Faculdade de Engenharia da Universidade do Porto

# Control of an Autonomous Underwater Vehicle in 6 Degrees of Freedom

**José Francisco Saraiva dos Santos**

Mestrado Integrado em Engenharia Eletrotécnica e de Computadores

Supervisor: Nuno Alexandre Cruz

Second Supervisor: Bruno Matias Ferreira

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# Resumo


Este trabalho apresenta o projeto feito no âmbito da dissertação do Mestrado em Engenharia Electrotécnia e de Computadores da Faculdade de Engenharia da Universidade do Porto.

O tema da dissertação é o controlo em 6 graus de liberdade de um AUV, partindo do princípio que este é já livre em 4 graus (*Surge*, *Heave*, *Pitch* e *Yaw*).

Inicialmente é feito um estudo sobre as missões, aplicações e manobras de AUVs no mundo real. São exploradas as várias áreas onde este tipo de sistemas são úteis e de que forma é que eles contribuem. São também descritas as características necessárias aos veículos para que sejam capazes de completar missões de forma eficaz e eficiente.

De seguida é feito um levantamento de atuadores atualmente disponíveis, quais as suas vantagens e desvantagens e são também discutidas quais as melhores opções a adotar para tornar o veículo exemplo, o MARES, controlável em 6 graus de liberdade. Dentro dos atuadores, os aspetos tidos em conta são principalemnte a maturidade da tecnologia e a replicabilidade da mesma.

Após uma breve discussão apresentada na dissertação, chegou-se à conclusão que para satisfazer os objectivos deste trabalho, os atuadores mais adequados a implementar são um sistema de massa rotativa interna que irá conferir ao veículo a habilidade de rolar sobre o seu eixo longitudinal e dois propulsores laterais que são capazes de fazer mover o veículo lateralmente. Estes propulsores, se utilizados diferencialmente, são também capazes de rodar no eixo vertical (*Yaw*).

Para a implementação destes atuadores é primeiro elaborado o modelo físico do veículo, baseado em equações e notações já utilizadas para este tipo de trabalhos. Este modelo é depois analisado de forma a serem identificados quais os elementos referentes aos graus de liberdade que pretendem ser adicionados (*Roll* e *Sway*). Desta forma é possível modelar e prever qual o comportamento do veículo quando os atuadores são accionados, assim como construir o seu controlador.

A implementação dos propulsores laterais é relativamente simples, pois o MARES já possui propulsores verticais que se comportam como aqueles que se pretende integrar no veículo, pelo que é apenas necessária a sua replicação. No entanto, o modelo precisa de ser adapatado para integrar estes propulsores. As alterações necessárias, que são evidenciadas no trabalho.

Para a massa rotativa, é também feito um estudo das alterações que são precisas fazer ao modelo do veículo. Este estudo é mais pormenorizado do que o primeiro, devido ao facto deste actuador ser uma tecnologia relativamente recente e ainda sob investigação. Assim sendo, é também criado um método para a otimização da massa a ser colocada. A sua forma é escolhida e as características são baseadas nos limites mais comuns para AUVs, nomeadamente o espaço disponível e o valor da massa a ser adicionada. Este método tem como objetivo obter a massa cujo centro de gravidade se encontra mais afastado do centro de impulsão do veículo. Desta forma é garantido o binário máximo para a rotação do veículo em torno do eixo dos $x$. A massa final tem a forma de uma secção anelar que se estende ao longo de uma parte do veículo.

Por fim é implementado o controlador para a massa rotativa interna, cujo objetivo é conferir ao veículo um grau de rotação e que este seja estável no regime estacionário. Para desenhar este controlador, a função de transferência que rege o comportamento do veículo face à rotação da massa

interna é obtida. Esta é baseada na modelação do veículo previamente feita e nas características inerentes à massa rotativa interna. Inicialmente, foi implementado um controlador PI em Matlab. No entanto, esta solução foi posta de parte devido a um resultado instável e muito oscilatório. Portanto, um outro controlador PID para a massa rotativa é implementado, analisado e discutido. Este controlador é muito mais promissor que o primeiro, pois o coeficiente derivativo aumenta o amortecimento do sistema, eliminando as oscilações, e permite também uma resposta mais rápida. No entanto, a rapidez de reposta não é o essencial no atuador, mas sim a estabilidade em regime estacionário. Também são discutidas as razões físicas do veículo que justificam o comportamento dos controladores e é sugerida também uma alternativa.

Finalmente, é escolhido um motor servo para a massa interna rotativa, que deverá receber comandos que indicam o ângulo de *roll* que o veículo deve ter e atua sobre a massa.

Todos os passos tomados, modelos usados e técnicas de optimização e controlo podem ser replicados em outros AUVs semelhantes ao MARES e, portanto, o trabalho constitui um manual de como implementar os dois DoF abordados.

# Abstract

This work is presenting the project made as a master's degree dissertation in Electrical and Computer's Engineering in the Faculty of Engineering of University of Porto.

The proposal is the control in 6 DoF of AUVs, assuming that it already has the ability to be controlled in 4 DoF (Surge, Heave, Pitch and Yaw).

Initially, a study is done regarding the missions, applications and maneuvers of AUVs in the real world. The areas in which these systems are useful are explored and also how they are useful. The main characteristics that are crucial for the vehicles to be capable of completing missions efficiently and accurately are also pinpointed.

Next, the available actuators are reviewed and analysed. What are their advantages and disadvantages, and a discussion to decide which actuators to implement on MARES (our vehicle) is made. The main aspects analyzed in this section is the maturity of the actuator technology and how replicable it is.

To satisfy the objectives for this work, the conclusion is that the best actuators to implement are an Internal Rolling Mass (IRM) system, that is capable of rolling the vehicle (around its $x$ axis) and two extra lateral thrusters, that are used to move the vehicle sideways and, if used deferentially, can rotate the vehicle around the $z$ axis.

To implement these actuators, it is first developed a vehicle model based on already known and used equations and notations for these kind of works. This model is then analysed in order to identify the elements directly linked to the added degrees of freedom (Roll and Sway). Building on this, it is possible to model and predict the behaviour of the vehicle when the new actuators are used, as well as build their controllers.

The implementation of the lateral thrusters is quite simple since the model for the original vehicle already contemplates two vertical thrusters which behave in the same manner as the lateral ones that are to be implemented. However, the model has to be adapted to contemplate these two new actuators. The adaptations needed are described in the work.

For the Internal Rolling Mass, a study and a model are made. This study is more detailed than the first one, due to the fact that this actuator is a new technology which is still under research. Given this, it is also created a method to optimize the mass that is going to be added. Its shape and characteristics are chosen, based on the common limits for AUVs, namely the internal space available and the mass that is going to be added. The objective of this method is to obtain the mass which center of gravity is the farthest away possible from the buoyancy center of the vehicle. In this way, it is guaranteed the maximum torque for the rotation of the vehicle around the $x$ axis. The final form for the mass is an annulus sector elongated along the body of the AUV.

At last it is implemented a controller for the internal rolling mass, which objective is to give the vehicle a rolling angle and that this is maintained in the steady state. To develop this controller, a transfer function that represents the behaviour of the vehicle based on the rotation of the IRM is determined. This function is based on the vehicle model and the characteristics that define the actuator. Initially, a PI controller was implemented. However, this solution was thrown away due

to a unstable and oscillatory result. Therefore, a PID controller was designed instead. This controller was then analysed and discussed. This solution is much more promising that the first one, for the derivative gain enhances the damping of the system, eliminating the oscillatory behaviour and enabling a faster response. In any case, the speed of the response is not crucial for this actuator. The most important factor is the steady state stability. There is also a final discussion of the physical reasons that explain the controllers results and it is also suggested an alternative.

Finally, the servo motor for the Internal Rolling Mass is chosen, which should receive a command that indicates the desired roll for the vehicle and then actuates on the mass.

Every step in this work, the used models and optimization and control techniques can be replicated in other AUVs similar to MARES and, therefore, this work acts like a manual for others that wish to implement the same actuators.

# Agradecimentos

Quem me conhece, sabe que não sou muito dado a este tipo de textos, mas não posso deixar de tentar expressar o quanto devo a muitas pessoas.

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José Francisco Saraiva dos Santos

*“Nothing truly valuable can be achieved
except by the unselfish cooperation of many individuals.”*

Albert Einstein

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# Abbreviations

| | |
|---|---|
| DoF | Degrees of Freedom |
| AUV | Autonomous Underwater Vehicle |
| ROV | Remotely Operated Vehicle |
| UUV | Unmanned Underwater Vehicle |
| VBS | Variable Buoyancy System |
| IRM | Internal Rolling Mass |
| CG | Center of Gravity |
| CB | Center of Buoyancy |

# Chapter 1

# Introduction

Humans have been conducting ocean exploration since the colonial times where our oceans and seas where first described. Since then, our focus has been changing from surface exploration to underwater exploration. However, due to the challenges presented by the complexity and danger of exploring the deep sea, we must come with new and improved ways to seek what we are looking for.

## 1.1 Contextualization

Unmanned Underwater Vehicles (UUVs) are a remarkable achievement in marine systems technology. ROVs (Remotely Operated Underwater Vehicles) and AUVs (Autonomous Underwater Vehicles) have been a critical help in all sorts of underwater missions in a vast spectre of areas for the last decades and their potential is endless. Due to their capacity of getting to hard to reach areas where a human would struggle, they offer a way of expanding our knowledge of perilous marine environments.

This work will be focused on AUVs which are self-driven vehicles that are capable of completing tasks without the need of human intervention, as their name suggests. Although most of the vehicles have a torpedo-shaped body, there are others that were created with a specific objective in mind that made their developers choose a different shape for their vehicles. The first concept that appeared and was put to use regarding AUVs were the Underwater Gliders. These autonomous vehicles use Variable Buoyancy Systems (VBS) that are able of changing the position of the buoyancy center of the vessel and use this to move in an up-down trajectory in the water while gathering data. More powerful and complex AUVs use other ways to propel and drive themselves, such as thrusters or water-jets, with rudders (fins) to maintain stability and confer a method to change the direction of movement, while also using VBS to change their depth. The maximum depth that an AUV can get to depends on its construction, so there are vehicles that are made for shallow and coastal waters (<200m) while there are others that can reach up to 6000m in depth, due to their high pressure resistance hull. Apart from depth limitations, AUVs can have movement limitations, in the sense that it can be have only some Degrees of Freedom (DoF). These are the axis where the vehicle can move and rotate along, so a full movement liberty would have six degrees of freedom i.e. move and rotate, respectively, in *X (surge and roll), Y (sway and pitch)* and *Z (heave and yaw)* (see fig.1.1). Usually, vehicles that can move in all DoF tend do be big and not really hydrodynamic, while vehicles that resemble a torpedo can only move in certain directions that are pre-studied to fully so that the AUV can handle the designed mission.

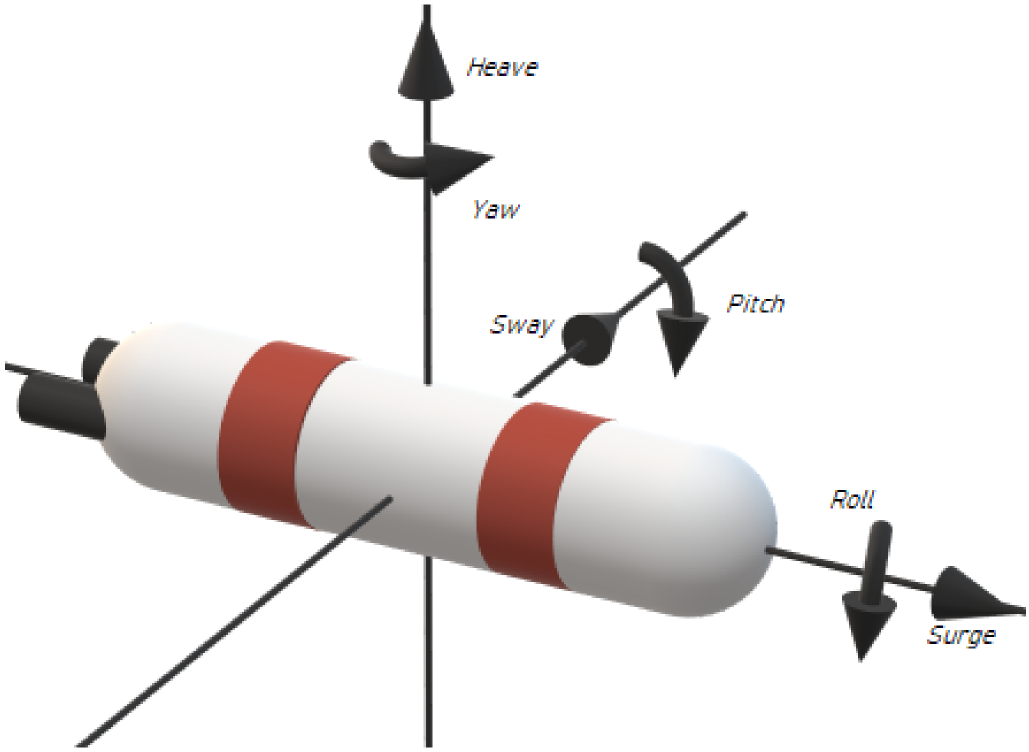



Figure 1.1: Degrees of Freedom

The typical AUV mission starts with the deployment of the vehicle from a support vessel, like a boat for example, where the responsible team can supervise the entire journey. During the mission, the AUV uses a variety of sensors, such as velocity and depth sensors, to know its position in the water, since the GPS signal does not work underwater (the vehicle can always resurface to check its position via GPS), as well as other payload sensors that are specifically chosen for the task, like water quality sensors, video cameras or side-scan sonars.

The vehicle has to run several control algorithms, not only for each of its propulsion methods, but also for the whole mission planning, so that it accomplishes the purpose in the best and most optimized way. Each of these features require an energy source to power them, which is very limited in an AUV. A tethered ROV can use its cable to draw energy from a source present on the support vessel, but an AUV has to work with the limited power that its batteries provide, this is why it is important to develop good optimization algorithms, and also fault diagnosis algorithms so that the vehicle does not get lost if some error or accident happens.

Since their first use that these vehicles have seen an increasing interest in their development on account of all the fields in which they excel. The range of tasks where AUVs can be or are already applied is wide and for all sorts of purposes: political, military, science and in industry. Some examples of these tasks are: search missions [11], oceanography [14][15][16], ecosystems study [10][17], surveillance and defense [18][19], geology [20], archaeology [21], deployment and maintenance of underwater structures [22][23], etc.

## 1.2 Motivation

There are numerous ways in which the current AUV technology can be improved and, more importantly, there is also the need for that improvement. Our current knowledge of the deep ocean is not fully developed, new species have been discovered in a recent dive made by Victor Vescovo in a single person submersible to almost 11 kilometers, confirming that we do not fully understand what is down there. Furthermore, this dive also showed that human-made debris has made its way down the sea, and is potentially harming the wild life that lives there [24]. This clearly shows how important it is for us to create ways to study and oversee the deepest parts of our oceans and get to know the ecosystems better, as well as the apparent influence that we have on them. Another great potential use for AUVs would be to create a swarm of vehicles capable of filtering water and/or cleaning underwater trash, like plastic bags, that would work on a daily basis, keeping our oceans clean and sea life safe. On another example, due to climate change, the oceans temperature is rising, even in the great depths where biodiversity is understudied [25] which makes a system capable of diving to such depths a great help to study these underwater creatures and the effects of climate change on them.

Although the deep sea exploration is a promising future for the application of Autonomous Underwater Vehicles (AUV), there is also interest in low depths mission handling. Portugal has proposed an extension to it's Exclusive Economic Zone in 2009 which needed a careful bathymetrical, geological and geophysical characterization of the ocean surrounding the country's territory [26]. To fulfill the requirement, the Luso ROV was used to study and map the ocean floor [27]. In 2021, this proposal process will be closed and Portugal will be 97% water, with a vast new territory that will bring economic power due to maritime resources [28], and also the need of gathering and defending the latter.

Even though the planet Earth is our main focus for developing new AUV technologies, outer space also offers ambitious objectives to our study. Jupiter's satellite Europa is believed to be covered in a sheet of ice with a great water body beneath it [29]. There are already projects to develop AUVs capable of performing missions in Europa's (presumed) ocean, like EurEx-LUNa [30]. These vehicles have to have outstanding characteristics, for from the moment they leave our planet they have to be fully autonomous: deployment, mission handling, data transmission and recharge.

Given these, it becomes clear how important and interesting it is to study how can we improve the efficiency and endurance of Autonomous Underwater Vehicles. Their potential utilization for political, military, science and industry driven missions, motivates their study to great extent, making a it a perfect subject for this work.

The main focus of this master thesis is to review and propose 6DoF control techniques and actuators for AUVs. It will specially analyze the roll DoF, for this is the least studied one and not many AUVs have the capability to control this. The reason that explains why the roll is not as needed as the other degrees of freedom is because it is simply not needed for a conventional mission. However, there are tasks where it can be a great help such as stabilization for highly detailed analysis. Other way in which the roll can be applied is to use one sensor for various tasks, for example: in under ice exploration, a vehicle has not only to maintain its distance from the floor, but also from the ice cover above it. If a vehicle has the capability to roll, the same sonar can be used to assess the distance from the bottom and from the top of the vehicle.

## 1.3 Problem Definition

Controlling an AUV in full 6 degrees of freedom is not really common. The majority of the vehicles usually leave one or two degrees of freedom always stable, for example, using fins it is possible to stabilize the roll. This is because of extras costs and complexity of the vehicle wouldn't justify the control on all degrees of freedom. However, if there is a vehicle that is fully autonomous in all degrees of freedom, it has potential to run missions where, for example, two different vehicles were needed (AUV+ROV), reducing the total costs of the expedition and, therefore, justify the extra cost and work on the AUV. Moreover, the vehicle would be able to be stabilized in all directions, assuring that the data recovered is the best that it can get.

The Ocean Systems Group at Faculty of Engineering of University of Porto has designed and developed MARES (Modular Autonomous Robot for Environment Sampling) [9], which is controllable in four degrees of freedom (surge, yaw, pitch and heave), leaving two passively stable (roll and sway). Currently, MARES moves with a roll offset of around $3^o$ due to the reaction that it's body has to the torque induced by it's two thrusters in the aft section. Also, when the ocean currents are too strong, the vehicle has to move slightly curved to counteract the drift, making it less efficient. Therefore, controlling the sway and roll of MARES would not only turn the project more elegant, but also more efficient.

## 1.4 Objectives

The main objective for this work is to confer the missing DoF to MARES. Since the vehicle already has two vertical thrusters to actuate the vehicle in the heave DoF, having the ability to control the roll would make (in some sense) the sway DoF available, when the vehicle is rolled $90^o$. Of course, this wouldn't be at the same time so, truthfully, the vehicle would only have 5DoF at a given time. However, vehicle movements underwater are slow and discrete, specially for the two DoF that are missing from MARES. What this means is that, roll (when not used to stabilize the vehicle) and sway are movements that are not commonly used, and for the latter, the drawbacks from having only heave or sway at a given time are not to worry about. However, there is going to be made a simple proposal to enable the vehicle to move freely in the $y$ axis (heave). So, if all actuators are implemented in a single vehicle, it should have full controlability in all 6 DoF.

## 1.5 Structure

This work is structured as follow:

In the next chapters, the reader can find, the state of the art for this work. At first, in Chapter 2, the AUV applications in the real world are presented. Then the actuators that are currently used are reviewed. And finally it is presented how can a vehicle of this type have 6 DoF.

Next, in chapter 3, it can be found the models that aim to represent a 6 DoF AUV. The starting point for this chapter is the current model which contemplates 4DoF for the vehicle. The objective is to model the two extra DoF that are going to be implemented (roll and sway). Some assumptions are made and the problem is simplified given the characteristics of the model's equations and the vehicle's body.

