INTERNSHIP REPORT: MODELLING AND IMPLEMENTING UNDERWATER DISTURBANCES INTO A SIMULATOR

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Abstract

This project was initiated for Naval Group in collaboration with Flinders University and ENSTA Bretagne. The aim of this project is the improvement of a simulation environment to make it as realistic as possible. It contains two main tasks, the first one consists in modelling currents and creating a space and time varying current field in a simulated environment. The second is the most realistic wave modelling possible, still with the aim of implementing it in a simulated environment. The main outputs are plugins to implement these two phenomena in a simulation environment. The project outputs are important because they will allow Naval Group and its academic partners to test their underwater vehicles in a more realistic environment.

Résumé

Ce projet a été initié pour Naval Group en collaboration avec Flinders University et l'ENSTA Bretagne. L'objectif de ce projet est l'amélioration d'un environnement de simulation pour le rendre le plus réaliste possible. Il comporte deux tâches principales, la première consiste à modéliser les courants et à créer un champ de courant variant dans l'espace et le temps dans un environnement simulé. La seconde consiste à modéliser les vagues de la manière la plus réaliste possible, toujours dans le but de l'implémenter dans un environnement simulé. Les principaux résultats sont des plugins permettant de mettre en œuvre ces deux phénomènes dans un environnement de simulation. Les résultats du projet sont importants car ils permettront à Naval Group ainsi qu'à ses partenaires universitaires de tester leurs véhicules sous-marins dans un environnement plus réaliste.

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1 Introduction

Unmanned underwater vehicles (UUVs) are increasingly being used for submarine operations. They are used in research fields for underwater surveys, in the military field for mine clearance or anti-submarine warfare, but also in the industrial field where robots can inspect structures [1][2]. UUVs are either remotely controlled through a wire (Remotely Operated Vehicles) or completely autonomous (Autonomous Underwater Vehicle) [3]. These vehicles can therefore perform tasks more safely and more efficiently at a lower cost [4]. AUVs are controlled by sensors and algorithms, the marine environment does not allow wireless communication or remote control [5]. These vehicles must be completely autonomous and be able to adapt to a changing and complex environment. Before launching a UUV to carry out a mission, it is therefore necessary to test its behaviour in the conditions found at sea. Of course, these tests cannot be carried out initially in real conditions as there is a risk of damaging the vehicle and thus losing a lot of money. The best way to test such vehicles today is computer simulation.

The simulator used by the stakeholders of this project is UUV simulator. It is a simulator that runs on the Gazebo software in connection with Robot Operating System (ROS). This simulator contains several worlds and UUVs that already allow to test algorithms. Underwater physics is implemented with the consideration of buoyancy, added mass and fluid friction forces with the Fossen equations. However, some elements are missing to have a realistic simulator that reproduces as well as possible the disturbances encountered underwater. For example, waves are not implemented, currents are only stationary and irrotational.

Underwater several factors can affect the behaviour of a UUV. These include currents, waves, tides, whirlpools... Classifications were made to see which phenomena had the greatest effect in function its strength and its occurrence. Both tidal and ocean currents greatly influence the control of a UUV and therefore need to be modelled in a simulator first. Then waves are also to be considered even if their impact is limited to a thin layer on the surface and are more important in coastal areas. Their modelling and implementation in the simulator are therefore important.

Currently the simulator contains a few plugins that simulate the effect of wind and irrotational currents. The project will provide a documentation on the modelling of currents and waves and the process to implement a plugin that modifies the environment. This will be useful to Naval Group and its academic partners to test new vehicles and algorithms in a safe and realistic simulation environment, as well as to enable future improvement of environmental effects.

2 Presentation of the Context

This internship is part of Nicolas Baudin's internship initiative in Australia [6]. This was initiated between the French Embassy in Canberra, French and Australian universities and the French companies Thales and Naval Group. This research internship undertaken with Naval Group took place in the Centre for Maritime Engineering, Control and Imaging of Flinders University in Adelaide. This research centre works mainly on research in the field of Autonomous Underwater Vehicles (AUV) and everything related to this field. It is in this context, under the supervision of Professor Sammut, director of the Centre for Maritime Engineering, Control and Imaging and Professor Clément, professor at ENSTA Bretagne, that this internship took place.

Unfortunately, due to COVID-19 crisis and travel restrictions I was not able to go to Australia as planned. However, thanks to adaptations I was able to carry out this course from France despite the constraints of distance and time difference. With about one meeting a week and job-related email conversations with my supervisors, I was still able to achieve the goals I was given and get help when I needed it. To conclude, even if this internship didn't go as planned and it's a real pity that I couldn't go there to discover and immerse myself in the atmosphere of the research centre, I'm nevertheless happy to have been able to work on a very interesting subject.

3 Project Objectives and Values

The main objective of this internship is to improve realism on an underwater simulation environment. The mission was therefore to integrate marine disturbances into this environment. The problem is, how to model and implement two of the factors that most influence the control of an underwater vehicle, currents and waves.

This subject is of major importance at a time when the development of increasingly complex and autonomous underwater vehicles is constantly increasing. A project such as this one will increase the possibilities for simulation testing of new control algorithms or new UUV geometry. This can have direct economic consequences for the project's stakeholders who will improve their testing capacity, it will be a gain in safety that implies less loss of money for damage during testing and, above all, less loss of time for testing and therefore faster and cheaper development. The development of UUVs will also allow progress on a social and ecological level. The AUVs will carry out tasks that are dangerous for humans (mine clearance, etc.) and will contribute to scientific research (biology, geology, meteorology, archaeology, etc.).

The first task was to model the currents. It is important to study this phenomenon because it has an effect whatever the area of operation of an underwater vehicle. Currents are a phenomenon that has been widely studied and modelled by scientists. Its action on underwater vehicles is also well known and used in particular for route optimisation. The success of this objective with the implementation of a plugin allowed to move on to the second part of the course, with the modelling of wave action. This subject is more complicated and required adaptations in the objectives due to lack of time and research on the topic. Wave action modelling was done but could not be tested for lack of experimental results at first, it was decided to research an experimental strategy to monitor wave action on a UUV. The model studied could not be implemented on the simulator, but the research carried out on an experimental protocol will make it possible to develop and test new models.

Finally, we can distinguish two main type of values in this internship. Theoretical values, the modelling and implementation method, and practical values, the plugins to add the environments effects in the simulator.

4 Project Outputs

4.1 Currents modelling

Currents are continuous water movements. They are the result of several factors such as wind and tides at the surface and salinity and temperature deeper down [7][8]. Their circulation speed is measured in meter per second or knots (1 knot = 1.85 kilometres per hour). They can reach a maximum speed of 1 meter per second in coastal areas. The relatively high velocities of these currents combined with unpredictability, the effect on UUV control can induce difficulties. In order to avoid these problems, it is useful to model these currents on a simulator. This is what is undertaken in this part. The research around the currents is pretty well done and we have a lot of information. Analytical models exist to recreate current maps from mathematical expressions, but in recent years they have been developed using advanced techniques.

4.1.1 Predictive model analysis

A lot of data is available on ocean currents. For some regions of the world, we have very precise data on the ocean environment thanks to a combination of techniques such as HF radar surface current measurements, satellite observations [9]... The reliable and daily updated open source predictive tools that can be used are : Global Real-Time Ocean Forecast System (RTOFS-Global) [10], Regional Ocean Model System[11] and NavyCoastal Ocean Model [12].

For this project I used RTOFS-Global. I used this tool because it provides three-dimensional current maps and these maps include time variation. I used mainly the model of the American west coast, it allowed to have the finest resolution with about 9 kilometres. The time step for each model is 3 hours. In the figure below we can see the area I used framed in white.

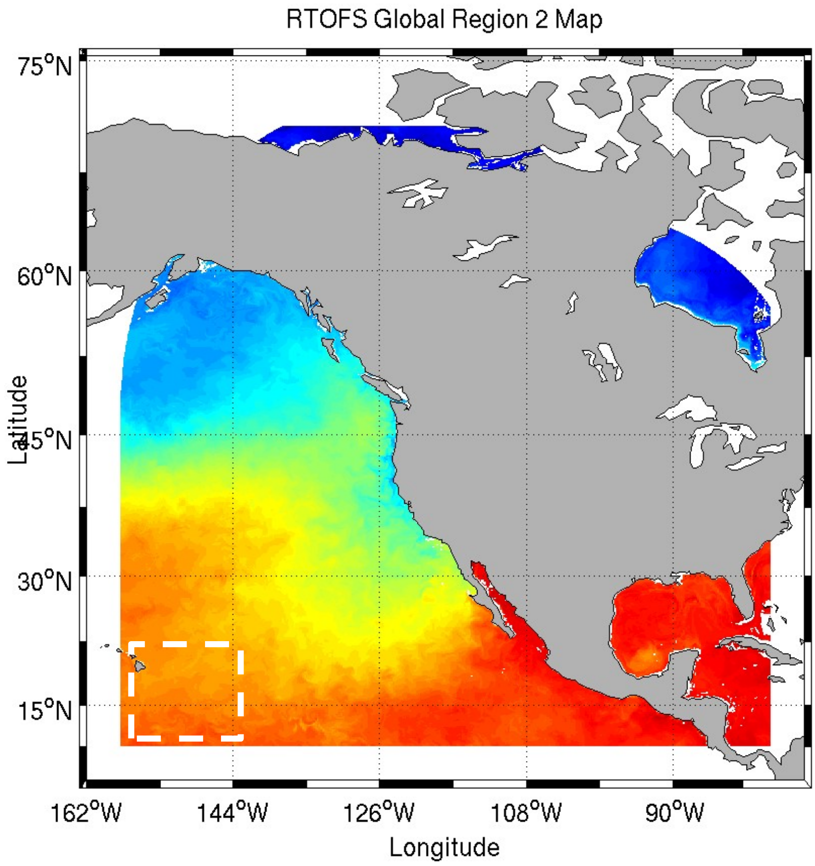

Figure 1: US West Coast RTOFS map

With this tool we can display a vector field representing the velocity of the current for a given depth and time.

