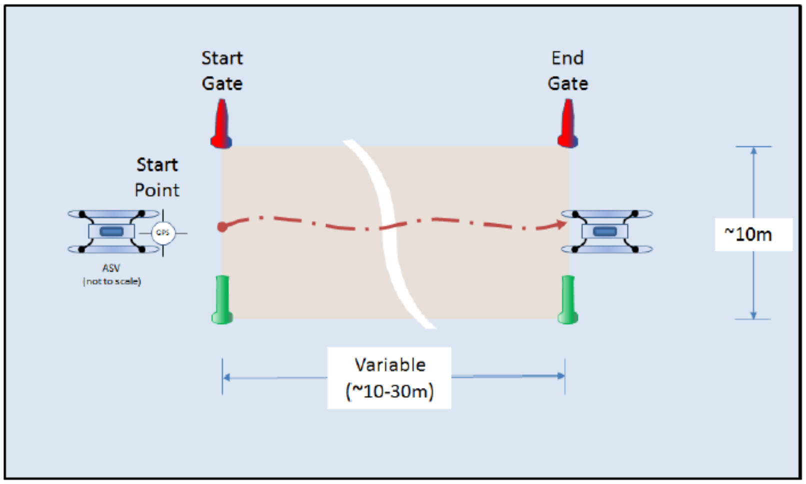

Figure 2 Navigation and Control

2.2 Finding Totems and Avoid Obstacles

The unmanned system must be able to enter the obstacle from any direction, avoid colliding with black buoys, and navigate to totems with correct markings and circle them in correct direction.

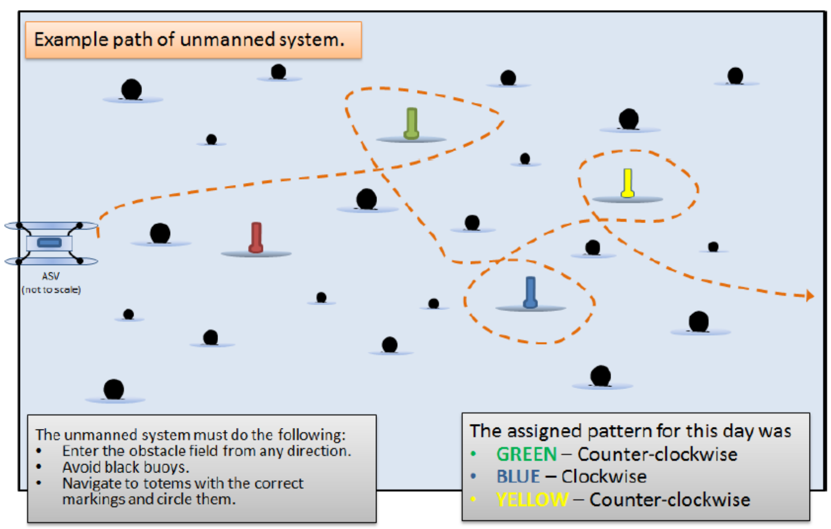

Figure 3 Finding Totems

2.3 Identify Symbols and Dock

The system must dock in the correct bay which is identified with certain shapes and in the correct order.

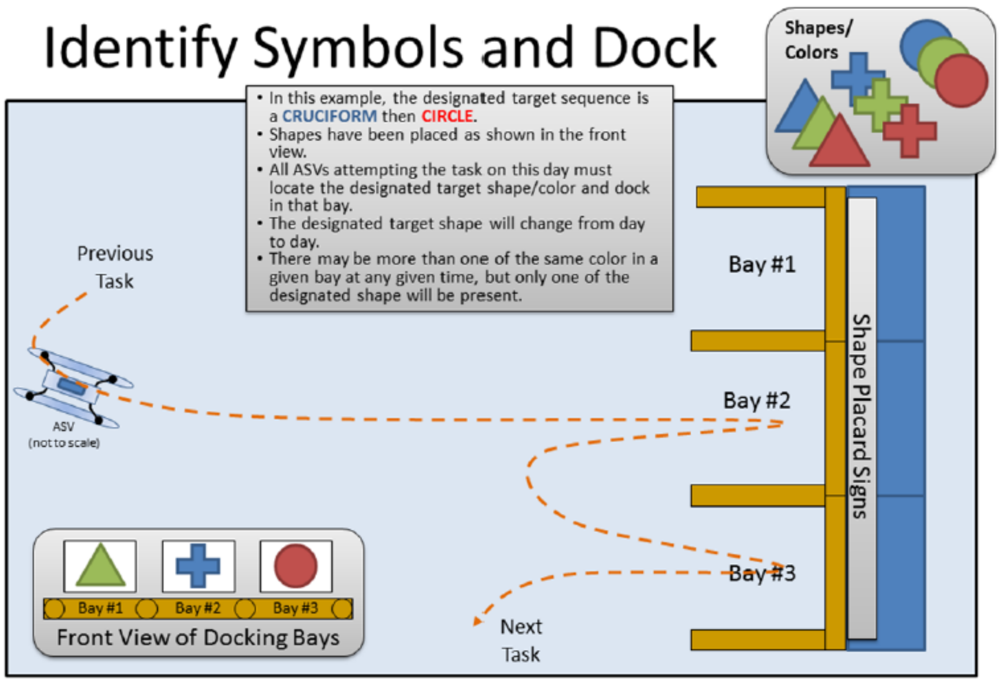

Figure 4 Identify Dock

2.4 Scan the code

The system must detect the light sequence of the buoy and report the color to the judges autonomously.

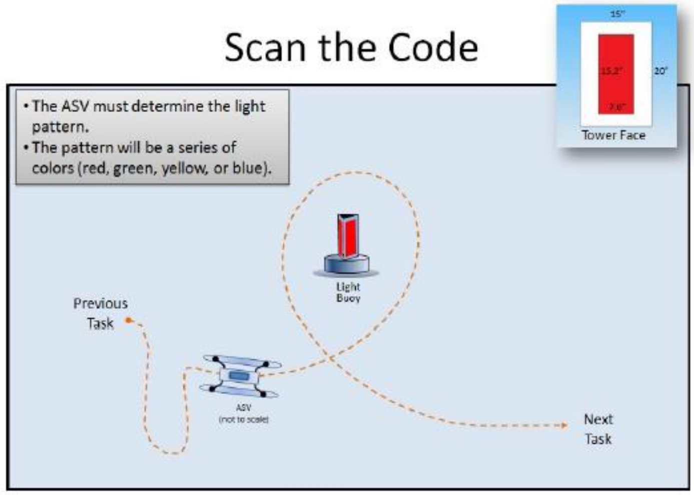

Figure 5 Scan the code

2.5 Coral Survey

The system must locate object on the seafloor given an assigned quadrant relative to a reference buoy. The system must report the shape to the judges autonomously.

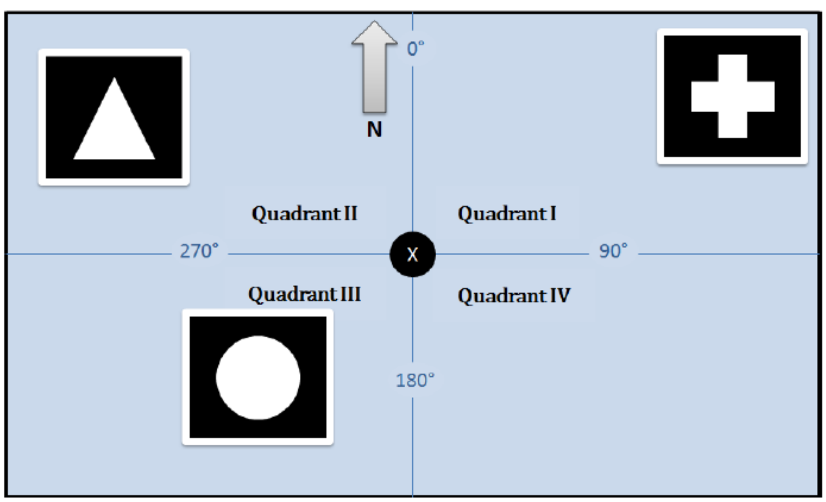

Figure 6 Coral survey

2.6 Find the Break

The system must be able to report the number of orange strips between the two yellow markings.

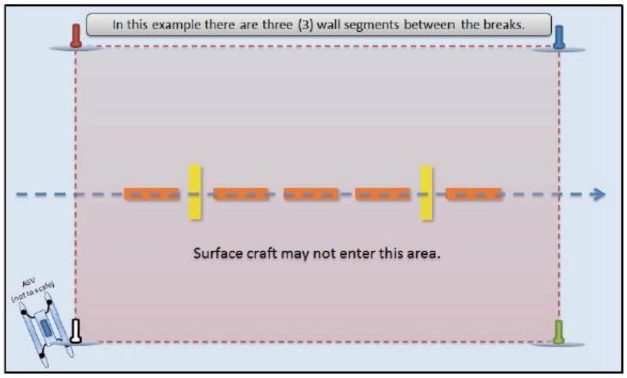

Figure 7 Find the break

2.7 Detect and Deliver

The system must deliver or shoot object through holes on the correct side of a floating platform.

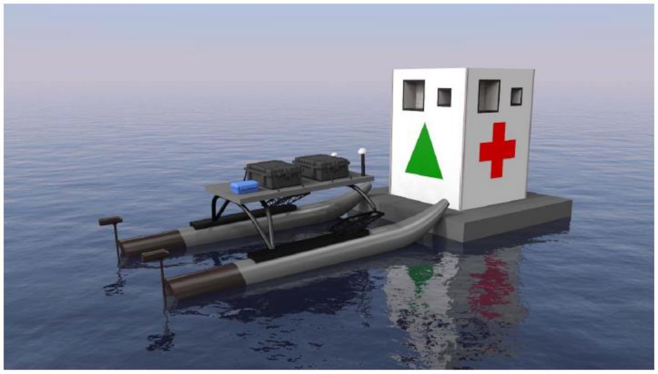

Figure 8 Detect and deliver

2.8 Acoustic Pinger-Based Transit

The system must enter and exit the gates of correct frequencies.

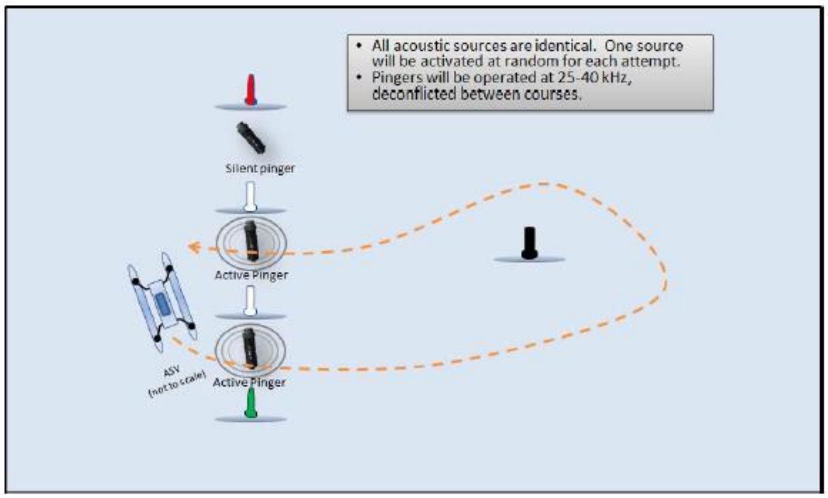

Figure 9 Acoustic Pinger-Based Transit

3. Literature Review

3.1 Autonomous Surface Vehicle

Autonomous Surface Vehicles (ASV), sometimes referred as Autonomous Surface Crafts (ASC) are unmanned vehicle capable of conducting mission without any human interference. As its name suggest, the capability is limited to the ocean surface. Thus, its physical embodiment must have sufficient buoyancy to keep it afloat. The first ASV was develop from MIT Sea Grant Challenge Program in 1993 and was used to conduct simple collection of bathymetry data and has limited range and application [1]. The early generation of ASVs are designed or modified from a manned vessel such as kayak or a small boat. But more recent development has eliminated the manned space to optimize performance and space use. The catamaran design has become a preference in choice due to its stability and ease in deck access.

Figure 10 ROAZ II with its double HDPE hull catamaran design [2]

The significance of ASV with its air-sea interface provide a platform for radio frequency and underwater acoustic transmission. Thus, the military picked this up quickly and developed interest in developing them for many purposes such as surveillance, electronic warfare, and combating pirates. The Republic of Singapore Navy has invested in a locally developed Venus ASV for maritime security purposes. The ASV is capable of reaching speed of up to 40kt and has endurance of 36 hours [3] and will be used to patrol Singapore waters.

Figure 11 Venus 16 weighs 22tn and is 16m by 5m [3]

For this thesis, the Wave Adaptive Modular Vessel (WAM-V) will be used and is developed by a US company, Marine Advanced Research (MAR). It features double hypalon fabric hull and has a pair of suspension system put in place to absorb shock and ride through waves while maintaining the stability of its payload tray in heave, pitch and roll directions.

Figure 12 16’ WAM-V

Purchased in the third quarter of 2016, the WAM-V is fitted with sensors and a set of propulsion system to provide the base for navigation and controls. The maximum payload is 220kg (250lbs).

The table below shows the major specifications of the ASV.

Table 1 Specifications of WAM-V 16 [4]

Length	4.85m (1.91 in)
Beam	2.44m (96 in)
Height	1.27m (50 in)
Vessel weight as delivered	154kg (340 lbs)
No load draft	8.9 cm (3.5 in)
Maximum additional load	220 kg (485 lbs)
Full displacement weight	374kg (825 lbs)
Full load draft	16.5cm (6.5 in)

3.2 Autonomous Underwater Vehicle

The AUV that will be used for this launch and recovery system will be the Bumblebee 3. Completed in late 2015, this AUV has participated in two competitions; Singapore Autonomous Underwater Vehicle Challenge (SAUVC) 2016 and International Robosub Competition 2016. The AUV has multiple capabilities which includes hovering, acoustic ping detection, sonar ranging and imaging, as well as manipulation via pneumatic actuators. It weighs approximately 55kg and is 1.4m by 0.5m by 0.45m.

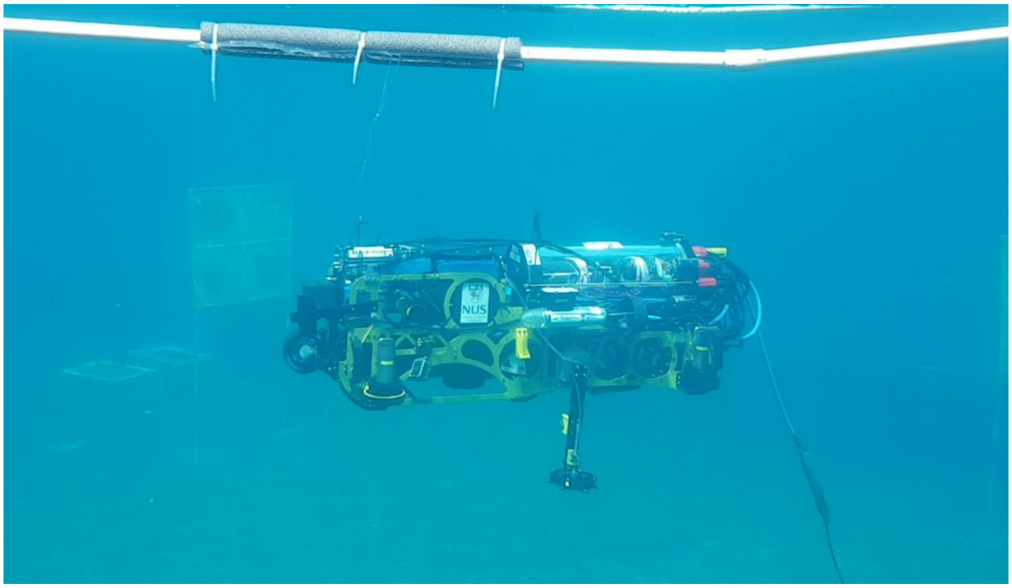

Figure 13 Bumblebee 3 performing object grabbing at Robosub 2016

3.3 Launch and Recovery System

The launch and recovery system (LARS) has been around since remotely operated vehicle (ROV) are made. No matter how seaworthy or deep the ROV/AUV can reach, it will be rendered useless if it cannot be deployed. Thus, a launch and recovery system is vital to utilize the platform. The main objective of a LARS is to move the vehicle, may be combined with a tether management system (TMS), through the splash zone and to allow the vehicle to work safely in a certain range of depth. They are designed to launch vehicles which can weigh several tons and to recover them in choppy seas. LARS comes in many forms and can be as simple as using onboard crane to hoist an ROV down into the water. More specific and safe way of the system is an A-frame, which can be built onto a ships' stern or its side. In general, there are two types of deployment techniques: free-flying/direct deployment and TMS-based deployment.

3.4 ROV LARS

3.4.1 Free-flying/direct deployment

3.4.1.1 Direct deployment method

This kind of deployment is usually done for microROVs such as the VideoRay where it is light enough to be thrown into the sea by hand. They are usually made to withstand such impacts as well.

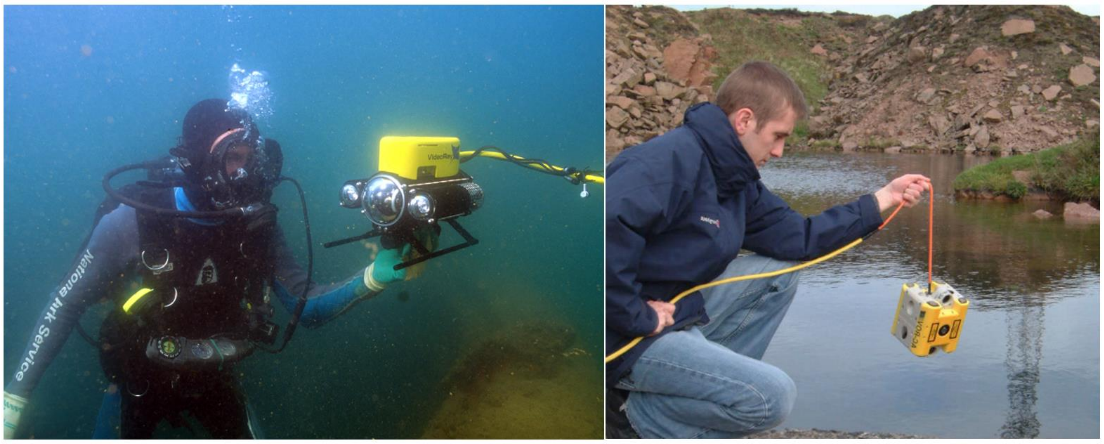

Figure 14 microROV Videoray [5], AC-CESS AC-ROV [6]

The Bumblebee 3.0 falls under this category as well when it is used as a standalone AUV platform. It is currently launched with at least two people carrying them on shore. Depending on the situation, a diver may need to assist the entry of the AUV at the splash zone.

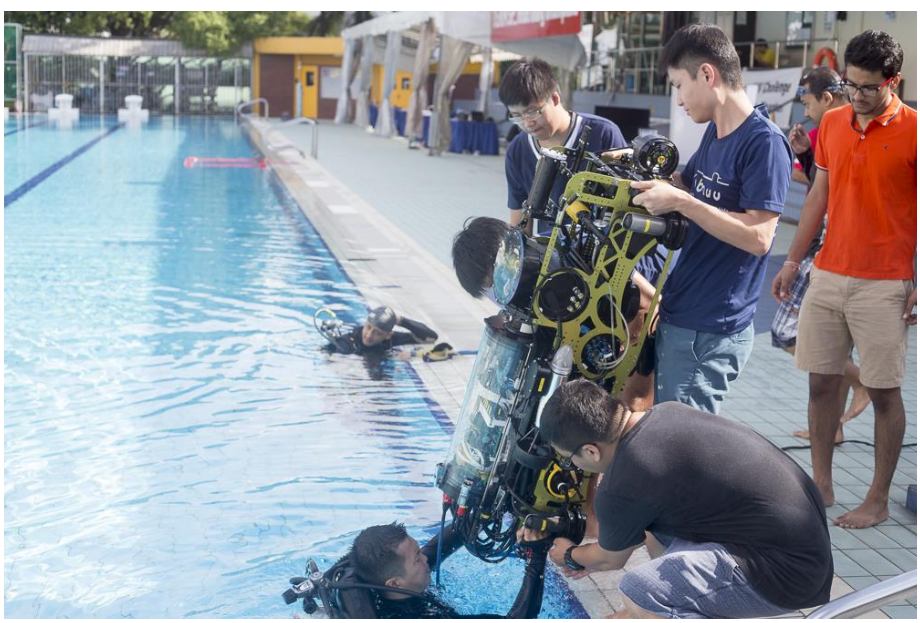

Figure 15 Bumblebee 3.0 deployment [Photo Credit: Alex Foo]

3.4.1.2 Tether management system

The vast range of vehicles and its deployment techniques made the definition of a TMS in the industry blur. In conventional definition, a TMS is defined as "the entire subsea mechanism from the end of the umbilical (umbilical termination to the clump/depressor weight, cage or top hat) to the beginning of the tether" [7]. But a TMS can be as simple as discussed in this section or as complicated as the next section.

For this direct deployment method, its TMS can consists of a clump weight or a small cage. The clump weight is used to manage the tether easily because most of the drag experienced by an ROV is due to tether drag. This simple mechanism "absorbs" the cross-section drag of current, immediately reducing the thrust needed to move the ROV in the water.

There is also a cage deployed ROV in the industry whereby its primary purpose is to protect the ROV when it is deployed through the splash zone. The situation is such that an ROV cannot be deployed safely in rough seas because of the dynamic motion of waves that may cause the ROV to swing around and hit the sides of the vessel. A vessel deploying an ROV usually have dynamic positioning capabilities as well to accurately deploy the ROV into a targeted work zone, but this means that the vessel's thrusters are also running at the same time. Thus, cages are included to protect against such possible damages. The cages also serve as a clump weight.

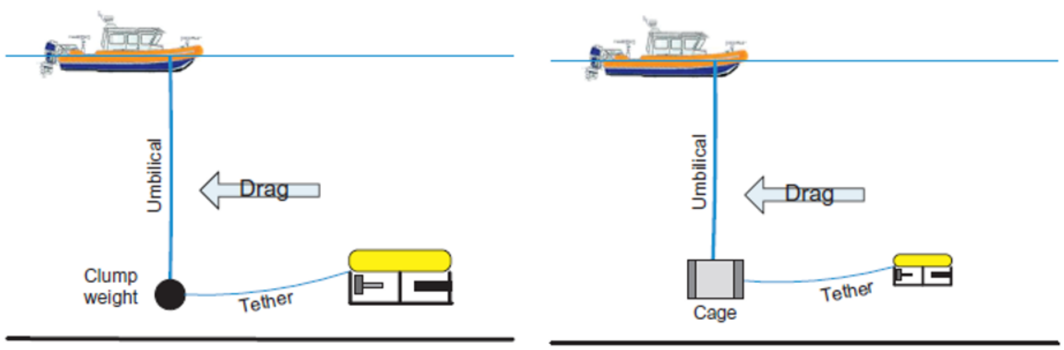

Figure 16 Clump Weight and Cage deployment methods [7]

3.4.2 TMS-based vehicle deployment

As the ROV gets bigger, its supporting equipment increases in size as well. The increase in number of equipment and size is needed to ensure smooth operations and safety. The types of LARS vary and the differences in design is due to considerations such as depth of operation (which determines the length of umbilical), weight of ROV (which determines the size of crane), vessel of deployment (which determines the amount of space available) and many more. However, the very basic ROV LARS still can be generalized to the system shown below. It consists of

i) hydraulic power unit (HPU),

ii) winch,

iii) lifting crane,

iv) tether/umbilical

v) TMS and

vi) the ROV itself.