After the models are computed, the strategy for the physical implementation of the roll and sway are proposed in chapter 4. In this chapter, the proposed actuators are analyzed and optimized for the constraints of the vehicle.

Next, in chapter 5, the control strategy for one of the actuators, the most complex one, the Internal Rolling Mass, is proposed and tested. The results are shown and analysed.

Finally, in chapter 6, the conclusions, contributions and the future work are presented.

# Chapter 2

# State of the Art

Autonomous Underwater Vehicles are already widely used by the scientific community to conduct missions in a variety of fields. They are used for data collection, visual inspection and even intervention work. In order to be able to complete such tasks, AUVs have a set of actuators and controllers that enable them to move around in the water and control their position. In this chapter, the missions and actuators will be reviewed.

## 2.1 AUV Employment

In order to implement a suitable control scheme (actuators + controllers) for an AUV, it is necessary to know what is its objective before, so that we optimize its navigation. For this, there is a necessity in studying what the AUVs are currently applied on and what are the requirements for each mission. The objective of this study is to classify AUV missions based on their trajectory, so that it is possible to create a systematic way to know which are the actuators that will work the best for a given mission. Moreover, the vehicles in each mission will be analysed for their degrees of freedom and if they would perform the task more efficiently if they had six degrees of freedom (in the case they do not have already).

### 2.1.1 Marine Geoscience

Autonomous Underwater Vehicles have been revolutionizing marine geoscience study for the past two decades, for their utilization enhances data gathering in a great deal. For coastal waters, information is collected from boats, which is enough due to low depth study targets. For deeper waters however (>100m), a boat is not capable of providing detailed maps **[31]**. Due to the distance that exists between hull mounted sensor systems and their targets at high depths, the obtained maps lack in resolution and a lot of features remain unseen. A solution for this problem was to use the

Deep Tow technique, in which the tool (sensor, receiver, etc.) was towed behind the boat at the end of a tether so that the instrument was closer to the ocean floor. Although Deep Tow helped, it has poor efficiency at its cost, as well as a still limited variety of data that it can gather and its quality **[32]**. So the development of AUV systems that are capable of cruising close to the ocean floor is a key factor to get highly detailed maps.

One of the various applications of AUVs in marine geoscience is to study underwater volcanism and other phenomena related to it like hydrothermal venting, cold seeps and marine life cohabiting these places. The main purposes of these missions are: making of high resolution bathymetric and magnetic field maps, find locations of high volcanic activity underwater and provide detailed information about areas of interest **[33]**. Finding this type of places opens new doors to other scientific areas, because it is known that sites with irregular bathymetry, like mounds, pockmarks, etc. can be associated with cold seep communities and/or seismic activity. **[34]**.

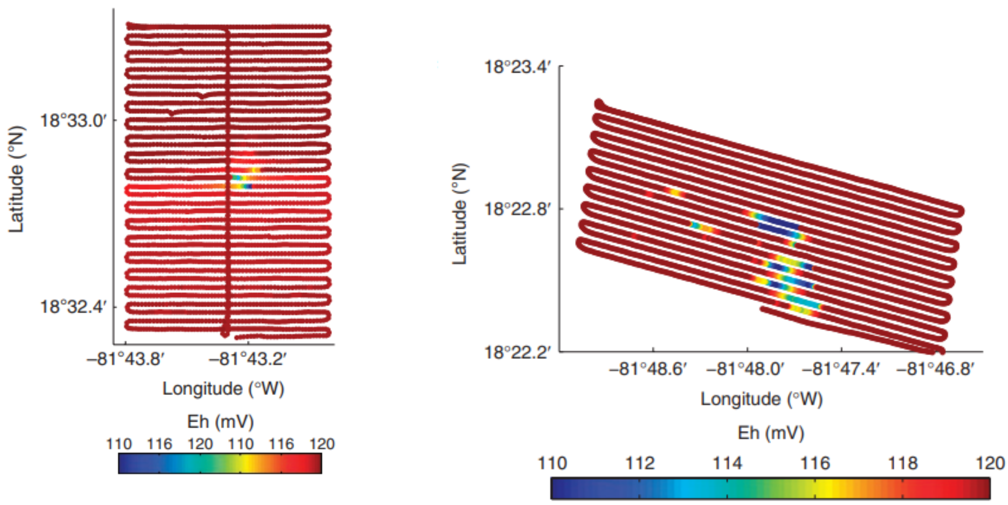
This type of missions requires a previous knowledge of the study area, which is achieved with a boat, so that the AUV is not used in vain. After the initial mapping, and if there is potential in the area, the AUV is deployed to map the zone with greater resolution. The best way to map a zone using an AUV is using the "lawnmower" path, which consists in covering an area by moving back and forth in straight lines, with each line being parallel to the last one. This movement, only needs three degrees of freedom (surge, yaw and pitch), since it's only requirement is to do a straight line and, at the end, curve to start another. Pitch helps in altitude keeping. However, as it is going to be shown, there are cases in which the vehicle, due to ocean currents, drifts from its original trajectory, making the sway DoF desirable.

*Conelly et al.* **[1]** used an AUV *Autosub6000* **[35]**, in a cooperative mission between boat, ROV and AUV, to detect and study two different hydrothermal vents, one of which is the deepest vent known, at 4960 meters deep. Located in the Mid Cayman Spreading Centre (MCSC), near the Caribbean Islands, these two hydrothermal vents are called Von Damm Vent Field (around 2500 meters deep) and Beebe Vent Field (around 5000 meters deep). The latter was the first one to be documented.

After a boat survey strongly suggested the presence of hydrothermal activity in the area, the AUV was deployed for closer inspection. The vehicle's sensors read a temperature anomaly and also strong redox potential signals (Eh), further implying the existence of the vent field. This mission is described by a "lawnmower" path where the vehicle traveled 1 km long lines, spaced 100 meters apart, to a total of 65 km long mission, within a 24 hours time **[33]** (see figure 2.1).

Von Damm Vent Field had a similar mission, with the vehicle being used after previous probe readings. The AUV traveled 1.5 km long lines, spaced 75 meters apart, in a total of 28 hours mission time (see figure 2.1). During both missions, the vehicle used a near-bottom principle, maintaining a 60 meters altitude from the ocean floor.

Although without the capability of controlling its sway, *Autosub6000* is an AUV designed for missions up to 6000 meters in depth, so it is a big and heavy vehicle which helps a lot in fighting the drift due to ocean currents, although they are not really strong in high depths. This explains why the AUV is capable of maintaining nice straight lines in the surveys that can be seen in figure 2.1. For the case of this work, since the used vehicle is not as heavy as *Autosub6000* and it's maximum working depth is up too 100 meters, where the ocean currents are more prominent, there must be some kind of control of it's horizontal movement to fight this drift.




(a) Beebe Vent Field (b) Von Damm Vent Field

Figure 2.1: Mission Paths on discovering MCSC Vent Fields [1]

*Nakamura et al.* [2] used the same principle to study an hydrothermal vent field around the Southern Mariana Through. The AUV *Urashima*, which is, once again, a large and heavy vehicle travelled 100 meters above the ocean floor at around 2 knots, at a constant depth of 2720 meters, covering an area of 2 km x 2 km in the same "lawnmower" path lines, collecting magnetic and bathymetric data (see figure 2.2). This survey differs from the one in figure 2.1 in the fact that in this one is clear the horizontal drift. This horizontal drift can be problematic because, apart form moving the vehicle away from its destination, the data retrieved by sonars and sensors of the same kind is distorted and needs more processing after the mission to be good enough to be useful. A solution for this problem would be to put the vehicle moving in an angle to counteract the effect of the current drift, but this decreases the vehicles efficiency and, therefore, the total range of it's missions. A way of controlling the sway DoF in this case, such as an horizontal, thruster would be advantageous.

Also, in *Baker et al.* [3] a whole caldera was explored by the *Autonomous Benthic Explorer (ABE)* AUV [36] and its successor, *Sentry* [37]. In 2007, *ABE* performed seven different dives, to survey the Brothers Caldera, in the Pacific Ocean, while *Sentry* was used in 2011 to complete the mapping, for the previous expeditions by *ABE* didn't fully accomplish their task. The caldera has roughly 1500 meters of diameter and its floor its situated around 2000 meters deep, with a double cone structures that rise to 1200 and 1300 meters of depth.

To map the caldera and cones, *ABE* was firstly used with the same idea as in [1] and [2], but a bit more complex, because in *ABE* missions the lines weren't really straight, but curved instead, so

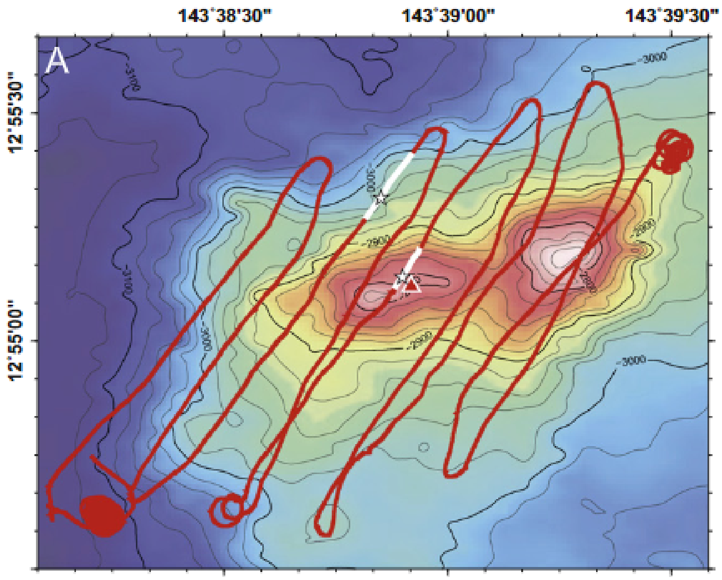



Figure 2.2: Mission path of *Urashima* - red triangle is the Pika Hydrothermal Site [2]

that the vehicle would follow the slope of the caldera and the cones. For most of the expeditions, the lines were spaced around 50 meters, and the AUV kept an altitude between 46 and 60 meters. Then, two fine-scale surveys were done, where the spacing between lines decreased to between 7 and 20 meters. The altitude also differed, for in the caldera it stayed around 45 meters and in the cones it was around 20 meters.

Later, in 2011, *Sentry* was used to complete the caldera floor and cones mapping. Here, the spacing between tracks was around 50 meters and the altitude stayed around 30 meters. *ABE* and *Sentry* are big vehicles that manage to maintain a good trajectory due to three distanced aft thrusters that control 4 DoF (on *ABE*) and four different maneuverable fins with thrusters behind each one that confer 5 DoF (on *Sentry*). Both the vehicles managed to get high resolution magnetic and bathymetric data of the whole structure, following the "lawnmower" and near-bottom path lines (see figure 2.3).

At this point, it becomes obvious that swaying is not common in high depth AUVs due to the lack of high velocity ocean currents, but looking at figure 2.3, although the drifts are relatively small to the total dimension of the surveys, its clear that they exist, so giving a vehicle the ability to control this DoF is clearly advantageous.

*Wagner et al.* [34] used the *Sentry* to look for cold seep communities in the pockmarks of Blake Ridge Diapir located in the East Coast of the United States of America. One of the pockmarks was already known to be home to a seep community, but the survey confirmed the existence of many more, in the surroundings of methane-rich fluid escape structures. The AUV made two separate paths, both covering an area of 360 per 360 meters, at 2155 meters deep. The first one at an altitude of 5 meters from the seafloor, the vehicle travelled 70 track lines, with the whole length of the objective area, spaced 5 meters apart. This path had the purpose of taking photos of the seafloor, and gather data from a sidescan sonar. In the second path, at an altitude of 20 meters, the

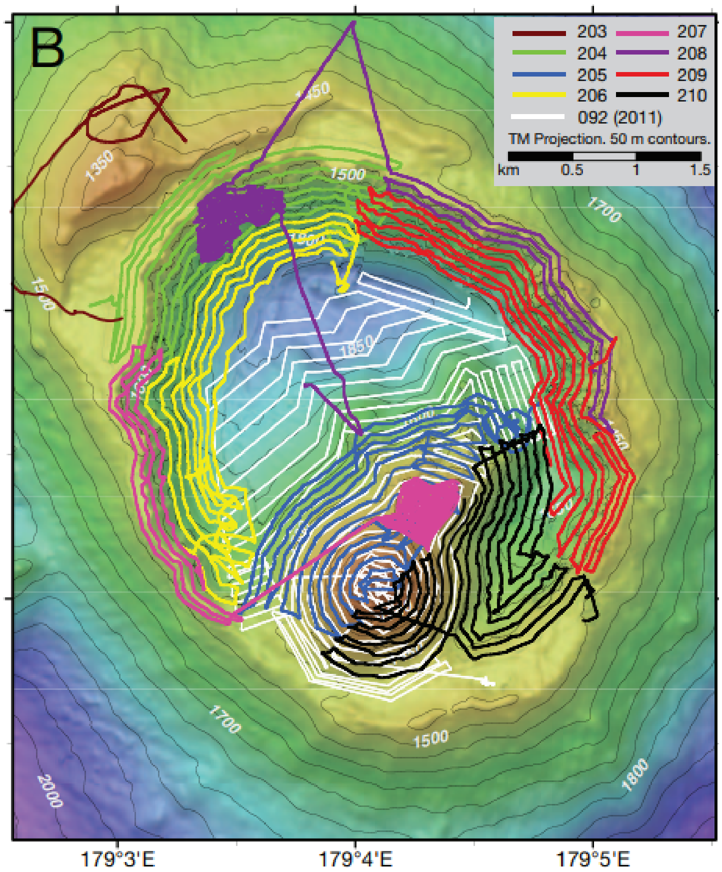



Figure 2.3: Mission paths taken by *ABE* and *Sentry* to map Brothers Caldera [3]

vehicle only travelled 14 track lines, because on this turn they were spaced 25 meters apart and the length was the same.

To sum up, when the objective is to map an area on the ocean floor, the best way to do it is to make an AUV go through a "lawnmower" path, following the terrain, until the whole place is mapped. Adding to the necessity of reaching the desired depth, the vehicle has to be able to maintain its direction in the water as well as fine-scaling its depth so that it can follow slopes in the terrain and evade obstacles. The application of roll in these types of missions will focus on the stabilization of the vehicle, as it will always, and for some specific cases where the vehicle would take advatage from rolling, for example, to take photos of the side of some target. Regarding most of the vehicles that perform marine geoscience surveys, since they work at high depths where the ocean currents are not too strong, do not need to worry a lot about drifting, because the rate at which they stray away from the original path line is pretty low. However, the situation is different when the surveys are near the surface where the currents are way more prominent as it is going to be shown in the next section.

### 2.1.2 Marine Ecosystems

AUV application in marine ecosystems study is getting more and more usual over the years. Their capability to provide data including optical imagery of communities on the seabed (and not only) is considerable, since they can be configured and programmed to accurately and slowly follow the terrain while gathering information. Also, they can go to areas significantly understudied (due to their hard reachability with the current methods) that can contain untouched structures that can tell us a lot of details about them, such as benthic habitats.

Benthic habitats compose the ecological zone at the highest depth of a given body of water. What characterizes this place is that all or almost all creatures here have a strong bond with the floor, some are even permanently attached to it. These habitats are important study objects for some reasons, one of them is the fact that, in some places as we will acknowledge further in this work, they are pretty much understudied. Other reason is the fact that some living beings that thrive in the benthic zone, such as corals, can tell us a lot about the state of the sea regarding climate change and other external stress, for corals are extremely sensitive [38].

For this section, we will look into the exepeditions of two particular AUVs, the SeaBED AUV [39] and the Sirius AUV.

*Williams et al.* [4] used the Sirius AUV to document biological communities along a reef in South Easter Tasmania, beyond water depths that are typically places for common diving. The surveys were comprised of 19 dives, covering around 70 linear kilometers, with a range of 2.5 km to 6.5 km for each dive. The tracklines of 6 out of 7 of these dives can be seen in figure 2.4. It is clear that the vehicle has to move away from the land while covering quite a bit of ground on the way. It also has to control its altitude, for the mean distance to the ocean floor for each dive was 2 meters.

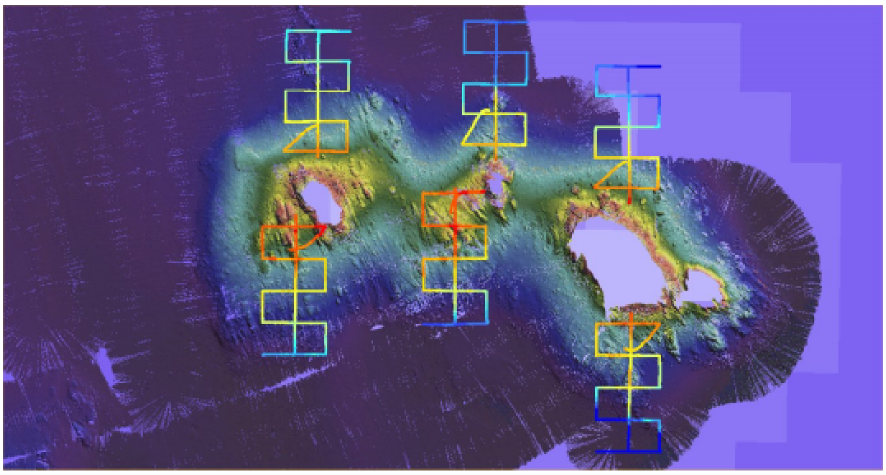


Figure 2.4: Tracklines of 6 dives around the Hippolytes. (adapted from [4])

*Williams et al.* [5] continued using the same AUV later in a program to provide physical and biological observations of benthic habitats around Australia. These observations are aimed to help researchers infer the long term effects of human intervention and climate change on the benthos. Before these surveys took place, the AUV mapping technique showed in the previous section of this work was used to map the seafloor, and the results show a detailed 3-D representation of it, which, by any other means, would not be cost efficient (see figure 2.5).

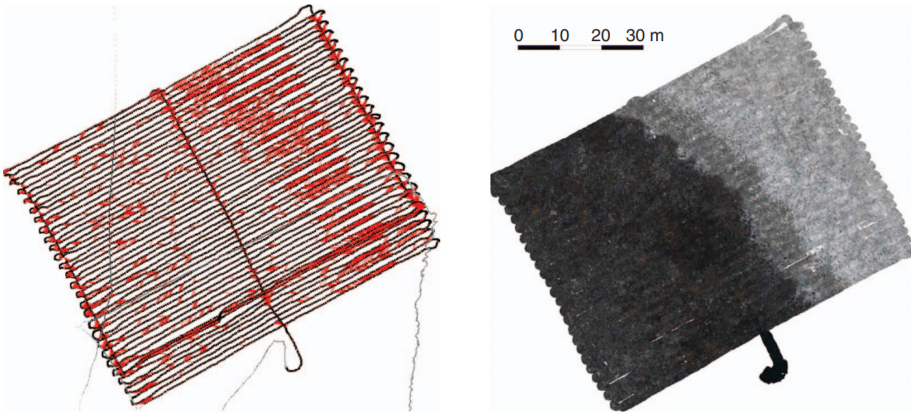



Figure 2.5: AUV mapping survey tracklines (left) and 2D representation of the seafloor (right) (adapted from [5])

The program held surveys that provided broader-scale analysis of the seafloor, using sparse grids in the order of 500 to 1000 meters per side, to determine how the reef biotopes changed along a large space. Furthermore, few areas were selected for a more detailed survey, where the AUV performed small scale surveys (similar to the "lawnmower" technique) to provide a full coverage mapping, for these sites are to be repeatedly studied along the years. These surveys were done at various depths (from 15 to 250 meters), showing that the AUV is not only capable of maintaining a good trajectory to create a grid, but can also do it while cruising up and down in the water column. These surveys can be seen in the figure 2.6. With the help of the color codification in the figure, we can see at which depths the AUV was during the survey. The Image axis in the figure represents the pictures that the AUV was taking during its work, these images would be processed by a cluster algorithm to represent various types of seafloor formations. These images and results won't be analysed in this work, although it is useful to note the AUV's capabilities of providing optical imagery while cruising at low speeds. Also of great importance, is the fact that Sirius AUV is capable of hovering at a given depth, maintaining its position in the water column, which is crucial for detailed analysis. Apart from this, the Sirius AUV is not torpedo shaped. Its body is composed by two torpedos, one on top of the other, with two beams, perpendicular to the torpedo bodies, separating and also holding them. This is important to refer, as this morphology for the AUV gives an extra stability in roll and pitch to the vehicle, since the heavier components (such as batteries) are in the bottom torpedo and the lighter ones are in the upper one. Roll stabilization allows single torpedo vehicles to be compared to Sirius like AUVs, regarding this DoF.

