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Project title: Multi-domain coordinated motion for autonomous surface and underwater vehicles

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Student's name: Gregoire Ohanyan - H00334040

Supervisor: Dr. Yvan Petillot

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Final Mark ......

Declaration of Authorship

I, Gregoire Ohanyan, declare that this thesis titled 'Multi-domain coordinated motion for autonomous surface and underwater vehicles' and the work presented in it is my own. I confirm that this work submitted for assessment is my own and is expressed in my own words. Any uses made within it of the works of other authors in any form (e.g., ideas, equations, figures, text, tables, programs) are properly acknowledged at any point of their use. A list of the references employed is included.

Signed: Gregoire Ohanyan
Date: 23 April 2020

Abstract

The underwater domain is one of the most extreme environments for humans. Robots have long been used to support or replace human beings to perform important tasks such as exploration, construction and maintenance of subsea infrastructures. The problem is compounded by the lack of GNSS (Global Navigation Satellite System) underwater making navigation and localisation very challenging.

This project aims at pairing an ASV (Autonomous Surface Vehicle) with an AUV (Autonomous Underwater Vehicle), where only the ASV has access to GNSS and uses acoustic communication to estimate the position of the AUV. The two robots communicate through a physical tether for data exchange and use acoustic sensors for range-only localisation. Different approaches will be compared through simulation. An approach that uses Extended Kalman Filter and one that uses trilateration will be implemented and evaluated for the localisation part. Then, a virtual-target approach and one using Fisher Information Matrix will be compared to coordinate motions.

In this portfolio, the objectives of this project are introduced, then a literature review introduces the different concepts and methods that will be used during the project. Finally, a project plan details the different tasks to do during this project.

Abbreviations

ASV - Autonomous Surface Vehicle
AUV - Autonomous Underwater Vehicle
DR - Dead Reckoning
DVL - Doppler Velocity Logs
EKF - Extended Kalman Filter
FIM - Fisher Information Matrix
GIB - GPS Intelligent Buoys
GNSS - Global Navigation Satellite System
GPS - Global Positioning System
KF - Kalman Filter
PF - Particle Filter
LBL - Long Baseline
LSM - Least Square Method
NLS - Non-Linear Least Square
OWTT - One Way Travel Time
TWTT - Two Way Travel Time
ROS - Robot Operating System
ROV - Remotely Operated Vehicle
SIR - Sampling Importance Resampling
UOWC - Underwater Optical Wireless Communications
USBL - Ultra Short Baseline
WIFI - Wireless Fidelity

Contents

1 Introduction

1.1 Motivation

For a long time, robotics have been used to assist humans in tasks they are more efficient to perform or that humans cannot do. That is the case for example in marine environment where the conditions does not permit a easy access for a human being. For this reason, marine robotics is a subject of research to permit different sort of missions such as archaeology, pipe inspection, mine countermeasures, bathymetric surveys and others.
Most of the time, these tasks require just one Autonomous Underwater Vehicle (AUV), but recent research subjects showed that using swarm robotics or pairing an AUV with an ASV (Autonomous Surface Vehicle) leads to higher performances and greater efficiency.
If only AUVs are used, access to GNSS (Global Navigation Satellite System) signals will not be possible, as radio frequencies cannot propagate underwater. To localise themselves, AUVs use Dead Reckoning to estimate their position, but the navigation error grows unbounded because of noise and biases in the measurements. Some other robots goes back to the surface to get access to GNSS, but it is time and energy consuming.
This paper will focus on a multi-robot system consiting of an ASV and an AUV. The ASV can be used as a communication Hub with a remote operator and a navigation aid (it has access to GPS) for the AUV. This robot will have access to GPS and could stream orders from the human leading the operations via WIFI, and gather information from the swarm of AUVs. These can communicate using a tether or acoustic sensor networks[1]. The latest will permit to reduce any constraints in the robot motions, but acoustic communication is also limited due to a low bandwidth.