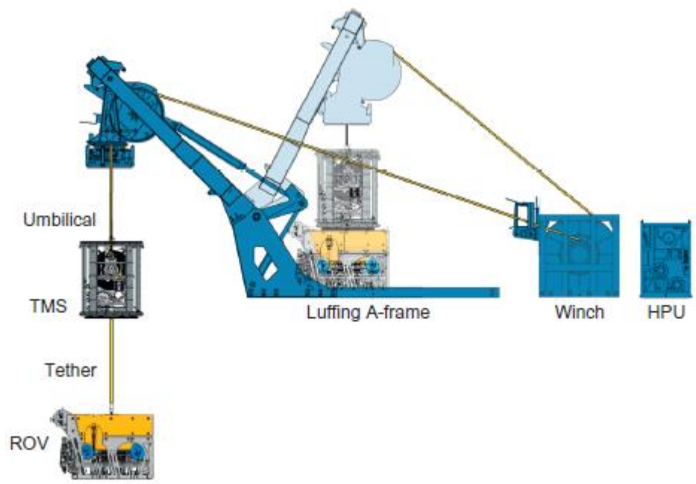

Figure 17 A typical LARS setup [7]

3.5 Components of ROV LARS

3.5.1 Hydraulic Power Unit (HPU)

A hydraulic power unit is the heart of any hydraulic power system. It generally consists of a motor, pump and fluid reservoir. The principle of operation is based on Pascal's principle, which takes advantage of the incompressibility of fluid. The result is that hydraulic system delivers much more power than electrical or pneumatic systems. It can be scaled up accordingly to deliver more power by having larger actuators, pump, and motor. As most ROV system weigh up to several tons, hydraulic is the prime choice to operate a LARS. A HPU can be used to power the winch, crane, and other systems simultaneously through careful planning flow control via solenoids.

Figure 18 A 300hp HPU [8]

Smaller HPU exists and are commonly used to run equipment in smaller vessel. For example, this Raymarine constant running pump is used to power inboard steering or rudders. Though smaller than the 300hp HPU, hydraulic system itself is generally heavier due to the need for a reservoir, solenoids and its components are tough-built (heavier) to withstand the higher pressure. Hydraulics are also inflexible because parts like hoses are fixed once crimped for a specific length.

Figure 19 Raymarine Constant running pump [9]

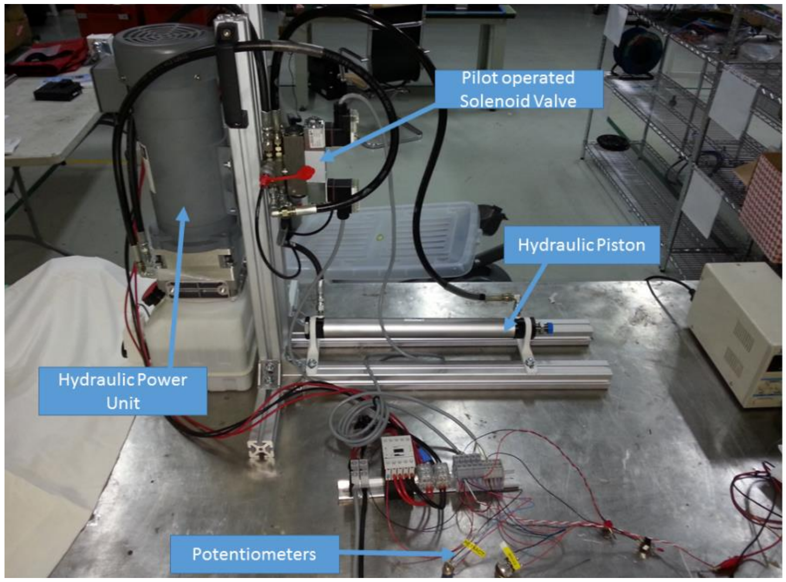

Figure 20 The basics of a hydraulic setup [Photo: Kee Yeow]

Shown above is a setup of a simple hydraulic system controlled by potentiometer to vary the speed of actuation. Though demonstrated is proportional capability, it is unnecessary for the scissors lift designed in section below as the AUV should be lowered down at constant speed.

3.5.2 Winch

Currently, the Bumblebee team reels in the Ethernet cable connected to the AUV via a hand crank located at the side of the cable spool. This method is not effective because a large amount of cable is reeled out initially and left at the side of the pool to allow the cable to be dragged into the water when its needed. The current way of reeling the Ethernet cable is not feasible in open sea because the drag encountered is a large function of the drag caused by the Ethernet rail. Thus, the cable needs to be reeled in as much as possible up for it to be just enough for the corresponding depth of operation.

This part explains the considerations and mechanisms behind a typical winch used in the industry.

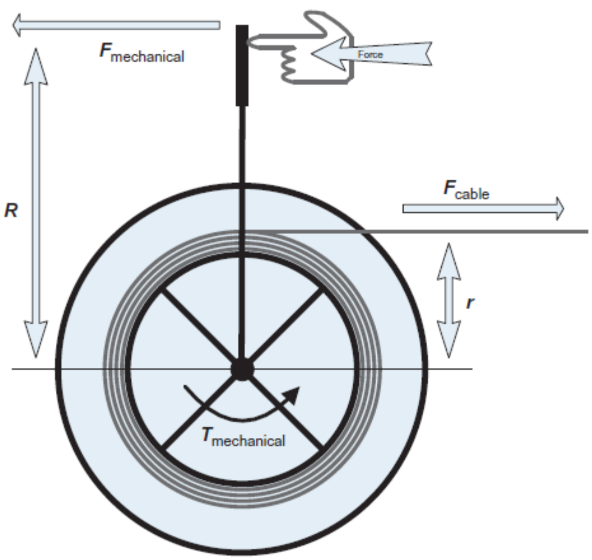

Figure 21 Forces acting on a winch [7]

A motor which provides the motive force (expressed in Nm) is replicated by a force exerted by a hand F_{me}, at a distance R (meter) away. The resistant experienced by the hand is of magnitude F_{cable} multipled by r (meter), the radius of the spool at that coil. This is because as the radius of the spool increases and decreases depending on the amount of cable being reel in or out. When the spool is stationary, the torques (T_{me} and T_{cable}) cancels out each other. For example, at R= 2r, the spool reached static equilibrium. The forces is expressed as, F_{cable} =(R/r)F_{me}. Thus F_{cable} = 2F_{me}. This shows that the torque is multiplied by a factor of two. As the size of the spool increases with every layer of cable, the torque needed by the motor to drive the cable in increases. Thus, the maximum torque on the motor for a fixed tension on the cable must be based on the largest radius of the spool.

To accurately determine the torque specifications for the motor, many other considerations such as the diameter of cable, fleet angle resistance and safety factors must be taken [7]. If the fleet angle is too small, the cable will pile up at a certain location and eventually roll away when a certain height is reached. This sudden jump will cause a loss in tension and will damage the system. It will also cause localized cable wear and exert excessive pressure on the windings. If the fleet angle is too large, the cable will complete across the spool prematurely, leaving gaps behind. Over many overlaps, the cable will “pluck” against each other. In short, every winch has their specific fleet angle and it must be determined to ensure smooth and efficient operations.

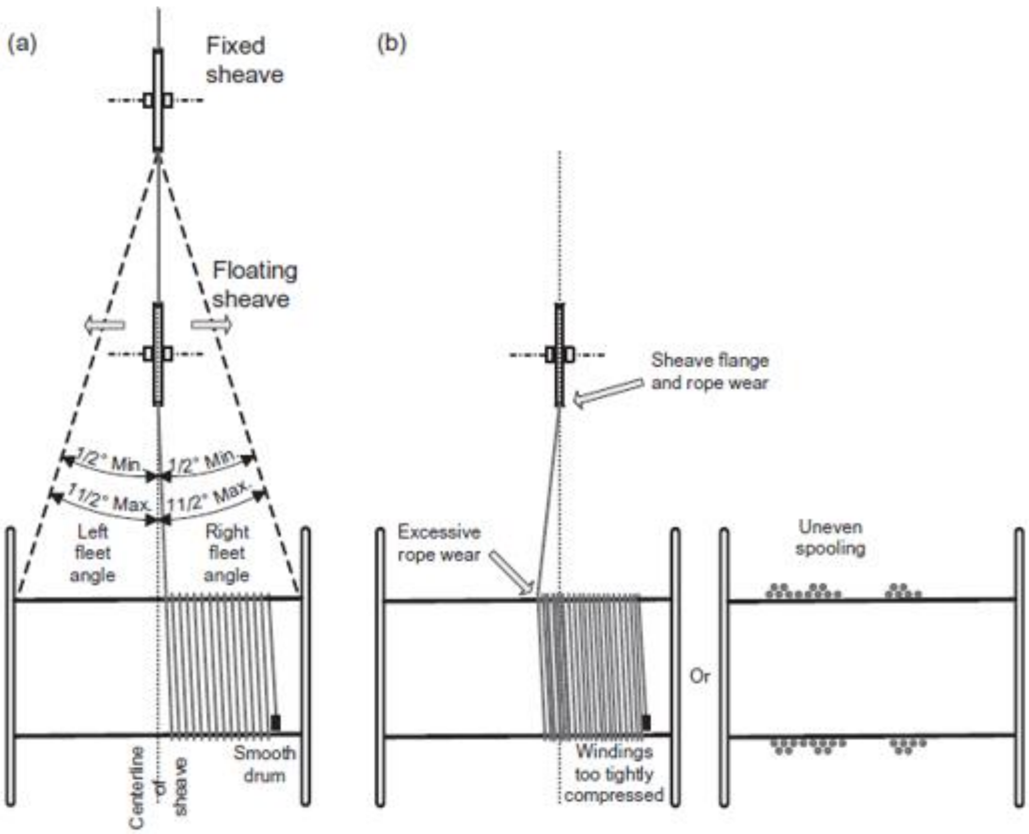

Figure 22 Left: Example of winch arrangement Right: Effect of fleet angle being too small

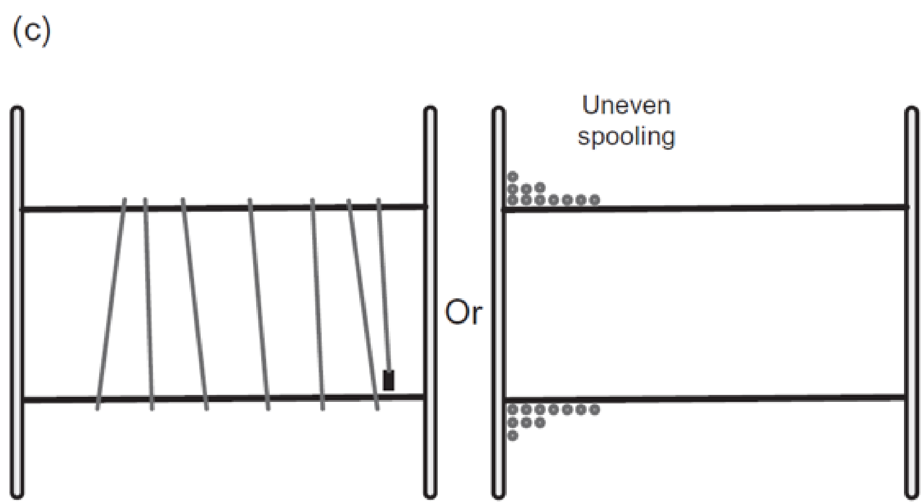

Figure 23 Effect of fleet angle being too large

In the industry, winches are highly regulated systems which requires certifications. Winches must have fail-safe braking system in which the winch will stop rolling should the motor lose its power. Again, most winches in the industry is hydraulically powered and for a static braking system, it is also the same. The brake is linked to the motor's hydraulic system and it is only released once sufficient hydraulic pressure is applied to the motor.

Winches are rated and classified according to the following few configurations:

1. Safe working load. This is the maximum operating load allowed and is set by the manufacturer.
2. Maximum line pull. This is the nominal stalling point of the winch.
3. Line speed. This is how fast the line is travelling out or in the spool and is usually specified in various units such as feet per minute (fpm), meter per second (m/s), or meters per minute (mpm).
4. Drum capacity. Specified in meter of cable of a specific diameter.

When the length of cable reaches thousands of meters, the round-trip time becomes very significant and is affected by the line speed. This is because the cost of operating a subsea vessel is very expensive per day. If a winch's line speed is 50mpm, and the depth of operation is 5000m, it will take the vessel 100 minutes to lower the ROV. The return trip from the bottom will cost another 100 minutes of time. The time consideration is important for us since competition rounds have limited time as well.

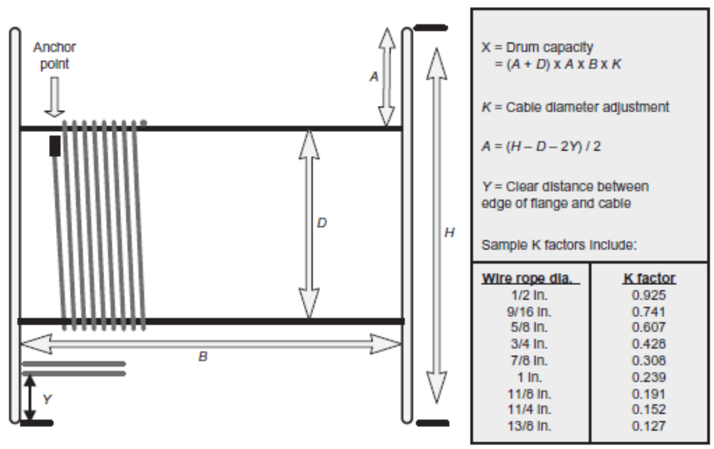

Figure 24 Drum size computations [7]

Again, winches in the industry are large and weighs up to several thousand kilograms. They are also equipped with heave compensation system to assist in high seas operations. There are two types of heave compensation: active and passive. Active heave compensation system takes in the vertical motion of the operating vessel from several sensors located on the vessel and compute the amount of vertical motion that is experienced by the ship. The system then sends signals to the motor to pay out or roll in the appropriate amount of cable to ensure the cable is not overstressed.

Figure 25 Teledyne Motion Sensor for heave compensation [10]

Passive heave compensation (PHC) system is based on the tension of the cable. The cable is held at a predetermined tension value which is deemed safe for the cable. This method is more mechanical and some of the common implementations include the use of springs, shock absorbers and compensators. In general, the active heave compensation system is more accurate because it is based on true positional difference rather than tensional force which can vary due to unexpected forces such as friction.

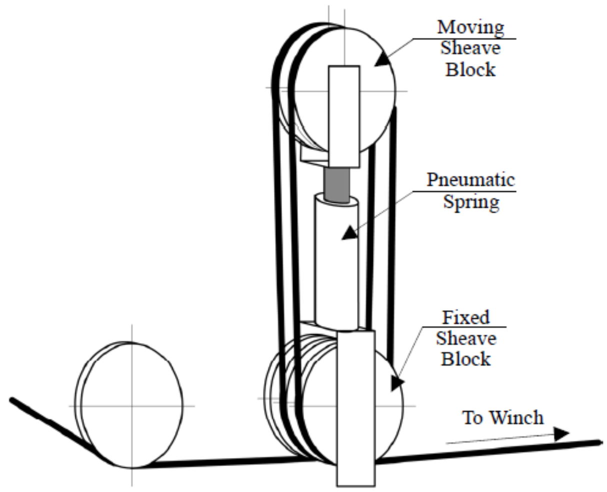

Figure 26 Passive heave compensation system using springs [11]

Figure 27 Lidan Marine's WROV winch with SWL of 12 ton [12]

Mechanically, winches are designed with internal planetary gear to save space and to allow reversal of rotation.

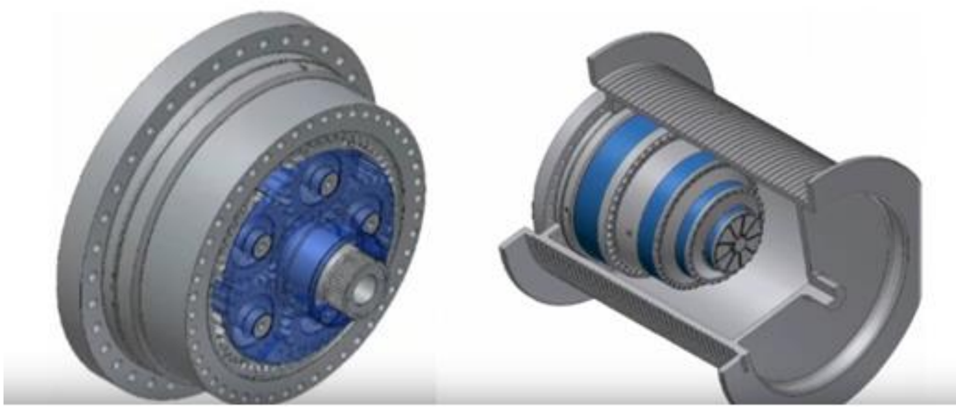

Figure 28 Planetary gears inside winch drum

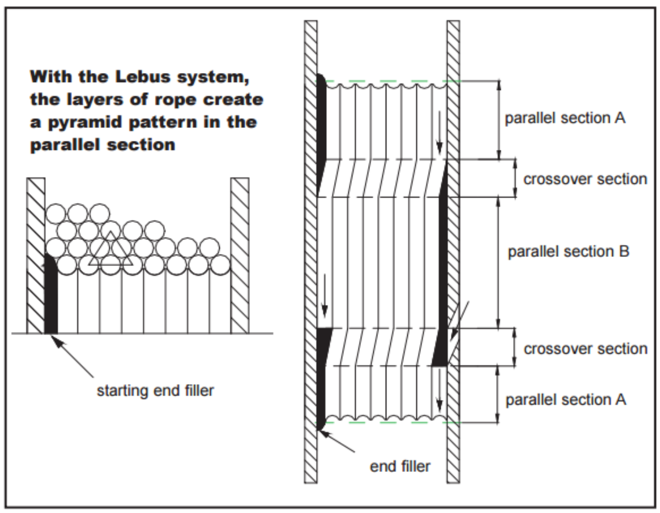

Figure 29 Lebus groove enables tether to be stacked in uniform triangle layers [13]

To further improve the reliability and spooling efficiency of the drum, Lebus groove design are implemented on the drums. Every Lebus drum is customized to the diameter, length and construction type of the umbilical/tether used. Tether are uniformly stacked upon each other which helps in distributing the loads down the layers. “The continuous groove in the drum is parallel to the flange except for two crossover points on each revolution where the groove moves across the drum half a pitch to give a full pitch of movement for each revolution” [14].

Another positive side of using a Lebus groove is the ability to conduct FEA to inspect the forces acting on the drums because of the uniformity in forces in a well arranged tether in the spool.

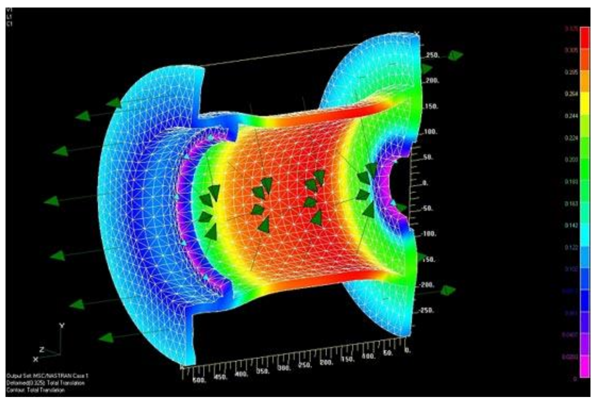

Figure 30 FEA on drum [14]

The degree of customization in the design may cause costs may escalate as the Lebus groove is machined independently and installed via bolts onto an ‘empty’ drum.

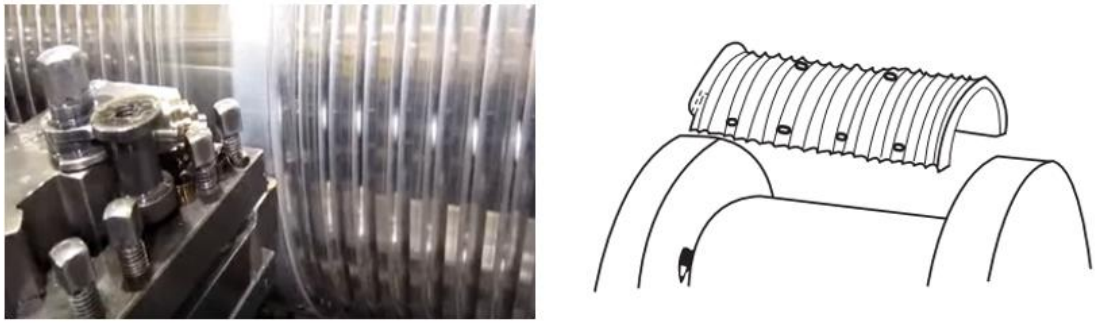

Figure 31 Machining and installation of Lebus groove [15]

3.5.3 Crane/A-Frame

The crane or A-frame are part of the whole launch and recovery system that allow the ROV to be put into the water from the vessel's deck. Some of the cranes are part of the vessel's equipment but A-frame can come in modular form which can be transferred or removed from vessel. It will be explained in the section 3.6 Types of ROV LARS.

3.5.4 Umbilical/Tether

In the industry, a tethered system has a cable that is used to transfer mechanical load, power and to provide communication means. The size of the ROV, weight, communication protocol and operating depth determines the cable type. These cables, often referred as electromechanical cables, are divided into two subcategories; umbilical cable (from vessel to TMS) and tether cable (from TMS to ROV). There are three main initial considerations for the cable: power, signal, and strength requirement.

3.5.4.1 Power Requirement

All ROV does not have their own power supply onboard such as batteries. Thus, the cable design should accommodate for power transfer. Suitable material with low resistance for current transfer such as copper is commonly used. When current is involved, a cable must be insulated properly to prevent cable meltdown in case of current overdraw. Thus, operating condition such as environment temperature and power requirement is crucial when it comes to choosing the right cable.

For BBAUV, it has its own batteries which can last up to 3 hours of operations. Therefore, its cable does not need to supply power to the AUV. However, future implementations may include recharging capability which requires a tether to have power lines.

3.5.4.2 Signal Requirement

Communication between the AUV and the ASV is critical as both vessels execute a mission as a pair. Information relays between the two is needed to know their relative position to each other so that their own boundary space is understood. Every kind of signal transmission experience attenuation to a certain degree, be it electrical or optical. Copper conductors are commonly used because it is less expensive and can be used to transmit electrical signals at tolerable bandwidth.

Signal cables are also prone to interference, which is why they are often designed together with a shield to prevent electromagnetic interference (EMI) and radio frequency interference (RFI). On the other hand, fiber optic cables are known for their high speed and high bandwidth transmission. They are also much less susceptible to interference, losing only 3 percent of date over 100 meter cable length compared to copper which losses 94 percent over the same length [16]. The setback of fiber optic cable is that they are more expensive and termination can be a delicate problem. Thus, these factors are important when selecting a cable.

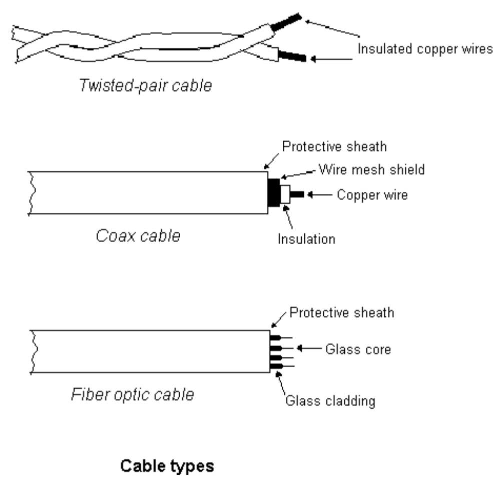

Figure 32 Types of Signal Cables [17]

3.5.4.3 Strength Requirement

The strength of the cable is required for factors such as weight of AUV and dynamic loads. It also should withstand abrasion as well as stretching under the unpredictable seas. The most common way to reinforce a cable is using steel. It is excellent in tensile strength, abrasion resistant and can be coated to prevent corrosion from sea water. The setback of this is that they are heavy and thus the whole TMS should be scaled up to accommodate for this.