Differently from the previous section, at these depths the ocean currents are stronger, and by analysing figure 2.5 and figure 2.6 we can assume that Sirius AUV suffered from some drift. In the first figure, although it does not seem deteriorated, since the 2D representation is quite good, it has some blank spots that could potentially have been avoided if the AUV had some kind of control on the sway degree of freedom, which it does not. If Sirius AUV had a way to control this, the gathered optical imagery would be enhanced.

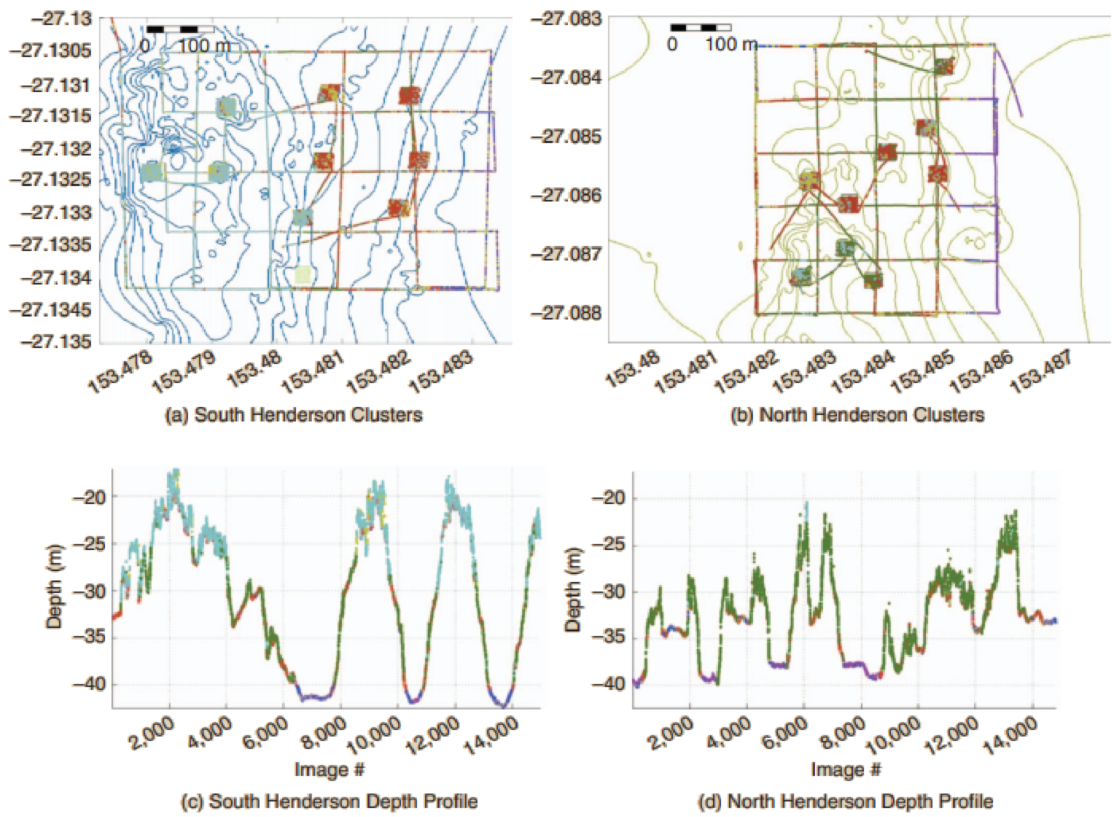



Figure 2.6: (a) and (b) are the tracklines of the AUV surveys; (c) and (d) are their respective depth profiles (adapted from [5])

Finally, it is crucial to further point the importance of altitude keeping in surveying benthic habitats. As it is shown in [6] and in figure 2.7, one of the important features for a benthic habitat mapping AUV is the capability of following the floor at low distance from the ground (between 3 and 4 meters in this case) and where the slope can get very significant. In this mission, SeaBED was capable of taking 200 photographs with an on board camera capturing different coral species that cohabit along a shelf reef in Puerto Rico, with a seafloor slope of 75%. This vehicle is passively stable in both pitch and roll, which is a great feature to photograph the ocean floor, nevertheless, given the opportunity, an AUV would benefit from 6 DoF in taking pictures. Pitch and roll control would help in positioning the camera to take photographs of the sides of corals, for example.

### 2.1.3 Archaeology

Underwater archaeology is commonly performed by SCUBA divers, which creates stricter depth and time constraints. Divers can safely dive up to 50 meters, but beyond that point it is risky for

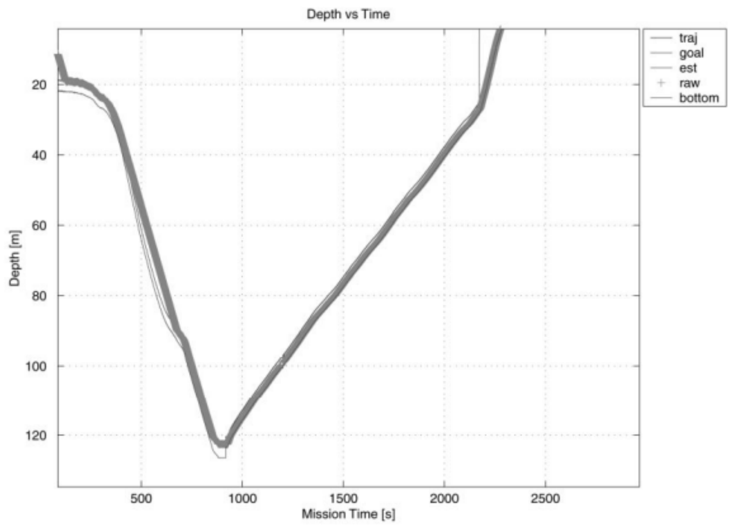


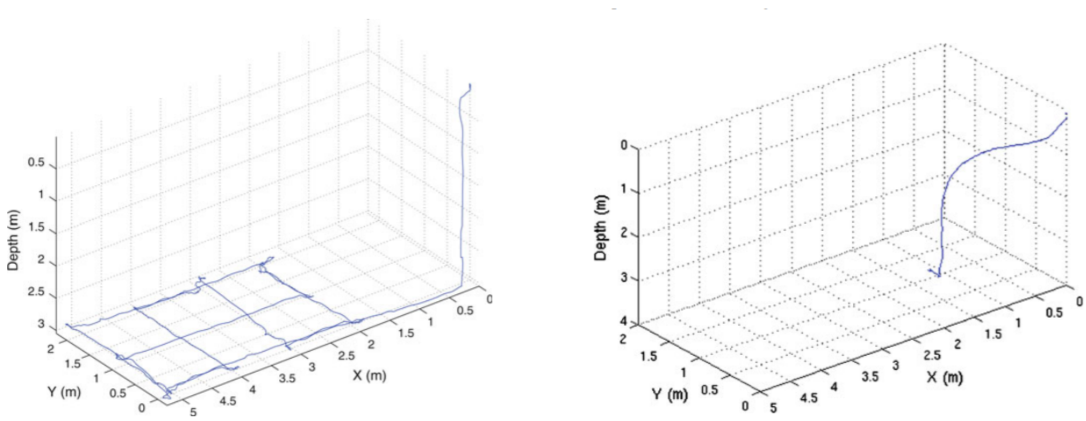

Figure 2.7: Depth plot for a dive of SeaBED AUV [6]

the user and the costs also increase. This is the main reason that contributed for the development of machines and techniques that help archaeologists dive into deeper depths and find what has been there hiding for centuries.

Usually, deep archaeology missions were taken under the use of manned submarines or ROVs. Since 1989 that scientists have been using ROVs with an archaeological research end, but beyond being more costly than AUVs, these types of vehicles didn't manage to overtake the depth constraint, because they need to be tethered to a support vessel [40]. This fueled the research and development of capable AUVs that can map an entire region to look for underwater wrecks (using multibeam surveys or magnetometers), and then make a closer inspection of points of interest (using digital still cameras) [21]. AUVs to help archaeologists must have a design that ensures that the vehicle can handle large area mapping and small area detailed photography without putting the ancient objects in danger. Previously, there was a clear distinction between vehicles aimed to map and vehicles aimed to minute analysis [40]. The first ones would be torpedo shaped vehicles to enhance the travel at medium to high speeds, while the latter ones would be bigger hovering vehicles which objective is station keeping above the target. Nowadays, there are already several torpedo shaped vehicles with the capability to hover, using variable buoyancy systems (VBS) or vertical thrusters [9] [10]. A 6 DoF AUV that could do both the survey mapping and the hovering would be a great addition to this industry since it can reduce the costs of the missions and its complexity, for there would be no need to retrieve the survey vehicle and deploy the hovering one.

In [21] we can once again see the "lawnmower" trajectory to map zones with archaeological potential, further assuring the importance of this survey design. New in this work, is the utilization of lightweight AUVs to perform archaeological surveys and a methodology to perform these.

Surely, one of the most important features that help in underwater archaeology is the one represented and tested in [7], [41] and [42] which is a robotic arm attached to an AUV. This robotic arm is capable of retrieving materials from the seafloor and returning them to surface unarmed for scientists to study. This feature further points out the importance of hovering and roll motion for these archaeological research destined vehicles, for this motion is not only essential for manipulation, as it adds an extra DoF to the manipulator, but also for taking detailed optical imagery. In figures 2.8 we can see a the trajectory adopted by the vehicle in **[7]**. These show how a usual archaeology mission is done, with the first deployment to map while close to the floor (2 to 3 meters above the seafloor) and a second deeper one to retrieve the target (a black box in this case). Notice how the vehicle is able to perform a controlled descent above the target without much horizontal drift and then keep its position, making it easy to take photographs with high resolution and little blur. Moreover, the work from **[7]** proves what was stated previously in this section. Although the AUV *Girona500* only has liberty in 5 DoF (it does not control roll), it is well suited to do both survey and object recovery. However, the vehicle body is quite different from the one to be used in this dissertation. *Girona500* has two torpedo shaped bodys, one above the other one, and the properties of this shape were already analysed. MARES is a single torpedo vehicle and, although this might come as a disadvantage in some aspects, like space available for actuators, it helps in the sense that, with only one body, is easier to control the roll DoF.




(a) AUV trajectory in mapping survey (b) AUV hovering trajectory in detailed analysis

Figure 2.8: Typical archaeological complete mission (from **[7]**)

### 2.1.4 Oil Industry

Underwater surveys are essential components for any oil or gas exploration. Oil companies need to study the seafloor, before starting any construction, to assure that the exploration is safe and compensatory. Throughout the working years, they also need to keep under surveillance the quality of the structures: check for leakage in the pipelines, stability of foundations etc. An AUV with control over all DoF in this industry would excel in structures supervision, for it would be able to carefully analyse all of the sides of a given target, decreasing the probability of leaving some problem behind unnoticed. Finally, when the structure is ready to be decommissioned, the company needs to check that everything is left as it was found, so that the sea does not get polluted with man made objects and structures. Even outside the exploration of oil and gas we can find the use of AUVs in this industry, for example, in [43] path algorithms are developed to identify and detail oil spills, with a swath based trajectory. This algorithm designs a path so that the AUV tries to find the point with greater density of oil per sea water, by finding, on a given path, the point were the peak is. Then the vehicle does a diagonal so that it centers itself with that peak and makes a transect, finding another peak. This algorithm is repeated until the spill is analysed.

In [32] there is a description of various AUV applications in this industry. In similarity to what was already approached, an early stage for any exploration is based on *hydrocarbon vents search*. This is usually based on hull mounted sensors, but the capabilities of an AUV to give more detailed data about a location are already known. With their help, its possible to better evaluate the potential of an area and to plan greater exploration programs. In the same work, under the title of *Environmental-baseline surveys*, the author tells us that AUVs are being used by oil companies to assure a sustainable exploration, without harming or polluting the oceans. What this means is that vehicles are used prior to a construction to document the conditions of the seafloor, and keep being used on a long term monitoring to maintain under surveillance the state of the ocean during the construction and the operation of a given drilling zone. Other applications in this work are for example: surveys to optimize and design foundations and pipelines deployment, 3D and 4D highly detailed sea floor and subbottom mapping and also inspection and search works. All these applications are based on survey missions already characterized earlier, *i.e.* "lawnmower" trajectories and also the utilization of hovering capabilities of some AUVs.

As it can be seen, this industry, as it is the most common area of AUV applications, fuels the further development of these vehicles and their technology. The work of [44] and [45] is an ongoing project that aims to deliver an AUV and docking station that, together, constitute a station to provide repeated and long-term oil and gas structure observation, while being submerged for long periods of time.

### 2.1.5 Military

According to [46], sea mines are still legal and widespread around the world, and while there are countries that do not produce them, there are around 30 countries that do, and some of these export to the rest of the world. Even if there was no sea mine production, there are still a lot of mines underwater left behind by previous wars that put in danger everything related to maritime travel. This is why it is so important to develop methods and systems capable of finding and neutralize these weapons.

Various works ([8], [46] and [47]) defend that a mine countermeasure (MCM) work is based on three different phases: survey, identification and neutralization. During survey phase, the AUVs use the already known "lawnmower" technique to map the ocean and find mine like structures. During the second phase, the AUV has to detail the regions of interest found during the survey and, to do this, it can do a second smaller "lawnmower" or hover around the target photographing or video taping it. The third and final phase is usually not done with an AUV. Better AUVs with full liberty in all DoF could possibly turn all phases of MCM operations doable with a single vehicle, which would decrease the cost of all operation.

The recent works around this industry are on how to optimize the survey, to make sure that the probability of finding mines gets bigger and the probability of false positives is decreased. We can see in [48], that an algorithm is developed to optimize survey track lines based on seabed formations and other criteria, this is called Adaptive Survey. This work is further analysed in [8] where an AUV adapts his trajectory in real time so that it can properly detail an area with a more complex seabed formation (see figure 2.9). In the same work, the idea of various vehicles, multi phase and a system of systems based MCM operations is introduced, which is a way for safe surveillance of large areas. However, there would be no need of ASV (Autonomous Surface Vehicles) and UAV (Unmanned Aerial Vehicles), if the AUVs were capable of doing all the phases of MCM operations, as was already said earlier. However, these auxiliary vehicles are also there to help in localization, but there are currently works being done in AUV Swarms (various AUVs working towards the same objective), which can potentially eliminate the need for auxiliary vehicles.

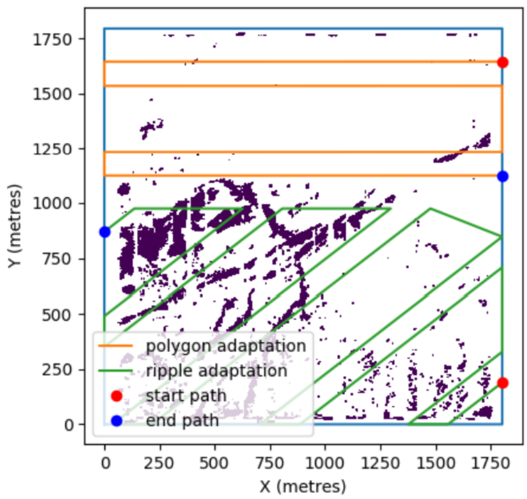



Figure 2.9: Adaptive survey - the operation first starts with the orange track lines due to a smooth sea bed that does not require a much complex survey. Once sand ripples are discovered, the AUV changes its trajectory to the green lines so that it can view the sand ripples from an angle increasing the probability of finding mines [8]

### 2.1.6 Discussion

In this section it is reviewed the most common AUV applications in various industries. The objective of this is to have a good database of vehicles trajectories and maneuvers, so that the future development of actuators and controllers is as complete as possible in the sense that the chosen components can give the AUV the ability to perform all the missions and, therefore, be used in all industries. Also, it helps on assessing which missions would benefit from a 6 DoF vehicle.

To simplify the conclusions, missions were divided in two categories:

1. **Area survey**

   Missions where the AUV has to analyse a whole area at different depths. This category is characterized by the typical "lawnmower" path and also the large grid trajectory. The objective of these missions is to map the ocean floor while also gathering information about the quality of the water. The speed and depth of the vehicle are greatly dependent on the payload, for there are sensors that work best further away from the ground and there are others that are to be used closer. Although almost all of these survey missions are done with vehicles with 3 or 4 DoF, it was seen that, in some cases, a 5 or 6 DoF AUV would contribute to improve the quality of data gathered in the survey, for example, when the vehicle drifted from its trajectory due to ocean currents. A better trajectory control would not only enhance the data, but also make the vehicles localization easier to predict, for it wouldn't stray away from the original path design.

   **Key features:**

   - Long lines where the vehicle has to keep its trajectory, fighting against wave and current drift;
   - Relative sharp curves and high accuracy when starting a new line;
   - Altitude keeping;
   - Localisation estimation.

2. **Hover with detailed analysis**

   This is the most demanding category for an AUV. Apart from the need to travel to the designated mission area, the vehicle needs to have the ability of small adjustments to its position and keep it (station keeping) in order to do precision work like taking photos, video, manipulation, etc. This category is the one that would benefit the most out of a vehicle controllable in all 6 DoF. Usually, intervention hovering vehicles are ROVs, for their manipulation is more precise and exact, since it is an operator commanding them and they are usually bulky with a lot of control inputs. Fully autonomous vehicles, which control could be comparable with the ones from ROVs, assuming that the mission handling algorithm was adequate too, would reduce the costs of the missions in a great deal. ROVs are usually heavy, require a surface vessel to give it power, the tether limits its movement and need an operator to run it, increasing the whole cost and complexity of the mission. Deploying AUVs from the coast or even an auxiliary boat that can complete all the mission with little to no supervision is the next challenge.

   **Key features:**

   - The vehicle has to be able to hover;
   - AUV has to do small corrections to its position;
   - Slow and precise movements;

## 2.2 AUV Actuators

In this section, the most common actuators for an AUV will be revised and categorized. In short, the usual selection of actuators are not different from the original counterparts of AUVs. Last century's manned submarines used propeller thrusters to move forward and backwards, while a system that is capable of retaining and expelling sea water controlled the vehicle's buoyancy, making it go up or down in the water column. Nowadays, the principles are the same. For smaller unmanned submarines the challenging points are making these systems efficient and reliable in that scale, as well as creating and implementing a control system and algorithm for the vehicle, for it has to be autonomous.

For clarity purposes, a categorization for the actuators will be done, taking into account the maturity of the technology in question, namely, commercial availability, existence time and how optimized and studied it already is. Three categories will be created:

- **Category I - Commercially available technology** - In this category are the actuators that are used in almost all AUVs. They are good choices because they have been around for decades, a lot of studies were already done about them, so they are quite optimized and efficient, and they are present in the market, meaning that they can be bough easily and with great confidence;

- **Category II - Widely independently used technology** - This category is comprised by technology that is widely used in commercially available AUVs, but is not available by itself. This means that the technology is tested and used by companies that develop AUVs, but each of them is created for a specific vehicle or case. If an actuator from this category is chosen, it will have to be custom made for MARES;

- **Category III - In research technology** - Here are found actuators that are not used in the market. Neither by themselves, neither in commercially available AUVs. The actuators from this category are used in research vessels and laboratories that seek to know their potential;

### 2.2.1 Thrusters

Propeller based thrusters are the most common AUV actuators. These devices are widely used in boats since the 19th century which also makes them the most studied way to give velocity to a water vessel.