1.2 Project Description

For all mobile robots, an essential requirement for correct and safe functioning is the ability to maintain an accurate pose estimate. AUVs have some unique challenges related to this task because they lack direct access to the GNSS signals that aerial and many terrestrial robots can exploit. This is especially problematic for mid-water operations where currents limit the usefulness of Doppler Velocity Logs (DVLs) that can provide accurate velocity measurements when close to the sea bed.
This project will implement approaches to improve the robustness of AUV navigation by pairing an underwater vehicle with an ASV that has access to GNSS and can act as a relay via a physical tether or acoustic communications. Working in simulation, the aim is to develop autonomous behaviours for an AUV/USV team performing a sub-surface inspection task.

1.3 Objectives

Update COVID-19 *Due to the exceptional circumstances related to the COVID-19, the objectives have been adapted and all the work will be done only in simulation*

The aim of this project is to model the integration of aiding signals from the USV into the navigation system of the AUV. This will enable the AUV to know its global position based on the GPS position of the USV and range-only measurements from the surface. One way and two ways communications will be explored. Also, the use of a sonar from the ASV to localise the AUV might be explored.
A second objective aims at developing behaviour rules for the vehicles that will allow them to work around an inspection target, taking into account their physical and navigational constraints while allowing the AUV to benefit from the external position information. The constraints to respect will be to keep the tether between the USV and the AUV manageable during the motions.
The objectives of this project are to develop multiple strategies to evaluate in terms of robustness and stability of the vehicles' motion under differing levels of GNSS and communications noise and different environmental conditions.

1.4 Expected Outcomes

This project will explore different methods for acoustic localisation and for the coordinated motions between the AUV and ASV.
A ROS package that works in simulation with ROS kinetic, including the different strategies evaluated, will be submitted at the end of the work period. Will be evaluated in terms of efficiency and accuracy, a Kalman filter-based methods and a trilateration-based method for localisation. For the second part of this project, a virtual-target approach as well as a Fisher Information based one will be compared.

2 Literature Review

2.1 Underwater Communication

Radio frequency signals are widely used to robustly and efficiently share a large amount of information in long distance communication. But due to the nature of the underwater environment, radio frequency waves are highly absorbed and therefore cannot be used properly. One option that can be used to pair an ASV with an AUV is to link them with a tether. This solution, although simple, can become a constraints in the motion of the robot, and limits the number of robots to use for the operations. Wireless communication can be performed underwater whether by acoustic or optical sensor network.
This section will focus on these three different ways of communication underwater and the limitations of each of them.

2.1.1 Communication with Tether

Some unmanned vehicles such as ROV need a reliable and high capacity communication with the surface during their operations. To do so, they use a tether as the communication interface. The tether should validate some criteria that are defined in [2] : tethers should have a small diameter, be light weight, present a good flexibility and a good abrasion resistance, permit high power transmission and data transmission at a high bandwidth, and be bidirectional.
The pros and cons of a tethered communication are developed in [2][3][4][5]. This permit to power supply the robot, and so it will not be dependent of its battery autonomy, and be lighter. It also permits a robust communication with a high bandwidth. But the main issue of using a tether is that it can constraint the robots mobility and can be used only for short distance communication.

2.1.2 Acoustic Communication

Acoustic communication is widely used due to the possibility to use it for long range communication, as for short ranges. But acoustic communication remains really challenging for researchers as "it is impossible to simultaneously achieve high data rates and long communication distances"[3]. Also, it requires high power when it is about sending data at long distances.
Also, acoustic communication suffers from different factors due to the environment that affects temporal and spatial variability. The following factors are listed in [3][6][7]: Transmission loss, noise, multipath, doppler effect, high and variable propagation delay.
Transmission loss are caused by attenuation and geometric spreading. The first one is provoked by absorption due to the heat of acoustic energy. Geometric spreading depends on the propagation distance as it increases with it, but is not depending on frequency.
Noise can be man-made, due to machinery or other sensors, or ambient noise mainly due to surface motion but also thermal noise or turbulences.
Multipath is an important physical phenomenon that is affecting acoustic communication.

It is caused by reflection and refraction. Because of the low speed of sound underwater, propagation delays are different in different paths. This is more true for long distances.
When the transmitter or receiver is moving, Doppler effect appears and can cause frequency shifting and bandwidth spreading.
"Due to the characteristics of underwater acoustic channels, sound propagation is dependent on the signal frequency and transmission distance"[3]. A relation between range and bandwidth available is shown by Akyildiz et al. [7] in Table 1. In practice, the bitrate is much lower than the theoretical one. The values should be divided approximately by 10.