Modern cables using synthetic fibers such as KEVLAR has been used in underwater cabling [18]. These types can be expensive but can make significant differences in weight. For deep water systems, using synthetic fiber is the only way to achieve reliable deployment weight. Fiber optic cables are more fragile as well (as explained in next section). More considerations must be taken if this new communication protocol is used.

3.5.4.4 Slip Rings

A slip ring is a device that allows transmission of power and signals from a stationary to a rotating structure. In this case, the stationary structure will be the system that holds the tether spool while the rotating structure is the spool of tether which is turned by an electric motor. Just like a termination point, slip ring poses risks of insertion loss and should be minimized whenever possible.

There are many types of slip rings such as mercury-wetted slip rings and wireless slip rings but in the ROV industry, the two commonly used slip rings are the electrical and fiber-optic slip rings.

3.5.4.5 Electrical Slip Rings

The smallest electrical slip ring by MacArtney is the Model 180 at 0.1m diameter and it is rated at IP66. The initial market research puts their costs at around ten thousand.

Figure 33 Macartney electrical slip ring model 180 [19]

3.5.4.6 Fiber Optic Rotary Joints

Known as FORJ, its primary function is the same as electrical slip ring. Depending on the number of passes, the basic operation of FORJ remains the same which is to refract the beam from a fiber into a graded index lens (GRIN) by passing through a medium (air or clear fluid) and back to another GRIN to obtain back the beam signal on the other side. Again, the increase in number of passes will increase the insertion loss. Non-subsea FORJ comes in small sizes.

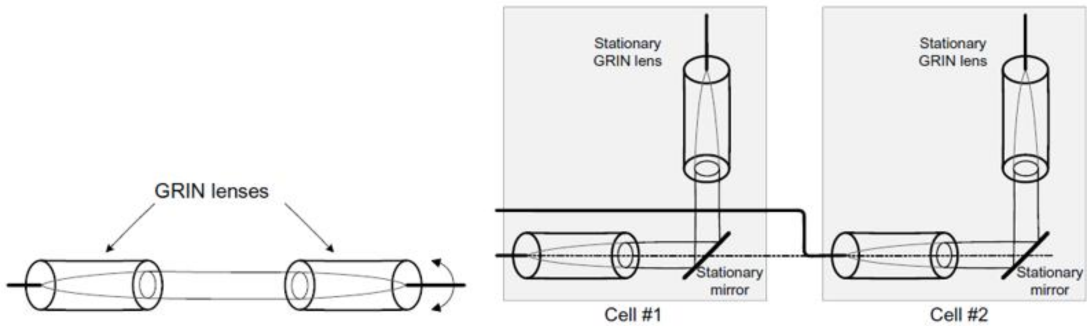

Figure 34 Left: Single-pass FORJ Right: Multi-pass FORJ

3.5.4.7 Fiber Optic Cable

As the team explores new modes of electrical architecture, fiber optic communication is explored. The general construction of a fiber optic cable consists of the core, cladding and coating. The core is where light transmission takes place and can be made of plastic or glass. The larger the core, the more light is transmitted. The cladding ensures the light stays in the core by serving to provide a medium of lower refractive index. The outermost layer is the coating and it serves to provide strength, absorb shock, and is made of various materials to provide different buoyancy.

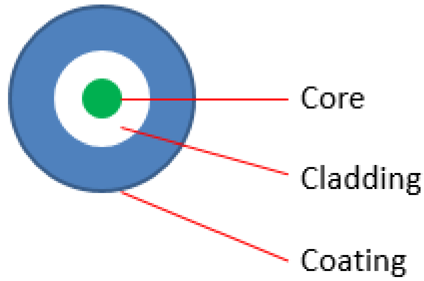

Figure 35 Fiber optic construction

Fiber size are stated in a set. For example, 50/125/250 means its core is 50µm, cladding of 125 µm and coating of 250 µm. There are two types of fiber cable: multimode and single-mode. Multimode fiber core can be either step index or graded index. In this section, we will explore more on the mechanical characteristics of fiber cable.

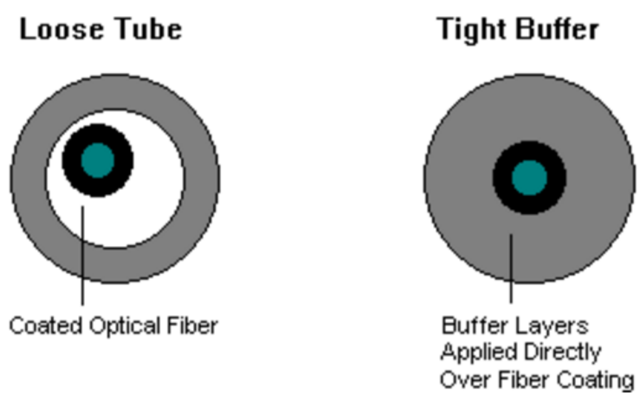

Figure 36 First level fiber protection [20]

There are two level of fiber protection. The first level is within the fiber itself and consists of either a loose tube or tight buffer construction. The loose tube has a coating layer that is considerably bigger than the outer diameter of the cladding and is filled with gel material to absorb shocks. In general, it provides a stable transmission characteristics under continuous mechanical stress.

On the other hand, the tight buffer construction is made by extruding a layer of plastic over the basic fiber coating. The result is a much stronger, yet smaller cable that can withstand higher impact and crush forces. The setback is that the bending radius is significantly reduced due to increased rigidity. This will affect the size of the winch spool. The tight buffer construction also come with a breakout design whereby it is shielded further with aramid yarn and jackets of PVC. This additional layer increases tensile strength with ease installation processes. The characteristics of the cable is summarized below:

Table 2 Cable structure tradeoffs [20]

Cable	Cable Structure		
Parameter	Loose Tube	Tight Buffer	Breakout
Bend Radius:	Larger	Smaller	Larger
Diameter:	Larger	Smaller	Larger
Tensile Strength: (Install):	Higher	Lower	Higher
Impact Resistane:	Lower	Higher	Higher
Crush Resistance:	Lower	Higher	Higher
Attentuation Change at Low Temperatures:	Lower	Higher	Higher

Fiber optic cables are prone to micro bending which results in attenuation and fatigue effects. Thus, strength members such as fiberglass epoxy rod (FGE), steel or aramid are always added to increase its tensile strength. Aramid yarn is much stronger than steel by weight. However, FGE and steel offers better stability under cold temperature operations such as deep sea.

The use of fiber optic in the industry involves delicate procedures. Engineers are often sent for specialized training (MCTS company) before they can handle them. Because of this and all the factors above, fiber optic is not the chosen over CAT5/CAT6 cable.

3.5.4.8 Tether Termination

Tether termination provides the mechanical strength to transfer the force from the winch to the tether and from the tether to lifting the AUV. There are various types of termination: spelter socket, Kellems grip and Yale grip.

Figure 37 Spelter socket [7]

Spelter socket is by far the most common termination for steel strength member tether. The setback is its large profile compared to others. Molten zinc or epoxy is poured into a 'socket' with the tether/umbilical held in the middle. Yale grip is very compact and lightweight because they are made of Aramid fiber. It is also effective for varying diameter whereas a spelter socket has predetermined sizes.

Figure 38 Yale grip termination [21]

Figure 39 Kellems' Grip [Photo: Sea and Land Technologies]

3.5.5 Tether Management System (TMS)

The winch system is responsible for handling the TMS, which is usually attached to the ROV. In this section, the focus will be on the TMS which handles the tether from the ROV to the end of the umbilical-TMS interface. There are two types of TMS: the top hat and caged system. Under the caged system, there are two categories, which are the slipring and baling arm systems. Most of the top hat system are slipring system.

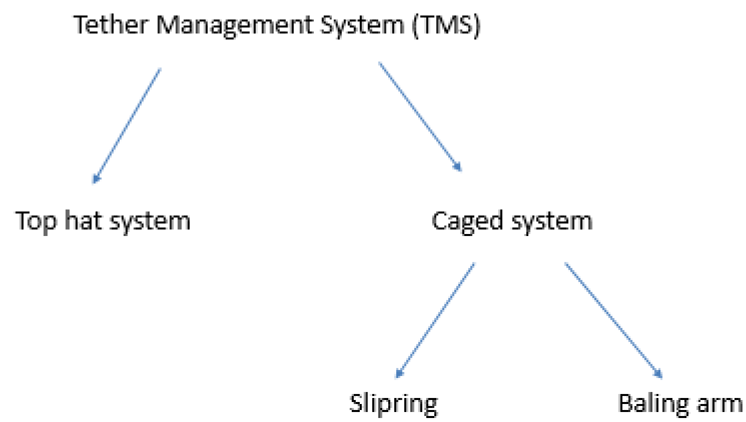

Figure 40 TMS classification

The TMS allows an ROV to be kept and deployed at a much later stage of deployment when a desired depth is reached. The system allows isolation of the ROV from the motion of the vessel on the surface against waves. TMS has many advantages which includes [22]:

1. Accurate deployment to the work site
2. Provides safe parking platform during in-between tasks (underwater)
3. Protection for the ROV during launch and recovery operations (garage-type)
4. Drag effect can be better controlled by changing length of umbilical and tether simultaneously
5. Removes the effect of underwater current especially for very deep operations where current varies from layers to layers, this produces easier

control because of reduced drag

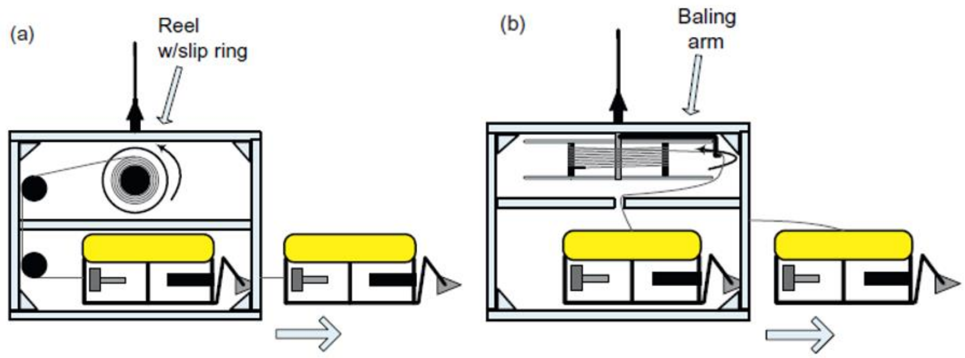

Figure 41 (a) caged system with slip ring (b) caged system with baling arm

However so, a TMS can be expensive because it is an additional system which must be launched and recovered from the vessel. A TMS can also be extremely heavy with mass ranging from 500kg to an excess of 5000kg without the tether alone [23]. Thus, designing a top-hat TMS to be deployed on the WAM-V may not be a choice.

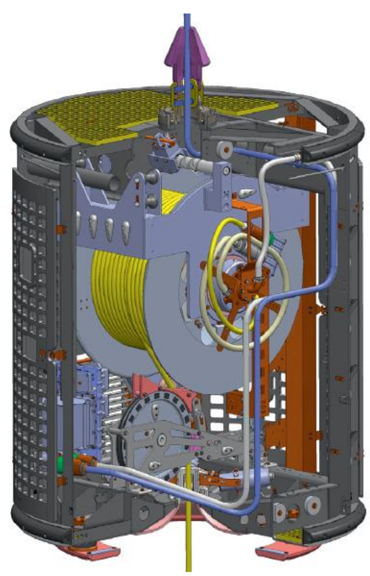

Figure 42 Cross-section of Schilling Robotics top hap TMS [7]

3.5.5.1 Bailing Arm Design

Initially, the bailing arm TMS is preferred because of its simplicity relative to using a slip ring system. Thus, numerous spinning and bait-casting reels used in fishing are studied carefully for its design. This method of reverse engineering proves to be useful as it provides a head start in the design concept.

Figure 43 SeaHawk Micra with its eccentric cam design

The first fishing reel is the SeaHawk Micra M800. The spooling mechanism is via an eccentric cam design. The drive gear, which is at the center of rotation of the handle is designed with an eccentric cam in a shape of a ring. It is slightly smaller than the size of the follower. The follower in turn is attached via a pin to the main shaft. The rotational motion is translated into linear motion by turning the handle of the reel at the center of rotation. The gear ratio is determined from the ratio of gear in the drive gear and pinion gear.

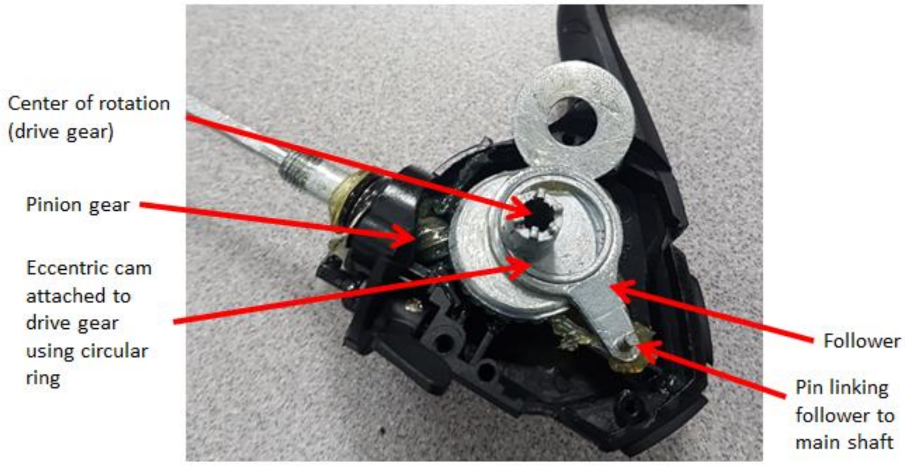

Figure 44 Parts of the eccentric cam design

The next fishing reel that was examined is Sense 6000. This reel is much bigger in size compared to SeaHawk and has different construction. Noticeably, it has more bearings supporting turning axis at places such as the drive gear. There are five ball bearings in this model. It is worth noting that the more ball bearing in a reel design, the smoother its operation will be as rotating axes are well supported and balanced. Some high-end models from Shimano contain up to 13 ball bearings but costs a few thousands. The transverse cam design has a stronger built profile compared to the circular cam design but performs the same function which is to drive the main shaft up and down to produce the cable arranging capability.

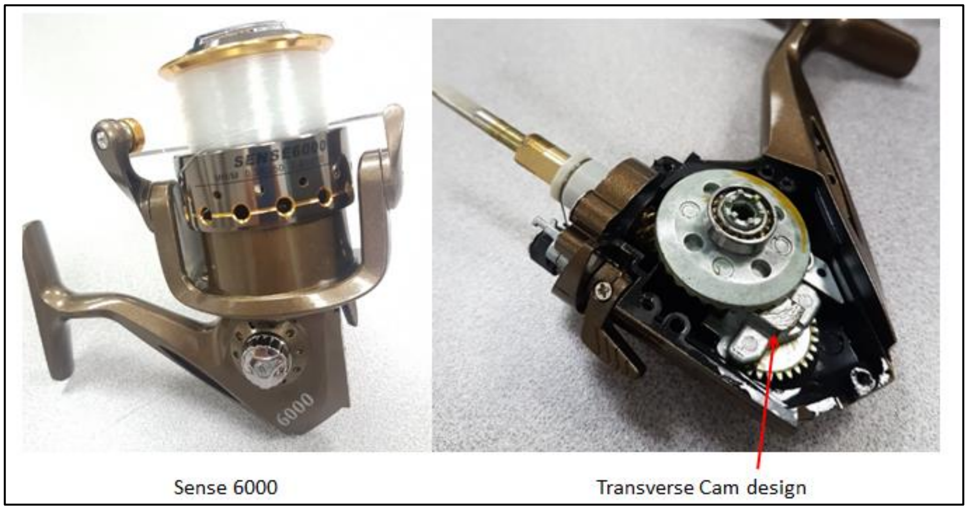

Figure 45 Sense 6000 with its transverse cam design

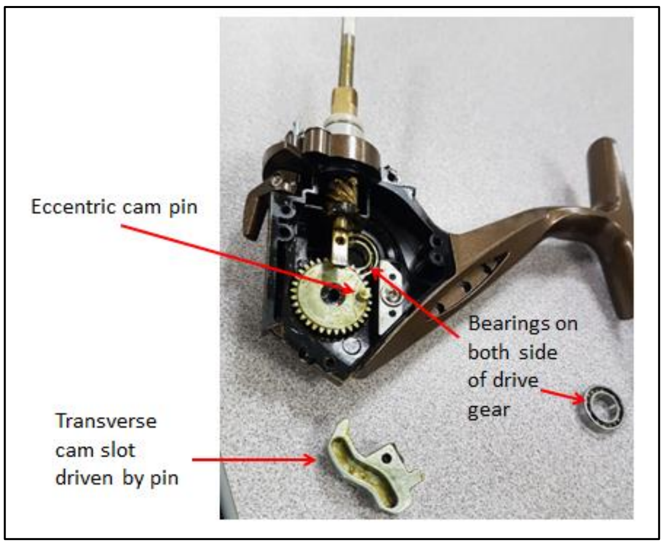

Figure 46 Parts of transverse cam design

The last design examined is the bait casting fishing reel by Shimano. The compact design render its line spooling mechanism to be of different way. It uses carefully grooved diamond gear to drive a crescent pin across a linear distance. The end of the diamond gear has features that reverses the direction such that the line winds back and forth continuously. The setback of this mechanism is that the diamond gear must be designed and machined carefully to fit the tether used.

Figure 47 Shimano CSO 100

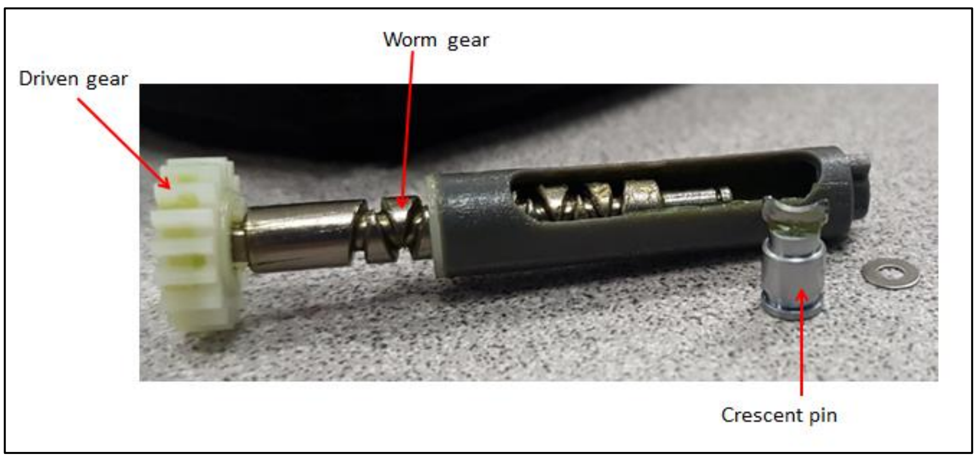

Figure 48 Cable arranging method via diamond (worm) gear

Scaling up the fishing reel design and placing a motor to replace the hand spool is not feasible because the bailing arm must withstand much larger cantilever force. Industrial bailing arm TMS consists of two major motors; the traction motor and the spooling motor. Thus, a decision was to use a slip ring TMS.

3.6 Types of ROV LARS

3.6.1 Moonpool LARS

The moonpool LARS is consists of a specially designed vessel that has a moonpool door system in the middle of the deck to allow access to the sea at times. Handling of moonpool-based LARS is safer as crews are protected from the external elements such as heavy rain or storms. The WAM-V is an approximation of the moonpool concept for its open mid deck.

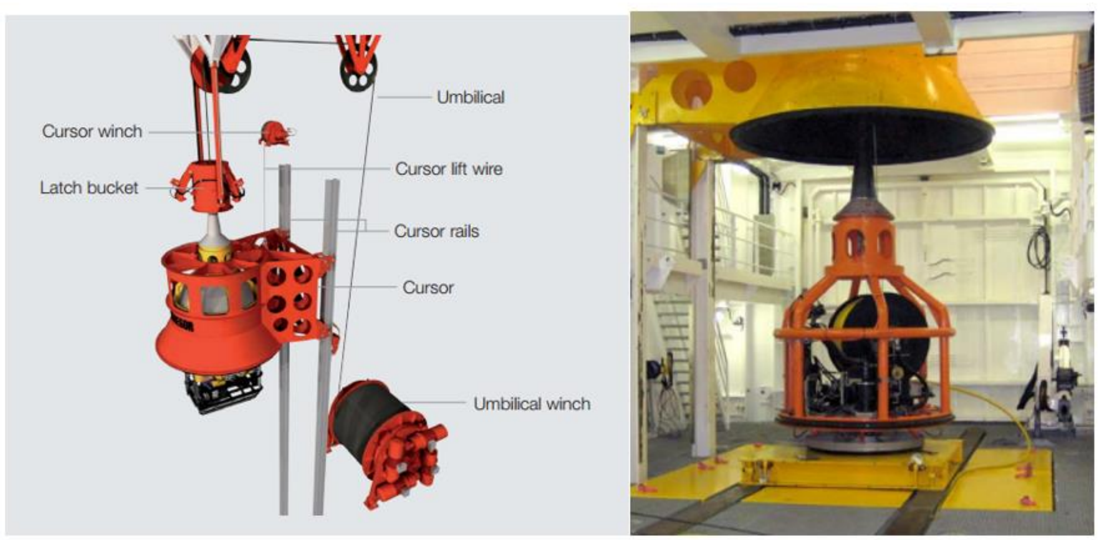

Figure 49 Left: A cursor allows parking of ROV at specific heights. Right: The yellow door on deck will open up to give access to the sea [24]

3.6.2 Deck/Skid-mounted overside LARS

The deck mounted LARS usually consists of an A-frame mounted on the deck of a support vessel. Hydraulics powers all these A-frame. The A-frames can be either center-rigged, knuckle-jib or telescopic version. Some of the frame are permanently attached to the deck of a vessel while some can be detached and assembled to another ship. For example, the deck-mounted LARS by MacGregor even has a travelling rail so that the whole A-frame and the ROV can be moved into a sheltered deck for easy maintenance.

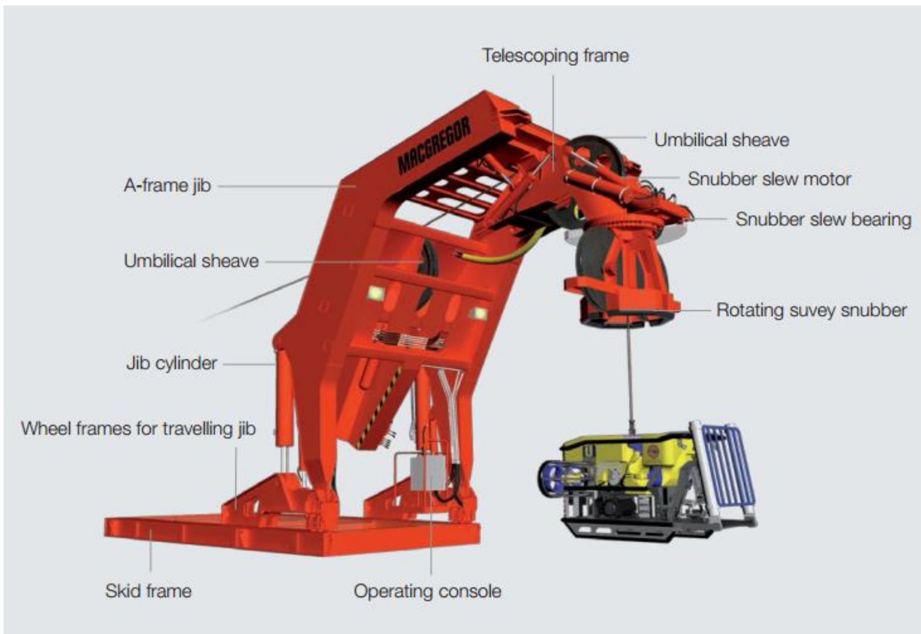

Figure 50 MacGregor Deck-mounted LARS equipped with travelling rail [24]

3.6.3 Overhead-mounted (overside) LARS

The overhead-mounted LARS is designed when there is a lack of space or there is a need to keep the ROV inside a sheltered deck. The setback of this system is that the payload capability is lesser because the overhang telescopic beam could take lesser load structurally at such cantilever position. Such system by MacGregor has a telescopic snubber that reduces pendulum motions and allows the locking of load to prevent rotation.