Various works have been done on efficiency optimization for AUV thrusters, including blade shape modeling. An example is the work of *K.P.D'Epagnier*, who studied methods to improve the efficiency of AUV propellers, based on the final specifications for the robot **[49]**. Designing a new propeller means calculating a lot of parameters that work towards efficiency, such as blade geometry, number of blades (there are options with single bladed propellers **[50]**), RPMs, hub diameter, etc. Using brushless DC motors (which is the most used option to power this propulsion system) and following the steps of this work, the efficiency of thrusters can go up to around 76%. Although it is tempting to design and develop an optimized thruster for our case, the total vehicle cost and complexity would increase. It is much cheaper and easy to buy off-the-shelf and already tested thrusters which are usually good enough for the purpose.

What makes thursters highly desirable, besides the availability, is how modular they can be. There already highly capable AUVs which actuators are purely thruster based, such as **[9]**, **[10]**. These vehicles have horizontal thursters which are the basis for any vehicle, but also have vertical thrusters that confer the heave degree of freedom (see figure 2.10). What is special about vertical thrusters is the capability of hovering and station keeping. Usually, an AUV needs forward movement to also move up and down (utilizing fins), making it impossible to stay in the same place. With vertical thrusting, this problem is solved. There is also AUVs like the one in the works of *Ridolfi et al.* **[51]** and **[52]**, that use thrusters to also control the sway and yaw degrees of freedom. This concept uses 6 thrusters (two at the back, two vertical and two horizonal; it can be 5 if only one main propeller at the back is used) to control the vehicle in 5 degrees of freedom, leaving the roll.

In the same work, it can be seen one concept (and test) of thrusters that are already in use, the rim driven thrusters. This type of thrusters are quite better underwater than the typical counterpart. Given the fact that they lack a central hub, debris can pass through this gap and not damage nor stop the propeller. Counter rotating propellers are also another option that work towards greater power and stability.

Thrusters are also able to be designed so that the thrust direction is manipulable, this is called vectorial thrusting and can be applied to water jet propulsion too, as it will be viewed later. Various works and concepts have been done: *Masmitja et al.*, in **[53]**, has designed a system that is capable of rotating thrusters placed on the wings of an AUV, enabling, with the same pair of thrusters, motion on the heave and surge degrees of freedom; *Vega et al.*, in **[54]**, created a reconfigurable magnetic coupled thruster, combining the advantages of magnetic coupling and vectorial thrusting; *Liu et al.*, in **[55]**, used three pneumatic actuators in a cone geometry to control a single thruster at the aft of an AUV and *Cavallo et al.*, in **[56]**, has used a quite complex spherical parallel mechanism to give three degrees of freedom to a thruster at the back of an AUV.

As it was showed, thrusters are a well developed technology that is easy to get, apply and control, making them a potential choice for this work. However, they come with some disadvantages, one of them being the efficiency. As it was said earlier, thrusters are able to be optimized for a single vehicle, but this is time consuming, increases cost and also the complexity of the vehicle. Therefore the chosen thrusters would potentially be far from being as effective as they could be. Other disadvantage is the fact they get corroded with normal use (highly due to cavitation phenomenons) and can also get damaged by debris present in the water. For the cavitation problem there isn't much to be done. It is possible to attenuate this problem but, due to different operation depths, water salinity/density/temperature as well as different rotation velocity for the propellers, the cavitation phenomenon is slightly altered, so it is very hard to eliminate it completely.

Currently MARES has 4 thrusters, two main ones at the aft and two vertical ones, at the front and at the back (as it can be seen in figure 2.10). Since the vehicle is modular, one solution can pass through the implementation of two extra horizontal thrusters, perpendicular to the main ones, such as the AUV showed in [51] and [52]. With this design, MARES would gain one extra DoF, the sway one, and the yaw DoF (that can already be done with differential propulsion in the main thrusters) would get facilitated.

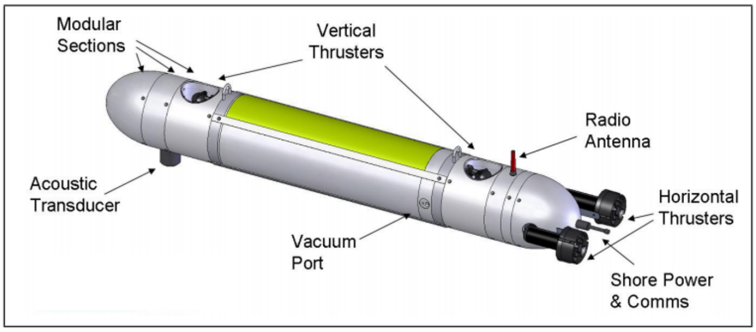



Figure 2.10: MARES 3D model [9]

### 2.2.2 Fins

Fins (or rudders) are probably the most studied and simpler actuator on this list. Just like the rudder on a boat, fins are used to orientate the water that flows through the body of the AUV, changing the drag and lift of the vehicle and, therefore, changing the pitch, yaw or roll of the AUV.

These surfaces can have a passive or active work on an AUV. An active work consists in the control of the fins (e.g. with servo motors), giving the ability of rotating over any axis of the vehicle. In this situation, fins can be called actuators. In a passive work, fins are not movable and they are pure control surfaces that create drag and lift, which makes it hard for the vehicle to rotate in a given direction. An AUV system with fins is highly nonlinear, so there are works like [57] that were dedicated to study and model the behaviour of this type of vehicles, simulating their capabilities.

Due to their simplicity, low cost and low power consumption, fins are a good option to confer more degrees of freedom to a vehicle. However, they have to be custom made for each vehicle, based on its final specifications. Because of how different fins can be, depending on the target vehicle, these structures are not sold by themselves. Nonetheless, because of the already exposed reasons, these actuators are used in various commercially available AUVs, such as *REMUS* and *HUGIN*.

There are several ways to apply fins to an underwater vehicle. One of them can be seen in [10], where these structures are right behind the thrusters. In this topology, the accelerated water is directed as soon as it leaves the thruster. Although this application ensures quick maneuvering, it also creates a great drag and pressure on the fin body. However, this permits a slender body to the AUV, which can be a great advantage in missions where the terrain is sinuous. This system is represented in figure 2.11. A second way to apply fins, and maybe the most common one, is to put them perpendicular to the vehicle, such as in [14][21][35]. In this manner, these structures take advantage of the normal flow of water through the whole body of the AUV.

Although these actuators are typically used as simple control surfaces, there are works being done that explore the potential to replicate the behaviour of fishes in vehicles using fins, once again showing how biomimetics is extremely present in this area. One specially interesting concept is the BOSS Manta Ray AUV, from Evologics [58], that uses water-jets and thrusters when it needs to do precise movements, but when the objective is to just travel through the ocean, it uses pure fin movement just like a manta ray to propel itself forward. Even though this concept is interesting, this type of application won't be used on this work for the following reasons: biomimetics is a pure research area at the moment, this means that the traditional use of actuators is still more efficient than trying to replicate living beings; the control of biomimetic actuators is more complex than for the actuators we already know, making this option unnecessarily complex.

Fins surely have great potential to be used on our vehicle, MARES, but they also have a great disadvantage which forces a second thought. In any form application, these structures take advantage of the flow of water, redirecting it and creating a torque that induces rotation to the vehicle. The great disadvantage comes when there is no flow. Hovering vehicles, that have to stop in the water to take pictures for example, are not under influence of any water flow (besides currents), and therefore fins become useless. Since our objective is to build a control scheme for an AUV with 6 degrees of freedom, capable of performing any type of mission, fins are not a really suitable solution, for they wouldn't be used while the vehicle was maintaining its position in the water. Other disadvantage is the fact that they are protruding parts, which can brake easily. A solution for this problem is to make them from a flexible material, which is already implemented by many developers.

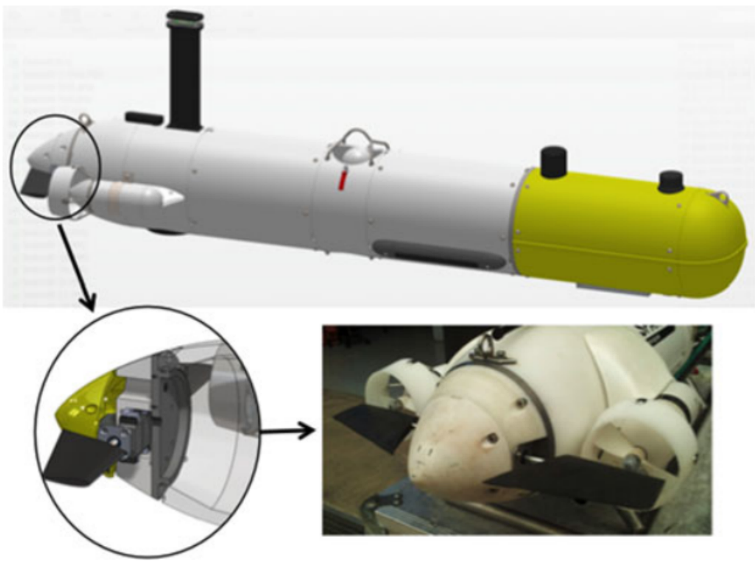


Figure 2.11: Sparus II Fins system [10]

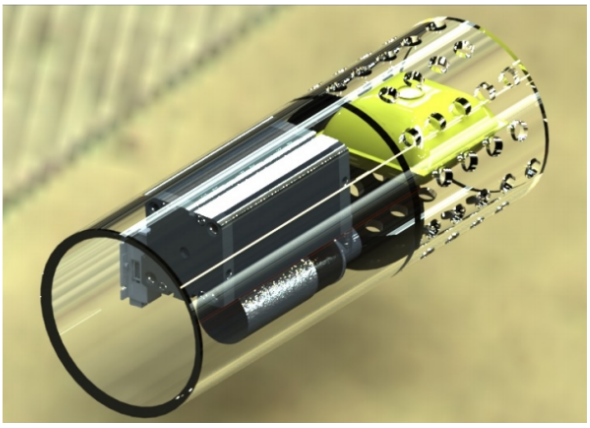
### 2.2.3 Variable Buoyancy System

Variable Buoyancy Systems are a technology that resemble how traditional submarines move up and down in the water column. A typical submarine has an empty compartment that can be filled with seawater. While close to the surface, it is just necessary to open the valves that lead to this space to enable water to start rushing inside and increase the mass of the body while maintaining its volume. The result is a heavier body that keeps sinking until the force of gravity matches the buoyancy force, stopping the submarine at the target depth. In this situation, the vehicle is said to be neutrally buoyant. If the objective is to go up in the column of water, then water pumps must be activated to expel water from the compartment into the sea, decreasing the vehicle's mass. This system is really interesting from the point of view of energy consumption. When there is a desire to change the depth of the vehicle, and there is no possibility in doing that with passive flow of water (e.g. to go up), the pumps only need to be activated until the desired buoyancy is reached, then the submarine starts going up effortlessly. For an AUV though, the challenge is to make this system energetically efficient in smaller sizes. It is also important to note that VBS is of slow action, so it is not suited to be used in missions where the change of vertical motion is required to be quick or frequent.

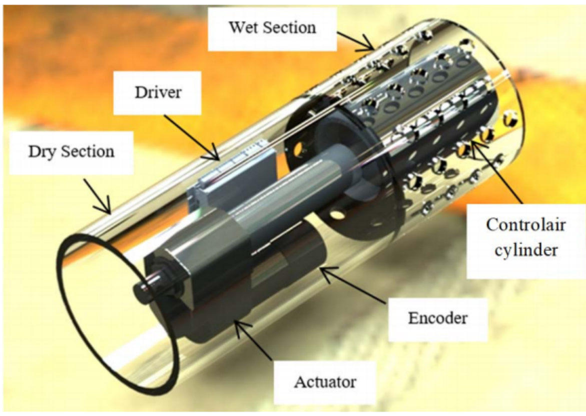
In AUV technology, the most common VBS uses internal bladders or mechanical systems to change the center of buoyancy and gravity of the vehicle, making it heavier or lighter (to move up and down) or (if the VBS is not centered) to change the pitch of the vehicle. The typical ocean glider uses this system and fins to move in the water: a VBS system tilts the vehicle forward, by moving its center of gravity to the front of the vehicle, and then wing like fins give enough lift force to the AUV so that it moves forward, gliding through the water. There is also the possibility of using vertical thrusters and VBS at the same time, for example, to go deep in the water and then do a triangular survey, in which the vehicle would need to move up or down intermittently. If this movement was based on the VBS alone, it would have a really slow transition between going up and going down and would not be as efficient as using thrusters for this end. Also, depending on the amount of time that a vehicle has to be underwater, thruster based option for the heave degree of freedom can be more efficient, although, for hovering type missions, VBS is significantly more advantageous than vertical thrusters **[59]**.

Just as in the previous actuator, variable buoyancy systems are not commercially available. However, the equipment that they require are available to be bought, such as pumps, motors, etc. Due to this reason and to the fact that they decrease the energy consumption, specially in deep sea missions, these systems are widely integrated in AUVs. For each vehicle, a new design has to be made, and there are various works that develop VBS and its control. The challenge with these type of systems is reaching the required power to move mass (water/oil to external bladders or mechanical pistons) in the pressure created by the water in the environment. Carefully motor selection and structure design has to be made so that the system is more efficient than using simple thrusters, for example.

To our specific objective, which is giving MARES 6 degrees of freedom, there isn't much need in using VBS, since the vehicle already has two vertical thrusters capable of assuring the work of a VBS, which is actuating in the heave and/or pitch degrees of freedom. However, there are already concepts created to put VBS on MARES [60][61] (see figure 2.12), since it is shown that for high depths (even for relatively low ones, depending on other aspects of the mission) VBS is advantageous over the permanent use of thrusters. Both electrohydraulic and electromechanical systems have been designed for our vehicle.



(a) Electrohydraulic[60]




(b) Electromechanical[61]

Figure 2.12: Two different prototype VBS systems for MARES

### 2.2.4 Internal Mass

The internal mass displacement has the objective of changing the center of gravity of an AUV. This technology, although not as efficient as fins and still under research, holds great potential, linked to the fact that it can alter the roll or pitch of a vehicle with it being still in the water. Thrusters also have this capability but, as already pointed out in the previous actuator, they have to be constantly working for the vehicle to maintain the desired angle. With internal mass, that can be a simple added mass or a part of the vehicle (such as the batteries), the idea is similar to VBS, meaning that it has to be actuated once and then the vehicle stabilizes around the target position.

An internal mass can be used to alter the roll **[62]** or pitch **[63]** DoF on AUV. For our vehicle, the interest is using a rolling mass along the perimeter of the body of the vehicle to confer the roll degree of freedom to the AUV by changing the position of the of $C_G$ relatively to the $C_B$ .This actuator will, therefore, be called Internal Rolling Mass (IRM) from now on. There is already some research done in using a rotation internal mass to control and stabilize the roll DoF **[62]** that developed mathematical models for this kind of system. The results of this work show that an internal mass can be used to control the roll of the AUV with up to $1^o$ of accuracy. However, the objective for this work is not only control the roll degree of freedom to maintain the vehicle stable (for MARES travels with an offset of around $3^o$ due to the induced reaction torque from the motors), but also to actively change the roll position of the AUV.

Even though this technology is simply under research and there isn't a lot of work done on it, it seems that it is the most efficient way to confer the roll DoF to MARES, given that it is wanted for it to have this DoF while being static under water. The concept shouldn't be too complex to design and the vehicle's dynamic models can be adapted to add this extra internal rotating mass.

### 2.2.5 Water Jet

Water-jets are not really common in AUVs, although they have been around for decades in boat propulsion. In the work of *Alvarez et al.* **[63]** an AUV is developed which propulsion system is purely water-jet based and in the same work it is briefly explained the advantages and disadvantages of using water-jet. The main disadvantage is essentially the efficiency, for thrusters are more efficient than water-jets. This is quite important because, nowadays, the interest is to construct AUVs that can endure more and more time in the ocean, continuously gathering data. In terms of utility for endurance AUVs, thrusters are a more desirable option, since water-jets do not bring any advantage when the mission is, for example, surveying an area. However, they still have some advantages over the commonly used propellers: *Alvarez et al.* explains that the chosen propulsion is water-jets due to the mechanical design, overall cost, robustness and safety. Since they have no protruding parts, water-jets are more reliable in the sense that they are harder to get damaged, due to fall or even debris present in water, as well as being safer to sea life or divers. For the specific case of *Folaga AUV* (the vehicle in **[63]**), the hull cost would also be lower with the water-jet option. Water-jets can also get to higher speeds, in which their efficiency also increases. This is particularly important if AUVs start to be used in Search and Rescue (SAR) missions. In **[11]**, an effort is made to develop a jet propulsion system for a SAR AUV (see figure 2.13). However, as seen in the first section of this chapter, the majority of missions that are currently done do not require speed, but precision.

Although they are not preferable to be the main propulsion, water-jets have some potential in disturbance rejections. They have a great instantaneous power, which can be used to control the trajectory of an AUV while it is surveying an area. They are applied with this purpose in **[63]**

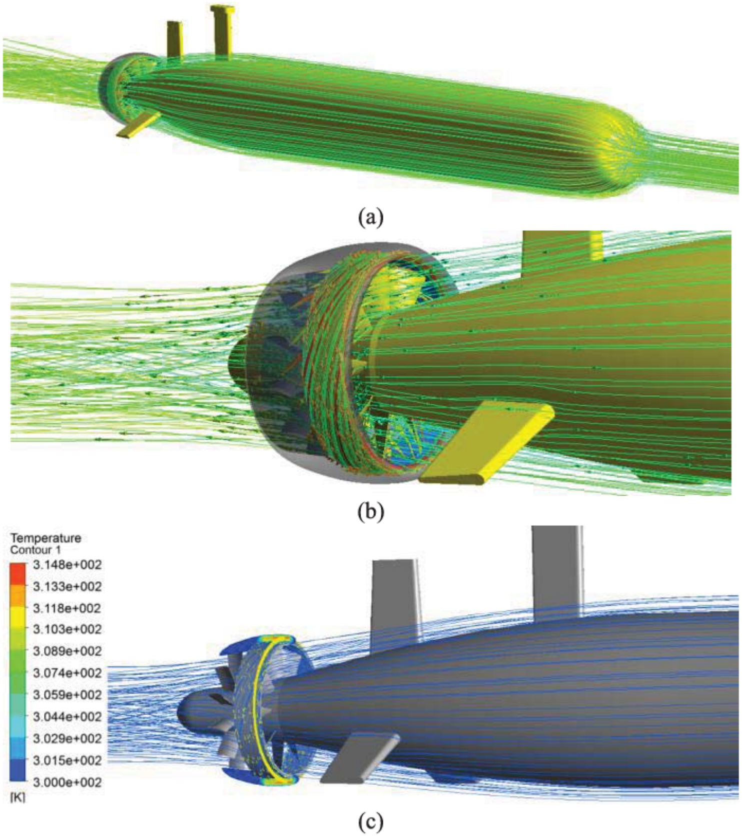



Figure 2.13: Water-Jet System for AUV propulsion water flow dynamics [11]

and [64]. In the latter work, the results for the disturbance rejection show that water-jets behave equally to thrusters, so there is no advantage in using this option, besides the slight reduction in drag. What is interesting about this work is the fact that the system is bio inspired. This is called biomimetic. In the research field, biomimetics its an interesting approach in developing concepts for robotics. The philosophy is to look at nature and copy it, believing that it has the best and most efficient solution, which is not always true. However, the concepts are usually really interesting and its very present in AUV research.