	Range [km]	**Bandwidth[kHz]**	**Bitrate (theoretical) [kb/s]**
Very Long	1000	< 1	< 2
Long	10 - 100	2 - 5	4 - 10
Medium	1 - 10	≈ 10	≈ 20
Short	0.1 - 1	20 - 50	40 - 100
Very Short	< 0.1	> 100	> 100

Table 1: Range-Bandwidth relation for underwater acoustic communication [7]. The bitrate has been calculated with the Shannon-Hartley theorem, with a signal-to-noise ratio = 3.

2.1.3 Underwater Optical Wireless Communications

A third way of underwater communication is using optical transmitters and receivers. This way of communicating is becoming important in the research field, as it results a good bitrate for a wireless method. Papers [8][9][10] agree on the following points. Underwater Optical Wireless Communications (UOWC) perform very high bitrate that can reach some megabits per seconds, compared to acoustic systems that can only reach some kilobits per seconds. Also, the latency is low as it is only a few milliseconds, whereas acoustic systems' latency is a 100 times higher.
But to perform these good results, UOWC are used only at short distances, usually less than 100 meters. This range limitation is mostly due to turbulence and multi-scattering effect in this environment. Also, chromatic dispersion and optical waves absorption is influencing the performance, but using a blue / green light appears to reduce these phenomenon. Finally, the presence of ambient light affects the communication, but for deep sea operations, where the natural light is low, this remains a good option.

2.1.4 Comparisons

The need to pair an ASV with an AUV can be done in many different ways. The solution has to be chosen depending on the nature of the operation, and on the environments constraints. Table 2 resumes the differences between the three communication ways that could be used.

To increase performances, hybrid systems could be used, this is the reason why our robots will need acoustic communication for localisation matters, and a tether for data sharing.

	Tether	**Acoustic**	**Optical**
Accuracy	+	-	$\sim$
Transmission rate	+	-	+
Freedom during the motion	-	+	+
Range	-	+	-

Table 2: Tether-Acoustic-Optical underwater communication comparisons

2.2 Target Localisation

"Underwater target localization refers to the task of estimating the positions of fixed or moving underwater targets by using range measurements between the targets and one or more autonomous surface vehicles (ASVs), called trackers, undergoing trajectories that are known in real time"[11]. To be able to localise itself, and to get a correct use of the coordinates given by the ASV, the first thing is to localise the AUV relatively to the ASV. To do so, AUVs can simply send their estimated position from Dead Reckoning (DR) to the ASV, but DR is not reliable for anything but short operations as the error growths through time. This section will show several cooperative methods to localise precisely the robots during missions.

2.2.1 Range-Only Measurement

Different acoustic transponders can be used for localisation. Ultra-Short Baseline (USBL) and Long Baseline (LBL) are widely used for this purpose. USBL is used for range and bearing measurements, whereas LBL is used for range-only measurement [12]. In this project, range-only localisation will be investigated. To apply this measurement method, the distance of an acoustic message that contains data including its transmitter's position have to be measurable [13].

To measure distances while using acoustic sensors, two methods exists, assuming that the celerity of the acoustic wave is known in the environment. The first methods is the One Way Travel Time (OWTT) that requires the two robot's clocks to be synchronised. The second one is called Two Ways Travel Time (TWTT) and does not require the two robot's clock to be synchronised in time. Basically, TWTT might be cheaper to implement than OWTT as no synchronisation is required, but might require more time to transmit information.

2.2.2 Trilateration

"Trilateration refers to the process of calculating a node position based on measured distances between itself and a number of anchor points with known locations"[14]. It requires to have a number m of observation points strictly superior to a number n of parameters, or dimension of the system [15]. Trilateration is the result of the intersection of the m spheres [16][17]. The position is computed by resolving this equation:

$$(p_i - p_0)^T(p_i - p_0) = r_i^2$$

p_0 : unknown position of the object
p_i : known position of the i^{th} reference point
r_i : known distance between p_0 and p_i

However, due to the uncertainty of the measurements, the spheres might not intersect all in the same point, or intersect at all. Figure 1 shows different cases that could occur using this method. Non-Linear Least Squares (NLS) methods might be used to obtain a good approximation of the position [18][19].