Figure 51 MacGregor overhead-mounted overside LARS [24]

3.6.4 Portable containerized LARS

This design incorporates every system that is needed for a LARS including TMS, spooling winch, control panel, electro-hydraulic power unit, telescopic handling arm, and even the ROV. The main advantage of this design is that the whole system can be shipped as a container around the world. The setback to this is that the system is limited to the size of the container, which essentially affects the size of the ROV and length of tether.

Figure 52 MacGregor containerized LARS has a built-in crane on top [24]

Figure 53 Seabotix Containerised Delivery System (CDS) in a standard 20ft container [25]

The Seabotix CDS comes with a fully furnished control room and a 3m overboard reach with its extendable boom. It's surface winch has 4300-meter-long tether because the company specialize in mini-ROV, which allows more storage space of tether in the container.

3.7 AUV LARS

3.7.1 Containerized AUV LARS

Figure 54 Hugin 1000 being launched from its stinger LARS [26]

For the HUGIN, the AUV is tilted down into the water and released by a mechanism when the ship is moving forward. When the AUV is ready for retrieval, the vehicle is hooked up at its recovery nose and connected to a winch. The vehicle is then pulled up onto the stinger and will be retracted back into the container once it is seated properly. The whole process is done when the ship is moving at the speed of around 1 to 2 knots [26].

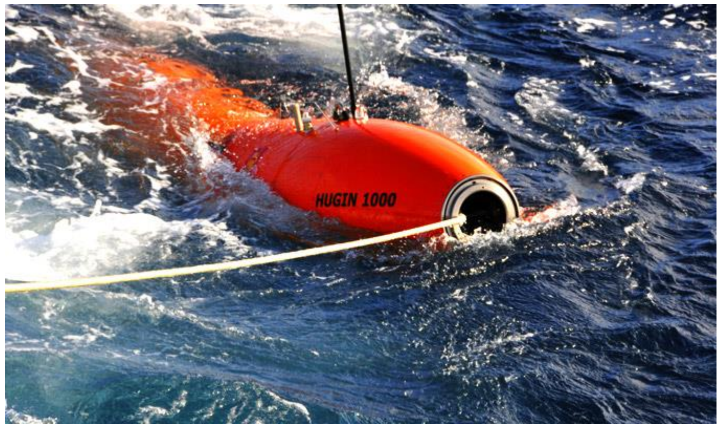

Figure 55 HUGIN 1000 being towed from the recovery nose

3.7.2 Non-containerised AUV LARS

3.7.2.1 Cradle/Dock

The REMUS 600 has a dedicated cradle design that assists in both launching and recovery. The AUV sits inside the cradle during the launch and is driven out and into the cradle using Wifi or float line [27].

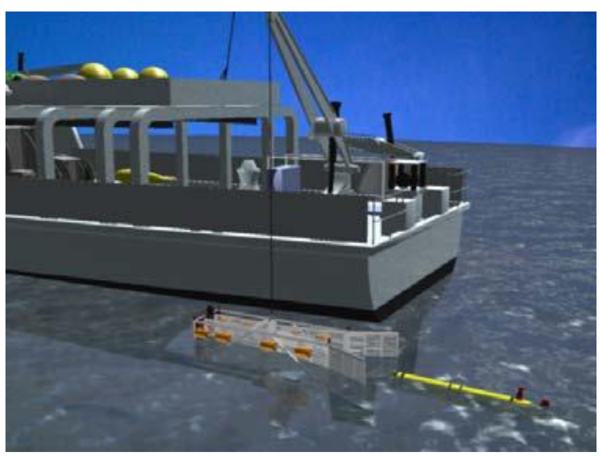

Figure 56 REMUS 600 LARS setup

Another version of REMUS AUV, the REMUS 100 is launched and recovered using a docking mechanism. This docking mechanism are part of the US Navy experiments. Docking mechanism are extensively tested by AUV to include features such as recharging batteries and data recovery [28].

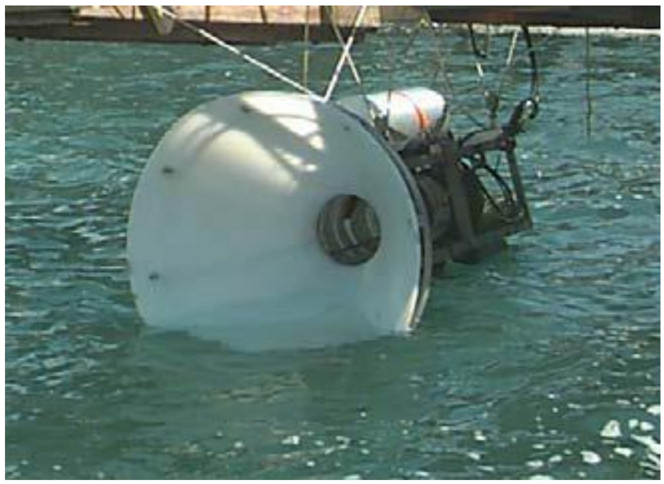

Figure 57 REMUS 100 Dock [27]

3.7.2.2 Net

As some AUV are not retrofitted with recovery nose or hook to assist in recovery, they are recovered using a fishing net instead. This method is very reliable since a large surface are of net can be casted to increase the chance of capture. However, this method requires high visibility and is piloted by an operator.

Figure 58 Atlas Fox is being hoisted up by a davit [27]

Figure 59 Atlas Fox is launched by releasing series of latches [29]

3.7.2.3 Single Lifting Point/Spud

AUVs are rarely launch and recovery using only a single point because it poses risk of damages if not secured properly using multiple points during high sea states. Owing to the large flat surface area, the SEA Otter AUV can be launched using a crane equipped with snubber-like system to prevent the rotation of the AUV. The AUV is equipped with a buoy tied to a 40m recovery line that is used to engage with the crane for recovery process.

Figure 60 Recovery process of SEA Otter AUV [30]

3.7.2.4 Hook

Teledyne conducted a recovery method using a nosecone hook design to utilize standard onboard cranes. The result is not as promising because, as mentioned above, the single-point attachment causes the AUV to swing around during recovery and hit the side of the ship.

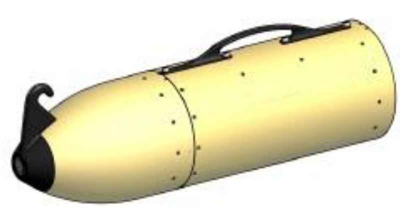

Figure 61 Teledyne Gavia Nosecone hook design [31]

3.8 Sea State

The sea state describes the condition of the sea or a large open body with reference to the waves and swell at that particular moment and location. World Meteorological Organization categorizes the sea state and it describes the height of the wave and its wave characteristics. Since the size of the wave is affected by the wind speed, in general, the stronger the wind, the higher the waves.

Table 3 Sea State Categories [32]

Code	Wave Height (meters)	Characteristics
0	0	Calm (glassy)
1	0 to 0.1	Calm (rippled)
2	0.1 to 0.5	Smooth (wavelets)
3	0.5 to 1.25	Slight
4	1.25 to 2.5	Moderate
5	2.5 to 4	Rough
6	4 to 6	Very rough
7	6 to 9	High
8	9 to 14	Very high
9	Over 14	Phenomenal

Another commonly used scale is the Beaufort Scale. Named after a Royal Navy officer, Francis Beaufort, the scale is based on an empirical measure that relates the wind speed to observed conditions at sea or land. It is easier to use this scale because a direct measurement of wind speed can be referred to the corresponding sea state. Below is the table of Beaufort scale:

Table 4 Beaufort Scale [33]

Beaufort Number	Wind Speed (m/s)	Seaman's Description	Appearance of Wind Effect
0	<1 (<2)	Calm	Mirror-like sea
1	0.3 – 1.5 (1-3)	Light air	Ripples with appearances of scales; no foam crests
2	1.6 – 3.3 (4-7)	Light breeze	Small wavelets; crests of glassy appearance, no breaking
3	3.4 – 5.4 (8-12)	Gentle breeze	Large wavelets; crests beginning to break; scattered whitecaps
4	5.5 – 7.9 (13-18)	Moderate breeze	Small waves, becoming longer; numerous whitecaps
5	8.0 – 10.7 (19-24)	Fresh breeze	Moderate waves, taking longer to form; many whitecaps; some spray
6	10.8 – 13.8 (25-31)	Strong breeze	Large waves begin to form; whitecaps everywhere; more spray
7	13.9 – 17.1 (32-38)	Near gale	Sea heaps up and white foam from breaking waves begins to be blown in streaks
8	17.2 - 20.7 (39 – 46)	Gale	Moderately high waves of greater length; edges of crests begin to break into spindrift; foam is blown in well-marked streaks
9	20.8 – 24.4 (47-54)	Strong gale	High waves; dense streaks of foam and sea begins to roll; spray may affect visibility
10	24.5 – 28.4 (55-63)	Storm	Very high waves with overhanging crests; foam is blown in dense white streaks, causing the sea to appear white; the rolling of the sea becomes heavy; visibility reduced
11	28.5 – 32.6 (64 -72)	Violent storm	Exceptionally high waves (small- and medium sized ships might be for a time lost to view behind the waves); the sea is covered with white patches of foam; everywhere the edges of the wave crests

			are blown into froth; visibility further reduced
12	32.7 – 36.9 (73-82)	Hurricane	The air is filled with foam and spray; sea completely white with driving spray; visibility greatly reduced

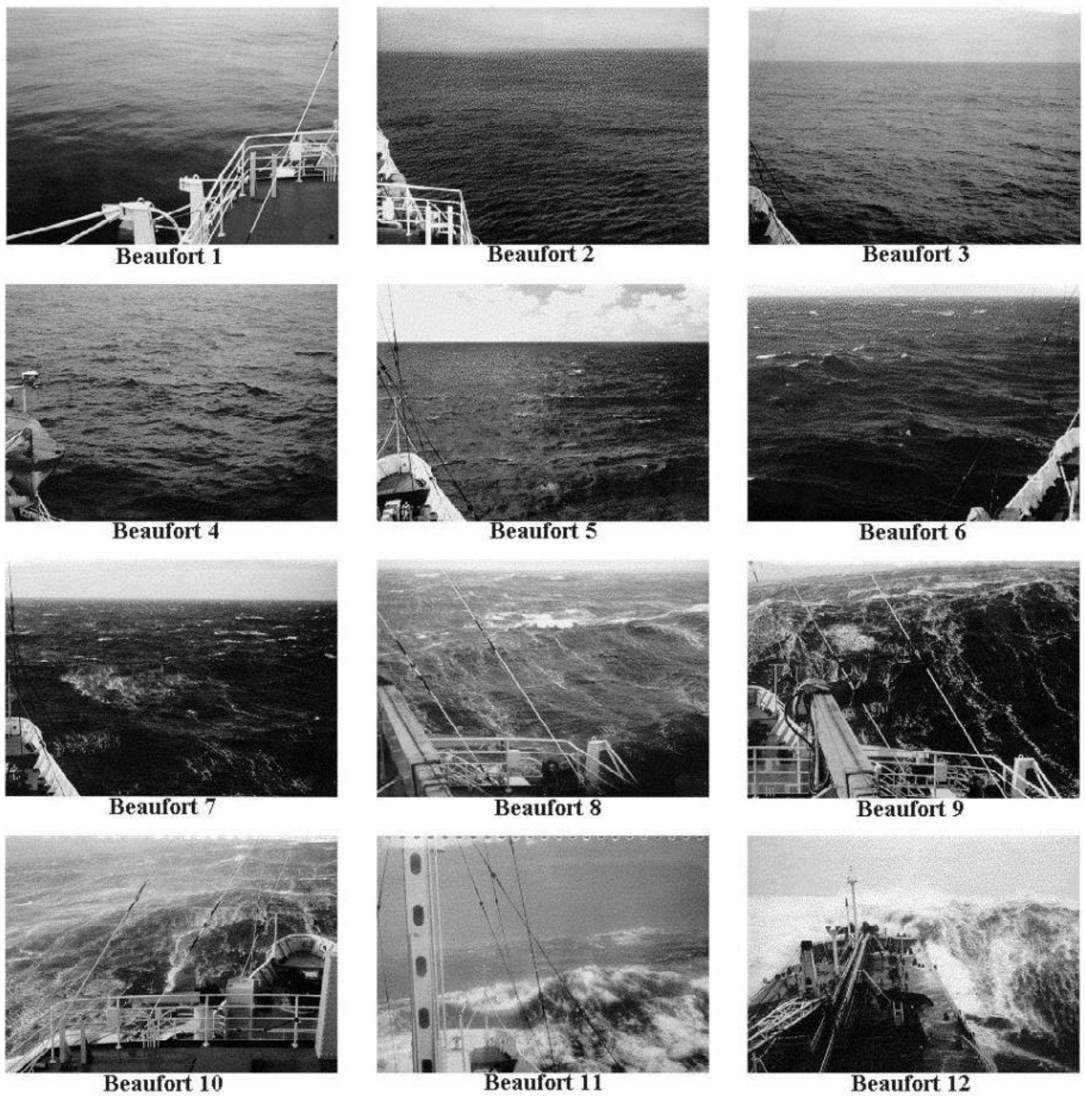

Figure 62 Sea condition in relation to Beaufort scale [34]

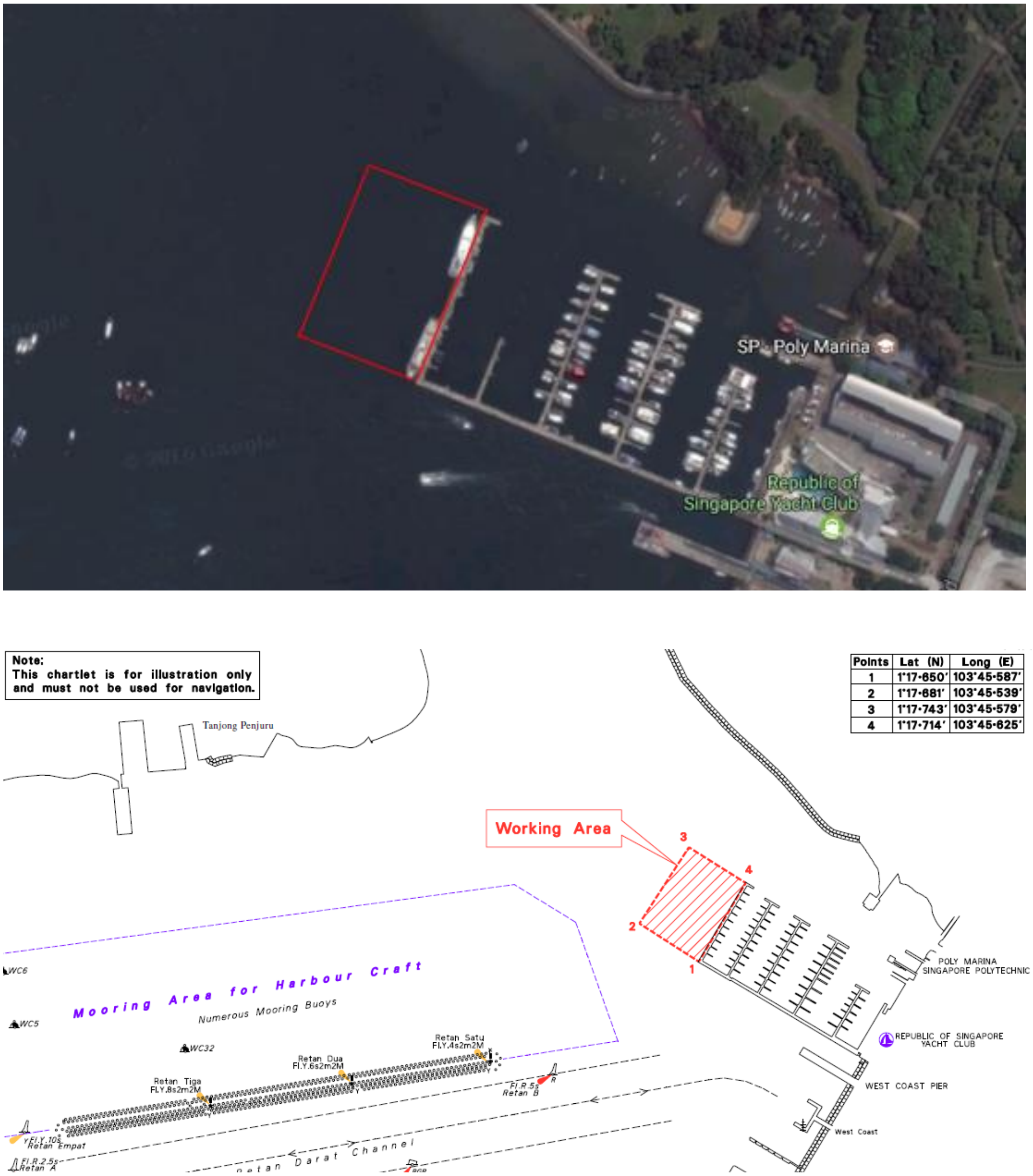

Figure 63 Allocated Testing Site (Source: Google Maps & Maritime Port Authority)

The wind speed in Singapore is affected by many local weather systems such as thunderstorms, squalls, and rainstorms. Gusty winds during non-thunderstorm (NTS) period can reach up to 23.8m/s but sustained for only a short period of time while gusts during thunderstorm period (TS) is even higher [35].

The testing site of the LARS is proposed to be at Republic of Singapore Yacht Club (RSYC). Three months of development on the ASV's base capability allows us to know firsthand the maximum sea state experienced there. Occasionally, the team will be caught in the middle of thunderstorm while testing and from the experience and observation of wavelets formation, sea state 3 or Beaufort scale 4 is derived. In these situations, testing is halted as it is deemed too dangerous (unstable floating platforms) and most of the on-shore electronics such as laptops that supports the testing are not weatherproof.

For safety reasons, the team concludes that testing will only be done during calm weather. Thus, the LARS is designed to operate in sea state 2 for now.

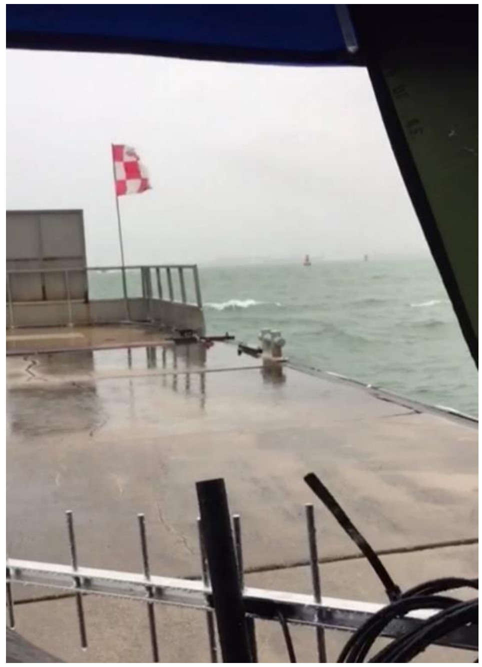

Figure 64 Still image from a video captured during a thunderstorm at RSYC dock. Some whitecaps are clearly visible [Photo Credit: Chia Che]

4. Design of Bumblebee Launch and Recovery System (BBLARS)

4.1 Design 1

The design approach of the LARS was to focus on the suspension system, the scissors lift and the latching system first. The winch or tether paying system will be designed later stages.

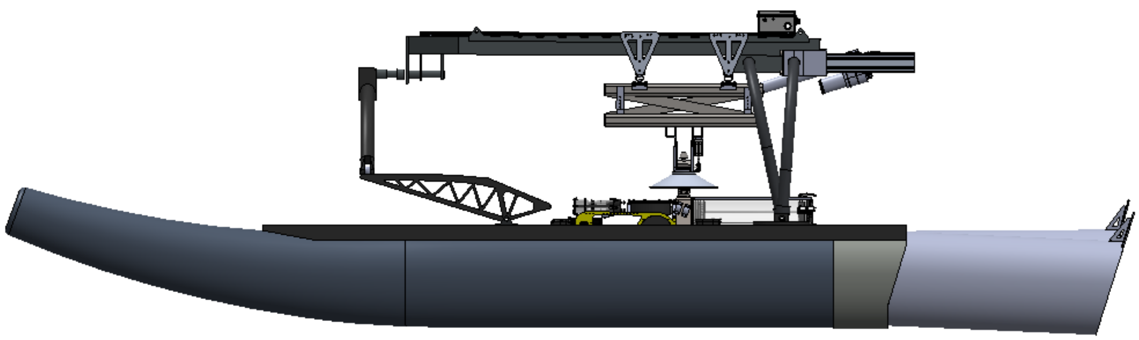

Figure 65 Side view of integrated latch and scissors lift on ASV

The system can be divided into three main parts: suspension system, scissors lift and latching system.

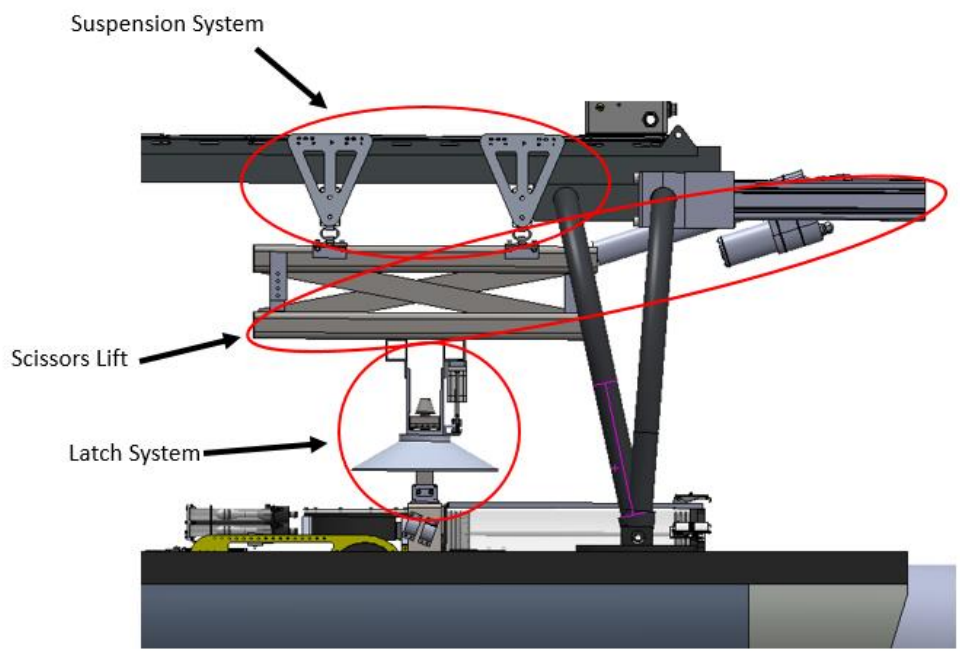

Figure 66 Classification of components

4.1.1 Suspension System

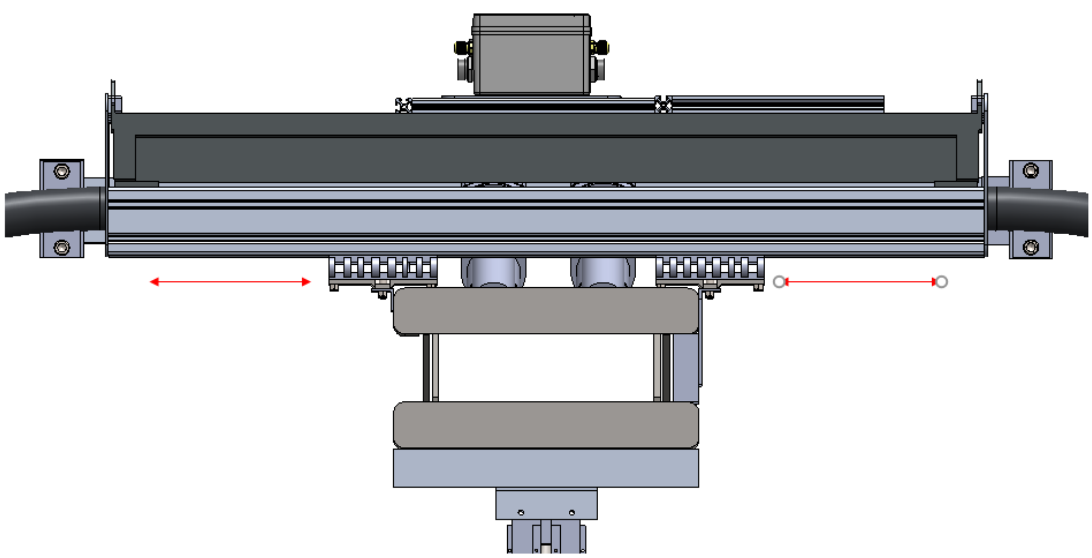

Figure 67 Adjustable CG via use of profiles

The suspension system is designed to hold the weight of the scissors lift, the latching system and the AUV itself. It consists of profiles mounted via plates at the side of the payload tray. The use of profiles allows easy adjustment of the components to shift the center of gravity to where it can be stable on the ASV. This is because many new components on the ASV are unconfirmed yet and a fixed design would not be feasible.