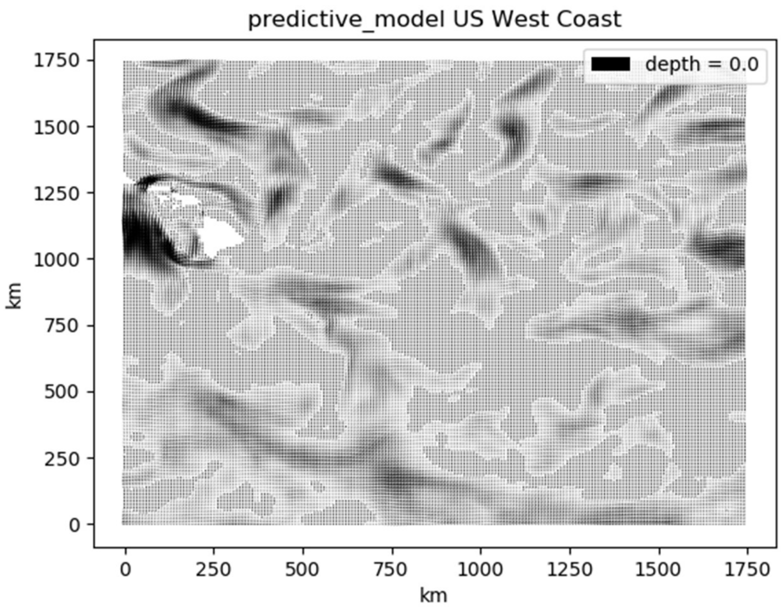

Figure 2: Current velocity field in surface

Using a tool like this one to simulate the marine environment could be a good idea because we would have something very realistic, however the spatial and temporal resolution is not very suitable. In the UUV simulator, we have 2000mx2000m environments, which is not even a step in the grid of the predictive model. However, this model will allow us to refine an analytical model that we will create.

4.1.2 Creation of an analytical model

Creating an analytical current model finally seems to be the best solution to implement variable currents in the simulator. The current map must be as realistic as possible.

4.1.2.1 Hypotheses

Ocean environments are generally characterized by very little vertical motion. The difference in scale in the horizontal to vertical proportions reinforces the impression that the currents can be approximated in 2 dimensions. For very deep areas we will use a 2-dimensional layer structure. This layer structure and 3D management will be presented a little later.

4.1.2.2 Mathematical Model

I tried to create a vector field in 2 dimensions that could be like a current velocity field. To achieve this, I used Lamb vortices randomly placed in our plane [13]. These vortices give a speed to each point of the plane.

$$V_x(\vec{r}) = -\Gamma \frac{y - y_0}{2\pi(\vec{r} - \vec{r_0})^2}\left(1 - e^{-\frac{(\vec{r}-\vec{r_0})^2}{\delta^2}}\right) \tag{4.1}$$

$$V_y(\vec{r}) = -\Gamma \frac{x - x_0}{2\pi(\vec{r} - \vec{r_0})^2}\left(1 - e^{-\frac{(\vec{r}-\vec{r_0})^2}{\delta^2}}\right) \tag{4.2}$$

Where $\vec{r} = \begin{pmatrix} x \\ y \end{pmatrix}$ and $\vec{r_0} = \begin{pmatrix} x_0 \\ y_0 \end{pmatrix}$ are respectively the position of the point of application and the centre of the vortex and Γ, δ are parameters related to the strength and the radius of the vortex.

Let's suppose there are n vortices.

$$V_{c_{pred}}(\vec{r}) = \sum_{i=1}^{n} V^i(\vec{r}) \tag{4.3}$$

With $V^i(\vec{r})$ is the velocity vector of the vortex i on the point of position $\vec{r}$ given by:

$$V^i(\vec{r}) = \begin{pmatrix} {V_x}^i(\vec{r}) \\ {V_y}^i(\vec{r}) \end{pmatrix}$$

Each point of position $\vec{r}$, have a velocity vector $V_{c\_pred}(\vec{r})$ which considers the action of all the vortices of the plan.

Finally, ocean forecast contains an uncertainty that needs to be integrate in our model [9]. We add a gaussian noise that evolve with the time. We complete our current velocity field with:

$$V_{c_{sim}} = V_{c_{pred}} + X_c \quad (4.4)$$

Where: $X_c = \mathcal{N}(0, \sigma_c)$ with $\sigma_c = 0.005.\left(\frac{t-t_0}{\Delta t}\right).V_{c\_pred}$

4.1.2.3 **Results**

I used this model and plotted the vector field associated with it. I created a 1000mx1000m plane with a spatial resolution of 10m for both axes. This resolution is ideal for a UUV because the majority of UUVs are between 1 and 3 meters long. I then created vortices with a centre randomly placed on the plane. The parameter Γ was randomly initialized between 20 and 80 and δ between 20 and 50 for each vortex. The result is presented in the figure below.

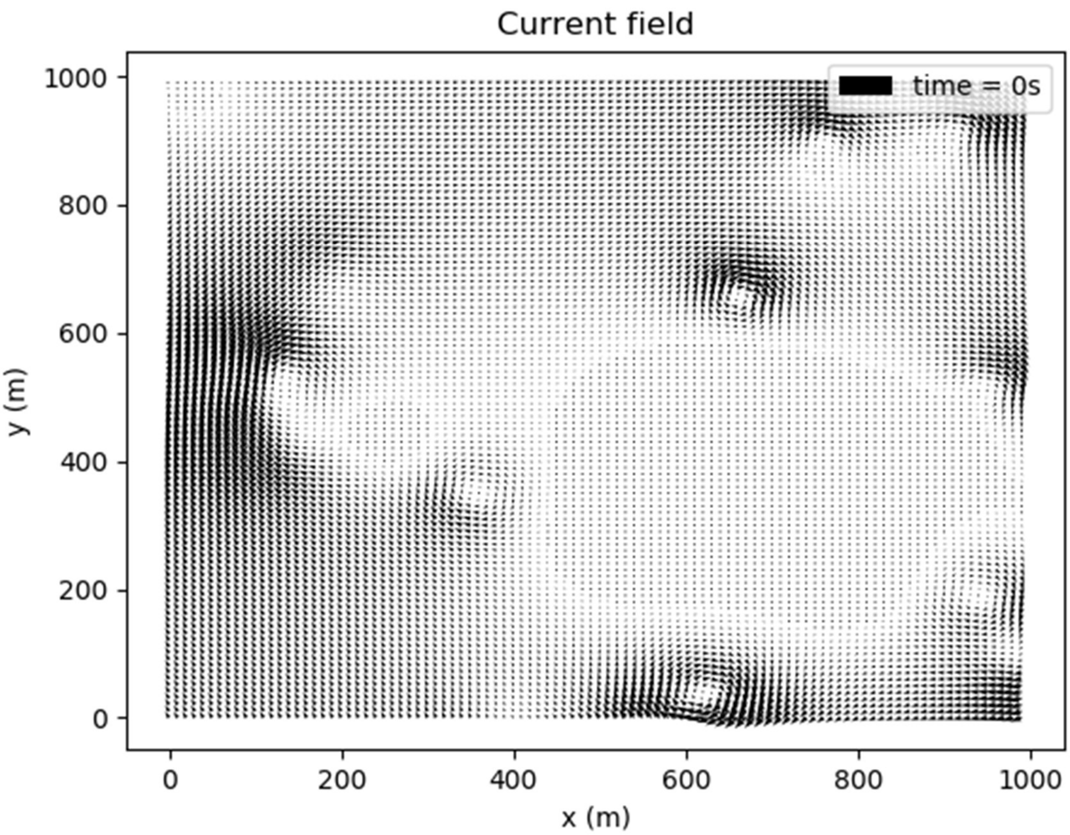

Figure 3: Current field generated with the analytical model with 20 vortices

In the figure above with 20 vortices, one can clearly distinguish the very round vortices. Looking at our predictive model we realize that this is not very realistic. Moreover, the average velocity of the current is about 0.1 m/s with a standard deviation of 0.05 m/s which is too low. We need to add more vortices to increase the speed and to have a more realistic pattern.

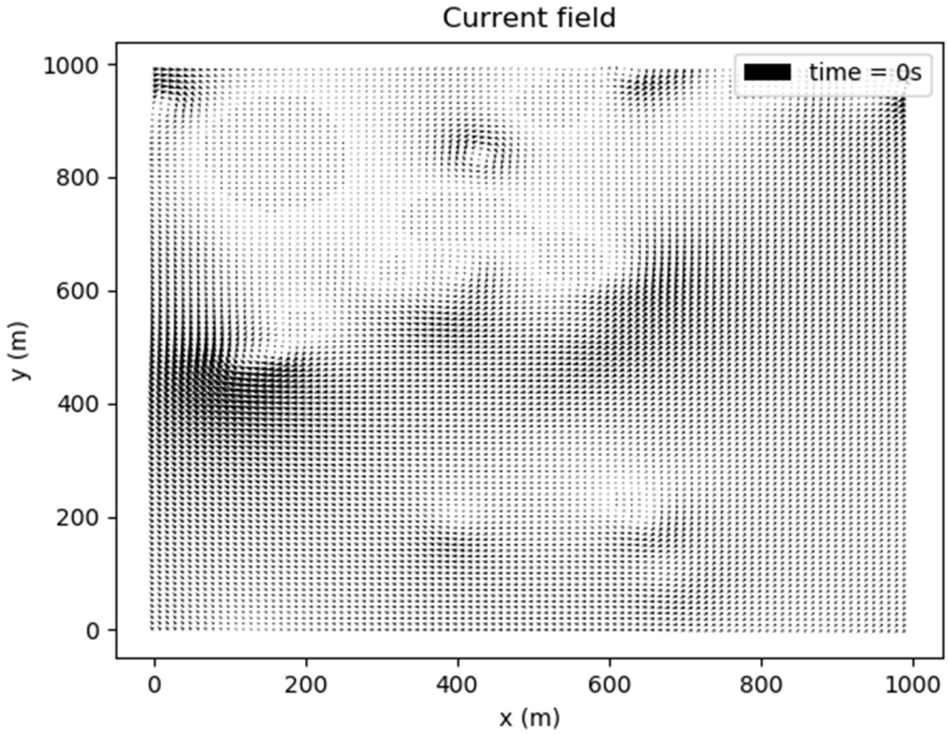

Figure 4: Current field generated with the analytical model with 50 vortices

In the figure above, we have 50 vortices. With this configuration we still have a low mean velocity, around 0,20m/s with a standard deviation of 0,10. The pattern looks much more realistic than with 20 vortices.