For MARES, water-jets are a complex option to take. Since they belong to category III, they are definitely not available to purchase, they would need to be custom made for our vehicle and would require a lot of testing and simulation beforehand, which is not optimal for this work. Besides, as it was shown, thrusters are a better option in almost all aspects.

### 2.2.6 Discussion

In the section above, all existing actuators for AUVs were reviewed. There are more works in this area that did not receive much attention for they are biomimetic based, which isn't of much interest for this dissertation. It is good to remind the reader that the objective to is give MARES, the vehicle

| Actuator | Category | Advantages | Disadvantages | References |
|---|---|---|---|---|
| Thrusters | I | High availability<br>Well-known<br>Maneuverable<br>Excels at shallow depths (<100m)<br>Able to change its angle *in-situ* | Highly susceptible to corrosion<br>Noisy | [9][10][49][50][51][52][53][54][55][56] |
| Fins | II | High efficiency<br>Widely available raw material<br>Passively stabilize the vehicle | Susceptible to corrosion<br>The vehicle has to be moving for them to work | [14][10][21][35][57][58] |
| VBS | II | Ideal for deep sea missions<br>Widely used<br>Available options for lower depths | Relatively large space requirements<br>Power requirement increases with depth | [59][60][61] |
| IRM | III | Provides good roll control<br>Can be used to actively change roll angle<br>Can change roll and pitch angle *in-situ* | More added mass to the vessel<br>New topology | [62][63] |
| Water Jet | III | Able of quick maneuvers<br>Great for high-speed options | Low efficiency for low velocities<br>Noisy<br>Relatively little study done | [11][63][64] |

Table 2.1: AUV Actuators

in figure 2.10, 6 degrees of freedom. Currently, the AUV has four thrusters, two horizontal and two vertical, which assure control in four degrees of freedom: surge, heave, yaw and pitch. There are two degrees of freedom missing, which are the roll and sway ones.

- **Thrusters** - these are a great option for our vehicle. Their modularity and already known control are two great advantages that these actuators have. Adding to this, they can be bought, being an off the shelf and quick option. To this specific case, they would be used to control the sway DoF. There are two options for this: use one right on the center of gravity of the vehicle or use two, just like the already implemented vertical ones. The most potential solution would consist in using two thrusters. Due to the body of the vehicle, moving it sideways would originate more drag than moving it forward. This has a great impact in power consumption, which can be decreased by dividing the needed thrust per two different thrusters. Also, this option would give redundancy to the yaw DoF, which is always a good point when constructing robust systems.

- **Fins** - fins are also a great option to confer a vehicle the roll and pitch degrees of freedom. They are easy to manufacture and of quick implementation on an AUV, which for this case is specially interesting. However, the fact that the vehicle has to be moving for them to work puts them behind a more suitable option. The objective is to develop a vehicle that can both do survey and inspection work, and fins would only help in the first one.

- **Variable Buoyancy System** - this system is the most efficient in changing the depth of an AUV. For our case, it would probably need to be integrated without removing the vertical thrusters due to the fact that VBS cannot alter the depth of an AUV quick enough and it is not efficient to make it work with high frequency. Since this system is already being developed for MARES by other authors, it won't be further analysed.

- **Internal mass** - internal mass is not, at first sight, an adequate path to follow. However, after some research, it is clear that, for static roll motion, it is most likely the only option. Surely fins are more efficient in frequent rotations, just like thrusters are more efficient that VBS in frequent up-down movement, but, just as VBS once again, internal rolling mass is the best option to maintain a specific roll angle for long periods of time. Once the internal mass has reached its final position, the vehicle is stable from that point on, and does not need more power to maintain its roll angle. Also, given that this is an internal system, the AUV gets more robust than if it used fins, which are protruding and, therefore, can get easily damaged.

- **Water-Jets** - After the research done, it is clear that this option is not viable for many reasons. Since water-jets for AUVs cannot be bought, it would have to be custom made and there isn't much work done in this actuator, so it would be highly experimental. In addition to this, these systems are inefficient at low velocities, which is actually what is wanted for this work. For this reason, water-jets won't be further analysed.

Given the conclusions above, the first assumption is that two actuators are going to be implemented for MARES in this dissertation: two extra thrusters to confer the sway DoF and an internal rolling mass to control the roll DoF. In the next section, AUVs that already have 6 DoF will be analysed, to have a better idea of the state of the art of these vehicles and to confirm the assumptions.

## 2.3 6 Degrees of Freedom Vehicles

When it comes to the control of underwater vehicles (ROVs or AUVs) in six degrees of freedom, the state of the art becomes scarce. There isn't much work done regarding this topic, particularly for AUVs. The reason for this is the fact that the majority of vehicles are movable in only 5 degrees of freedom, leaving the roll. As it was already shown, even though the applications are quite unique, there is an interest in developing fully maneuverable vehicles, for there are tasks that would take advantage of a 6 degrees of freedom vehicle. Some of these tasks include: optical analysis of underwater targets from all angles (example: taking pictures from every possible angle), underwater sinuous places exploration (example: underwater caverns that are hard for a vehicle to pass through), etc.

Most of the ROVs that are actually in use, by oil companies for example, are bulky and usually have 5 DoF (leaving the roll). These vehicles use a propulsion system purely based on thrusters because, due to their objective that is visually analyzing the infrastructures, its the option with greater control ability. Some examples of these vehicles are the BlueROV2 (from BlueRobotics) and the SeaDragon line (from TTRobotix) that can be seen in **[65]** as the state of the art of the work. *Binugroho et al.* then proceeds to develop eROV, a 5 DoF ROV with 6 thrusters to propel the vehicle which is, like the others, a bulky and big vehicle.

Regarding AUVs, 6 DoF vehicles are not commercially available. These types of vehicles belong to laboratories that develop, test and use them to scientific research. A vehicle of this kind that I find particularly interesting is the SUNFISH®, presented in **[66]**. This relatively light AUV (48kg) is capable of performing movements in all the 6 degrees of freedom, using its thruster based propulsion system.

As it was demonstrated, 6 DoF AUVs are a relatively under explored technology, hence the importance of this dissertation. Nowadays, most of the solutions to give this much freedom to a vehicle is by implementing thrusters where they are needed, since they are the most trustworthy actuators.

# Chapter 3

# 6 DoF in AUVs

In this chapter the model for the movement of an AUV in 6 DoF is going to be developed. It is not going to be presented the full modeling for these DoF as most of the vehicles have already 4 DoF, just like MARES. So this chapter will focus on the transition steps from 4DoF to full 6DoF movement and the challenges that it presents.

## 3.1 Solution for MARES

The main objective for this dissertation is to implement MARES, which has 4DoF, with 6DoF. As a small review, MARES can currently control surge, heave, pitch and yaw, so the two missing motions are roll and sway. As it was predicted at the end of section 2.2, the best way to do this is to implement two lateral thrusters for the sway motion and an Internal Rolling Mass for the roll motion.

The **two lateral thrusters** were chosen because of the current MARES model already contemplates two vertical thrusters. Due to the vehicle symmetry, the addition of these thrusters and their hulls will follow the same reasoning that was applied for the vertical ones, simplifying their implementation.

The **internal rolling mass** was chosen due to the fact that the vehicle is modular and the objective was to keep it that way, apart from the reasons already explained in 2.2.6. By having an IRM module capable of being trimmed (in mass/shape), the vehicle can be altered in each mission to satisfy the constraints of the payload. However, as it will be seen later on, the implementation of a rolling mass brings some challenges which need a way of solving them. The approach on this work makes sure that all steps are reviewed and certifies that the proposed control is possible.

The first task to do is to express how the sway and roll motion of the vehicle are modeled and identify the parameters that need to be taken into account.

## 3.2 Notation

For a vehicle moving underwater, in 6DoF the bibliography must start with the works of Thor I. Fossen, like the one that will be used here **[67]**. His brilliant research papers and books written on the modelling and control of UUVs make studying them much easier and intuitive.

In this section, the baseline for modelling and controlling UUVs will be defined, to make the rest of this work easier to understand and follow.

For a submerged vehicle, the usual variables that define is motion are:

$$\eta = [n, e, d, \phi, \theta, \psi]^T$$

$$\upsilon = [u, v, w, p, q, r]^T$$

Where matrix $\eta$ defines the position of the AUV in the world, in north-east-down and angles of orientation (roll, pitch and yaw, respectively) in the earth-fixed frame. The $\upsilon$ matrix defines the linear (surge, sway and heave, respectively) and angular velocities (roll, pitch and yaw, respectively) in the body-fixed frame. These frames can be seen in figure 3.1.

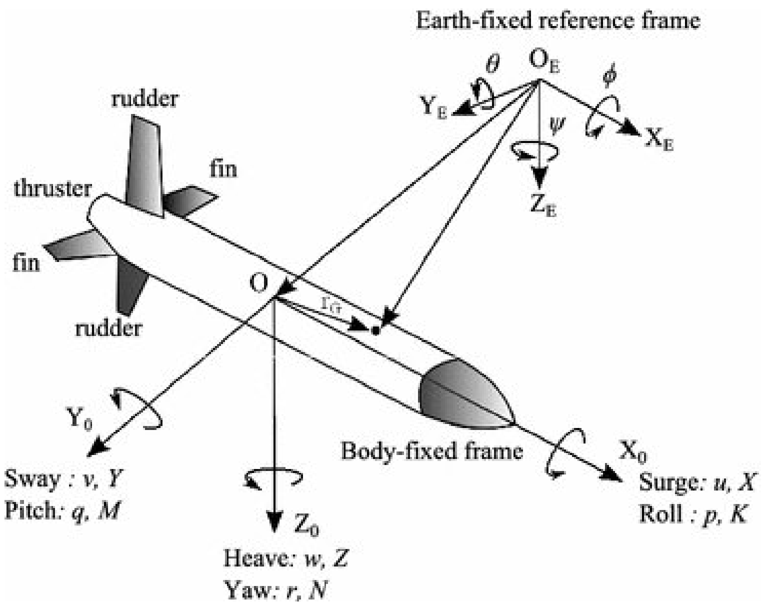



Figure 3.1: Representation of body and earth fixed frames **[12]**

## 3.3 Equations of Motion

In **[67]**, it can be seen that Newton's Second Law of motion can be expressed in the body-fixed reference to fully represent the forces actuating in the vehicle, whether it is submerged or at the surface.

The general equation is for the rigid body dynamics of a deeply submerged vehicle are:

$$M_{RB}\dot{\upsilon} + C_{RB}(\upsilon)\upsilon = \tau_{ext} + \tau_H \tag{3.1}$$

Where $\tau_H = [X_H\ Y_H\ Z_H\ K_H\ M_H\ N_H]^T$. The hydrostatic and hydrodynamic forces and moments ($\tau_H$) are due to added mass, Coriolis effect and the effect of gravity and buoyancy on the vehicle, so it comes:

**Added Mass**:

$$\tau_A(\dot{\upsilon},\upsilon) = -M_A\dot{\upsilon} - C_A(\upsilon)\upsilon \tag{3.2}$$

**Drag**:

$$\tau_V(\upsilon) = -D_V(\upsilon)\upsilon \tag{3.3}$$

**Restoring Forces**:

$$\tau_g(\eta) = -g(\eta) \tag{3.4}$$

**Propulsion**:

$$\tau_P = P \cdot f_P \tag{3.5}$$

And thus it comes:

$$\tau_A(\dot{\upsilon},\upsilon) + \tau_v(\upsilon) + \tau_C(\eta) + \tau_P(\upsilon,n) = \tau_H \tag{3.6}$$

So the total of the forces applied in the vehicle is derived by:

$$M\dot{\upsilon} + C(\upsilon)\upsilon + D(\upsilon)\upsilon + g(\eta) = \tau \tag{3.7}$$

Where: $M = M_{RB} + M_A$ and $C(\upsilon) = C_{RB}(\upsilon) + C_A(\upsilon)$ and :

- $M$ - system inertia matrix, with added mass due to water flow;
- $C(\upsilon)$ - Coriolis-centripetal matrix, with effect of added mass;
- $D(\upsilon)$ - Damping matrix;
- $g(\eta)$ - vector of gravitational/buoyancy forces and moments;
- $\tau$ - forces applied by control inputs.

The equation (3.7) can also be written in a component form as it is explained in **[13]** which is a more practical way that will help in defining the model for the vehicle:

$$(M_{RB} + M_A)\dot{v} = [C_{RB}(\upsilon) + C_A(\upsilon) + D_V(\upsilon)]\upsilon + g(\eta) + P \cdot f_P \tag{3.8}$$

Where $v$ is the velocity in the body-fixed frame, and $P \cdot f_P$ represents the forces and moments applied by the thrusters.

Take note that the drag matrix is usually represented using only the quadratic terms for drag. This is because for the common AUV velocities, the quadratic terms are dominant regarding the linear terms, so the latter can be neglected. However, they will be important in this work for the roll motion.

For a simple presentation, the matrices are in Appendix A and some simplifications, which will explained further in this work, are in Appendix B.

Because these equations and matrices are about a rigid body underwater, no matter its shape or maximum velocity, they have a some components that for a typical torpedo shaped AUV are negligible.

## 3.4 Challenges

Before any more development of this work, it is important to notify the reader for the issues that this approach will have: The main problematic of this work is the fact that most of AUV models simplify most of the terms due to the fact that the body-fixed frame of reference is usually centered at the center of gravity of the vehicle. In this work, this simplification won't be made. This will introduce some challenges to the model for the vehicle as a lot of parameters that would be nullified if the body-fixed frame was centered at the center of gravity of the vehicle. However, if this was the case, it would be also really hard to model the rolling mass since it would be stationary for the body-fixed frame, and instead we would have the center of buoyancy moving.

The correct way of modeling the vehicle so that the body-fixed frame of reference is centered at the center of buoyancy is actually do it from scratch. Coefficients like the moments of inertia, added mass coefficients, etc. are computed taking into account the fact that the body-fixed frame is centered at the $C_G$.

## 3.5 Simplifications

Since the identification of the coefficients is complex and time consuming, for this work, the coefficient values used will be the same that are already computed, i.e. the values are from the body-fixed frame centered at the $C_G$. Although this implies that the model will not be totally correct, the distance between the $C_G$ and $C_B$ of the vehicle is relatively small compared to the whole vessel, so the approximation will give results similar to the ones that it would give if the model was made from scratch. Before any IRM modeling, it can be assumed that the maximum distance between the $C_G$ and the $C_B$ of the vehicle, due to mass constraints, will be of about 2 millimeters. Since the maximum inner radius of the vehicle can be considered to be 8 centimeters, this corresponds to a displacement of 2.5%, which is negligible.

The terms for the moments of inertia $I_{ij}$ where $i \neq j$ are negligible **[13]**, assuming that the vehicle is almost symmetrical in all three planes. This simplifies the bottom right quadrant of the $M_{RB}$, because the matrix $I$ will turn into a diagonal matrix.

Regarding the $C_{RB}$ matrix, there are many possible representations for it, based on a root expression. The one chosen, and represented in Appendix A is the most suitable one for its simplicity. Note how the elements based on $r_g$ are not null.

For the added mass matrices: $M_A$ and $C_A$, simplification comes from the work of *Ferreira et al.* **[13]** where it is stated that, due to torpedo symmetry, some coefficients for $M_A$ matrix are null. This assumption will also alter some terms in $C_A$ matrix.

Matrix $g_\eta$ is already simple enough, however we can simplify it a bit more by stating that, since the body-fixed frame is centered at the center of buoyancy of the vehicle, the terms where $r_b = [0\ 0\ 0]^T$ appears are negligible. The existing MARES model has a similar simplification, considering that $r_g = [0\ 0\ 0]^T$.

Finally, drag forces which are expressed by a high order polynomial equation can be simplified for these kinds of vehicles which are moving at relatively low speeds: between 0.5 and 2.5 m/s. What this means is that the quadratic drag term will be dominant so we can assume that it will be the only taking part in the drag matrix.

All matrices that have been simplified can be seen in Appendix B

## 3.6 Model Adaptation

Now that the full behaviour as been shown, it is time to isolate the terms that take a role in the sway and rolling motion for an AUV. In this section a decoupled analysis is going to be made for the sake of simplicity and easier comprehension.

### 3.6.1 Rolling motion

The roll component for the rigid body dynamics, can be computed by solving the equation (3.1) only for the values that matter for this motion **[67]**:

$$I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] = K_H + K \quad (3.9)$$

This equation can be simplified for a torpedo shaped vehicle as it was explained in **[67]**. We end up with:

$$I_x\dot{p} + (I_z - I_y)qr + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] = K_H + K \quad (3.10)$$

Since the rolling motion will be created by moving an internal rolling mass which, as the name tells us, will be inside the vehicle, the terms $M_A\dot{\upsilon}$ , $C_A(\upsilon)\upsilon$ and $D(v)v$ won't vary, assuming that the this is going to implemented in an already existing vehicle which for are already known the values for these matrices. So, the only term that will need an adaptation is $g(\eta)$, which is:

$$g(\eta) = \begin{bmatrix} (W-B)\sin\theta \\ -(W-B)\cos\theta\sin\phi \\ -(W-B)\cos\theta\cos\phi \\ -(y_gW-y_bB)\cos\theta\cos\phi+(z_gW-z_bB)\cos\theta\sin\phi \\ (z_gW-z_bB)\sin\theta+(x_gW-x_bB)\cos\theta\cos\phi \\ -(x_gW-x_bB)\cos\theta\sin\phi-(y_gW-y_bB)\sin\theta \end{bmatrix}$$

Where $W$ and $B$ is the force of gravity and buoyancy, respectively, on the vehicle, given by:

$$W = mg \tag{3.11}$$

$$B = \rho g \bigtriangledown \tag{3.12}$$

As the body-fixed frame reference will centered at the $C_B$ of the vehicle, it's terms can be ignored:

$$g(\eta) = \begin{bmatrix} W\sin\theta \\ -W\cos\theta\sin\phi \\ -W\cos\theta\cos\phi \\ -y_gW\cos\theta\cos\phi+z_gW\cos\theta\sin\phi \\ z_gW\sin\theta+x_gW\cos\theta\cos\phi \\ -x_gW\cos\theta\sin\phi-y_gW\sin\theta \end{bmatrix}$$

Now, all the parts to compute equation (3.6) for the roll motion are found:

**Added Mass**:

$$\tau_A(\dot{\upsilon},\upsilon)_K = -K_{\dot{v}}\dot{v} - K_{\dot{p}}\dot{p} + a_3v + a_2w + b_3q + b_2w \tag{3.13}$$

**Drag**:

$$\tau_V(\upsilon)_K = -K_{|v|v}|v|v - K_v v - K_{|p|p}|p|p - K_p p \tag{3.14}$$

**Restoring Forces**:

$$\tau_{g(\eta)K} = -y_gW\cos\theta\cos\phi + z_gW\cos\theta\sin\phi \tag{3.15}$$

Although the rotation of the thrusters induces a torque in the vehicle, which makes it travel with a small offset of roll, in this work, it will be treated as an external disturbance, so it will be ignored:

**Propulsion**:

$$\tau_{P_K} = 0 \tag{3.16}$$

Re-arranging these terms in (3.1), we get:

$$\begin{aligned} &I_x\dot{p} + (I_z - I_y)qr + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] = K_{\dot{v}}\dot{v} + K_{\dot{p}}\dot{p} \\ &- a_3v - a_2w - b_3q - b_2w + K_{|v|v}|v|v + K_v v + K_{|p|p}|p|p + K_p p - y_g W\cos\theta\cos\phi + z_g W\cos\theta\sin\phi \end{aligned} \tag{3.17}$$

Assuming a fully decoupled roll, in the sense that it is only affected by velocities and accelerations directly related to it, and for $\theta \approx 0^{\text{o}}$, this equation can be simplified:

$$(I_x - K_{\dot{p}})\dot{p} = K_{|p|p}|p|p + K_p p - y_g W\cos\phi + z_g W\sin\phi \tag{3.18}$$

### 3.6.2 Sway Motion

The sway component of the rigid body dynamics is defined by:

$$m[\dot{v} - wp + ur - y_g(r^2 + p^2) + z_g(qr - \dot{p}) + x_g(qp + \dot{r})] = Y_H + Y \tag{3.19}$$

The sway motion is a simple lateral motion for which there is already an example to follow. This example exists due to the fact that MARES has already two vertical thrusters and the model is similar, since the vehicle can be considered to be almost symmetric in all planes.