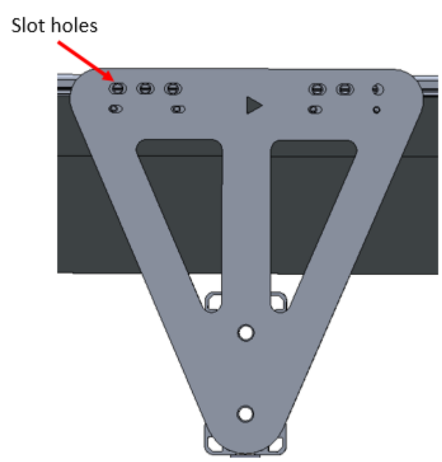

Figure 68 Slotted holes incorporated into Mounting Plate

On top of that, the mounting plates have slot holes to increase the range of tolerances. This is because the original WAM-V CAD file could not be released by the manufacturer. Thus, a student-designed WAM-V file is used and there are minor inaccuracies which is unavoidable. Also, this method of mounting eliminates the need to drill additional holes on the payload tray.

Figure 69 1/8" helical isolator [M4-110-10-S-F] (Isolator, n.d.)

The suspension system also features spring mounts which provides damping in multitude directions. Spring mounts are made of stainless steel cables winded in helical shape and clamped at two ends. This enables a suspended system to absorb shocks and responds in six ways: compression, tension, shear, roll, compression-roll and tension-roll. The stiffness of the cable will restore to its original position after force disturbance.

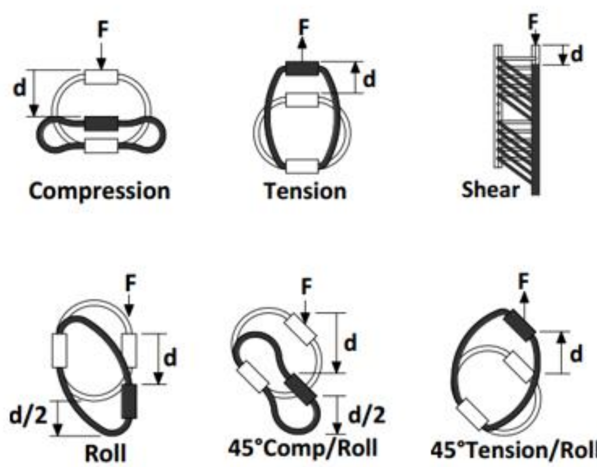

Figure 70 Behaviour of spring mount to dynamic forces [36]

The spring mount chosen are based on static forces (weight) with a safety factor of four. Finite element analysis and modelling is done to obtain data such as the natural frequency of system, shock pulse, and pulse magnitude to compute the system spring rate. This can be done once a much more complete ASV system is designed to represent its mass model.

4.1.2 Scissors Lift

A scissor mechanism is used because it provides a boost/amplification to vertical distance over a shorter linear actuator. The difficulties in selecting a linear actuator for the scissor lift that fits in marine environment is tremendous. Most land-based linear actuators are just IP54 rated or higher till IP69 but they come with wider range of actuating force up to 12000N in certain brands.

Underwater linear actuators are available and they even come with standard connectors from Subconn/Seacon, but the actuating force is very low at 450lbs 2000N).

Figure 71 The Ultramotion Linear Actuator only provides up to 450lbs force [37]

Most hydraulic linear actuators are made seaworthy because of its prominence in the subsea industry but they are also heavier.

Ultimately, standard linear actuator is chosen because higher actuating force can be delivered. The servo motor (from ServoCity) chosen delivers about 7kN of force each and can extend 203mm (8 inches). To ensure the motors can withstand the moisture environment of the sea, it will be sprayed with conformal coating before installation.

Figure 72 8” Super Duty Linear Actuator [38]

With very limited space, the actuators are mounted to an I-beam attached via heavy duty clamps at the rear arch of the WAM-V.

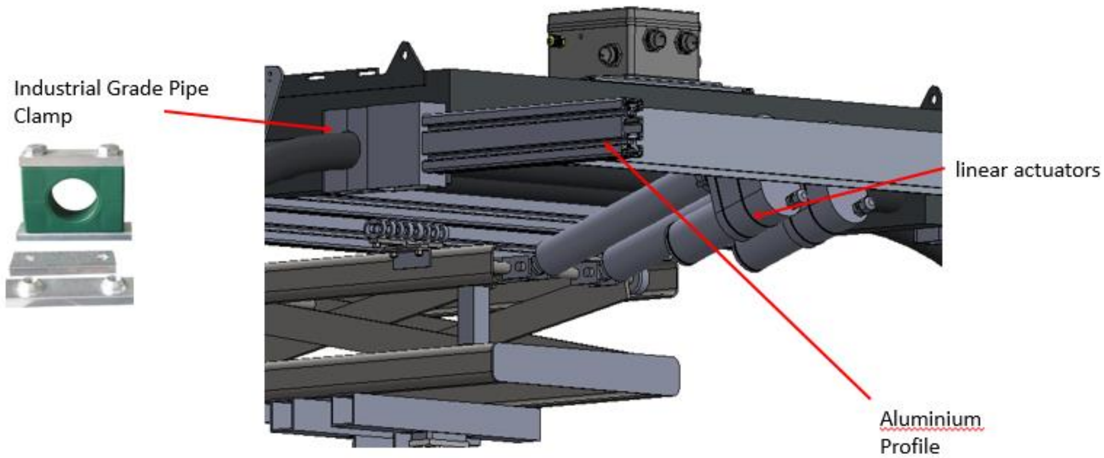

Figure 73 Linear actuators attachment points

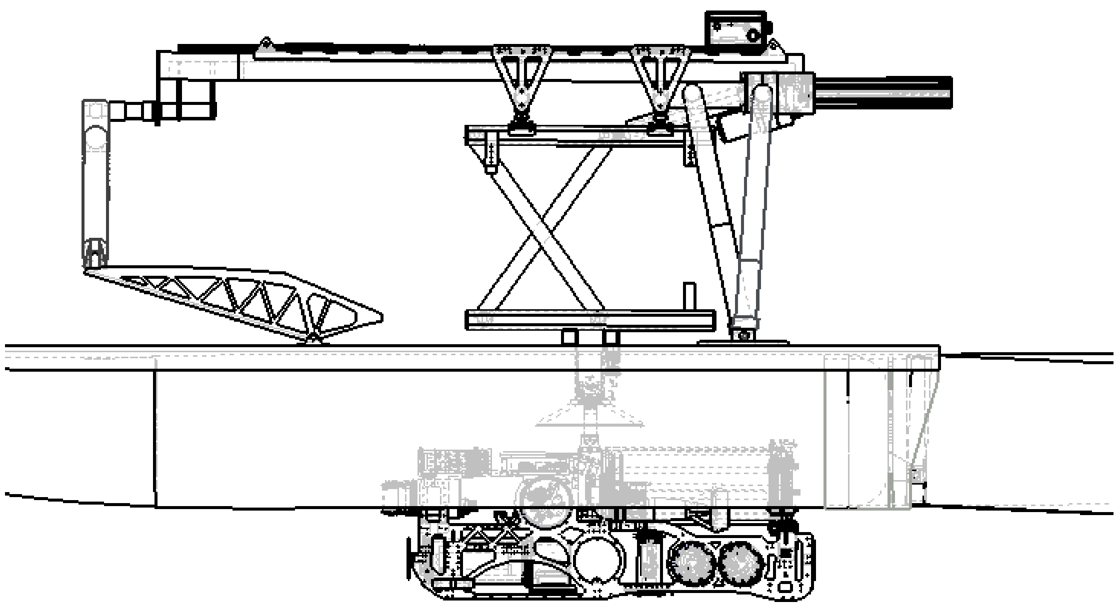

Figure 74 Maximum extension of scissors lift

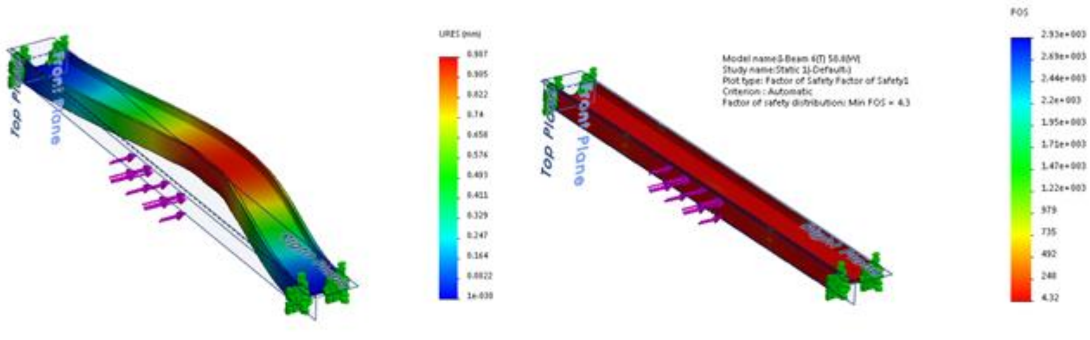

Figure 75 I-beam FEA

The I-beam which will be holding the two actuators can withstand a minimum of 7000N with a safety factor of four. The deflection under that load is less than 0.5mm.

As the forces acting on the linear actuator is a function of tan Ø, where Ø is the angle of the lift, there is a minimum angle that must be kept to prevent overloading the linear actuator. The angle is set at 10° [~8500N assuming a 1500N [W] payload) and is ensured by placing a mechanical blocker. This is also a common practice in conventional scissors lift.

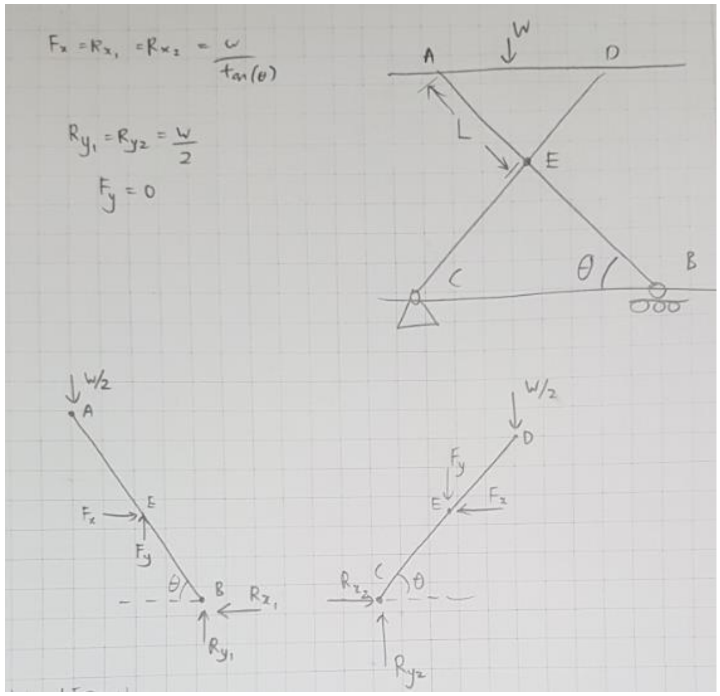

Figure 76 Free body diagram of forces acting on scissors lift

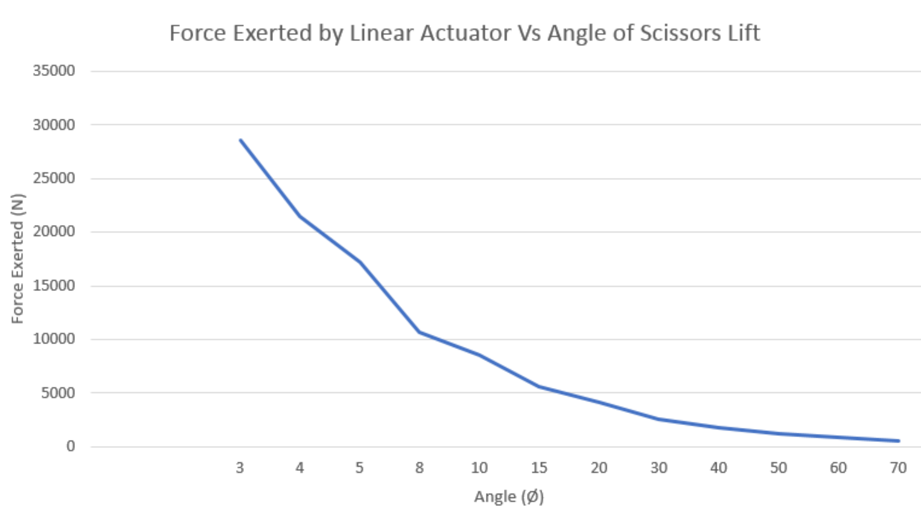

Figure 77 Graph of Force exerted by linear actuator vs angle of scissors lift

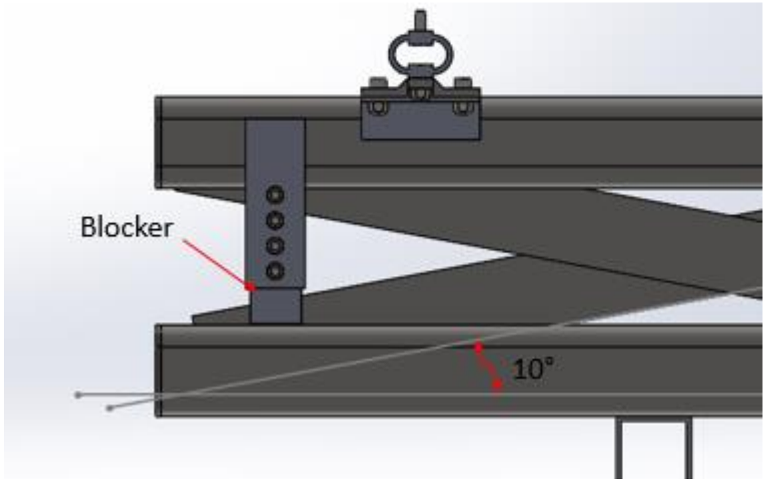

Figure 78 Fix block to prevent overloading actuator

4.1.3 Latching System

The latching system serves as a disconnection point when the AUV is launched from the ASV during a mission. It consists of several major parts such as the catch cone, bullet and a releaser.

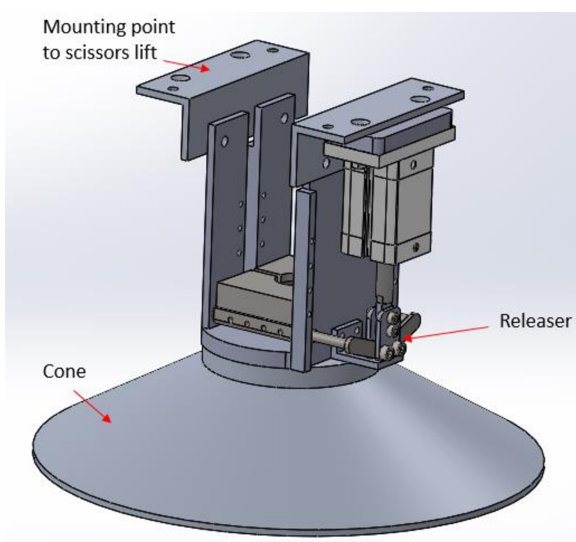

Figure 79 Latching mechanism

The cone is designed at an angle of 120° to minimize material use yet provides a large enough tolerance with an opening of 300mm. Counterbore holes are drilled into the internal part to serve as mounting point yet maintaining the smooth contour to ensure easy capture.

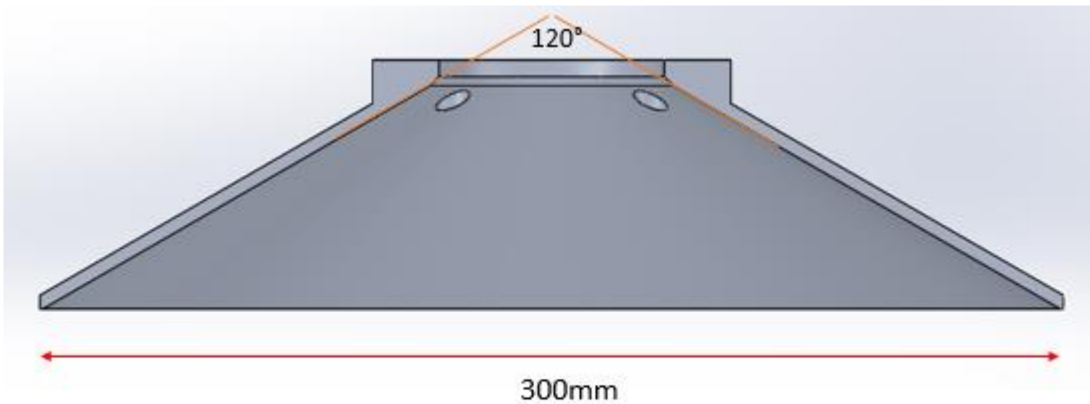

Figure 80 Cross-section of catch cone

Figure: Cross-section of catch cone

The releaser mechanism consists of a pneumatic actuator with an actuating force lesser than the dry weight of the AUV. This is to prevent accidental release when the AUV is not submerged in water or during onshore testing. When the AUV is submerged, the linear actuator will be able to overcome the weight of the AUV and the two resting blocks are rotated up, releasing the AUV from the latching mechanism. The spring return in the linear actuator will force the resting blocks to fall back in place once the bullet exits the assembly.

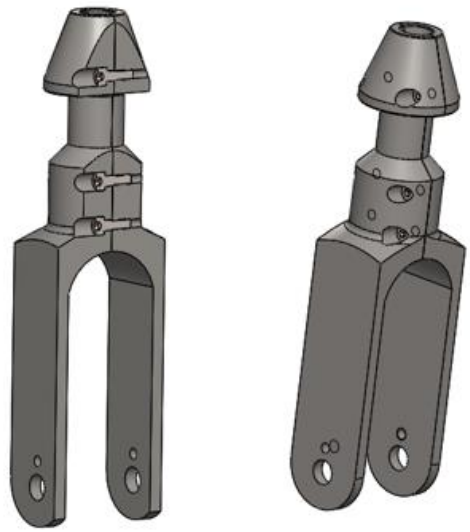

Figure 81 Bullet assembly

The bullet is a two-part stainless steel (SS304 for cost efficiency) piece that is designed with a hollow center to allow tether to go through. The bullet head is tapered to ease its sliding through the catch cone.

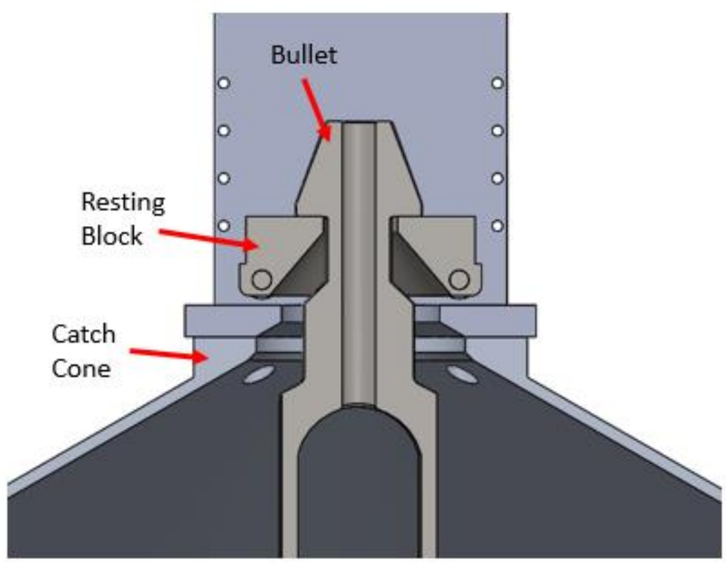

Figure 82 Cross-section of latch assembly

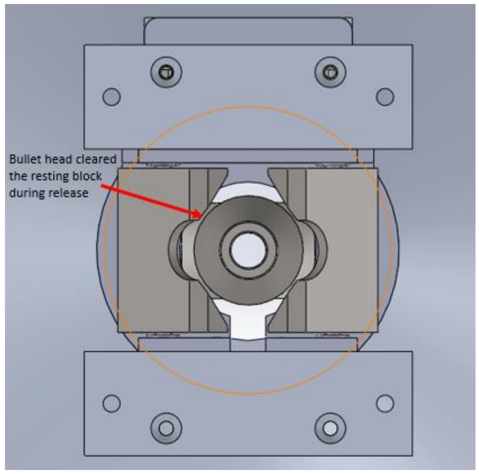

Figure 83 Top view of latch mechanism during release

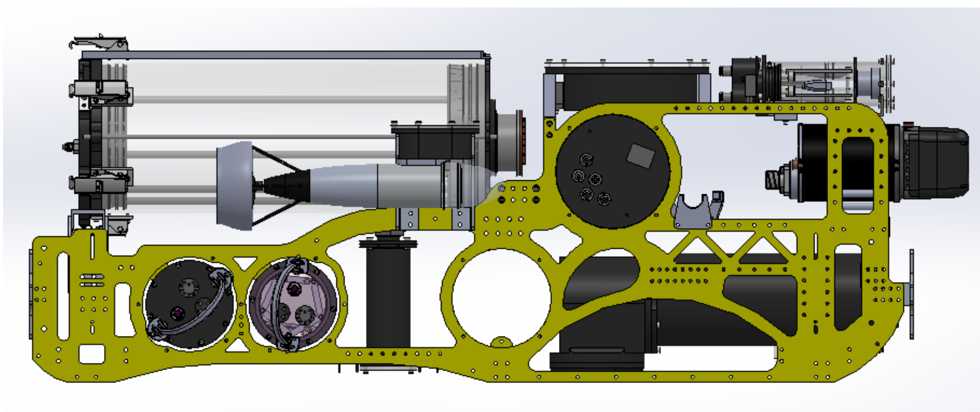

Figure 84 BBAUV3.0 without LARS component

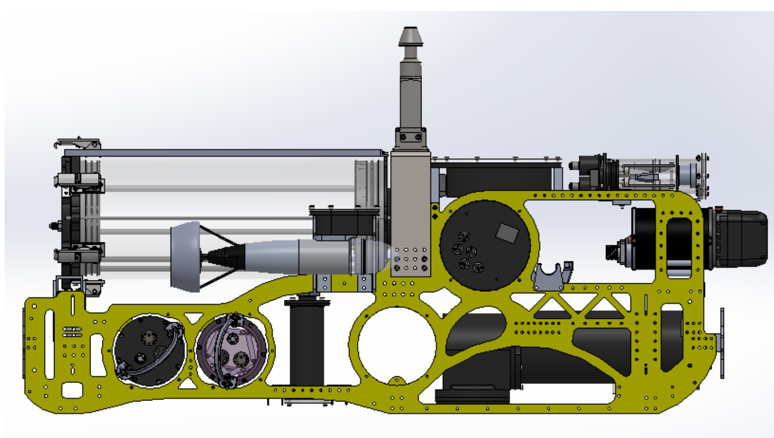

Figure 85 BBAUV3.0 with bullet attached

4.2 Design 2

Design 1 has left the system with only 50kg of weight budget for the entire ASV. This leftover budget is meant for the TMS. However, improvable performance during the RobotX 2016 has led to the redesign of the ASV which involves adding more batteries, thrusters, and electrical components. This means that the LARS will occupy a smaller percentage of overall payload mass and a need to reduce weight on LARS design is inevitable.