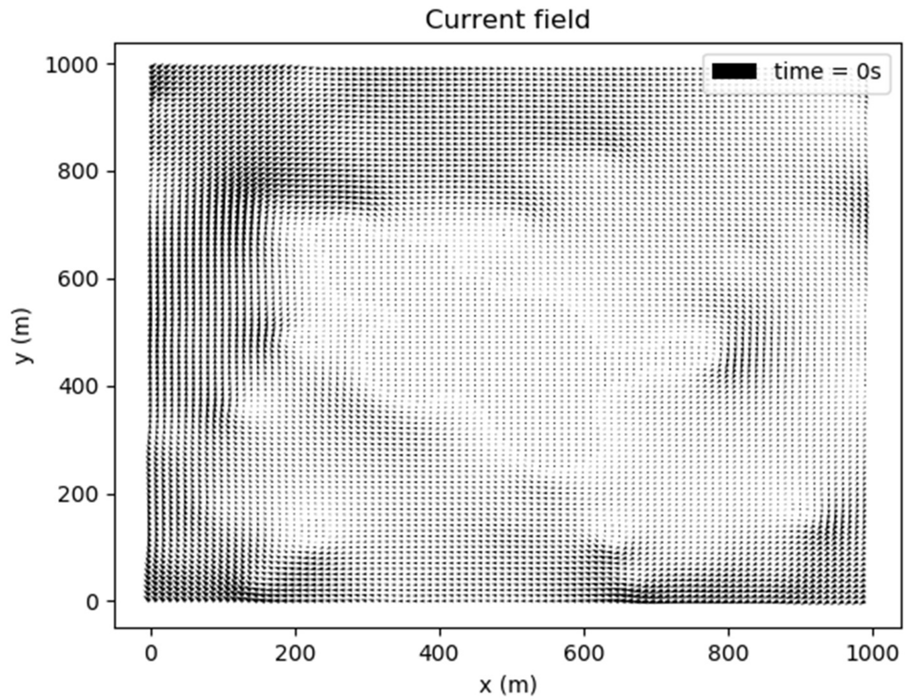

Figure 5: Current field generated with the analytical model with 100 vortices

With 100 vortices one has about the same current field shape as with 50 and the average velocity is not much better with only 0.25 m/s. Moreover, the temporal complexity is much higher with 100 vortices.

Finally, I will keep for my future tests and for the simulator a number of vortices between 40 and 60 with Γ and δ values as mentioned above. I will simply adjust the average speed by multiplying by 2 the final velocity vector. With this configuration I find a mean current speed of 0,50 m/s with a standard deviation of 0,30 m/s. This allows current speeds up to 1 m/s, which is approximately the average of the maximum current speeds recorded [14].

4.1.3 Depth axis variations

As we've seen before we've chosen to neglect vertical movements. However, the currents are not homogeneous over the entire depth of water. This variation will be integrated thanks to different current field layers in 2D. A first approach would be to define layers randomly and without correlation. This method, in addition to being very unrealistic, can give very unusual robot behaviours with discontinuities between layers.

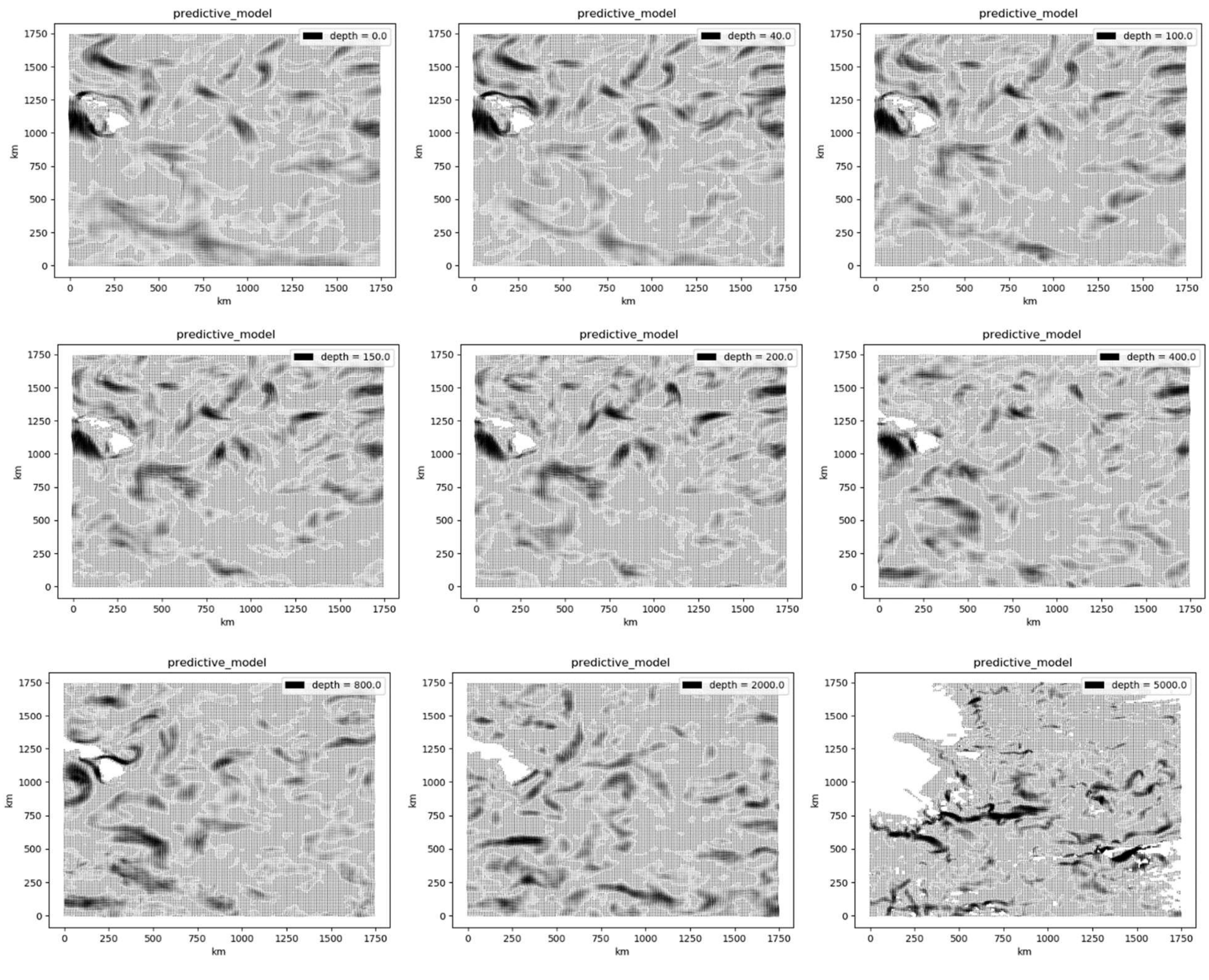

Figure 6: Evolution of current field with the depth (predictive)

The solution considered was to define the layers one by one from the previous one. We create the first layer on the surface in a random way, as seen previously, then to create the other layers instead of generating them randomly, they will be correlated to the previous layer. The problem now lies in finding how to generate these layers so that our model is as realistic as possible.

Since I couldn't really find any documents that could point me to how the currents vary with depth, I used the RTOFS predictive current models. I noticed that in the first 200 meters the currents vary little and then beyond 200 meters they become very different from those at the surface. This has been justified by some research [15], because beyond a certain depth, the currents are no longer subject to the effects of wind but are due in large part to the salinity and temperature of the water.

To adapt these observations to our analytical model, when creating the vortices for each layer I took the coordinates, strength and radius of the vortices of the previous layer and added random values. To be consistent with reality, the more the depth increases, the stronger these random values are to differentiate from the previous layer. The result is shown in the figure below.