One of the main adaptations that needs to be done here is in the identification of the coefficients of the body of the vessel, namely in the determination of the lateral projection, which is the one that is going to be altered by the introduction of two orifices for the lateral thrusters. This projection is then used to determine the moments of inertia of the vehicle (although the moments of inertia around the $y$ and the $z$ axis are already considered to be similar), added mass coefficients and drag coefficients. As it was already mentioned, this work will not focus in these details, so it will be assumed that the coefficients are the same, although they obviously different in some extent. For the reader that wants to know how to solve this problem and compute new coefficients, the work **[13]** can and should be consulted.

Apart from the alterations mentioned above, other adapation passes through the integration of two new thrusters and their contribution in for the propulsion force $\tau_P = P \cdot f_P$, which for the

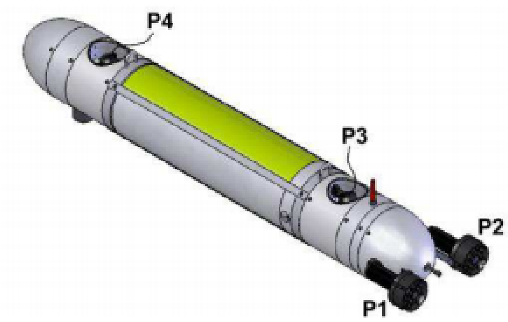



Figure 3.2: MARES thrusters configurations from [13]

current MARES configuration (see figure 3.2) are:

$$P = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ z_{P1} & z_{P2} & -x_{P3} & -x_{P4} \\ -y_{P1} & -y_{P2} & 0 & 0 \end{bmatrix} \qquad f_P = \begin{bmatrix} f_{P1} \\ f_{P2} \\ f_{P3} \\ f_{P4} \end{bmatrix}$$

Where matrix $P$ gives, for each DoF, the contribution of the force and momentum that each thruster applies, contemplating their position related to the body-fixed frame of reference.

So it can be easily understood that it is needed to add two thrusters to these matrices. In order to facilitate the comprehension of the following part, please note that the thrusters $P_3$ and $P_4$ will be called, respectively, $P_5$ and $P_6$ from now on. This makes sense because of the typical mathematical notation for the 3 main axis $\{x,y,z\}$. If this change was not made, these matrices would obey $\{x,z,y\}$.

The addition of two thrusters implies:

$$P = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ z_{P1} & z_{P2} & 0 & 0 & -x_{P5} & -x_{P6} \\ -y_{P1} & -y_{P2} & x_{P3} & x_{P4} & 0 & 0 \end{bmatrix} \qquad f_P = \begin{bmatrix} f_{P1} \\ f_{P2} \\ f_{P3} \\ f_{P4} \\ f_{P5} \\ f_{P6} \end{bmatrix}$$

The contributions of these additional thrusters will then be maximum for the Sway DoF, which is the objective. Although, as it can be seen by the analysis of the latter P matrix, their presence also contributes to the Yaw DoF and they will be ideal solution to actuate on this DoF. Ideally, the lateral thrusters should be implemented close to the vertical ones, so that the controller can be similar.

So now the equation (3.6) for the sway motion can be found:

**Added Mass**:

$$\tau_A(\dot{\upsilon},\upsilon) = Y_{\dot{v}}\dot{v} + Y_{\dot{p}}\dot{p} + Y_{\dot{r}}\dot{r} + a_3 p - a_1 r \tag{3.20}$$

**Drag**:

$$\tau_V(\upsilon) = -Y_{|v|v}|v|v - Y_v v - Y_{|p|p}|p|p - Y_p p - Y_{|r|r}|r|r - Y_r r \tag{3.21}$$

**Restoring Forces**:

$$\tau_g(\eta) = W\cos\theta\cos\phi \tag{3.22}$$

**Propulsion**:

$$\tau_P = f_{P3} + f_{P4} \tag{3.23}$$

Re-arranging these values and the ones in equation (3.9) in equation (3.6), we get:

$$\begin{gathered} m[\dot{v} - wp + ur - y_g(r^2+p^2) + z_g(qr-\dot{p}) + x_g(qp+\dot{r})] = Y_{\dot{v}}\dot{v} + Y_{\dot{p}}\dot{p} + Y_{\dot{r}}\dot{r} \\ + a_3 p - a_1 r + Y_{|v|v}|v|v + Y_v v + Y_{|p|p}|p|p + Y_p p + Y_{|r|r}|r|r + Y_r r + W\cos\theta\sin\phi + f_{P3} + f_{P4} \end{gathered} \tag{3.24}$$

As it can be seen, the full motion equation is quite complex so, in this work, it will be assumed that the sway motion is only due to the effect of the acceleration in the $y$ axis. This means that velocities in any other directions are null. This should give a good approximation of the linear behaviour of the vehicle.

It will also be assumed that the vehicle is, at first, stationary in the water with a null pitch and roll, which will contribute to further simplify the equation.

$$(m - Y_{\dot{v}})\dot{\upsilon} = Y_{|v|v}|v|v + Y_v v + f_{P3} + f_{P4} \tag{3.25}$$

# Chapter 4

# Implementation

In this chapter the discussion to select the final actuators, as well as their implementation, are going to be presented.

The Internal Rotating Mass, is the only option available (apart from even more thrusters) to give static roll ability and control to MARES, therefore it was an easy choice. However, its implementation and control won't be easy, and there is a lot of work do be done for this actuator since it is new for this AUV and a really recent technology. Moreover, due to the slender body of the vessel and the absence of fins to damp the rolling motion, the tuning of the IRM has to be precise, otherwise the vehicle will keep oscillating.

Regarding the thrusters solution adopted, an alternative would be to put only one thruster close to the center of gravity of the vehicle. Although this solution would probably do the job and is clearly cheaper (for the thruster is to be bought), in terms of energy efficiency and control, the two thruster solution is better, as it was already considered in section 2.2, due to how power consumption evolves with drag. This solution also represents some redundancy to the yaw DoF and, if the IRM is developed, it can also represent another way for the vehicle to move upwards, in case that the two vertical thrusters fail for some reason. Given the fact that two vertical thrusters are already implemented, two horizontal ones should be of easy implementation, for the model for this kind of actuators already exists and it just needs some adaptation to turn it 90$^{o}$.

The objective of the following sections is to analyse the thrusters solution and to design an IRM that can be applied to any AUV, under some assumptions that will be pin pointed. The first step is optimize the displacement of the center of gravity of the mass to be added, for the greatest challenge in implementing this actuator is the space and weight constraint inside an AUV, so there is a need to choose the best shape for the mass so that the $C_G$ is dislocated as much as possible from the center of buoyancy.

It is utterly important to mention that the majority of this study is based on **[62]**, which is, as far as I know, the only published work about an internal rolling mass for a torpedo shaped AUV and in **[13]** where the already applied vertical thrusters system is reviewed.

## 4.1 Internal Rolling Mass

To properly build an Internal Rolling Mass actuator to control the roll of an AUV, by changing the position of the $C_G$, it is first needed to model the whole system so that it is as efficient as possible, since the power management in this kind of vehicles is a great challenge. Furthermore, since the system is to be modular with the objective of using it whenever is needed, proper power management enables it to be used even with the heavier of the payloads.

In this section this problem is going to be approached by first making an easy to understand diagram to express how the system works. Next the equations that rule the motion roll of the AUV based on the IRM are going to be shown and developed to further find the best solution.

***Assumption*** *- The center of buoyancy and gravity of the AUV are able to be trimmed such that it is possible to coincide them with each other. In this way, there is no offset to the position of the center of gravity without this actuator, and its place is fully controlled by it.*

This assumption can be easily explained with the help of the equation for the general distance between the center of the body fixed frame (which is in the center of buoyancy of the vehicle) and the center of gravity.

$$R_{CG} = \frac{m_{vehicle} r_{vehicle}}{M} + \frac{m_{IRM} r_{IRM}}{M} \tag{4.1}$$

The assumption tell us that $r_{vehicle}$ is zero, due to the fact that such trimming of the center of gravity and buoyancy of the vehicle without the IRM is possible. In this way, the equation above is just:

$$R_{CG} = \frac{m_{IRM} r_{IRM}}{M} \tag{4.2}$$

Under the assumption above, the system gets a lot simpler than if the $C_B$ and $C_G$ of the vehicle had a prior offset distance between them. Evidently, this is relative, this means that if this distance compared to the whole inner radius of the AUV can be neglected, it will not interfere as much. Unfortunately, a lot of AUVs are relatively small, for example, MARES has only 20 centimeters of diameter, and its $C_G$ and $C_B$ are separated by around 5 millimeters. In this case, it is worth to take some time to trimmer the vehicle so that the roll is only affected by the IRM and the induced torque from the rotation of the thrusters. Although this implies that the vehicle will not be as stable at it was before with 0 degrees of roll, this problem is compensated with the actual roll control.

Another aspect to take into account when designing the actuator is that its axis of rotation crosses the center of buoyancy of the vehicle and that the whole system is symmetric regarding the $\{y_b\ z_b\}$ plane of the body fixed frame. In this way, the $C_G$ will never vary in the $x$ axis, assuming the value 0 for the body-fixed reference frame and, therefore, it is possible to simplify the problem to a 2D plane.

Given all the factors above, the problem can be modeled by figure 4.1.

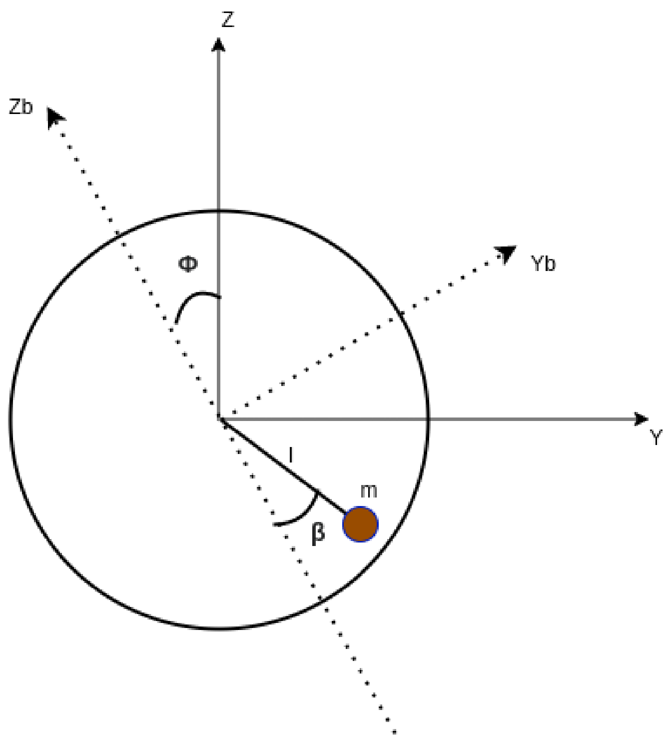



Figure 4.1: IRM Model in the body-fixed frame of reference

In the figure we can see a cross section of the body of the vehicle centered at the center of buoyancy ($Y_b$ = 0; $Z_b$ = 0), a point mass with mass $m$ which represents the center of mass of the IRM, the distance between the $C_B$ of the vehicle and the single point mass is given by $l$ and the angle of rotation $\beta$.

The variation of $\beta$ will effectively alter the position of the $C_G$ of the vehicle, which will correspond to the change of the point of application of the force of gravity (seen in figure 4.2). Due to the positions of $C_B$ and $C_G$, there will be an induced torque ($\tau$) that will result in the rotation the AUV around the $C_B$. Note that actual distance between $C_B$ and $C_G$ is just a part of $l$, which is because of the mass of the vehicle which is relatively much greater than the added mass.

To understand how this will change the roll of the vehicle, the positions of the new $C_G$ needs to be derived. With the help figure 4.1, we can derive the position of the default center of gravity of the vehicle in the body-fixed frame of reference, where the value for $x_g$ is 0 due to symmetry as it was explained earlier, and $y_g$ and $z_g$ can be found with:

$$x_g = 0 \tag{4.3}$$

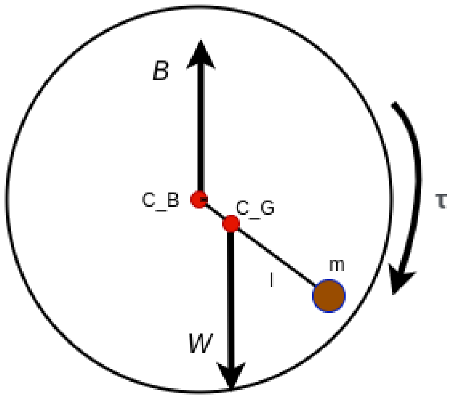



Figure 4.2: IRM induced torque in roll due to the relative positions of B and W in the body-fixed frame of reference

$$y_g = \frac{m}{M} \cdot l \cdot \sin(\beta) \tag{4.4}$$

$$z_g = -\frac{m}{M} \cdot l \cdot \cos(\beta) \tag{4.5}$$

Where $M$ is the total mass of the vehicle and $\beta$ is the angle of rotation between the IRM and the $z$ axis.

These equations will help in choosing the adequate mass to be implemented because the main aspect of it is the maximization of both $y_g$ and $z_g$.

An adequate mass is the one that, for the given constraints, increases the distance between the $C_B$ and the $C_G$ of the vehicle the most, which increases the torque to rotate the vehicle. These constraints are:

- Inner radius of the vehicle;
- Maximum length for the IRM;
- Total mass that can be added;

## 4.2 Designing the IRM

When it comes to the actual design of the IRM, we have to consider not only the displacement of the $C_G$, but also how simple and robust it is. The best option is probably the one showed in **[62]**, in which the rotation of all battery sector (which is one of the heaviest part of the AUV) is used to move the $C_G$ around the $x$ axis. However, in this work, the aim is to develop a standalone IRM module.

For the shape of the IRM, we chose the annulus section (see fig. 4.3). This shape was considered among others like a spherical pendulum, cubic pendulum, circular section, etc. The annulus section was the chosen one because it does not necessarily need a beam connected to the shaft of the motor to actuate. Otherwise, the beam had to also be modeled. The annulus section also let us optimize its dimensions so that its center of gravity is as far away from the center of buoyancy as possible.

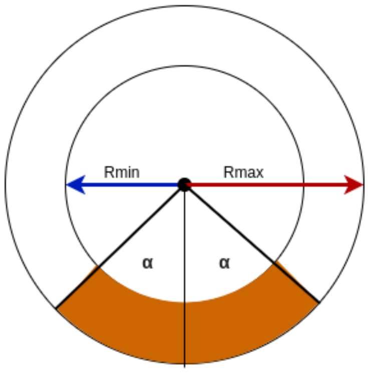



Figure 4.3: Annulus Section

The figure represents once again a cross section of a torpedo shaped vehicle, and an annulus section mass would rotate along the inner radius of the vehicle, which is going to be called $R_{max}$ here.

This geometry for the IRM permits the optimization of the displacement of the $C_G$ of the vessel because the center of mass of the IRM ($CG_{annulus}$) itself is controllable by changing the two variables that rule it: the difference between $Rmin$ and $Rmax$, and the angle $\alpha$.

Given that this geometry can be elongated along the $x$ axis, it is considered that it will use all the space that can be used without putting in risk the stability of the vehicle. This means that the length for the IRM module will be as long as it can be, so that the mass can be thin as possible, meaning that its $C_G$ will be further away from the center of buoyancy of the vehicle, in the $z$ axis of the body fixed frame. This will increase the torque that the IRM creates to roll the AUV.

Also, the mass $m$ and maximum radius $R_{max}$ of the IRM will also be the greatest that can be used. This means that, knowing which material will be used and its density, it is possible to know the volume that the IRM will occupy inside the vehicle, and using all inner radius of the vessel will further separate the $C_B$ of the AUV and the $C_G$.

## 4.3 IRM Optimization

For the optimization of the IRM, let us consider the variables from table 4.1.With these variables in mind we can also start to derive the equations needed to build the IRM.

$$V = \frac{m}{d} \tag{4.6}$$

Table 4.1: Values of IRM

| | | |
|---|---|---|
| $V$ | = | Volume of the IRM |
| $A$ | = | Area of the cross section of the IRM as represented in 4.3 |
| $M$ | = | Mass of the whole AUV |
| $m$ | = | Mass of the IRM |
| $R_{max}$ | = | Maximum radius that the mass can have |
| $R_{min}$ | = | Optimizable variable that refers to inner radius of the annulus section |
| $\alpha$ | = | Optimizable variable that refers to the angle between the vertical axis of the body-fixed frame and one of the ends of the IRM |
| $b$ | = | Length along the X axis of the IRM, which is the maximum achievable |
| $l$ | = | Distance between the CB of the vehicle and the CG of the IRM |

$$A = \frac{V}{b} \tag{4.7}$$

Where $d = 11340$ which is the density of lead in kilograms per cubic meter.

Now the area of the cross section must be found. It is a really simple calculation, because it is the difference between the areas of both circumferences (of radius $R_{max}$ and $R_{min}$) multiplied by the fraction of half of a circumference implied by $\alpha$:

$$A = (R_{max}^2\pi - R_{min}^2\pi)\frac{\alpha}{\pi} = (R_{max}^2 - R_{min}^2)\alpha \tag{4.8}$$

Now the equation for the $RG_{annulus}$, which is the distance between $CG_{annulus}$ and the center of the body-fixed frame of reference, which coincides with $C_B$, can be derived.

As told in [68], if one knows how to compute the center of mass for a circular sector, then the problem of finding the center of mass of a annular section ($z_i$, seen below) becomes simple.

$$z_i = \left(\frac{2}{3}\right)\left(\frac{\sin\alpha}{\alpha}\right)r_i \tag{4.9}$$

For two centers of mass:

$$M_i r_i + M_j r_j = (M_i + M_j) r_{combined} \tag{4.10}$$

Now if we assume: $M_{min}$ is the mass circular sector with radius $R_{min}$ and $M_{max}$ is the mass circular sector with radius $R_{max}$, then:

$$M_{max}R_{max} - M_{min}R_{min} = (M_{max} - M_{min})r_{combined} \tag{4.11}$$

$$\frac{M_{max}R_{max} - M_{min}R_{min}}{M_{max} - M_{min}} = r_{combined} \tag{4.12}$$

Due to the fact that the IRM has a uniform density, it is known that its mass is proportional to the surface area in a 2D plane, which is how it will be analyzed. So, $M_{min} = \alpha R_{min}^2$ and $M_{max} = \alpha R_{max}^2$. So, with $r_{annulus} = r_{combined}$:

$$RG_{annulus} = \left(\frac{2}{3}\right)\left(\frac{sin(\alpha)}{\alpha}\right)\left(\frac{R_{max}^3 - R_{min}^3}{R_{max}^2 - R_{min}^2}\right) \tag{4.13}$$

These two last equations (4.8) and (4.13) are the ones we need to optimize $R_{min}$. The first one, given that the IRM is going to have a fixed $V$ and $b$, implies a condition that has to be met which is a fixed area ($A$) for the cross section of the IRM. It becomes clear that the denominator of equation (4.13) is three times the area of the cross section and we can also replace the $\alpha$ inside the sin function with a variation of equation (4.8). We end up with an equation that outputs $RG_{annulus}$ in function of $R_{min}$, which is the only variable in the function:

$$RG_{annulus} = \left(\frac{2}{3}\right)\left(\frac{sin\left(\frac{A}{R_{max}^2 - R_{min}^2}\right)(R_{max}^3 - R_{min}^3)}{A}\right) \tag{4.14}$$

It is now possible to get the plot for this equation using software and, therefore, find the $R_{min}$ value for which $l$ is the maximum possible, given the constraints of the vehicle.