This had led to the use of load-bearing tether to lift the AUV in both recovery and launch processes. To solve the pendulum swing of the AUV after the splash zone as illustrated below, a telescopic mechanism is designed to lower the AUV in a controlled manner without it rotating. In the snapshots, a Seabotix engineer was using a string to restrain the ROV from further damping movements. Strings could not be used because they are too flexible and would flex easily without high tension.

Figure 86 Snapshots of Seabotix ROV swinging violently during recovery even during calm water [39]

4.2.1 Overhead Testing Frame

An overhanging frame is designed using aluminium profiles to test the concept. The width of the frame is the same as the width of the pontoons of the WAM-V to replicate as much as possible the actual scenario. As a safety measure, a replica of the actual size of the AUV is use instead of the actual AUV. COTS winch is used to lift the replica through the telescopic assembly and is placed at the top of the overhanging frame.

Figure 87 Commercial off-the-shelf winch

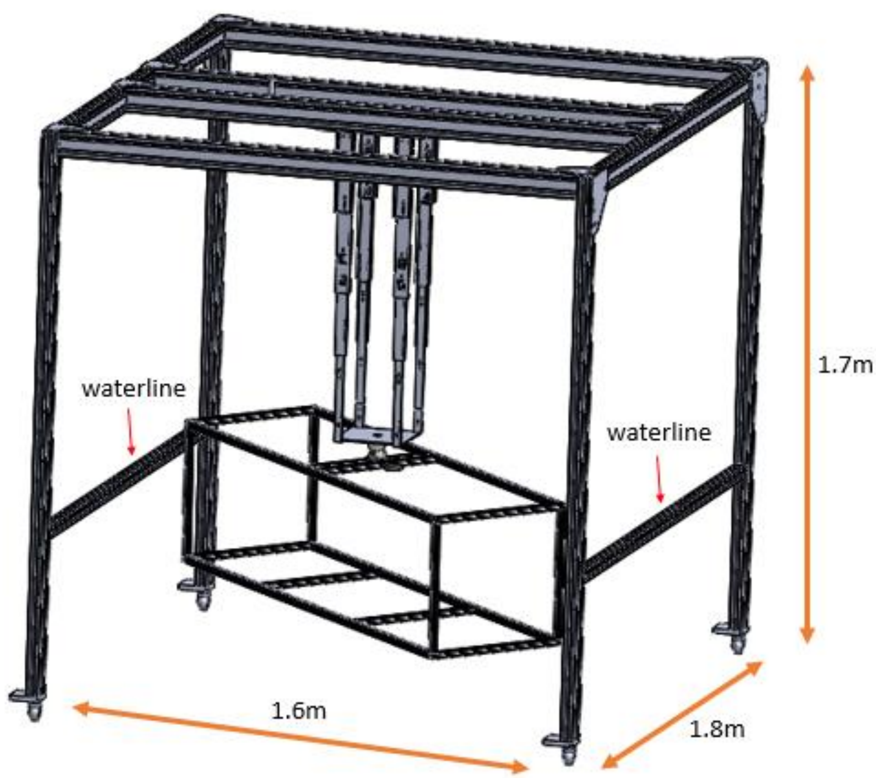

Figure 88 Overhanging frame assembly

Wheels are placed at the bottom of the frame to allow the whole frame to be shaken, which replicates the swinging motion of the AUV during launch and recovery.

Figure 89 Mock AUV in keeping position

Figure 90 Mock AUV in released position

To test the feasibility of this concept without expending too much manufacturing costs, 3D printing and cupboard rails are used instead of a full-fledge design. The cupboard rails extend to a maximum length of 900mm and retracts to 450mm. This is a suitable reciprocate of the full-fledge design whereby the AUV should be lowered by at least 900mm to have it submerged completely.

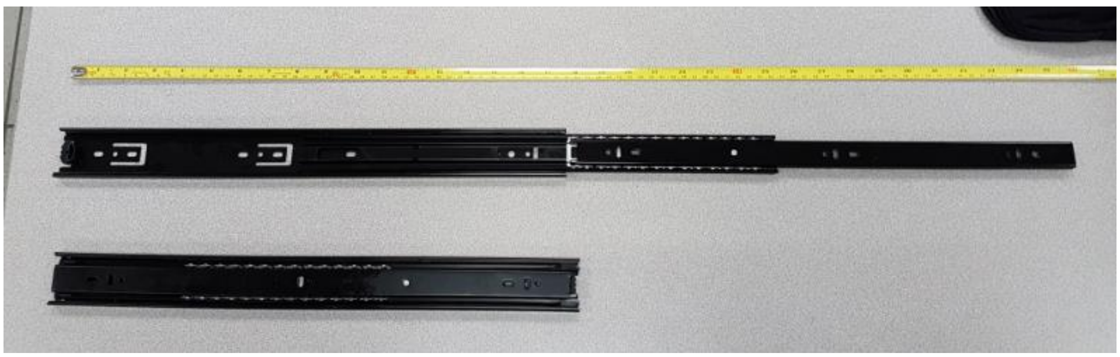

Figure 91 Cupboard railings when fully extended and retracted

Four pairs of rails made up the telescopic arm assembly and is held together with standard size bars and the male latch is placed at the bottom of the whole assembly.

Figure 92 Extended and retracted positions

4.2.2 Latch Cone Design

A new latching mechanism is also designed to replace the bullet used in Design 1. This new latch overcomes the rotational problem that exists in the earlier design by having curved contour on the sides of the latch. The groove is designed at a 45-degree profile to maximize the angle of capture at a total of 90-degree. During the recovery process, both the AUV and ASV must face the same direction to ensure the correct orientation of capture as illustrated below. If the bow of the AUV faces the stern of the ASV and recovery is initiated, the AUV will ended up facing a complete 180* in the opposite direction of the ASV. This will not be a major issue as the INS of the AUV should be able to detect the shift in orientation and calibrate its mission accordingly when it is launched again later.

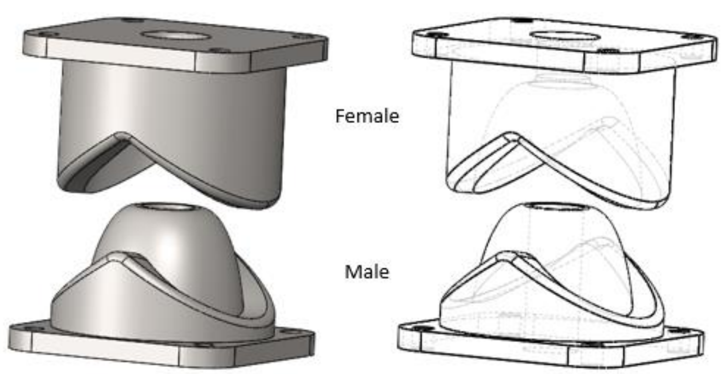

Figure 93 The latch assembly

To illustrate the concept, arrows are designed into the CAD file for reference. At a keeping position, both the arrows are aligned in the same direction. Let the female latch be the stationary part and the male latch be the rotating part (on AUV). The general capture scenarios are illustrated below.

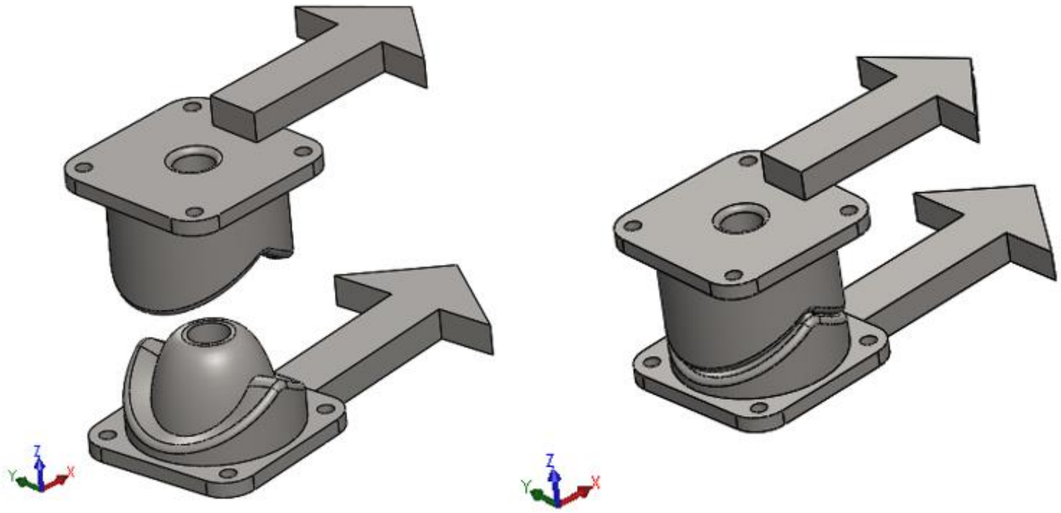

Figure 94 Scenario 1 – ideal capture orientation

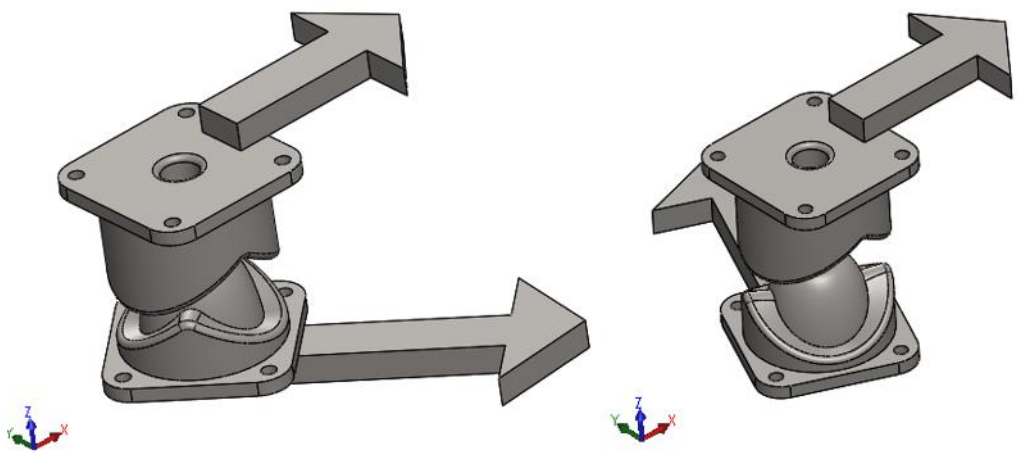

Figure 95 Scenario 2 – AUV (male latch) rotates less than 45* to the right/left along z-axis

Since the angle is less than 45 degrees, the vertex of the male latch will slide along the ravine and assumes the contour into the ideal capture direction.

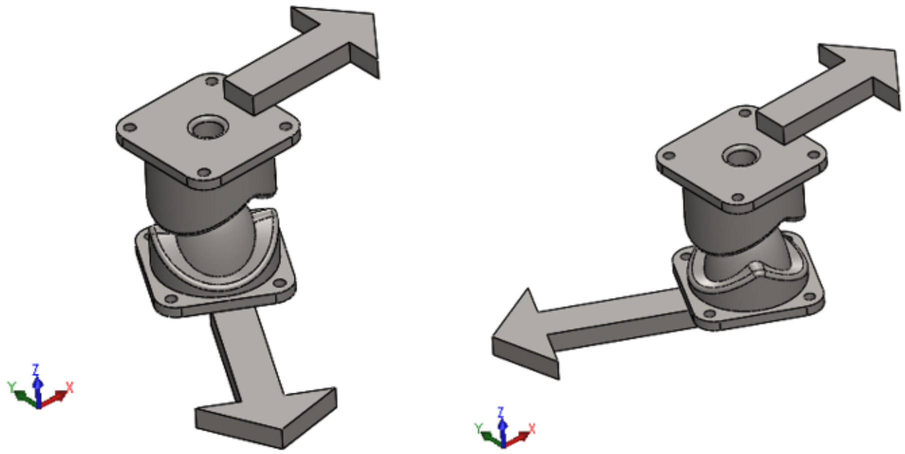

Figure 96 Scenario 3 - AUV (male latch) rotates more than 45* to the right/left along z-axis

In scenario 3, both the orientations will result in the AUV being locked in complete opposite direction during capture.

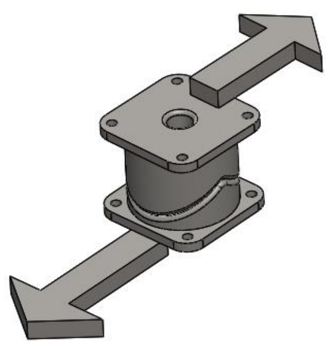

Figure 97 The AUV would have rotated 180-degree in scenario 3

4.2.3 Results

4.2.3.1 Latch Cone Modification

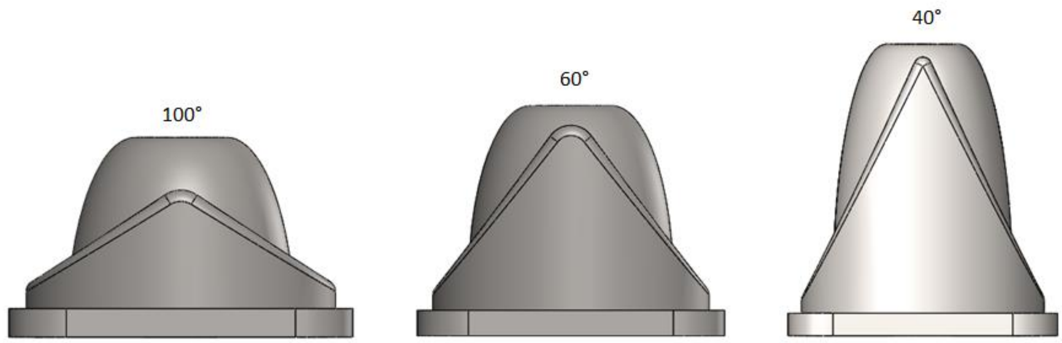

Figure 98 Different angles of latch cones

Multiple cone angles are examined and tested to observe the efficiency of restoring the correct orientation. The first cone design is at an angle of 100 degrees. It effectively restores the orientation of the AUV but only when it is near the end of the retraction.

On the other extreme, the 40-degree cone restore the AUV orientation the fastest. The steep angle allows the AUV to ‘catch’ on to the curved surface of the female part faster. However so, the high rotational rate causes high rotational moment as well. The whole telescopic structure is observed to experience high torsional stresses. After a few tests using the 40-degree cone, the 3D printed part failed. No further tests beyond that angle is done.

The 100-degree cone restores the slowest such that the AUV only fully restores its position at the very end of the telescopic retraction. This does not does not put the whole structure in high torsional load as total extended length has already been reduced significantly. In between the two angles, the 60-degree cone performs at intermediate range of the other two. It restores the position of the AUV halfway to the top. The restoring torque is not too high as to flex the telescopic arm significantly. For that, it is confirmed that the optimal angle is between 60 degrees and 100 degrees.

The initial tests conducted on the cones are to study the optimal angle. In all the tests, 100% catch rate is not achieved. This is because the male cone tends to get engaged and be stuck. The figure below illustrates the failed recovery.

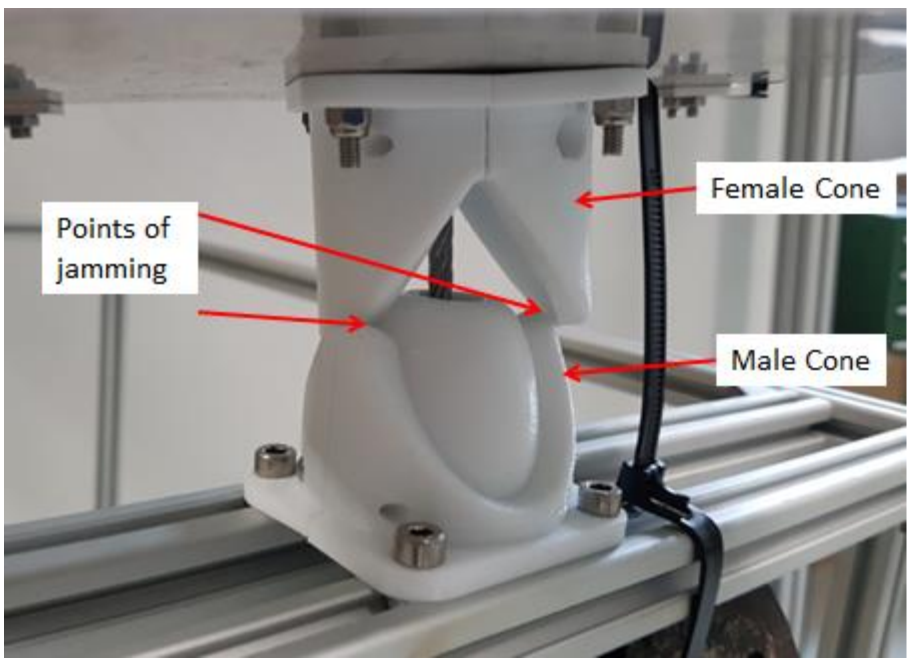

Figure 99 The contact points of failed recovery

At certain angle, the width of the female cone is caught between the two vertices of the male cone. This will cause both cones to be locked in the position as in the above picture. As the male cone rises further till the end of the retraction, the cones press hard against each other and dents are formed upon the small contacts (high contact stress).

This problem is solved by changing the overall size of either one of the cone. The new configuration is shown below. By having one cone larger than the other, the hollow portion of the female cone no longer fit the ends of the vertices of the male cone.

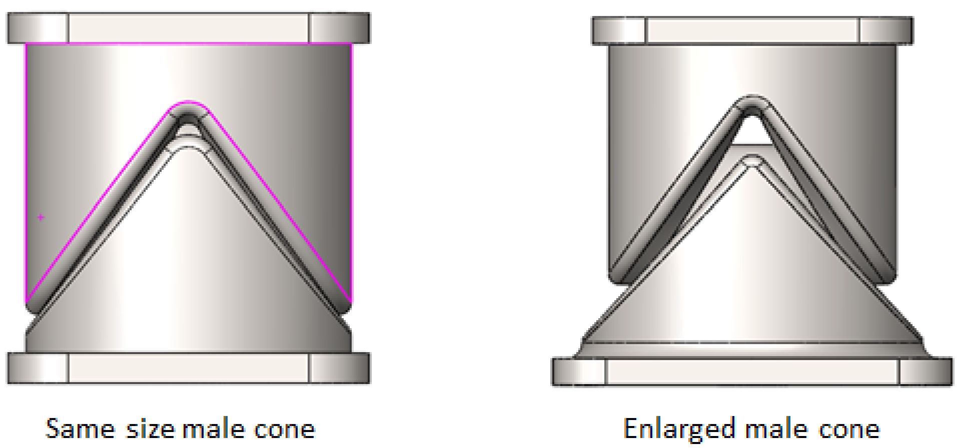

Figure 100 Size comparison of the enlarged cone

The enlarged cone had improved the rate of successful capture but still not a 100% yet. This is because at near perpendicular alignment (between AUV x-axis and ASV x-axis), the cones will still jam due to the sliding of the female cone along the inner fillet.

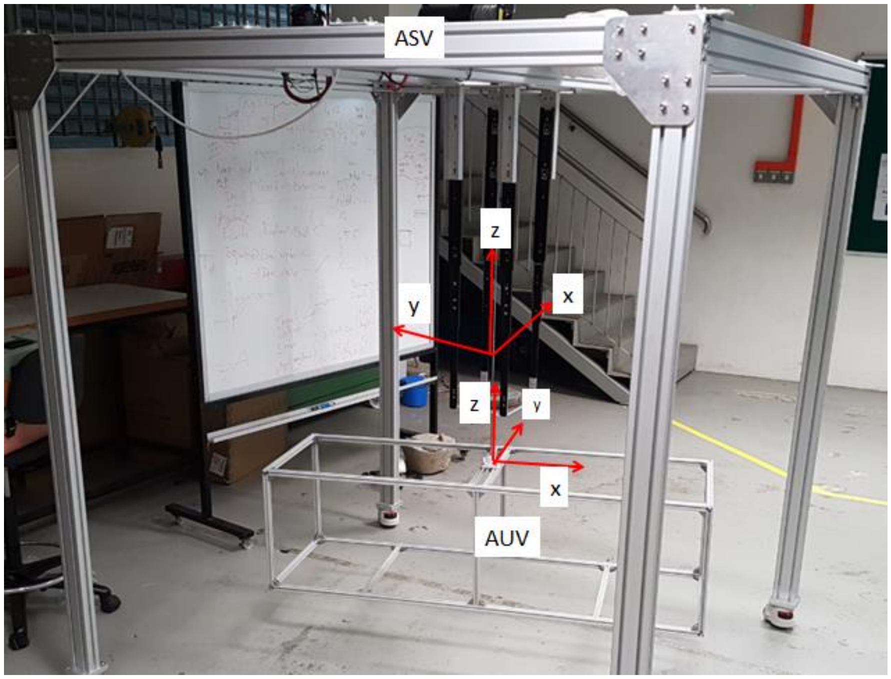

Figure 101 Axes of ASV and AUV (near perpendicular alignment of x-axes)

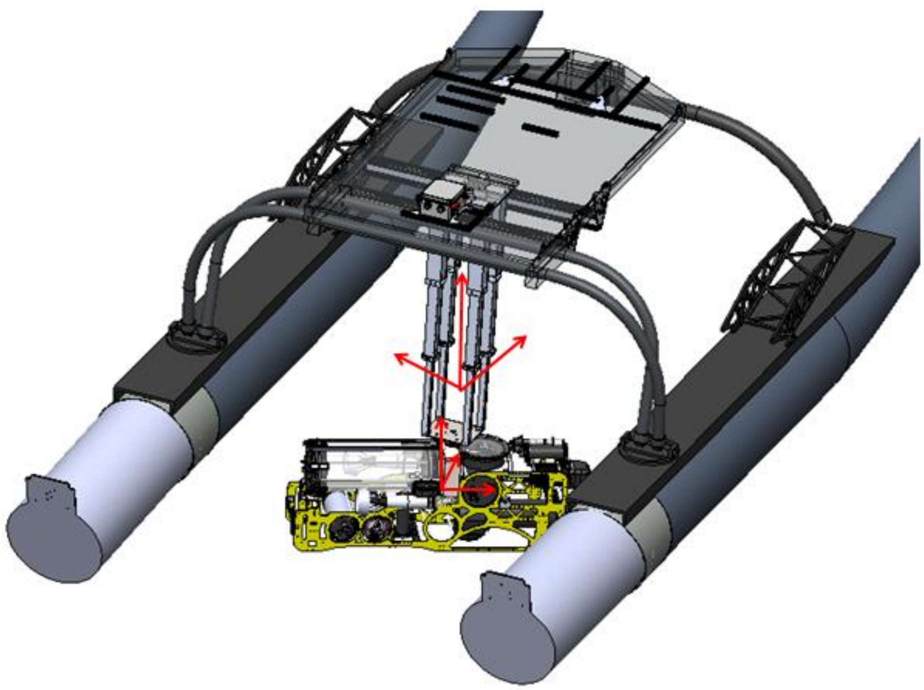

Figure 102 Axes on actual ASV and AUV

Further refinement on the cones include changes on the inner fillet from sloping inwards to sloping outwards. This fully solves the problem and ensures a 100% alignment rate. The figure below illustrates the change in design to the chamfer of the male cone.