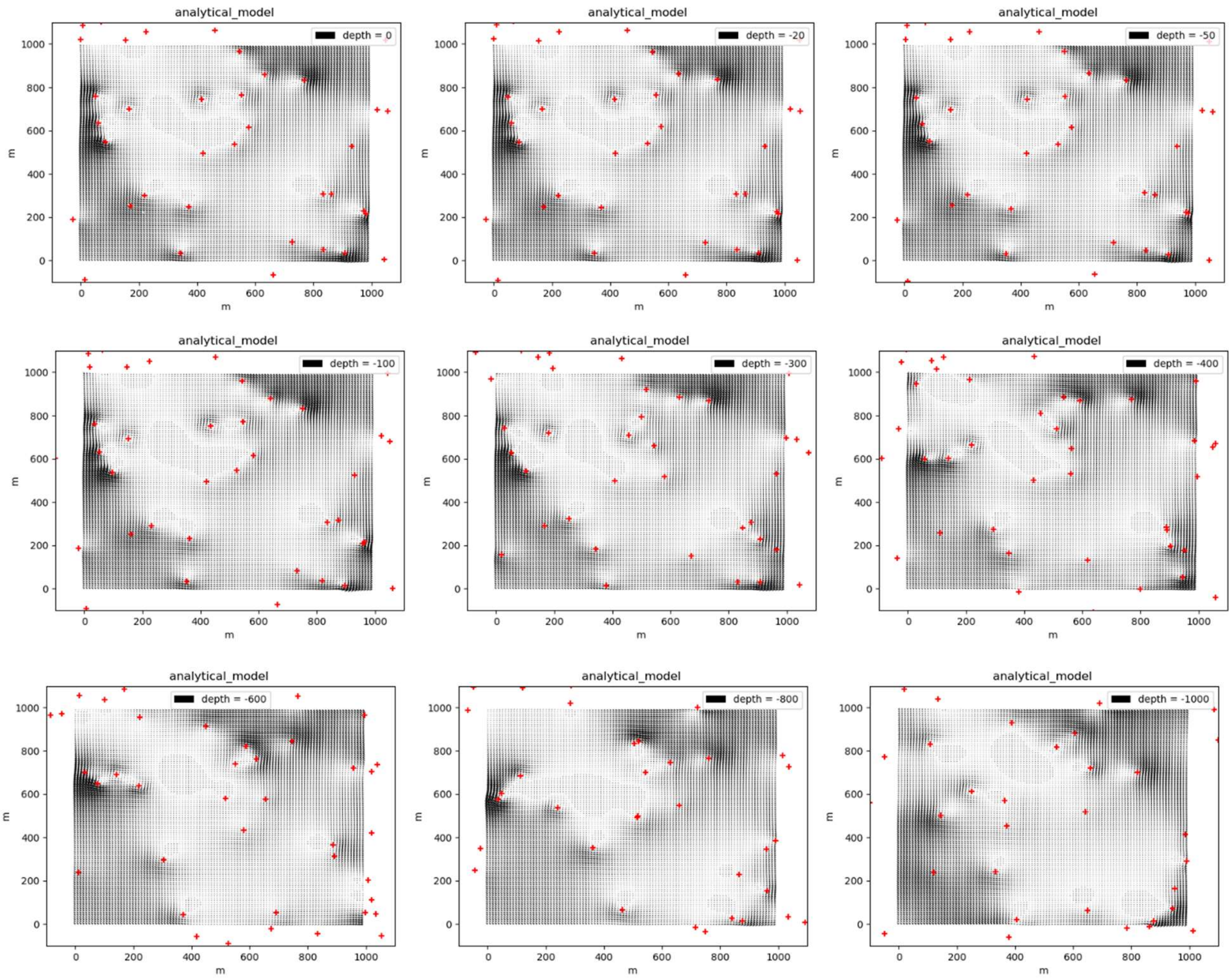

Figure 7: Analytical model of the evolution of the current field with the depth

Red crosses represent the centre of vortices. Up to 300 m depth the variations of the current field are very fine. After this limit the vortices move much more, and their parameters vary much faster. For this model I limited myself to 1000 meters depth, because it is quite rare to go beyond that on the simulator, the model "ocean_waves" for example is limited to 100 meters depth.

4.1.4 Time varying current

Ocean currents are not fixed. Their speed varies with time, as does their direction. But all these movements are quite slow. We can notice it thanks to the RTOFS data which have a time resolution of 3 hours. With a scale of 700 km by 700 km the variation is almost undetectable. It's clearer when we superpose the images or when we take a smaller scale.

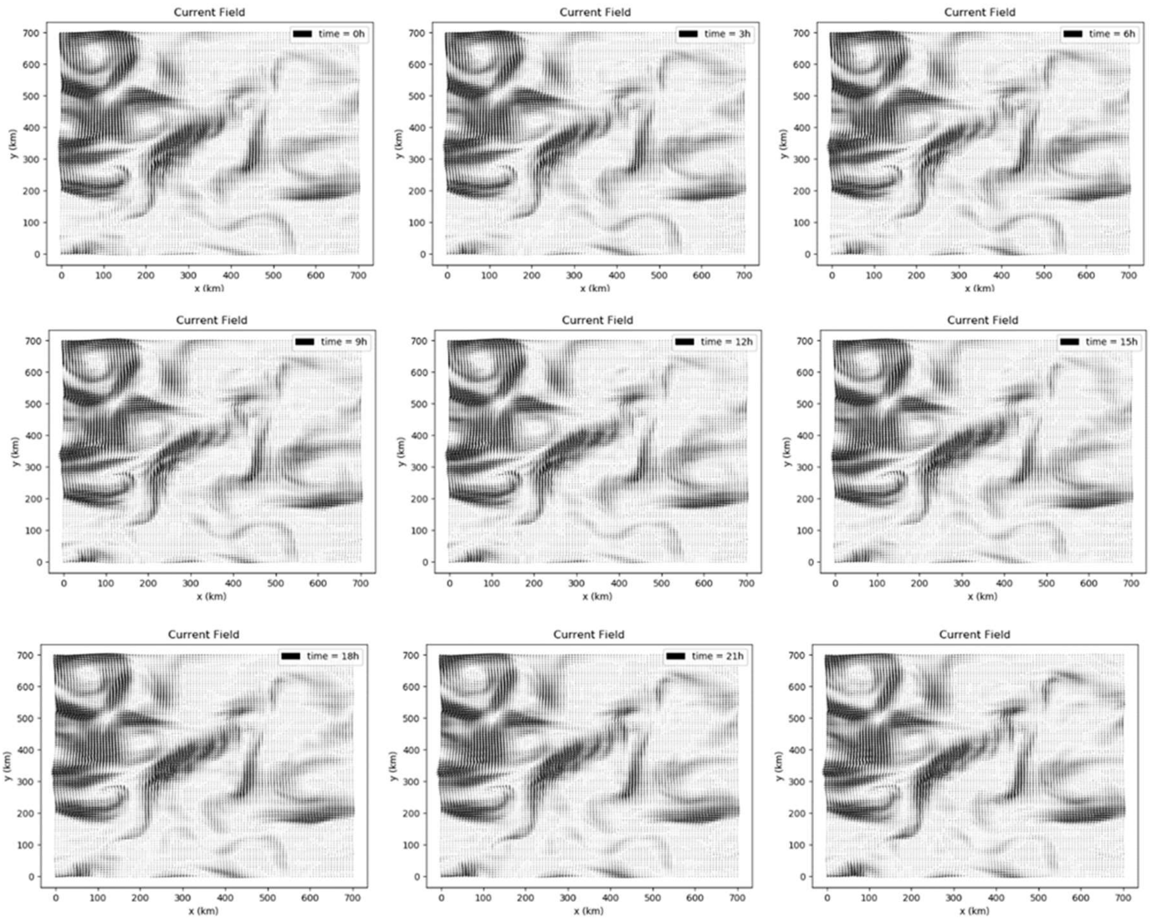

Figure 8: Variation of the current field over 24 hours 700x700 km

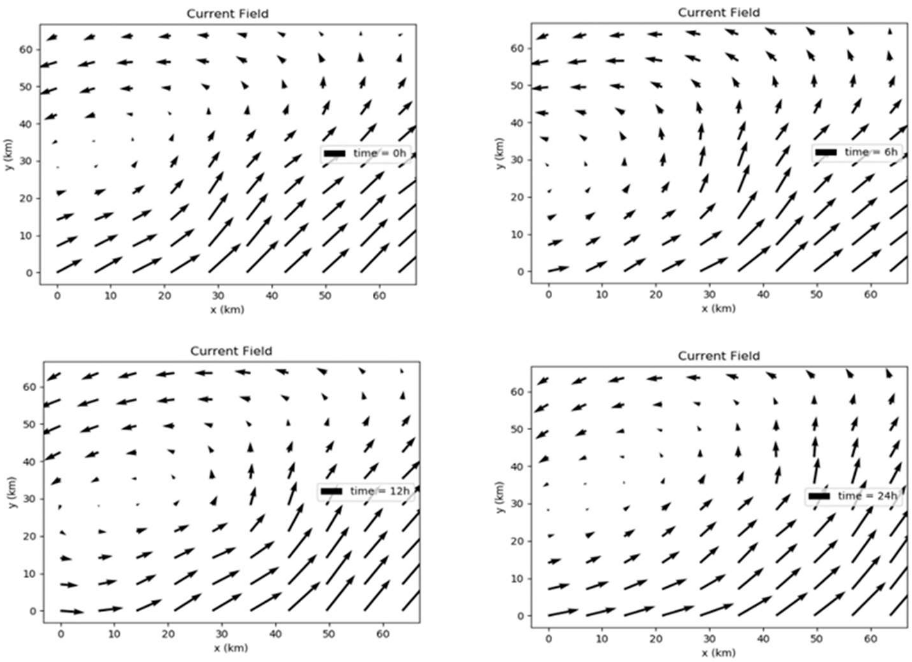

Figure 9: Variation of the current field over 24 hours 70x70 km

For our project, the goal is to study disturbances on a UUV. This fact forces us to have relatively low time steps with more variations than in the reality. The noise added to V_{c_pred} was not enough to have significant variations over time. To do that I was forced to add a random component to the position, the radius and the strength of vortices each time step to slightly modify the current field. For this application I used a time step of 60 seconds.