The values for MARES are show in table 5.1.

Table 4.2: Calculated values of IRM

| | | |
|---|---|---|
| $V$ | = | $88{,}18 \cdot 10^{-6} m^3$ |
| $A$ | = | $17{,}63 \cdot 10^{-4} m^2$ |
| $M$ | = | 42 kg |
| $m$ | = | 1 kg |
| $Rmax$ | = | 0.08 m |
| $b$ | = | 0.05 m |

By using these values to compute equation (4.14), we can derive the displacement of the $RG_{annulus}$ for different values for $R_{min}$. The plot for this function is represented in figure 4.4.

The analysis of this plot and the computation of its maximum value, outputs the greatest $RG_{annulus}$, which is also $l$ in figures 4.2 and 4.1.

$$RG_{annulus} = 0.066 \text{ m}$$

With this value, and equation (4.8), it is also possible to find the value for $\alpha$:

$$\alpha = 0.857 \text{ rads}$$

And the value for $l$:

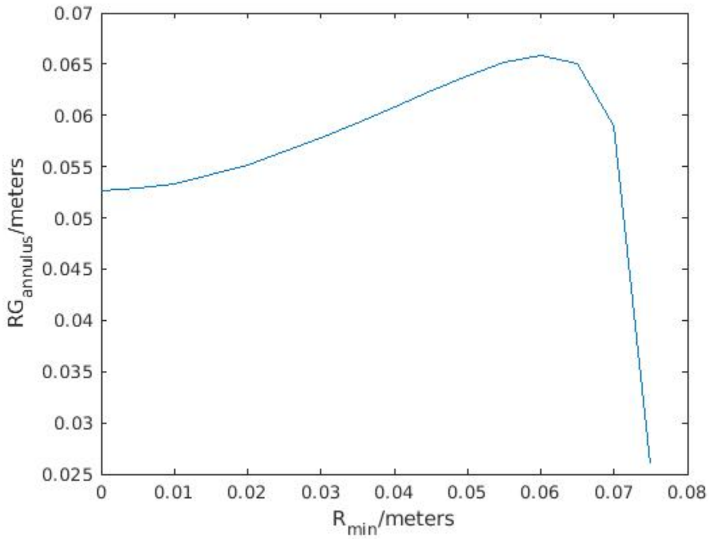


Figure 4.4: $RG_{annulus}$ variation in function of R$_{min}$

$$R_{min} = 0.061 \text{ m}$$

The total distance between the $C_B$ and $C_G$ can be given by equations (4.4) and (4.5), for $\beta = 0$:

$$y_g = \frac{1}{43} \cdot 0.061 \cdot \sin(0) = 0 \text{ m}$$

$$z_g = -\frac{1}{43} \cdot 0.061 \cdot \cos(0) = -0.00142 \text{ m}$$

Finally, the maximum rolling velocity is determined by:

$$p_{max} = \sqrt{\left(\frac{m}{M}\right)\left(\frac{l \cdot W}{K_{p|p|}}\right)} \tag{4.15}$$

## 4.4 Lateral Thrusters

As it was already mentioned, the implementation of the lateral thrusters should be of little complexity, since it is basically the rotation of 90º of the already existing vertical thrusters. The selected propellers, motors and even the hull shape, can be the same.

Two terms that are important to compute in order to make sure that the component selection is the best, are the maximum sway linear velocity and the maximum yaw angular velocity, given by the actuation of the lateral thrusters alone. The already implemented thrusters in MARES have a maximum actuation force of around 21.5N : $F_{pmax} = 21.5N$

For the lateral velocity, we assume that the vehicle travels at a constant velocity $v$ (after $y_B$) with a null yaw angle ($\psi = 0$). Also, for the velocities for the sway DoF, we can ignore the linear drag term $Y_v v$, which will have low values when compared to the quadratic term. Given this, we can solve for the maximum sway velocity **[13]**:

$$-Y_{v|v|}v|v| = F_{P3} + F_{P4} = -1.13 \cdot 10^2$$

And thus, the maximum sway velocity comes from:

$$v_{max} = \sqrt{\frac{2F_{pmax}}{-Y_{v|v|}}} = 6.17 \cdot 10^{-1}\text{rad/s} \tag{4.16}$$

For the rotational velocity in Yaw, we have to compute the contribution from only the lateral thrusters. This is due to the fact that these are better to control this DoF and the axis of rotation of both these acutators systems is different for the Yaw Dof. The actuation of both at the same time would give unexpected and highly non linear responses. The differential actuation of the main thrusters should still be used for minor alterations of the heading during the mission. However, for the pure Yaw control, only the lateral thrusters should be used.

# Chapter 5

# Roll Control

## 5.1 Transfer Function

To actuate the IRM, a controller for the variation of $\beta$ angle is needed in order to change the position of the $C_G$ of the vehicle. This variation was already defined in equation (4.14). Now that it is know where is the position of the new $C_G$ after the rotation of the IRM, using equation (3.18), which has this position as parameters, we can compute a transfer function for the roll of the vehicle based on the angle input $\beta$ given to the system. To make it easy to understand, the equations needed should be revisited first.

$$(I_x - K_{\dot{p}})\dot{p} = K_{|p|p}|p|p + K_p p - y_g W \cos\phi + z_g W \sin\phi \tag{5.1}$$

$$y_g = \frac{m}{M} l \sin\beta \tag{5.2}$$

$$z_g = -\frac{m}{M} l \cos\beta \tag{5.3}$$

Let us assume that the vehicle starts with the initial $C_G = [x_g\ y_g\ z_g]$. Remember that $x_g$ is always null. The new $C'_G = [x'_g\ y'_g\ z'_g]$ of the vehicle after the rotation of the IRM will be given by:

$$y'_g = y_g + \frac{m}{M} l \sin\beta \tag{5.4}$$

$$z'_g = z_g - \frac{m}{M} l \cos\beta \tag{5.5}$$

So now it is possible to use both the motion equation and the $C_G$ position equations to derive the transfer function that will enable the creation of the roll model for the vehicle:

$$(I_x - K_{\dot{p}})\dot{p} = K_{|p|p}|p|p + K_p p - y'_g W\cos\phi + z'_g W\sin\phi \tag{5.6}$$

$$(I_x - K_{\dot{p}})\dot{p} = K_{|p|p}|p|p + K_p p - (y_g + \frac{m}{M}l\sin\beta)W\cos\phi + (z_g - \frac{m}{M}l\cos\beta)W\sin\phi \tag{5.7}$$

Also note that $\dot{p} = \ddot{\phi}$ and $p = \dot{\phi}$, so (5.7) can be:

$$(I_x - K_{\dot{p}})\ddot{\phi} = K_{|p|p}|\dot{\phi}|\dot{\phi} + K_{\dot{\phi}}\dot{\phi} - (y_g + \frac{m}{M}l\sin\beta)W\cos\phi + (z_g - \frac{m}{M}l\cos\beta)W\sin\phi \tag{5.8}$$

In order to obtain a transfer function that outputs $\phi$ in function of $\beta$, it is first needed to obtain a linearization of the equation (5.8). As this is a pure analytical approach, it is first needed to make some assumptions.

***Assumption*** *- The rotation of the IRM will be slow. This ensures that the vehicle will roll smoothly, following the rotation of the IRM, and the difference between $\beta$ and $\phi$ will be kept small.*

***Assumption*** *- Due to the symmetry of the vehicle, the rolling motion will not be affected by the rotation angle of the body-fixed referential frame. As long as the x axis of the body-fixed frame is coincident with the x axis of the vehicle, the roll motion will be independent.*

The assumptions made make it possible for the equation (5.8) to be linearized around a small $\beta$ and $\phi$. This is due to the fact that the gravitational pull will always lead to vehicle stabilizing with the IRM at the bottom, no matter the input and the initial position. Besides, if the rotation of the IRM is slow, it can be assumed that the vehicle has enough time to roll, following the position of IRM. This practically implies that $\beta$ and $\phi$ can always be assumed to be small.

Following this, the linearization of the function is around the operating points $\beta \approx 0$ and $\phi \approx 0$, which imply that $\sin\phi \approx \phi$ and $\cos\phi \approx 1$, as well as $\sin\beta \approx \phi$ and $\cos\beta \approx 1$. This approximation will also lead to $y_g$ being small, and ignored. Also, let us assume that the quadratic drag $K_{|p|p}|p|p$ can be ignored and only the linear drag $K_p$ takes part in the equation. This is due to the fact that the roll velocity will be really small, so the quadratic term can be neglected when compared to the linear term. This makes it possible to derive the transfer function that outputs $\phi$ in function of $\beta$, using the Laplace Transform.

$$s^2\phi(s)[(I_x - K_{\dot{p}})] = s\phi(s)(K_p) - (y_g + \frac{m}{M}lW)\beta(s) + (z_g - \frac{m}{M}lW)\phi(s) \tag{5.9}$$

$$\phi(s)[s^2(I_x - K_{\dot{p}}) - s(K_p) - (z_g - \frac{m}{M}lW)] = (-\frac{m}{M}lW)\beta(s) \tag{5.10}$$

$$\frac{\phi(s)}{\beta(s)} = \frac{(-\frac{m}{M}lW)}{s^2(I_x - K_{\dot{p}}) - s(K_p) - (z_g - \frac{m}{M}lW)} \tag{5.11}$$

Transfer function (5.11) can be described by its coefficients:

$$\frac{\phi(s)}{\beta(s)} = \frac{k}{as^2 + sb + c} \tag{5.12}$$

Table 5.1: Calculated values for the Roll Transfer Function

| | | |
|---|---|---|
| $k$ | = | -0.5978 |
| $a$ | = | 0.3602 |
| $b$ | = | 0.0636 |
| $c$ | = | 0.6 |

## 5.2 System's Specifications

Now some realistic system requirements should be created to act as objectives for the controller that is going to be implemented. As it was shown in the state of the art for this work, AUVs are slow moving robots and that does not come as a disadvantage. Due to the dynamics of underwater systems, there is no need in gathering data in a precise time or location. This means that AUV actuators can take their time to control the vehicle in a stabilized way. For this reason, the IRM can be a slow acting actuator, which will also help in diminishing overshoots. Given these facts, realistic requirements are:

- Rise time - under 45 seconds;
- Settling time - under 60 seconds;
- Overshoot - less than 10%.

The idea is to use a servo motor to control the angle of rotation of the IRM. However, it will not be introduced here in this phase as the vehicle response to a step input should be slower than the motor's response. This implies that the dominant poles that will dictate how fast the response

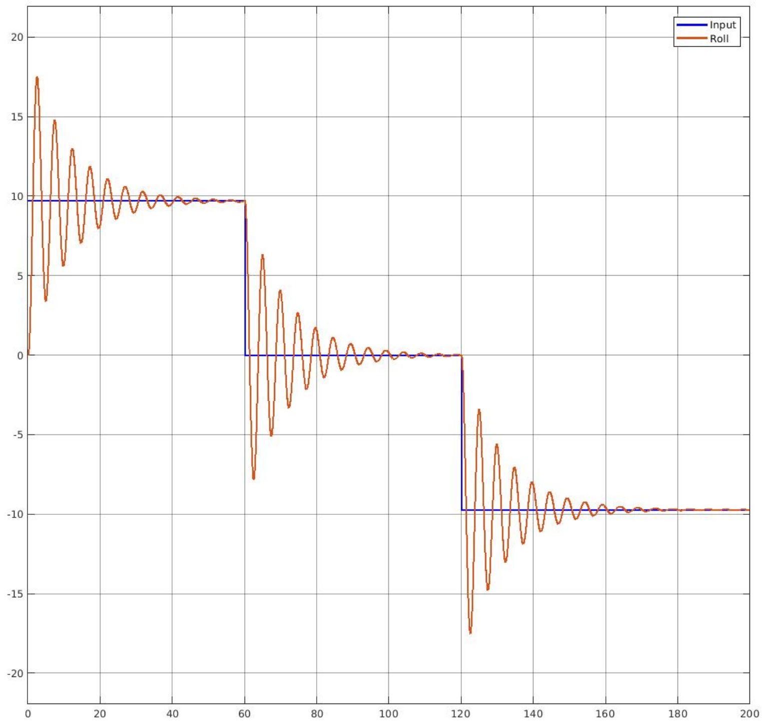



Figure 5.1: Open loop response in time (seconds) of roll of the vehicle (*phi*) to a three step input to IRM

is are going to be the ones defined here, so the later introduction of the servo to the system should not matter.

## 5.3 Controller Design

The characteristics that define this open loop transfer function are:

- Rise time - 0.85 seconds;
- Settling time - 44.08 seconds;
- Overshoot - 80%;

These values can be graphically shown by the response to a three step input [10º;0º;10º] in open loop. Note that the system had time to stabilize before the next step change.

By analysing figure 5.1, it can be seen that the vehicle already has a stable response to a step input in the IRM, which was expected. However, the great overshoot percentage induces oscillations in the vehicle which are undesirable.

Now we are able to start designing a Proportional-Integrator Controller (PI Controller) for the rotation of the IRM. This controller will help in stabilizing the vehicle by increasing the damping coefficient. In this way the vehicle will not oscillate as much, which is a problematic for MARES

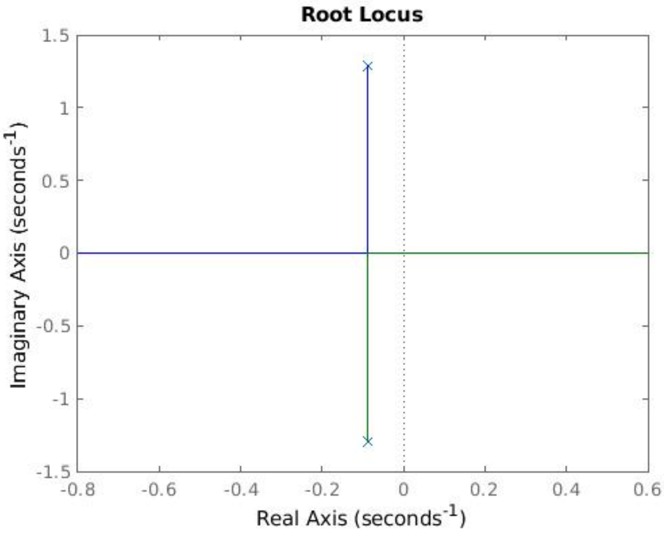



Figure 5.2: Root Locus of the open loop system

since it does not have any control surfaces that increase the rolling drag. The PI controller also should reduce the steady state error to zero.

The root locus method will be applied in order to analyse and optimize the response of the vehicle to the rotation of the IRM.

The open loop transfer function of this system has two complex-conjugate poles situated at:

$$p_1 = -0.0883 + 1.2880i$$

$$p_2 = -0.0883 - 1.2880i$$

Which can be seen by the open loop root locus plot in figure 5.2.

Let us try to simplify the application of the PI controller by defining the differences in poles and zeros that it will introduce to the system.

The control law that defines a PI control is given by:

$$u(t) = K_p e(t) + K_I \int_0^t e(\tau) d\tau \tag{5.13}$$

Where $u(t)$ is the controller input, $e(t)$ is the error, which is the difference between the input and the output of the system, and $K_P$ and $K_I$ are the proportional and integral coefficients, respectively. After Laplace Transform, the equation becomes:

$$U(s) = K_P E(s) + K_I \cdot \frac{1}{s} E(s) \tag{5.14}$$

$$\frac{U(s)}{E(s)} = \left( K_P + \frac{K_I}{s} \right) \tag{5.15}$$

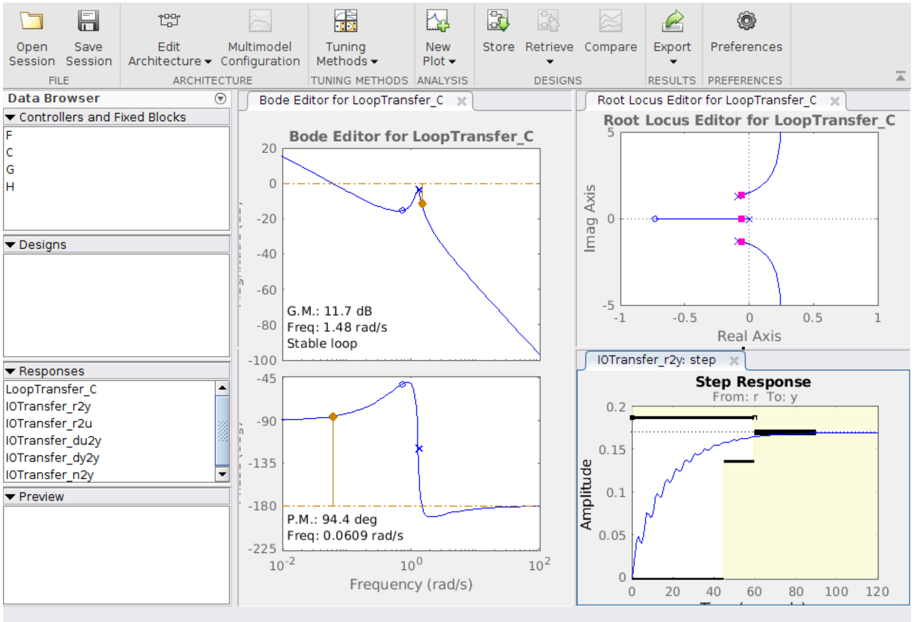



Figure 5.3: Control System Designer Toolbox - PI Controller

$$\frac{U(s)}{E(s)} = \frac{K_P(s + \frac{K_I}{K_P})}{s} \tag{5.16}$$

So the Transfer Function that defines the controller is:

$$C(s) = \frac{K_P(s + \frac{K_I}{K_P})}{s} \tag{5.17}$$

As it can be extrapolated from the function, this will add a pole in the origin and a zero at $\frac{K_I}{K_P}$. And now that this has become a simple zero placement, we can use software just like MATLAB Control System Designer Toolbox, which permits to add zeros and poles to the original function and see in real time the step response of the system, while defining the system requirements. In figure 5.3, it can be seen the Toolbox with the plots that help in building a proper controller. The system requirements are defined in yellow in the step response of 10º (0.17 radians). Note that, in order to properly consider the $\beta$ angle rotation, it is needed to introduce a negative gain to the closed loop function, otherwise the output will just sum infinitely, getting unsteady.

As it can be seen in the figure, there is an added pole in the origin and a real zero. These two define the contribution of the PI controller, and the only task left is to move the zero in the real axis and the tune the gain of the controller in order to have the desired response. Note that the system is steady for a limited set of gains. In the figure, this is already achieved.

The final gain and integral coefficients are: $K_P = 0.14$ and $K_I = 0.10$.

The step response for this transfer function with the PI controller is not optimal. The low real values for the poles give the system a low damping ratio, making it oscillate for a long period of time. Although it is quite a bad response, it is not unexpected. This response is due to the fact that

MARES does not have any control surfaces like fins. It has a slender body and the only protruding parts are the sonar hull and the antennas which are not enough to dampen the roll motion. This makes it clear that a way of optimizing the roll motion for MARES would be to implement fins so that the vehicle would be more stable to roll angle changes. Despite the fact that, by having fins, the required energy to roll the vehicle would increase, this is would be a good solution as the roll motion is not meant to be frequent. The main objective is that the vehicle has a null steady state error so that it can perform maneuvers and tasks with a given roll angle.