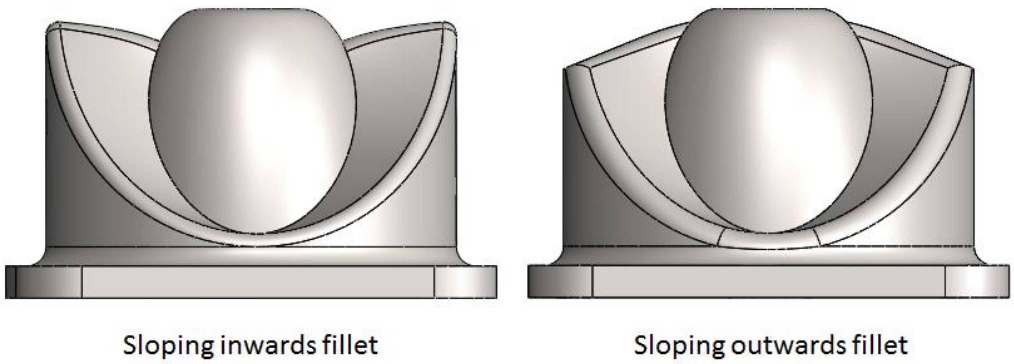

Figure 103 Modification of the male cone into sloping outwards fillet

There is only one situation whereby the cones can get stuck; that is when the AUV is completely perpendicular to the ASV. This will almost never happen because the AUV will be programmed to approach the ASV with both of their x-axes aligned or nearly aligned. Thus, the AUV still have control of its orientation and will align itself properly before initiating recovery. Plus, the design of the telescopic arm is such that the female cone touches the splash zone. This ensures the AUV starts aligning itself as soon as recovery is initiated and should not rotate till it is completely perpendicular to each other.

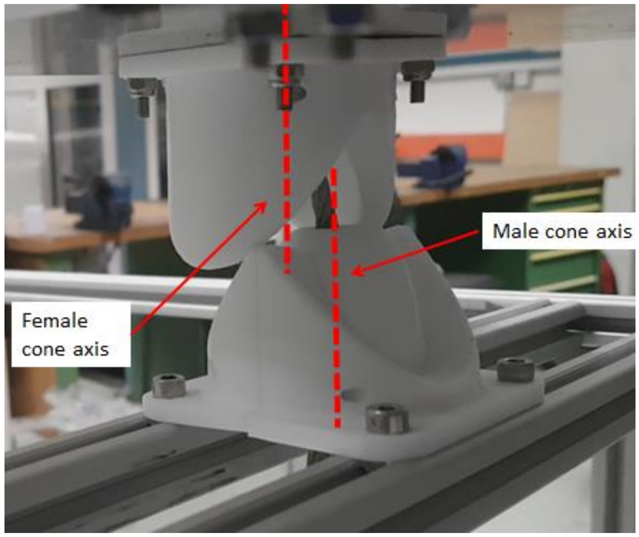

Figure 104 Configuration when the cones are stuck (completely perpendicular)

Overall, the final working design of the cones are shown below.

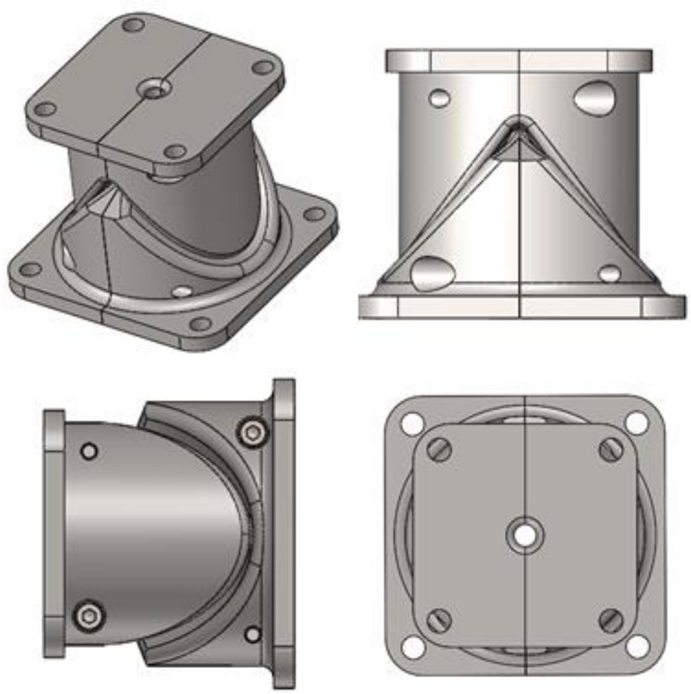

Figure 105 Finalized Design of Cones

4.2.3.2 Replacing weight with gas spring

Multiple steel weights are placed at the end of the telescopic arm to provide a downwards force on the female cone against the rising male cone. This proves to be effective as it allows the cone to slide along the contour as soon as it exits the water, reducing the pendulum effect quickly.

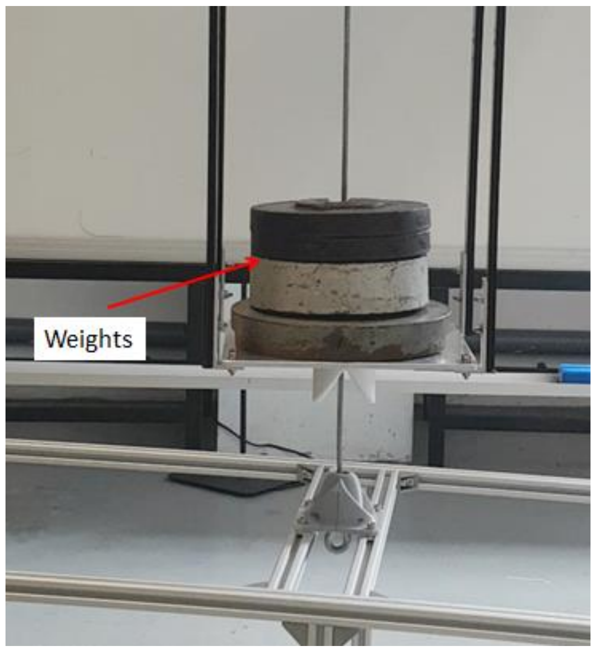

Figure 106 Weights on the bottom plate

Sets of weights at an increment of 5kg are tested and the optimum weight is found to be 20kg. However, using dead weights on the actual system may not be an effective way to provide the downwards force. So, gas spring are employed instead. The gas spring used in the testing is rated at 80N each. They provide a constant downwards force compared to wire springs which follows Hooke's law.

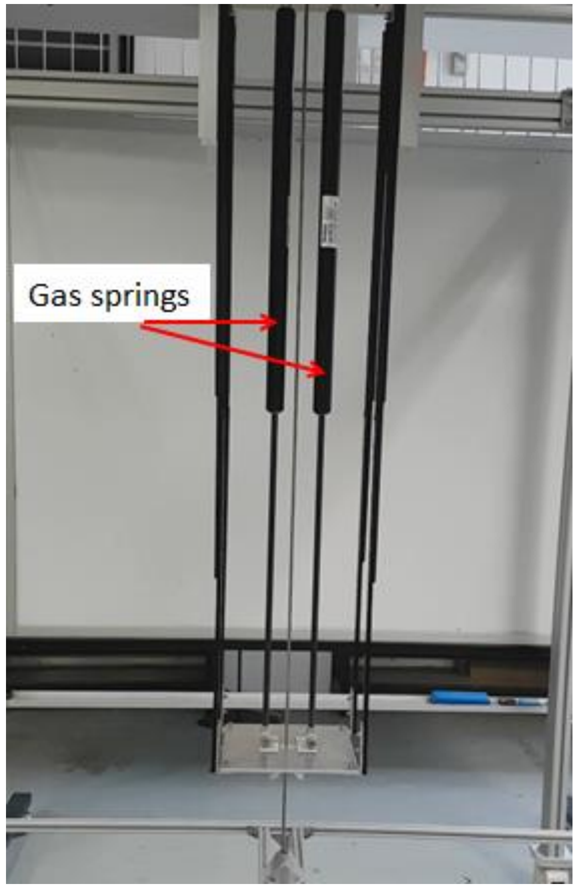

Figure 107 Gas spring replacing dead weights

4.3 Design 3

The third design encompasses a rigid structure that can withstand impact and loading better than a conventional drawer railings. In other words, it is customized to its function. This shape of the design is similar to design 2 but is made of a sequence of standard aluminium square tubes of smaller sizes than its preceding ones.

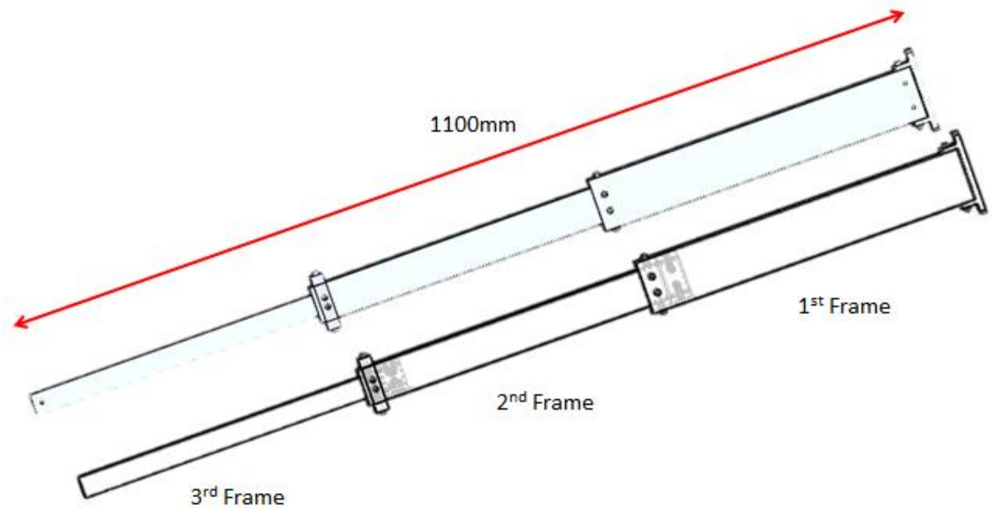

Figure 108 Each of the telescopic assembly consists of three aluminium tube arranged colinearly

Similar to design 2, four sets of tubing are bolted together to create the telescopic assembly. When the tubes are fully extended, it reaches a maximum length of 1100mm, just enough to allow the AUV to be completely submerged below the splash zone. The three-layer tubing system is vital to allow the telescopic arm to be kept at 480mm when retracted, enough to keep the AUV above the water line.

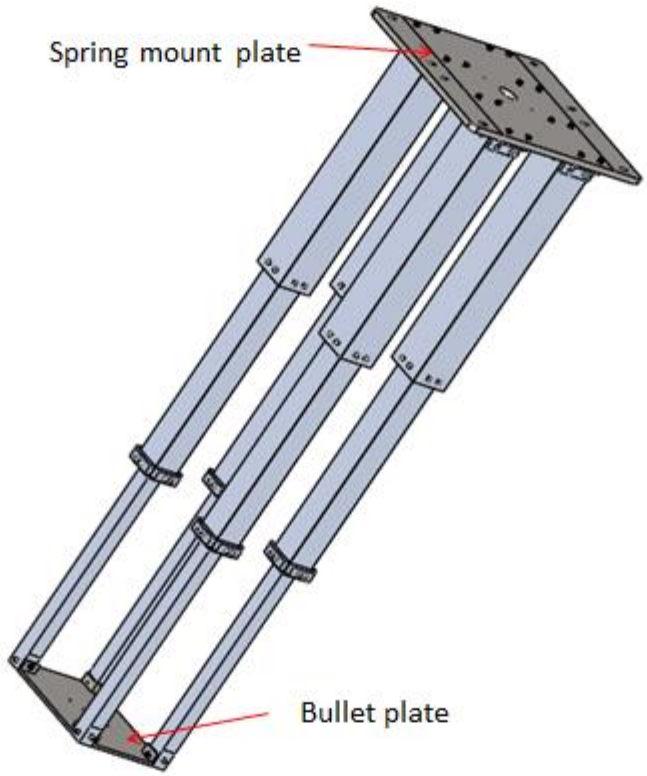

Figure 109 The full set assembly

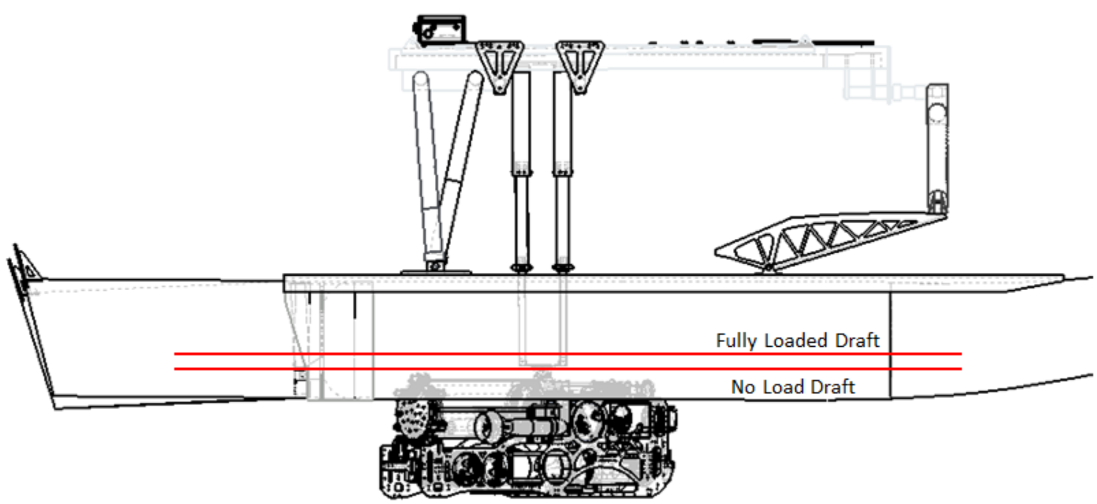

Figure 110 Fully extended configuration

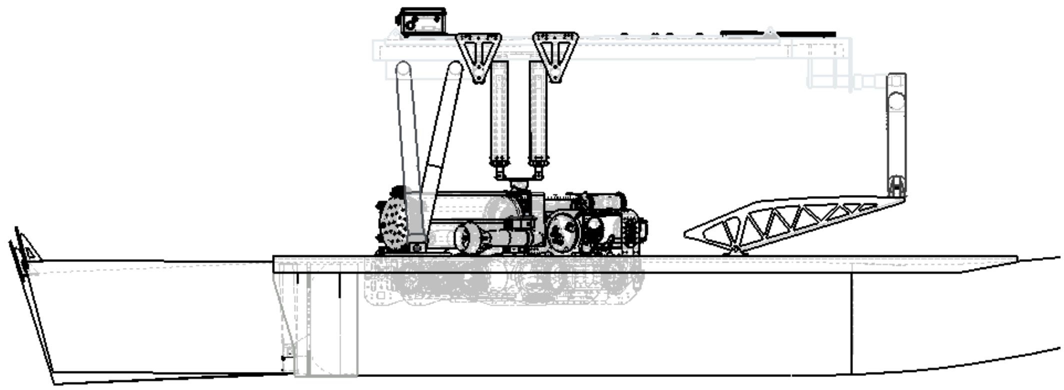

Figure 111 Fully retracted configuration

To ensure that the telescopic arm slides smoothly, Delrin is used as padding inside the tubes. The use of Delrin also ensures that it will not corrode over time in sea water environment. Its low water absorption rate ensures that the tight tolerances inside the tubes will not be compromised over extended duration.

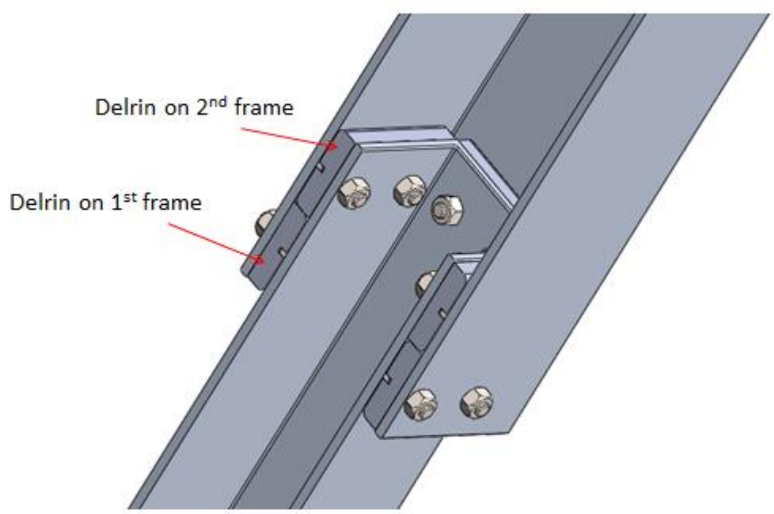

Figure 112 Delrin arrangement inside the tubes

The Delrin plates are attached to the ends of each tube to ensure that there are supporting the tube from end to end when sliding along the internal of the tube. This will ensure each section follows the contour of the larger tube properly.

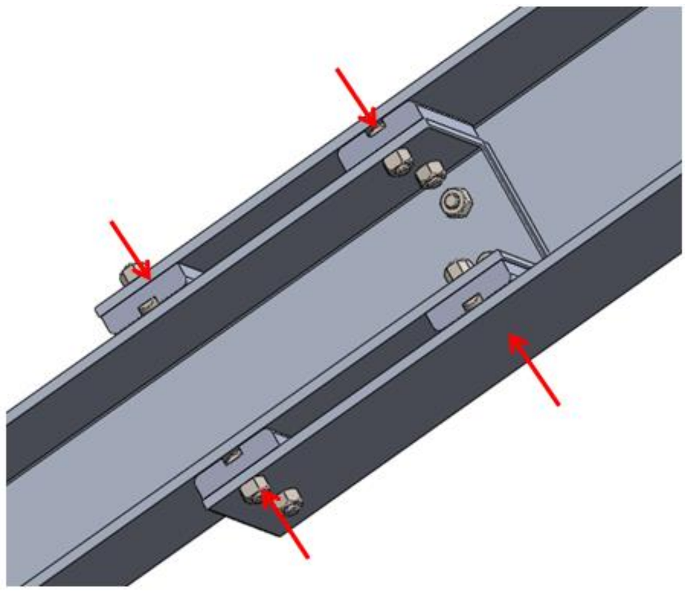

Figure 113 Contacts (red arrows) are maintained at the ends when the tube slides along the internal of the other

Each piece of the Delrin is chamfered at the ends to further increase the smoothness.

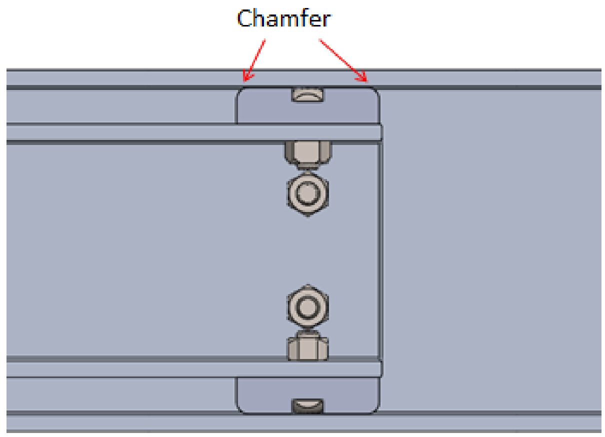

Figure 114 Chamfered edges

Finite element analysis is conducted to study the limits of the design. First, static analysis is done to the parts to ensure that they can withstand the weight of the AUV should tether management system fails and the telescopic arm should take the weight. Note that the weight of the AUV should always be taken by the load-bearing tether, and only the by the telescopic arm parts when an unpredictable event such as being stuck happens. The results showed that the parts will experience negligible deflection (<0.1mm) and will not exceed yield strength of 304 stainless steel (206MPa).

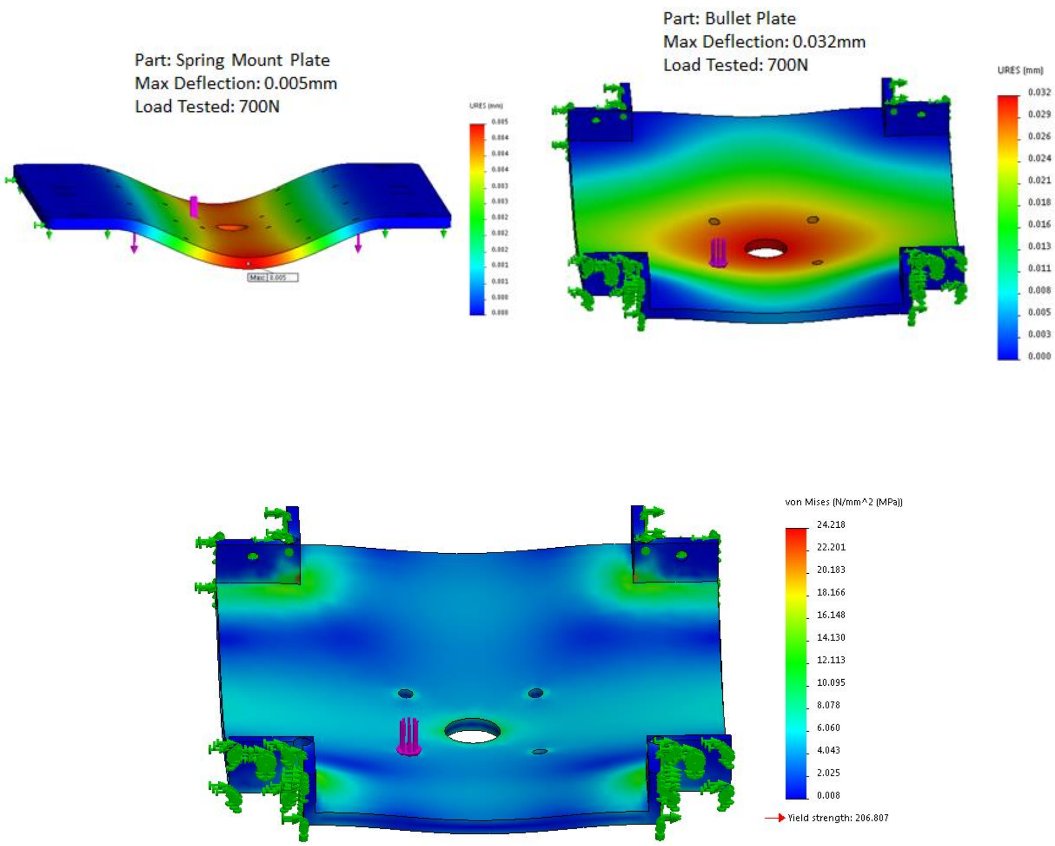

Figure 115 Loading tests on the plates

Similarly, each of the tubes are load tested to ensure that they will deform elastically should they take the weight of the AUV. Each tube is loaded at 700N and showed a safety factor of more than 10. This can be reduced to reduce the weight of the system, but it is not cost effective as standard aluminium tube sizes are limited. Customization will drive the cost up although weight can be reduced. Thus, the cost/Performance factor always take precedence in selecting the part.