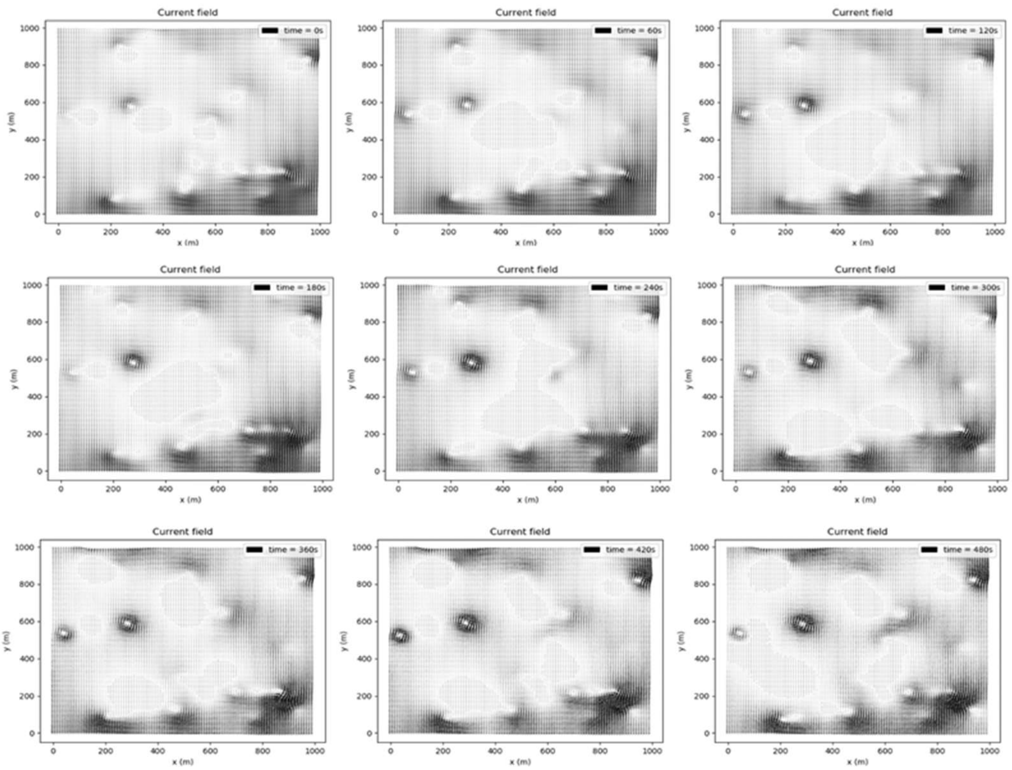

Figure 10: Evolution of the analytical model over 8 minutes

4.2 Plugin implementation

The aim of this section is to present how time and space varying currents can be implemented on a simulator environment. Pre-existing simulation environment in which the varying currents will be implemented is UUV simulator, which works with Robot Operating System (ROS) and allows visual rendering on the software designed for this purpose Gazebo [16]. This simulator already contains a system of currents, but they are stationary and irrotational. It offers a lot of test possibilities because many UUVs (RexRov, ECA A9, LAUV...) are already implemented in this simulator and additions have been or can be made (Sirehna Iver2, x300...).

4.2.1 Implementing varying currents into UUV Simulator

To implement space and time varying currents into UUV simulator, we need to follow the steps below. The creation of a plugin is necessary to add this phenomenon to the simulator. Similar plugins have already been developed, to simulate the effect of wind for example. This plugin will be a part of world plugins.

1. Plugin creation
    a. How will underwater objects be affected by the current?
    b. Creation of the vortices
    c. Time varying current field
    d. Computation of the current at the position of the underwater object
    e. Publishing the current velocity vector
2. Plugin use
    a. Link with the underwater object plugin
    b. Parameters to add to the world file

4.2.2 Underwater objects effects

UUV simulator uses the Fossen's equation of motion [17]. This equation takes into account the current velocity. In UUV simulator, the equation of motion is implemented in the `underwater object` plugin. Each object in the simulation running an instance of the `underwater object` plugin that will govern its movement thanks to numerous adjustable parameters in the robot description. This plugin controls the hydrodynamics of the object. When configuring the underwater object, it is possible to choose if we want it to use the global current or not, it means that if the parameter <use_global_current> is set to true, the object will use the current that is published on a global topic and the speed of the current will not vary depending on the position of the UUV. However, if this parameter is set to false, it will use the topic that matches its name. Thus, it will be able to retrieve the current speed vector that corresponds to its position.

In the plugin that we have developed we will pass a parameter that will have as value, the name of the topic on which to publish the message of the current velocity vector for each UUV.

Thus, we will only have to publish on the right topic the current velocity vector corresponding to the position of the object. Finally, this allows to have only one instance of the plugin, which will generate a single current field and publish the current velocity vector for each object. This simplifies the calculations and reduces the memory space used, because the vector field is stored only once and is not a parameter of each UUV.

4.2.3 Creation of vortices

The simulation environment of UUV simulator has no spatially and temporally varying currents. The goal of this plugin was therefore to create a current field that varies in space and time. For this, the analytical model seen previously was used.

The surface of the simulation environment is 2000x2000m. It is thus necessary to create enough vortices to have a realistic current field but not too many vortices so as not to have too many calculations which will be time-consuming. The choice was made to retain 80 vortices per layer and 10 layers with 10m between each layer. The storage of these vortices will be done by 3 arrays. The lines of these arrays will represent the layers. There are 3 tables of 10 rows and 80 columns. Of course, this can be modified depending on whether you add or remove vortices or layers. The first table will contain tuples representing the coordinates (x,y) of the vortex. The second and the third tables contains the strength and the radius of the vortex.

The filling of these tables is done in a function "giveVorticeCoordinates" that is called when the plugin is loaded. The tables are filled with random values corresponding to the analytical model seen above.

4.2.4 Time varying current field

The goal of this plugin is also to vary the current field as a function of time. As mentioned above, to recreate this, the arrays containing the vortices parameters will be modified with a random value at a given frequency. The current field will then change slightly.

To do this the user can enter a parameter which will be the period of change of the current field. Then in the function that is called each simulation step, a function to is called to change the current field if the period has passed.

To conclude the current field changes at a frequency given by the user by modifying the tables with random components.

4.2.5 Computation for each underwater object

The user can change a parameter named "update_rate". This parameter is the update period of the current speed for each robot. It is in the function that is called at each simulation step. However, it is not necessarily necessary to calculate the current speed for each robot as quickly. This would induce problems of temporal complexity. So, this period can be set and the current speed at the position of each object will be calculated only when this period has expired. The test of whether the period has expired or not is performed with an if statement.

After that the plugin will compute the current velocity for all the objects. To do this a for loop is made on the objects subject to the current. For each one of these objects the program recovers the position of this one. According to the vertical position of the object it is calculated the upper and lower layers of the object.

A layer-dependent function is then called to build the current velocity vector (Vc_pred). In this function we use the robot position (x,y) and a for loop is made on all the vortices of the layer and the current velocity vector is calculated from the action of each vortex.

To maintain continuity of the current velocity vector between two layers the current velocity vector is calculated on the layer above and below the (x,y) position of the object. An average of these two vectors is then weighted by the relative vertical position of the object between the two layers.

Finally, to match the analytical model developed above, a noise is added to the velocity vector created to elaborate the current velocity vector used in the simulation. A message of type Vector3 is then elaborated with this speed vector and published on the topic of the selected object.

4.2.6 Plugin use

The use of this plugin is quite simple, there are few parameters to enter. However, care must be taken when creating instances of the UnderwaterObjectPlugin. In this plugin there is a variable that allows the object to use its own topic for the current velocity vector. This variable is by default initialized to true and the object cannot use the current corresponding to its position created in the VariableCurrentPlugin plugin. You must therefore be careful when creating the object in the robot file, to pass use the parameter "<use_global_current> false </use_global_current>" in the UnderwaterObjectPlugin plugin.

Another important thing to choose will be the name of the topic on which the current will be published. By default, this name will be "name_of_the_UUV/current_velocity" but this can be changed by passing parameters when creating the object or plugin building the current.

Finally, the last thing to do is to modify the world SDF file to set the current. It is necessary to declare the use of the plugin and to set the models affected by the current as well as the name of the topic on which it will be published. It is also possible to change the publishing and the current changing period.

```xml
<plugin name="variable_current_plugin" filename="libuuv_underwater_variable_current_plugin.so">
  <current_obj>
    <name>x300</name>
    <link_name>x300/base_link</link_name>
    <flow_velocity_topic>x300/current_velocity</flow_velocity_topic>
  </current_obj>
  <update_rate>1</update_rate>
</plugin>
```

Figure 11: Example of the declaration of the plugin in an SDF world file

4.3 Tests

Once the plugin has been created, it is now a matter of testing it. Indeed, it must meet certain criteria to be as realistic as possible in order to be able to use this simulator for future tests in real conditions. The previous chapter presented how to implement currents varying in time and space, here we will focus on the tests of this plugin.

4.3.1 Trajectory tests with python in 2D

To test if the plugin works correctly and that the current field is realistic, I had the idea to look at the path of a UUV powered only by current, without any command given to it.

At first, I wanted to get an idea of the trajectory that an object would take in a current field. I used the tests done with python to create the analytical model. I then simulated an object with a given starting position. Then using a Euler method, the position of this object was updated with the current speed. I finally traced the trajectory of the object in superposition of the vector field that doesn't vary with time.

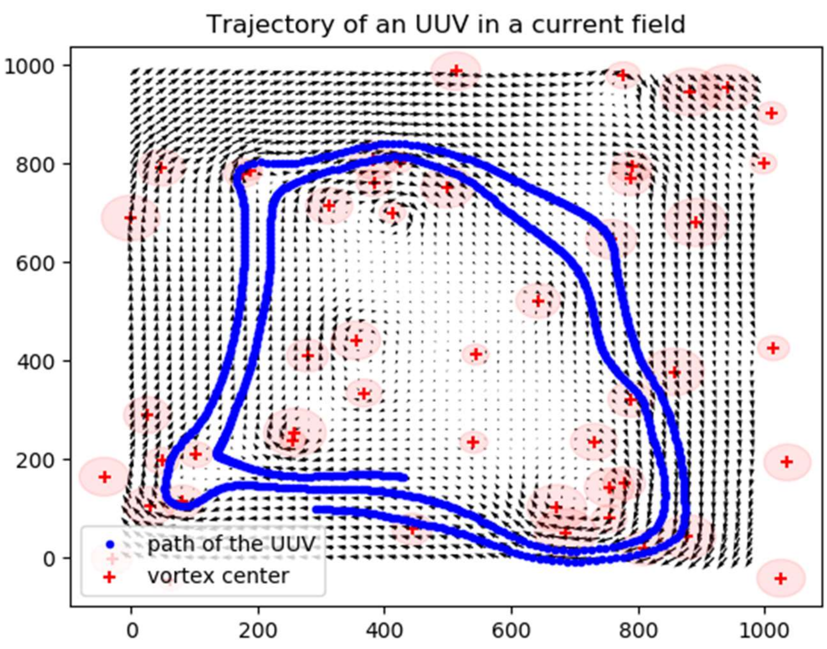

Figure 12: Trajectory of an object in a current field with python

This test with python is not realistic, it does not consider the inertia of the UUV and other factors that can modify the trajectory, but it gives a good idea of what should be the trajectory of the object on the simulator.