As it is not possible to add fins to the vehicle for now, their influence is going to be simulated by adding a Derivative term to the controller, making it a PID. This term will increase the damping ratio of the system. The controller should also be the solution to implement to the IRM until MARES has fins.

The equations that define a PID controller are:

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{de(t)}{dt} \tag{5.18}$$

Where $K_D$ is the derivative coefficient. After Laplace Transform, the equation becomes:

$$U(s) = K_P E(s) + \frac{K_I}{s} E(s) + K_D s E(s) \tag{5.19}$$

$$\frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s \tag{5.20}$$

$$\frac{U(s)}{E(s)} = \frac{K_P s + K_I + K_D s^2}{s} \tag{5.21}$$

So the Transfer Function that defines the controller is:

$$C(s) = \frac{K_D s^2 + K_P s + K_I}{s} \tag{5.22}$$

This means that the PID controller is based in the same pole at the origin that was already seen and two extra zeros, potentially complex. To build this PID controller, the same technique based on MATLAB System Controller Design was used, with the same requirements.

The final gains for this PID controller are: $K_P = 0.110$, $K_I = 0.096$ and $K_D = 0.072$. The final step response can be seen in figure 5.4.

## 5.4 Results

In figure 5.5, it is shown the expected behaviour for the roll movement with the same inputs from figure 4.4, for PI controller. Note that the servo motor is not considered. This is because the time

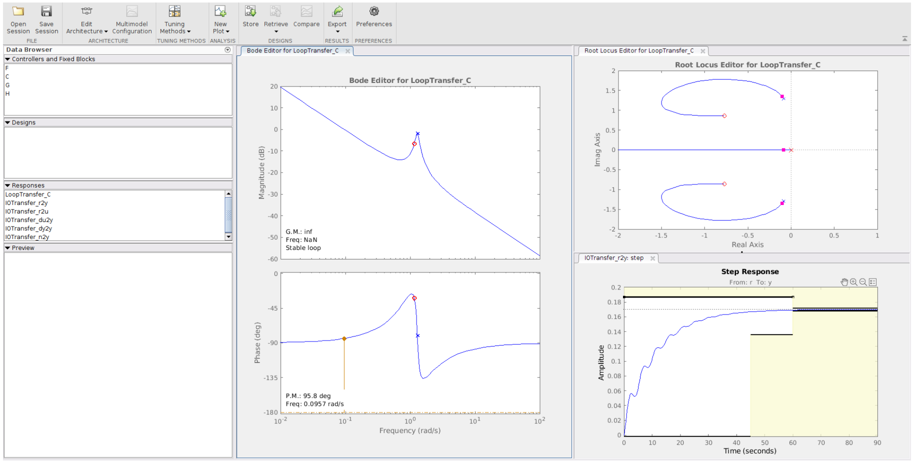



Figure 5.4: Control System Designer Toolbox - PID Controller

constant of the servo motor will be relatively much smaller than the time constant for the AUV, so it can be approximated by a common step function.

As it can be seen, this response oscillates a lot, but it is shown that the PI controller can diminish the steady state error to zero. Also, these oscillations are relatively small when compared to the whole rotation.

The response for a 10º input in the model of the whole vehicle is shown in figure 5.6. This response is not much different from the model that was done, but the oscillations seem to take a lot of time to stop. This is why a PID controller has been made.

With the PID controller the response is much better (see figure 5.7). This is due to the fact that this controller permits the tuning of the damping ratio of the system. This also shows how the fins would help, for their influence would also be the increment of the damping ratio.

It is also important to note that the system was tested for more angles of rotation and not only 10º. The response was similar in every tested angle. Furthermore, this model was also tested for a moving vehicle for which the stability was reached sooner. The reason for this is that movement induced drag is most likely helping in stabilizing the roll of the vehicle, making it achieve a null steady state error sooner.

The only task left is to choose an actuator capable of rotating the mass. The required maximum torque to move that mass is given by:

$$\tau_{max} = l \cdot m \cdot g$$

Which for the calculated mass is $\tau_{max} = 0.5978$Nm. This implies that the chosen servo should handle around 6kg/cm. As a secure choice, and since servo motors aren't an expensive option, the chosen actuator is MG996R 10 kg Servo from Tower Pro. This actuator can output a torque equivalent of 11kgf/cm which should be enough for this application. This constant time, as predicted, is far greater than the constant time of the vehicle, so it was a correct assumption to take the servo actuation for a step function.

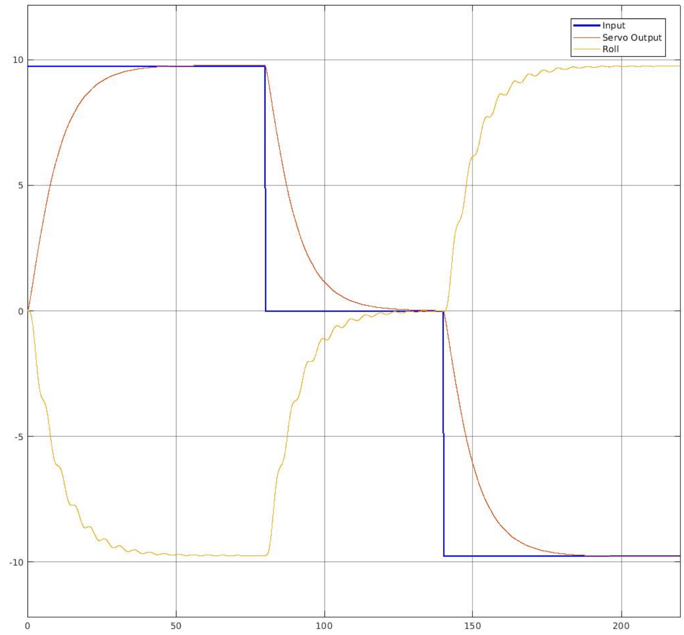



Figure 5.5: IRM Actuation Plot with a PI controller - angle response (*phi*) is in function of time (seconds)

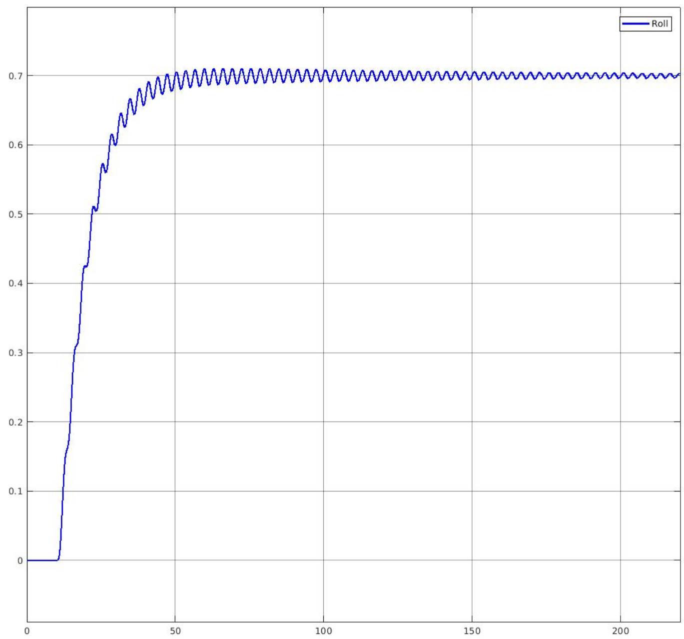



Figure 5.6: AUV roll response (*phi*) in time (seconds) to a 0.7 radians step input in the model of the whole AUV with the PI controller

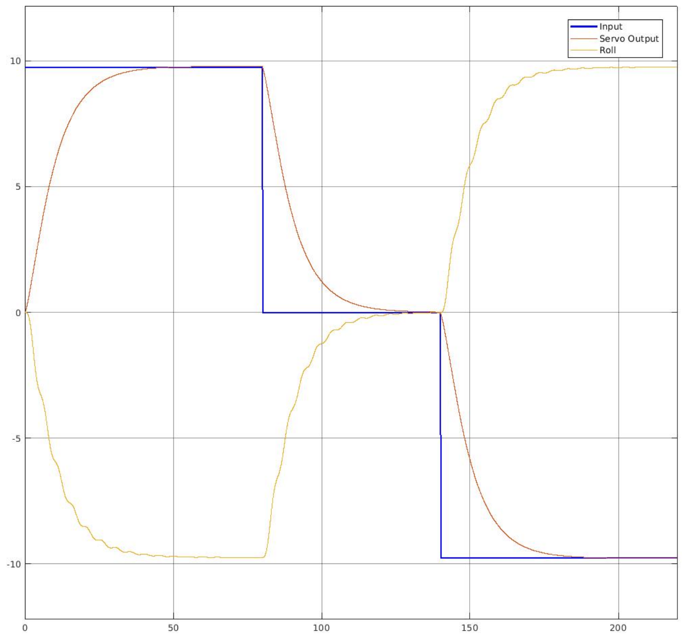



Figure 5.7: IRM Actuation Plot with a PID controller - angle response (*phi*) is in function of time (seconds)

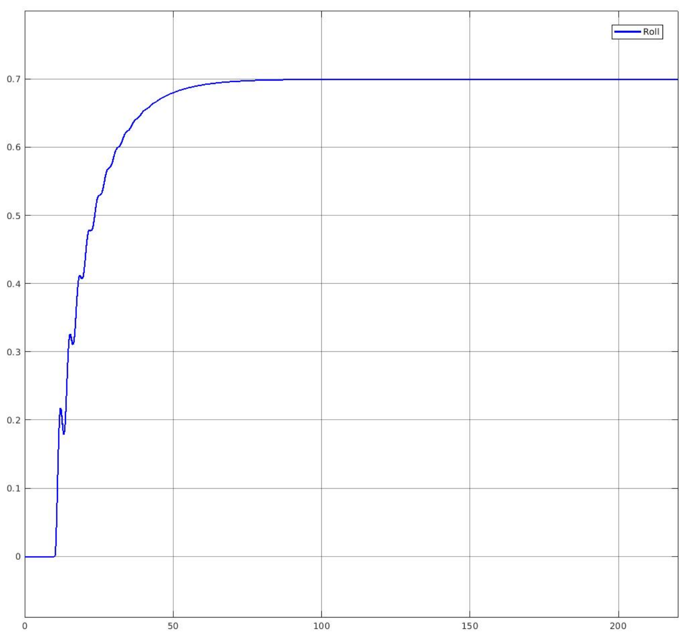



Figure 5.8: AUV roll response (*phi*) in time (seconds) to a 0.7 radians step input in the model of the whole AUV with the PID controller

# Chapter 6

# Conclusions and Future Work

## 6.1 Conclusions

This work is a manual for the reader that wants to know how and where the AUVs are used and how can they help in underwater tasks in various fields. The rich state of the art visits most of the applications for these kinds of vehicles, giving details on how they are used. Furthermore, it also reviews the actuators used nowadays and their advantages and disadvantages. Also, it gathers good quality literature for the reader that wants further knowledge about the topic.

In this work is demonstrated how to properly model an AUV for 6 Degrees of Freedom, by revisiting literature that shows how to control in the common 4 DoF and then stating the steps that are needed to take in order to get the full control of the system. Here can be found state space notation common in AUV systems and how to work with it to model the physical states that the vehicle can be in. Although simplistic, due to time constraints, the work done here follows every crucial step to a proper modeling of the system.

Two proposals of actuators, one for each missing DoF are presented. One, the lateral thrusters, should be of easy implementation, for this actuator is not new technology for these vehicles. Plus, the AUV that serves as an example, MARES, already has two vertical thrusters that can be replicated to implement the horizontal ones. Although it is not shown how to implement, there is an alternative which consists in using a single thruster for this DoF. The idea is to put it in the center of gravity of the vehicle, so that it can move the vehicle sideways without rotating it. Despite not showing the implementation of this single thruster, one should be able to use this work as a guideline, for the implementation process is the same for one or two thrusters.

The other one, an Internal Rolling Mass, capable of changing the roll angle of the vehicle is a quite complex actuator to implement. However, it is shown that a relatively light mass is sufficient to change the steady state roll angle for an AUV. The IRM needs a full review of the common center of gravity centered model for the vehicle and re-calculation of a lot of parameters. Even though this work skipped these calculations, it showed how to properly design an optimum IRM for any kind of vehicle, which is a great contribution for other colleagues that want to implement such actuator on other vehicles. Of course, as this actuator was not physically implemented, there will still be work to be done on it and probably some aspects that were not accounted for in this work.

Regarding the control of this actuator, it was not a simple task. At first the PI controller seemed a good option to take, since it should be sufficient for the vehicle to reach a steady state error of zero. Although this thought was not wrong, it proved no enough. The controller led the system to zero error but it took too much time to do it, not being able to nullify the oscillations. This was an unexpected result but, after some analysis it made sense. Due to the slender body of MARES, without any control surfaces, the vehicle had no way to dampen the roll motion. One of the solution is to had some fins. Although this implies that the IRM needs more power to move, the objective of this actuator is to have a null steady state error, and stabilize the AUV in a given roll angle. Since there is no possibilities of implementing fins in MARES due to time constraints, the adopted solution was to use a PID, which gave more promising results. The adopted approach of using the Matlab Simulink Software to develop and simulate the controller proved to be adequate for this work, for it has control tools that permit a flexible controller design.

To sum up, this work can act as a tutorial for the reader that wants to control and implement an AUV with 6 DoF, by gathering important literature for the common 4DoF and showing how to design the rest of the system.

## 6.2 Contributions

The nomenclature used in this work is widely used in the literature of this area of study, so it is easily understood by the rest of the scientific community that wants to further develop the advances made. The main contributions of this work to the rest of the scientific community are:

- Gathered literature about AUV missions and actuators;
- AUV body fixed frame of reference transition from the common $C_G$ centered to the $C_B$;
- Optimized Internal Rolling Mass design;
- AUV mathematical model adaptation;
- IRM controller design;

## 6.3 Future Work

As was mentioned throughout the entire work, this is a simplistic approach that aims to give a general answer to the problem of giving an AUV 6 degrees of freedom. Although showing the entire steps, the simplified sections need to be analysed in a more detailed manner to properly model and design actuators that permit the vehicle the movement in all directions and rotations.

Nevertheless, this work has showed that it is possible for a vehicle like MARES to be controlled in all 6 DoF, confirming that the implementation in the real vehicle is promising and it is also the next step. Adding to this, in order to properly control the real vehicle, the coefficients should be recalculated to make sure that everything is as good as it can be.

After the proper implementation in the vehicle, new opportunities are opened for the scientific community. For example, what was stated in the motivation of this work, an AUV that can rotate to enable its sonar to look for the ice sheet above it when doing missions under ice, can be tested. Not only this, but the various missions reviewed in the state of the art of this work that would benefit of a 6DoF AUV, can be improved, regarding efficiency and accuracy.

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# Appendix A

# Motion Equations Matrices

Here you can find all the matrices that compose motion equations:

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_x & -I_{xy} & -I_{xz} \\ mz_g & 0 & -mx_g & -I_{yx} & I_y & -I_{yz} \\ -my_g & mx_g & 0 & -I_{zx} & -I_{zy} & I_z \end{bmatrix}$$

$$C_{RB}(v) = \begin{bmatrix} 0 & -mr & mq & 0 & -mz_g r & my_g q \\ mr & 0 & -mp & mz_g r & 0 & -mx_g p \\ -mq & mp & 0 & -my_g q & mx_g p & 0 \\ 0 & mz_g r & -my_g q & 0 & I_{zz} r & -I_{yy} q \\ -mz_g r & 0 & mx_g p & -I_{zz} r & 0 & I_{xx} p \\ my_g q & -mx_g p & 0 & -I_{yy} q & -I_{xx} p & 0 \end{bmatrix}$$

$$M_A = -\begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} & X_{\dot{p}} & X_{\dot{q}} & Y_{\dot{r}} \\ Y_{\dot{u}} & Y_{\dot{v}} & Y_{\dot{w}} & Y_{\dot{p}} & Y_{\dot{q}} & Y_{\dot{r}} \\ Z_{\dot{u}} & Z_{\dot{v}} & Z_{\dot{w}} & Z_{\dot{p}} & Z_{\dot{q}} & Z_{\dot{r}} \\ K_{\dot{u}} & K_{\dot{v}} & K_{\dot{w}} & K_{\dot{p}} & K_{\dot{q}} & K_{\dot{r}} \\ M_{\dot{u}} & M_{\dot{v}} & M_{\dot{w}} & M_{\dot{p}} & M_{\dot{q}} & M_{\dot{r}} \\ N_{\dot{u}} & N_{\dot{v}} & N_{\dot{w}} & N_{\dot{p}} & N_{\dot{q}} & N_{\dot{r}} \end{bmatrix}$$

$$C_A = \begin{bmatrix} 0 & 0 & 0 & 0 & a_3 & a_2 \\ 0 & 0 & 0 & -a_3 & 0 & a_1 \\ 0 & 0 & 0 & -a_2 & -a_1 & 0 \\ 0 & a_3 & a_2 & 0 & b_3 & b_2 \\ -a_3 & 0 & a_1 & -b_3 & 0 & b_1 \\ -a_2 & -a_1 & 0 & -b_2 & -b_1 & 0 \end{bmatrix}$$

$$I = \begin{bmatrix} I_x & -I_{xy} & -I_{xz} \\ -I_{yx} & I_y & -I_{yz} \\ -I_{zx} & -I_{zy} & I_z \end{bmatrix}$$

# Appendix B

# Motion Equations Matrices

Here you can find all simplified the matrices that compose motion equations:

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_g & -my_g \\ 0 & m & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & m & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_x & 0 & 0 \\ mz_g & 0 & -mx_g & 0 & I_y & 0 \\ -my_g & mx_g & 0 & 0 & 0 & I_z \end{bmatrix}$$

$$M_A = -\begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 & X_{\dot{q}} & 0 \\ 0 & Y_{\dot{v}} & 0 & Y_{\dot{p}} & 0 & Y_{\dot{r}} \\ 0 & 0 & Z_{\dot{w}} & 0 & Z_{\dot{q}} & 0 \\ 0 & K_{\dot{v}} & 0 & K_{\dot{p}} & 0 & 0 \\ M_{\dot{u}} & 0 & M_{\dot{w}} & 0 & M_{\dot{q}} & 0 \\ 0 & N_{\dot{v}} & 0 & 0 & 0 & N_{\dot{r}} \end{bmatrix}$$

Although matrix $C_A$ has the same amount of coefficients, these are going to have less terms in their calculations:

$a1 = -X_{\dot{u}}u - X_{\dot{q}}q$ ; $a2 = Y_{\dot{v}}v + Y_{\dot{p}}p + Y_{\dot{r}}r$ ; $a3 = -Z_{\dot{w}}w - Z_{\dot{q}}q$
$b1 = -Y_{\dot{p}}v - K_{\dot{p}}p$ ; $b2 = X_{\dot{q}}u + Z_{\dot{q}}w + M_{\dot{q}}q$ ; $b3 = -Y_{\dot{r}}v - N_{\dot{r}}r$

$$D_v(v_r) = -\begin{bmatrix} X_{u|u|}|u| + X_u u & 0 & 0 & 0 & X_{q|q|}|q| + X_q q & 0 \\ 0 & Y_{v|v|}|v| + Y_v v & 0 & Y_{p|p|}|p| + Y_p p & 0 & Y_{r|r|}|r| + Y_r r \\ 0 & 0 & Z_{w|w|}|w| + Z_w w & 0 & Z_{q|q|}|q| + Z_q q & 0 \\ 0 & K_{v|v|}|v| + K_v v & 0 & K_{p|p|}|p| + K_p p & 0 & 0 \\ M_{u|u|}|u| + M_u u & 0 & M_{w|w|}|w| + M_w w & 0 & M_{q|q|}|q| + M_q q & 0 \\ 0 & N_{v|v|}|v| + N_v v & 0 & 0 & 0 & N_{r|r|}|r| + N_r r \end{bmatrix}$$