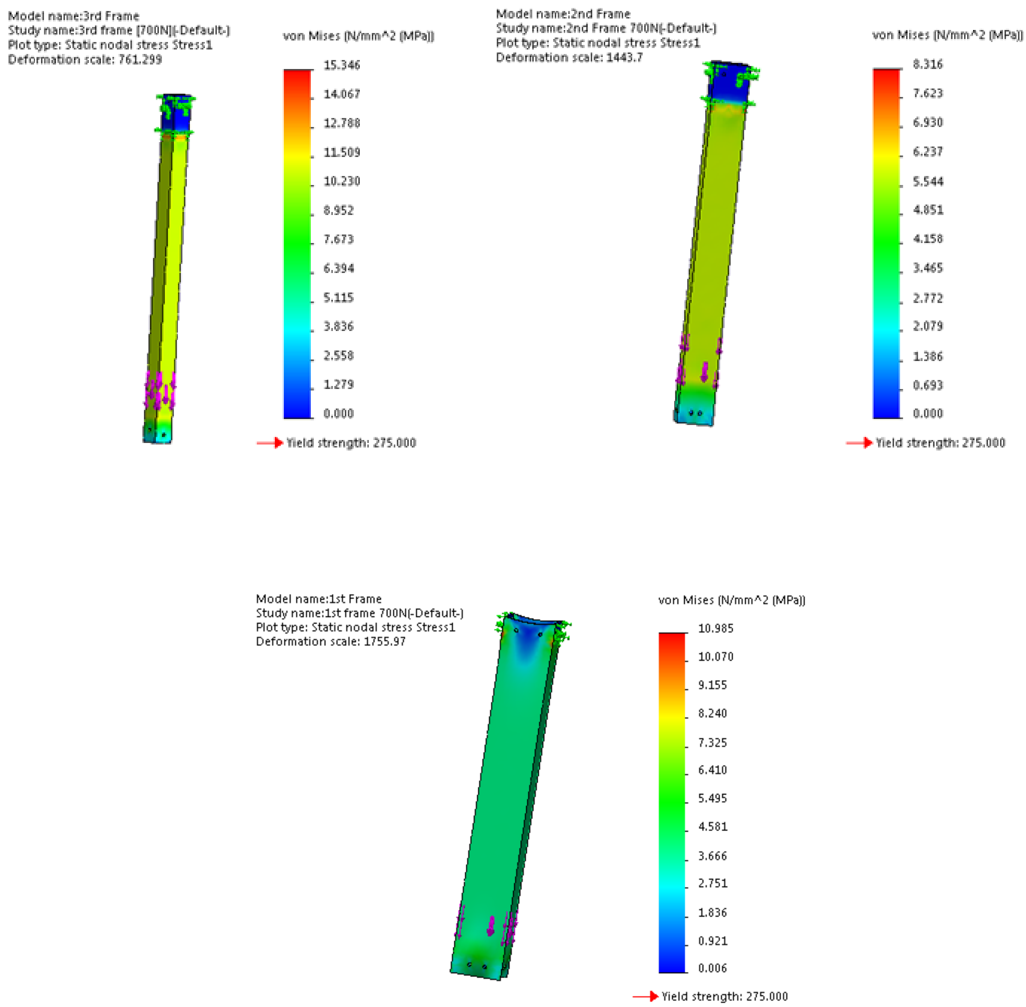

Figure 116 Static load on each of the square tubes

Similar to the latch in Design 1, the new cone must be fabricated in two pieces and will be held together by two M4x16 socket head cap bolt in a counterbore hole.

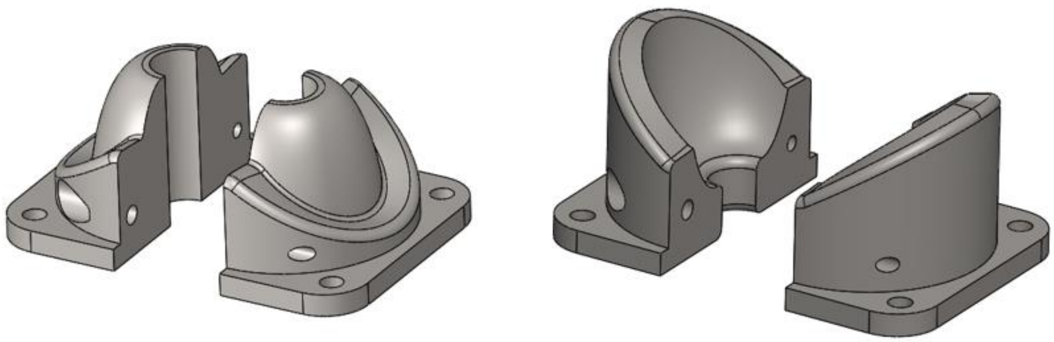

Figure 117 Left: Male latch Right: Female latch

Overall, the final design is as shown below.

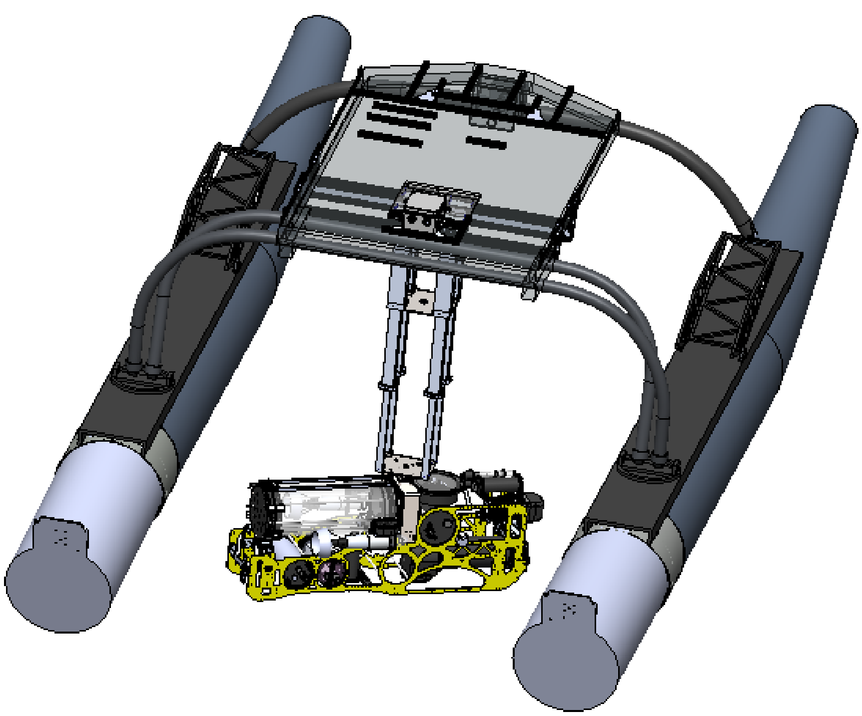

Figure 118 Telescopic arm mounted below payload tray

5. Conclusion

In this thesis, the feasibility of autonomous launch and recovery system is examined. Multiple existing LARS are examined and compared. Prototypes are fabricated and the concept of launch and recovery are proven feasible. All the designs and simulations are conducted on Solidworks. The prototypes have shown potential to be further developed into full-fledge systems.

Some of the achievements in this thesis includes:

1. In-depth study and understanding of industry LARS
2. Singled out the most feasible way to LAR, which is via the use of load-bearing tether
3. Successfully testing of prototype of telescopic arm, which orients the AUV correctly
4. Successfully eliminate the effect of splash zone transition via use of telescopic arm
5. Conceptualization of a custom and compact design of TMS for easier handover

The LARS will be used in the RobotX 2018 competition at Oahu, Hawaii.

6. Recommendations for Future Work

The prototype telescopic arm has proven to be useful in eliminating pendulum effect of the AUV while being hoisted out of water. However, prototype tests are not tested according to the real mass of the AUV. Thus, a proper telescopic arm should be fabricated and tested before deploying on the ASV. This may require some expenditures.

As the TMS goes into design requirement beyond competition rules, escalated costs are expected. Heavier components are expected on the ASV and its payload limit will be pushed to the maximum, affected its draft level. In the future, the system should just be designed to fit a particular purpose.

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Appendix A

Proposed Upgrades on ASV to ease LARS integration

Use of Jet Thrusters

The use of jet thrusters will eliminate entanglement problem. This is because jet thrusters does not have propeller blades, rather the water are channeled through a single hose at each side (significantly reducing the profile in the water). To use this on the WAMV, vector thrust configuration can be implemented. This might reduce efficiency but ensures a reliable station-keeping ability.

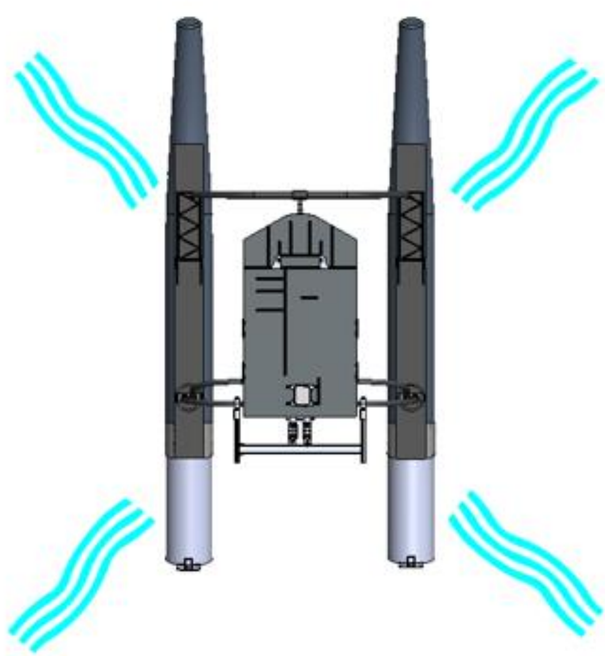


Figure: Vector thrust configuration on WAM-V

Holland Marine Parts offers an integrated system of water jet thrusters whereby a single central pump provides water jet throughout all four directions.

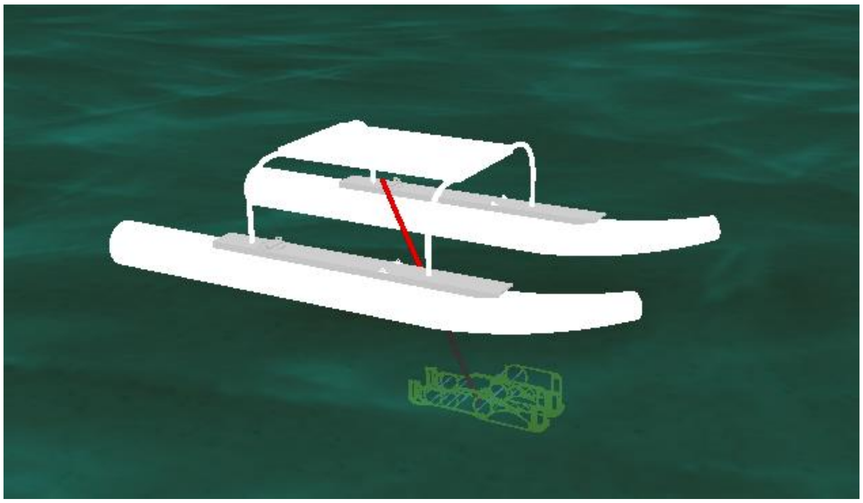
Figure: Single pump configuration [40]

Appendix B- Orcaflex Simulation

Orcaflex does come with its own 3D models but they are commonly used models in the industry such as FGRO and buoys. Thus, file format from Solidworks has to be imported in the format .obj to be used in Orcaflex. This kind of file defines the mesh vertices, normals, texture vertices and faces for the ASV. The limitation of this is that the file size must not be bigger than 350kb, as recommended, to improve rendering capability.

Modelling the Parts

Thus models used in the software are not detailed models as shown below. For the AUV, it consists of the frame held up by tensional rods.



Vessel

The ASV is modeled as a vessel. In Orcaflex, a vessel can be modeled with data sources such as time histories, harmonic motion and also external calculations. Time histories allow analysis of a certain event to find out cause of disaster, for example. Harmonic motion is simply a representation of a regular repetitive wave motion with a constant amplitude and period.

Vessel Data

Draught – could not be determined for not and must be estimated because of incomplete ASV design. Payload on the ASV is dependent on the electronics onboard. As a precautionary step, the maximum draught is used (16.5cm).

Appendix C- Stainless Steel Selection for Latch Cone

The design and mechanism of the latch means that the part will experience high contact forces. This may lead to deformation over high repetitive cycles of recovery. At the same time, the material of the design must be stainless steel to withstand a corrosive environment. The shape of the latch design would also require 5-axis CNC machining. Thus, the stainless steel chosen should ideally require no additional machining techniques. Conventional SS304 and SS316 may not work well under such circumstances. Thus, a new range of stainless steel is explored.

All stainless steels are at least 11% chromium (Cr) in composition to its base material – steel (iron with carbon). To create different range of stainless steel, additional elements such as Nickel, Copper, Titanium, Molybdenum and more are added in varying compositions according to its selected type. Thus, adjusting the composition and production process allows manufacturer to produce six types of stainless steel: ferritic stainless steel, austenitic stainless steel, martensitic stainless steel, duplex stainless steel, precipitation hardening stainless steel, and Mn-N substituted stainless steel.

Ferritic Stainless Steel

In general, ferritic stainless steel lacks ductility, poor weldability, susceptible to embrittlement at moderately high temperature, and most importantly it is notch sensitive. Most ferritic stainless steel are AISI 14XX designated. Their chromium compositions varies from 12-30%. [41]. Ferritic stainless steels are machinable as well.

Austenitic Stainless Steel

The austenitic stainless steel are the most common stainless steel used in the industry. The AISI 300 group is part of the austenitic series and is used in constructions of bolts, nuts, railing, lifts and so on. It is used so often that it can be found anywhere around us. An observant person would see stampings like ‘SUS304’, ‘A2-70’ or ‘SS304’ on structures such as MRT railing and bolts in an elevator.

It is also commonly referred as 18-8 steel due to its 18% Cr and 8% Ni composition. This class of stainless steel is well known for its good corrosion resistance, mechanical properties and fabricability. Type 316 and 317 has more alloy contents such as Ni, C, Si, P, S and Ti, making them highly corrosion and high-temperature resistant [42].

Martensitic Stainless Steel

Martensitic stainless steel are commonly used in applications where wear and tear is common such as bearings and knifes.

Duplex Stainless Steel

Duplex stainless steel are a mixture of more than one phases, but commonly restricted to just ferrite and austenite phases. The composition of DSS are 17-30% Cr and 3-13% Ni. Mn and Si are added to protect against oxidation and N and Mo are added to increase pitting corrosion resistance. The industry has found its way into the development of lean duplex stainless steel and has been used in the oil and gas industry for its increased strength while having comparable corrosion resistance like 316.

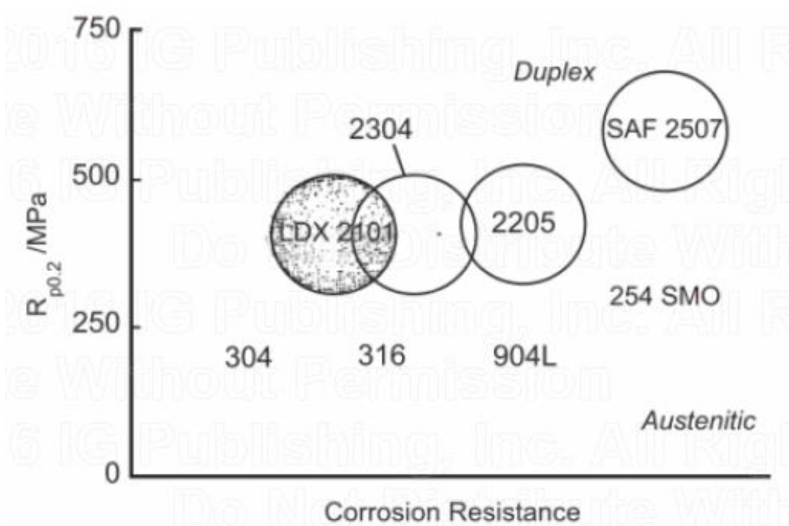


Figure: Duplex stainless steel is considerably tougher than austenitic steel with the same or more corrosion resistance [42]

Mn-H Substituted Stainless Steel

High Nitrogen content stainless steel are also developed rapidly with advancement in manufacturing technology. These are called Nitrogen substituted stainless steel. The advantages of adding N to stainless steel includes . However, different method of stainless steel production is employed to introduce higher N content which includes gas purging of molten metal, pressure electro slag remelting, arc slag melting, Argon Oxygen Decarburisation (AOD) and high pressure melting with HIP [42].

To summarize the above, the SLM165M or 1.4418 duplex stainless steel is chosen for its availability and its proven reliability in the oil and gas industry. However still, initial finding of its raw material costs may render it not justifiable for investment. The part itself has to be machined on 5-axis machines and most machining companies only machine aluminium to protect against wear of diamond tool. In that, this part may be fabricated using aluminium and then hard anodized (MIL8625).

Appendix D – Drag Calculation

In computing the drag experienced by a tethered system, two components causing drags are included: tether drag and vehicle drag. This is because when a tethered ROV needs to pull its body (hull) and the whole length of tether across the water in order to perform a specific task. Calculation of total drag is important in order for torque of the winch motor to be correctly specified. If the net thrust produced by the ROV is greater than the net drag, then the ROV can maneuver in the water.

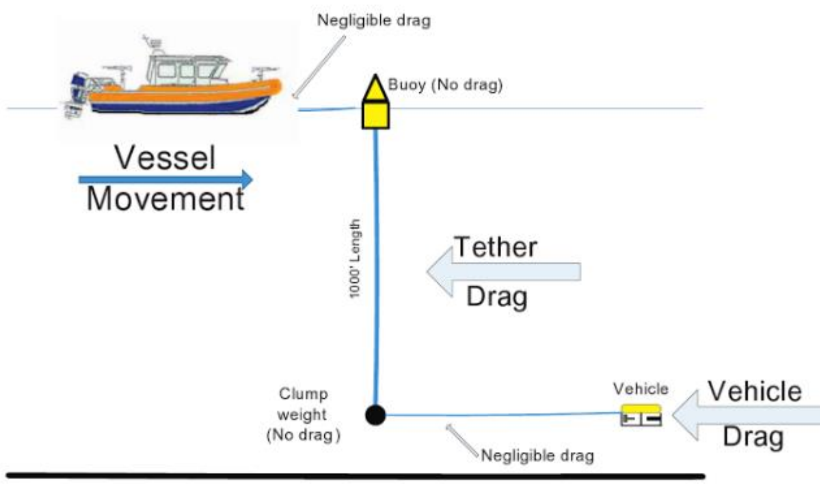


Figure: Drag experienced is the sum of tether and vehicle drag [7]

The total drag of the AUV is calculated as follows:

$$\text{Vehicle drag} = \tfrac{1}{2} \text{ X } \sigma A V^2 C_d$$

Where

σ = density of seawater/gravitational acceleration, where density of seawater = 1035kg/m^3 and gravitational acceleration is 9.8m/s^2

A = characteristic area, usually is the area of the front of the vehicle when projected on a flat surface

V = velocity of ROV in water (m/s)

C_d = non-dimensional drag coefficient.

In a ROV system, the drag of the tether is the highest because of vortex shedding phenomenon around a cylindrical profile. Referred as Von Karman shedding, the magnitude of shedding increases as speed increases. Both sides of the cylindrical profile experiences symmetrical and asymmetrical vortex cells. The effect of this is such that the cables are pulled back and forth in an oscillation manner, which results in more dynamical drag.

For the cables, the characteristic area is the cable diameter divided by 12, times the length perpendicular to the flow. The C_d for cables ranges from 1.2 for unfaired cables, 0.1-0.2 for faired cables, and 0.5-0.6 for hair-faired cable. Thus, the total drag of the system:

Total drag = ½ X $\sigma A_v V^2 C_{dv}$ + ½ X $\sigma Au V_u^2 C_{du}$ (where v = vehicle, u = umbilical)

The table below is a summary of the drag calculation on the system based on different kind of cable used. Some parameters here include:

Operational cable length: 50m

Velocity = 0.5m/s (1 knot)

Drag Coefficient = 1.2 (unfaired)

Cable Code	Company	Construction characteristics	Cable Diameter (mm)	Min Bending Radius (mm)	Weight in air (kg/50 m)	Breaking Load (kN)	Calculated Drag
Type 4480/K	Macartney	Cat 6, para-aramidic fibre strength member	16.1	161	16.5	20	12.7
Type 3010	Macartney	Single mode fibre, Inconel wire strength member	5.1	38	1.55	1.5 dynamic = 0.6	4.04
Type 4SM	Macartney	Single mode, PU jacket	9	76 Dynamic = 90	4.55	5.3 Dynamic = 1.8	7.12
Type 3409/B	Macartney	Single mode, Kevlar strength member	9.1	110 Dynamic = 145	4.5	2.5	7.20
FMXCAT52824K8	Falmat	Cat 5e, PU jacket	10.5	NA	6.69	3.62	8.31
FM022208-07	Falmat	Cat 6	12.0	NA	NA	NA	9.50

Appendix E – Isolator Calculation formula

EQUATIONS OF SHOCK & VIBRATION ISOLATION:

Listed are some of the basic equations used in shock & vibration isolation theory. It should be noted that these equations only provide a guideline for selecting an isolation system and do not take into account "real world" peculiarities associated with shock & vibration isolation. Factors such as equipment rigidity, coupling, drop conditions, etc... need to be evaluated before truly accurate results can be achieved. However, that is not to say that these equations do not provide a useful analysis tool. For many situations, they can be used effectively and with confidence in selecting an isolation system. For applications where greater accuracy is needed, a finite element analysis or actual test may be necessary. IDC Engineering can assist you with both of these.

I. Vibration (sine):

(1) $f_n = \frac{1}{2\pi}\left(\frac{K_v}{W}386\right)^{1/2}$ (2) $f_n = 3.13\left(\frac{1}{\delta_{st}}\right)^{1/2}$

(3) Frequency ratio $= f_d / f_n$ (see Transmissibility curve, pg 5, fig 4)

where: f_n = vibration natural frequency of isolation system (Hz).
f_d = disturbing frequency (Hz).
K_v = average vibration spring rate (lbs/in).
δ_{st} = static displacement (in).
W = equipment weight (lbs).

II. Shock (half sine):

(4) $f_s = \frac{1}{2\pi}\left(\frac{K_s}{W}386\right)^{1/2}$ (5) $f_p = \frac{1}{2T_p}$

(6) $\ddot{x}_o = 1.6\ \ddot{x}_i \frac{f_s}{f_p}$ (7) $\delta_d = \frac{W\ddot{x}_o}{K_s}$

where: f_s = shock natural frequency of isolation system (Hz).
f_p = natural frequency of shock pulse (Hz).
$\ddot{x}_o$ = response acceleration (g's).
$\ddot{x}_i$ = input acceleration (g's).
K_s = average shock spring rate (lbs/in).
δ_d = dynamic deflection (in).
T_p = half sine shock pulse duration (sec).

III. Shock (velocity):

(8) $\ddot{x}_o = \frac{Vf_s}{61.4}$ (9) $V = 246\ \ddot{x}_i T_p$ (half sine)

(10) $V = 27.8\sqrt{h}$

where: V = impact velocity (in/s).
h = drop height (in).