4.3.2 Trajectory tests of the plugin in 2D

To check if the current created in our plugin and if the behaviour of an object immersed in this current field is realistic, I plotted the trajectory followed by the UUV X300 in surface.

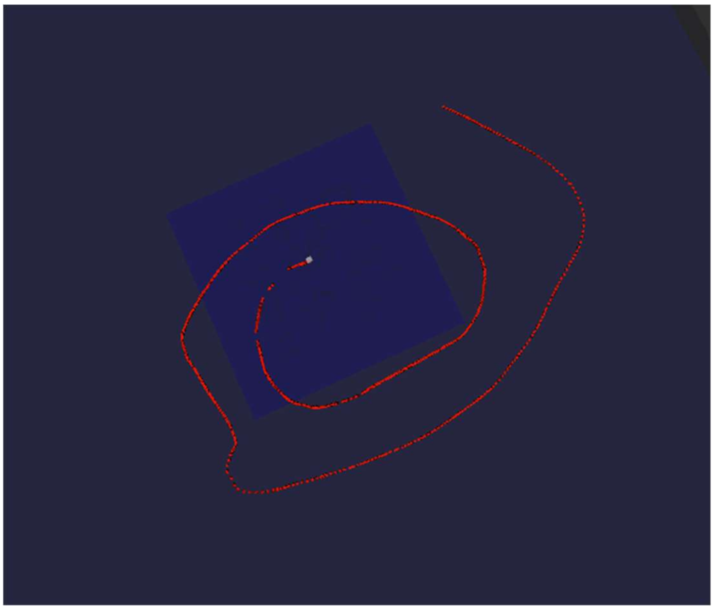

Figure 13: Trajectory of the UUV X300 in a generated current

We can see in this figure that the shape of the trajectory is quite the same as with the python simulation. It describes circles around a centre. Here the trajectory is not disturbed by a change in the current over time. There is no discontinuity, and the trajectory seems quite realistic. We can thus consider that the model corresponds, and that the plugin reproduces a current in 2D well enough for our use.

4.3.3 Trajectory tests of the plugin in 3D

Now that the plugin is quite realistic on a layer, in 2 dimensions, we can test if the depth axis management is correct. In this case I put the UUV X300 at 30 meters of depth. This UUV is made to resurface if it has no instructions. I let it drift in the current until it comes to the surface. There too we can see that the trajectory is continuous and that even if the current field changes slightly every 10 m the trajectory remains the same.

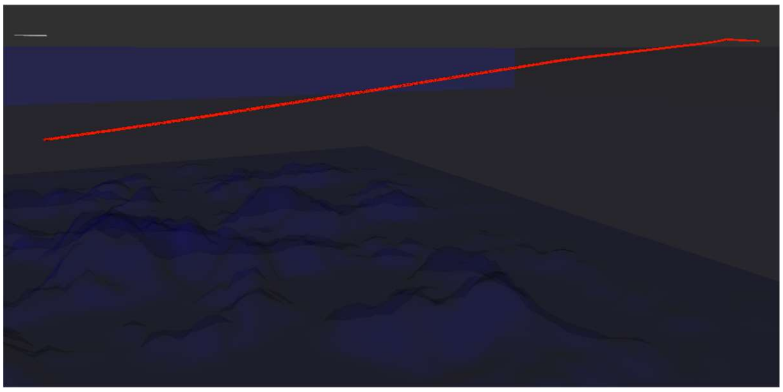

Figure 14: Trajectory of a UUV from -40m to 0m lateral view

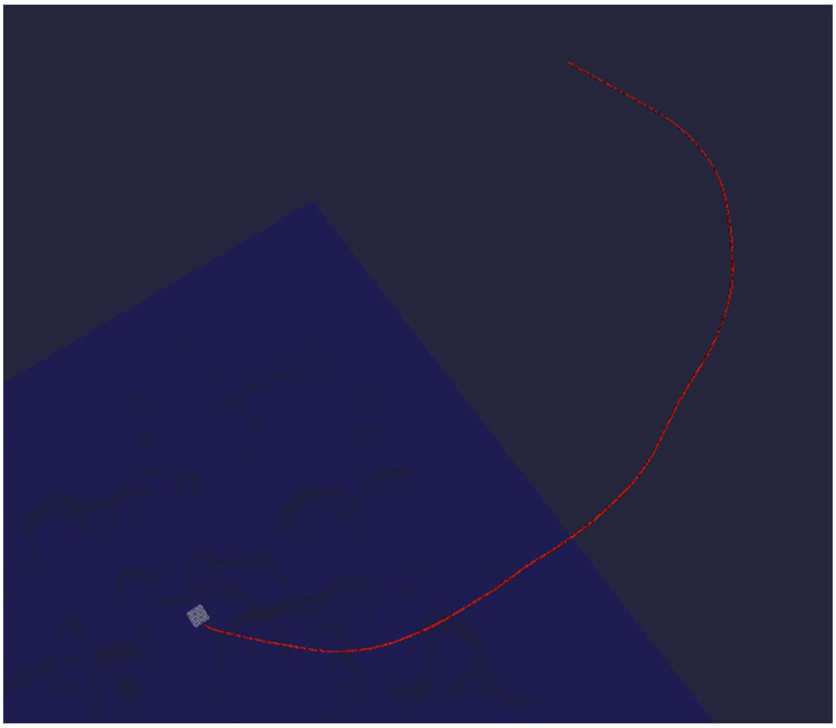

Figure 15: Trajectory of a UUV from -40m to 0m upper view

Figures 14 and 15 shows the trajectory of a UUV in the current from -40m to 0m. I placed the UUV at -40m and since it floats it gradually rises to the surface. With these two figures we can see that there are no discontinuities in the trajectory. This means that the layers are well correlated and that the transitions between layers are performed correctly.

4.3.4 Monitoring of the current velocity

Once the shape of the currents has been checked, in order for all this to be realistic it is necessary to check the speed of the currents. This must remain between 0 and 1 m/s. I plotted the speed of the currents at the position of a UUV for about 20 minutes. We can notice discontinuities due to the random variation of the vortices. These discontinuities remain acceptable as they do not exceed 0.05 m/s and the aim of the project is also to see how a UUV behaves in a rapidly changing environment. What has been plotted here is the velocity along the x-axis and the y-axis. These velocities do not exceed 0.75 m/s, so the norm for the velocity vector is always less than 1 m/s. The average of the norm of the velocity is around 0.30 m/s.

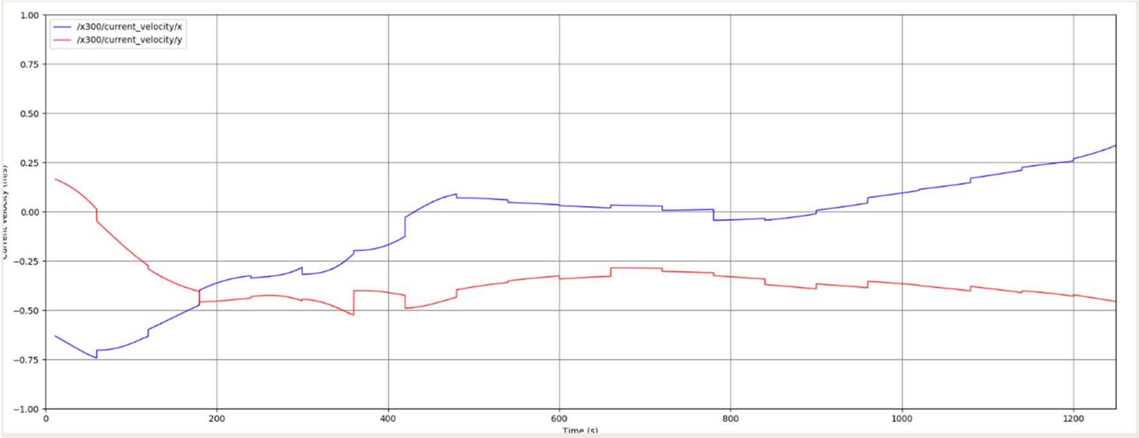

Figure 16: Current velocity in function of time

Finally, the speed may seem a bit low, this may be because there are only 80 vortices over an area of 2000x2000 m compared to 50 over 1000x1000 m in the simulations which allowed to refine the model. However, these speeds are still acceptable, and it is complicated to put more vortices because of the temporal complexity.

4.4 Wave action modelling on a UUV

Although waves are an extremely complex phenomenon dependent on multiple factors such as wind, currents, bottom topology, many scientists have proposed realistic models to model waves. The best known at present are the Pierson-Moskowitz spectrum and JONSWAP spectrum. In the framework of this internship, we are interested in the action of waves on a UUV and although these realistic models can be useful, they are far too complex at first. Therefore, we will not detail these models in this report. Most of the models we will deal with, will be based on a sinusoidal wave model.

4.4.1 Wave action

The equation of motion of a UUV given by Fossen models waves as an action to be added. The goal of this internship is to find an expression of this force and to add into the simulator.

$$M\dot{v}_r + C(v_r)v_r + D(v_r)v_r + g(\eta) + g_0 = \tau_{wind} + \tau_{wave} + \tau \tag{4.5}$$

This action may depend on factors such as UUV geometry and velocity, wave frequency, wavelength and height, and water depth. In the requirements set for this internship, we must take into account water depth to best model wave action in shallow water, where UUVs are most sensitive to wave action.

4.4.2 Need of experimental values

In this type of project, experimental values are very important. They can be used as starting values for the creation of a model, by machine learning or value interpolation. In this case, a lot of values are needed to get a precise result.

As this kind of experiment can be expensive and requires a lot of resources, very few have been carried out. The best solution is therefore to use it to test a model, possibly developed through numerical simulation.

A big problem encountered during this internship was the lack of actual data found. Therefore, research was undertaken that could lead to an experiment to collect data that could be used in the future.

Experiments to acquire wave action on a UUV can be carried out either directly at sea or in a wave tank. Both have their benefits and their drawbacks. A wave tank is difficult to find and to use but it allows to control all the parameters such as the frequency and the height of the swell. It is also more practical for the installation of sensors and the handling of the UUV, which does not require a boat, which is also subject to the action of the waves. Acquisition and processing are therefore much easier than an experiment at sea.

Figure 17: Remus AUV under wave action

For an experiment at sea, an accelerometer buoy will be needed to acquire wave height, frequency and wavelength. A current meter will also be needed because, unlike a wave tank, there will be a current.

Wave tank experiments were conducted by Gregory Sabra[18] as part of his thesis on wave effects on underwater vehicles in shallow water. He has conducted nearly 150 experiments with the AUV Remus. According to the waves he has recorded the sway and heave forces and the pitch and yaw moments. These experiments will be use in this internship to validate the model of strip theory presented below.

4.5 Strip Theory

Strip Theory has been used for many years and with great success for the seakeeping of surface ships. Strip theory was defined by Salvesen, Tuck and Faltinsen in their book "Ship Motions and Sea Loads" [19]. They have developed a theory that arose from this foundation, called STF. The STF and developments based on it have been the most widely used strip theory. Adaptations to this theory were made by Jerome H. Milgram [20] to create the model presented below adapted to underwater vehicles in finite depth.

4.5.1 Hypotheses

Assumptions were made for the model used for this course. First, the slender body approximation is used. This implies that surge force and roll moment are not considered. The main problem with this assumption is that the shape of some UUVs such as Rexrov, included in the UUV simulator, does not match. The second hypothesis is the finite depth of water. The theory presented here considers the depth of water and the diffraction of waves on the sea floor. Finally, the waves will be modelled by a sinusoid of fixed frequency and wavelength.

4.5.2 Model

The complete model used for this internship is explained by Jerome H. Milgram in the paper "Strip theory for underwater vehicles in water of finite depth" [20].

This model expresses the action exerted on the UUV by waves section by section. It uses diffracted waves, Froude-Krylov wave force called non-lifting contributions (p) and the fin lift forces(f). The resulting action is the sum of these forces.

$$F_i = {}_pF_i + {}_fF_i$$

To have the final action, we just multiply this force by $e^{i\omega t}$.

$$\tau_{wave_i} = F_i e^{i\omega t}$$

The indices 2,3,5 and 6 in the equations below, refer respectively to the sway, heave, pitch and yaw forces and moments. The equations below present the non-lifting contributions actions.

$${}_pF_3 = \rho\alpha\int (f_3 + h_3)d\xi \quad \text{(A-24)} \qquad {}_pF_5 = -\rho\alpha\int\left[\xi(f_3 + h_3) + \frac{U}{i\omega}h_3\right]d\xi \quad \text{(A-25)}$$

$${}_pF_2 = \rho\alpha\int (f_2 + h_2)d\xi \quad \text{(A-26)} \qquad {}_pF_6 = -\rho\alpha\int\left[\xi(f_2 + h_2) + \frac{U}{i\omega}h_2\right]d\xi \quad \text{(A-27)}$$

Where ξ is the longitudinal length, α is the amplitude of waves, ρ is the fluid density, U is the speed of the UUV, ω is the circular frequency of waves. The f-terms are Froude-Krylov wave forces, and the h-terms are wave forces due to the diffracted waves.

4.5.2.1 Incident wave action

The incident wave action is the Froude-Krylov wave force on each section of the UUV. We can express that with the equation:

$$f_j = \frac{g}{\cosh kh} \int_{C_x} n_j \cosh k(h+z) \exp\left[i\left(-kx\cos\theta + ky\sin\theta\right)\right] dl$$

Where k is the wavenumber, h the depth of water, n_j is the normal vector to the section, C_x is the contour around the section and θ the angle between wave propagation and UUV direction.

This is the Froude-Krylov force with a pressure:

$$p = \frac{\cosh(k(h+z))}{\cosh(kh)} e^{i(-kx\cos\theta + ky\sin\theta)}$$

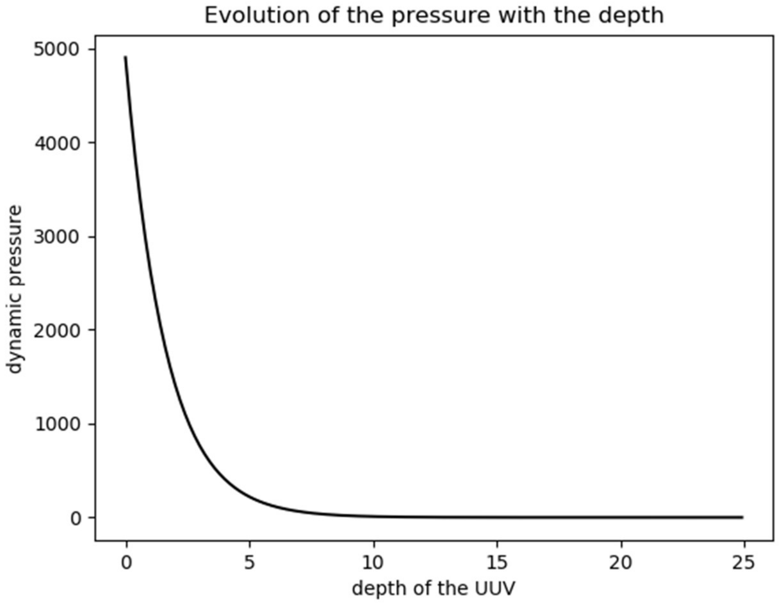

Figure 18: Pressure vs submergence of the UUV, H = 1 m, λ = 10 m, ω = 1 rad/s

With this pressure the effect of waves decreased exponentially with the depth and is almost zero when the depth exceeds one wavelength.

4.5.2.2 Diffracted wave action

The diffracted wave action coefficient is:

$$h_j = -i\omega \int_{C_x} n_j \phi_d dl$$

Where Φ_d is the diffracted wave potential.

4.5.2.3 Fin lift action

If the vehicle has fins, the waves will have an effect on them. It will depend on the waves but also on the geometry of the fins. On the figure below we can see the geometry of the REMUS fins. REMUS AUV has 4 fins, two horizontals and two verticals.

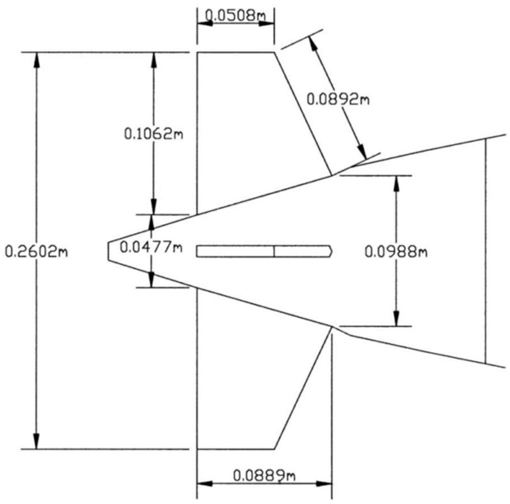

Figure 19: Fins geometry of REMUS AUV

For the forces expression we consider the fluid velocity induced by waves. For the heave force and pitch moment we take into account horizontal fins and for the sway force and yaw moment vertical fins.

$$ {}_fF_2 = \sum_{m-\text{Vertical}} \frac{1}{2}\rho U A_m C_{L\sigma m} \frac{-\omega_o \alpha \sin\theta_m}{\sinh kh} \exp[i(\omega t - kx_m \cos\theta_m)] \cosh k(h-s) $$

$$ {}_fF_3 = \sum_{m-\text{Horizontal}} \frac{1}{2}\rho U A_m C_{L\sigma m} \frac{i\omega_o \alpha}{\sinh kh} \exp[i(\omega t - kx_m \cos\theta_m] \sinh k(h-s) $$

$$ {}_fF_5 = \sum_{m-\text{Horizontal}} -\frac{1}{2}\rho U A_m C_{L\sigma m} x_m \frac{i\omega_o \alpha}{\sinh kh} \exp[i(\omega t - kx_m \cos\theta_m] \sinh k(h-s) $$

$$ {}_fF_6 = \sum_{m-\text{Vertical}} \frac{1}{2}\rho U A_m C_{L\sigma m} x_m \frac{-\omega_o \alpha \sin\theta_m}{\sinh kh} \exp[i(\omega t - kx_m \cos\theta_m)] \cosh k(h-s) $$

A_m is the effective area of the fin, x_m the centre of fin lift force and $C_{L\sigma}$ m is the lift coefficient per unit angle of attack.

4.5.3 Tests

This theory then had to be tested. For this I used a thesis by Jan A. Rybka [21]. In this paper, the author proposes an approximation of strip theory to express the forces exerted by the waves on a UUV in shallow water. So, he developed a Matlab code that I used. To make this code work, you have to give in parameters a file giving the geometrical characteristics of the UUV and its fins. I used the results of this code to see if this theory could be suitable. In order to do this, I had to simulate all the experimentally observed cases and then compare the results.

Finally, the tests are not very satisfying. For the forces and moments module the values are coherent. For the phase we can see that values are very far from expected. We can explain this phenomenon for several reasons. Either the model is not good, or the input files are not accurate enough.

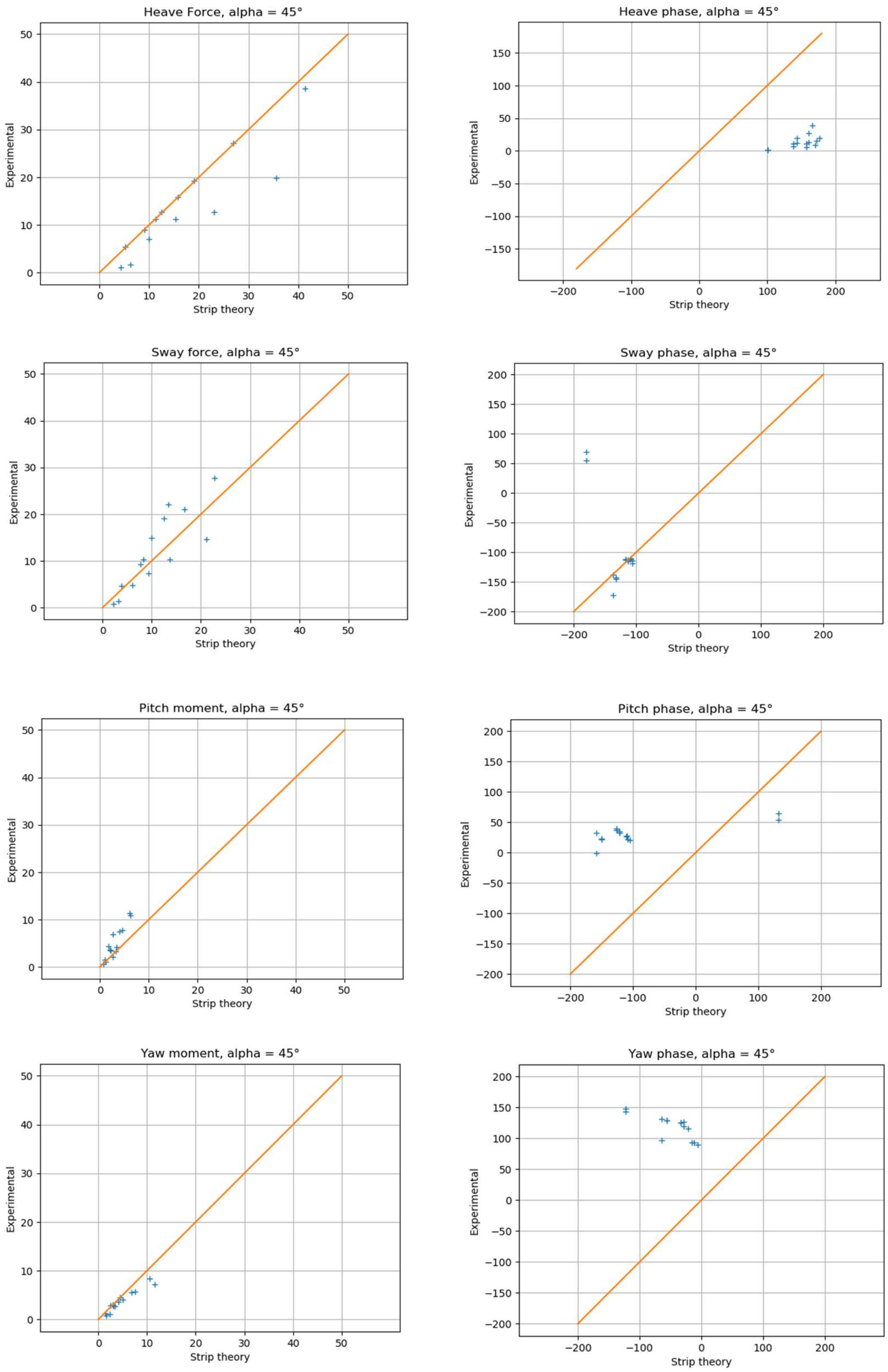

Figure 20: Comparison of experimental and theoretical values for a=45°

The problem here with this model is that it doesn't take into account the radiation forces. In his thesis Jan A. Rybka [21] can achieve very good results by combining the effect of diffraction and radiation. A lack of time did not allow to investigate this question and to develop a MATLAB code allowing to give the radiation forces.

5 Future work

Tracks can still be worked on and the proposed models and implementations improved. Wave action modelling with Strip Theory can be improved and tested on other AUVs, including the X300. This will require experiments in a wave tank as was done with Remus in order to be able to compare the results of the modelling with the experiments. If the strip theory model is deemed reliable and accurate enough, it will then have to be adapted for implementation on UUV simulator. Finally, this model will have to be tested on the simulator and determine if it is suitable for test applications.

6 Conclusion

Through this project a better understanding of the phenomena that can influence the control of a UUV has been gained. A fairly accurate and realistic modelling of space and time varying currents and an implementation on UUV simulator, will allow a better testing capability and realism during simulations. The modelling method used with Lamb vortices can also be used for other perturbation phenomena, as well as the plugin implementation method which can be reused for simple perturbations modelled by vector fields. The key for this project is the existence of experimental values. This has allowed the modelling of currents using existing maps and has limited the progress in modelling wave action. For wave action modelling, Strip Theory has a lot of potential and with a little more time I could probably achieve very good results. The research on experimental protocol, Strip theory code, and data formatting for tests can be the starting point for future research work to lead to the implementation of this model in the simulator. Finally, this project was carried out entirely from home and despite the difficulties inherent in this way of working, I was able to discover the world of research, learn a lot in the field of marine robotics and work in English.

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RAPPORT D'EVALUATION
ASSESSMENT REPORT

Merci de retourner ce rapport par courrier ou par voie électronique en fin du stage à :
At the end of the internship, please return this report via mail or email to:

ENSTA Bretagne – *Bureau des stages - 2 rue François Verny - 29806 BREST cedex 9 – FRANCE*
☎ 00.33 (0) 2.98.34.87.70 / stages@ensta-bretagne.fr

I - ORGANISME / *HOST ORGANISATION*

NOM / *Name* Flinders University

Adresse / *Address* College of Science & Engineering, GPO Box 2100, Adelaide, SA 5001, Australia

Tél / *Phone (including country and area code)* +61 8 82015051

Nom du superviseur / *Name of internship supervisor* Prof. Karl Sammut

Fonction / *Function* Director, Centre for Maritime Engineering

Adresse e-mail / *E-mail address* karl.sammut@flinders.edu.au

Nom du stagiaire accueilli / *Name of intern* Mr. Quentin Vintras

II - EVALUATION / *ASSESSMENT*

Veuillez attribuer une note, en encerclant la lettre appropriée, pour chacune des caractéristiques suivantes. Cette note devra se situer entre **A (très bien)** et **F (très faible)**
Please attribute a mark from ***A (excellent)*** *to* ***F (very weak).***

MISSION / *TASK*

- La mission de départ a-t-elle été remplie ? A
  Was the initial contract carried out to your satisfaction?

- Manquait-il au stagiaire des connaissances ? ☐ oui/*yes* ☒ non/*no*
  Was the intern lacking skills?

  Si oui, lesquelles ? / *If so, which skills?* ____________________

ESPRIT D'EQUIPE / *TEAM SPIRIT*

- Le stagiaire s'est-il bien intégré dans l'organisme d'accueil (disponible, sérieux, s'est adapté au travail en groupe) / *Did the intern easily integrate the host organisation? (flexible, conscientious, adapted to team work)*

A

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* Given the Covid situation, the internship was done remotely. Nevertheless Quentin worked diligently and always achieved his work on time. He also communicated well with the other team members despite the difficulties of having to do everything via teleconference.

COMPORTEMENT AU TRAVAIL / *BEHAVIOUR TOWARDS WORK*

Le comportement du stagiaire était-il conforme à vos attentes (Ponctuel, ordonné, respectueux, soucieux de participer et d'acquérir de nouvelles connaissances) ?
Did the intern live up to expectations? (Punctual, methodical, responsive to management instructions, attentive to quality, concerned with acquiring new skills)?

A

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ____________________

INITIATIVE – AUTONOMIE / *INITIATIVE – AUTONOMY*

Le stagiaire s'est –il rapidement adapté à de nouvelles situations ? A
(Proposition de solutions aux problèmes rencontrés, autonomie dans le travail, etc.)

Did the intern adapt well to new situations? A
(eg. suggested solutions to problems encountered, demonstrated autonomy in his/her job, etc.)

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* Quentin performed exceptionally well, especially given the circumstances of having to work remotely.

CULTUREL – COMMUNICATION / *CULTURAL – COMMUNICATION*

Le stagiaire était-il ouvert, d'une manière générale, à la communication ? A
Was the intern open to listening and expressing himself /herself?

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ____________________

OPINION GLOBALE / *OVERALL ASSESSMENT*

❖ La valeur technique du stagiaire était : A
Please evaluate the technical skills of the intern:

Quentin is a very capable student. He demonstrated excellent skills in researching the literature to find appropriate workable solutions that he then implemented and evaluated. He also demonstrated the capacity to work independently. I am very pleased with his work and only regret that he was not able to join us in person for his internship. His work has made an excellent contribution to our research work.

III - PARTENARIAT FUTUR / *FUTURE PARTNERSHIP*

❖ Etes-vous prêt à accueillir un autre stagiaire l'an prochain ?
Would you be willing to host another intern next year? ☒ oui/*yes* ☐ non/*no*

Fait à Flinders University, le 21/09/20
In ____________________, on ____________________

Signature Entreprise Prof. Karl Sammut Digitally signed by Prof. Karl Sammut Date: 2020.09.21 11:29:15 +09'30'
Company stamp

Signature stagiaire
Intern's signature

Merci pour votre coopération
We thank you very much for your cooperation