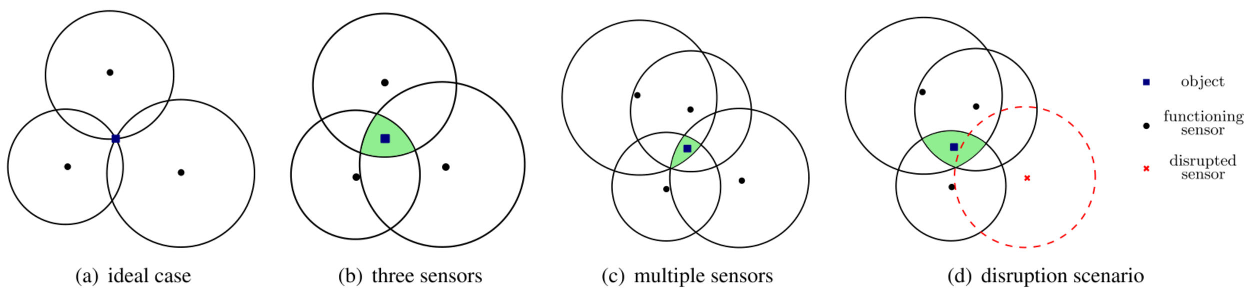


Figure 1: "Position error illustration in trilateration"[16]

2.2.3 Bayesian Filters

"The most general algorithm for calculating beliefs is given by the Bayes filter algorithm."[20] Bayes filters are recursive algorithms that calculates belief at time t, $bel(x_t)$, from the belief at time t-1, $bel(x_{t-1})$. It works in two steps: the prediction step and the measurement step. Algorithm 1 shows the structure of a Bayes filter, where x represents the state, z the observations, and u the controls of the system.

Algorithm 1 Bayes_Filter$(bel(x_{t-1}), u_t, z_t)$

for *all* x_t **do**
  $\overline{bel}(x_t) = \int p(x_t \mid u_t, x_{t-1})\ bel(x_{t-1})\ dx$
  $bel(x_t) = \eta\ p(z_t \mid x_t)\ \overline{bel}(x_t)$
end for
return $bel(x_t)$

Kalman Filter (KF) is a Bayesian filter that works with the assumption of a linear gaussian system. It uses different series of measurements that contains statistical noise and inaccuracies to estimate the most likely state of the system. It is used for fusing data from different sensors to get more accurate ones. As the linearity of the system in underwater environment could be hard to maintain, the Extended Kalman Filter (EKF) permits to outpass this assumption.
Algorithm 2 details the Extended Kalman Filter algorithm, where $\bar{\mu}_t$ is the predicted state, μ_t the corrected state, $\bar{\Sigma}_t$ and Σ_t represent the covariance related to $\bar{\mu}_t$ and μ_t, R_t the motion noise, Q_t the measurement noise, and G_t and H_t are two jacobian matrices.

Algorithm 2 Extended_Kalman_Filter$(\mu_{t-1}, \Sigma_{t-1}, u_t, z_t)$

$\bar{\mu}_t = g(u_t, \mu_{t-1})$
$\bar{\Sigma}_t = G_t\ \Sigma_{t-1}\ G_t^T + R_t$
$K_t = \bar{\Sigma}_t\ H_t^T\ (H_t\ \bar{\Sigma}_t\ H_t^T + Q_t)^{-1}$
$\mu_t = \bar{\mu}_t + K_t\ (z_t - h(\bar{\mu}_t))$
$\Sigma_t = (I - K_t\ H_t)\ \bar{\Sigma}_t$
return μ_t, Σ_t

Particle Filter (PF) is a Bayesian Filter that can handle non Linear and non Gaussian process. It requires an a priori map of the environment to work. It "works by representing a probability distribution $p(x)$ as a set of samples"[21] :

$$p(x) \simeq \frac{1}{N} \sum_i \delta_{x^{(i)}}(x)$$

where N is the number of samples, $x^{(i)}$ is the state of the sample i and $\delta_{x^{(i)}}$ is the impulse function centered in $x^{(i)}$. The higher the density of samples $x^{(i)}$ is in a region, the more likely the current state is in that region.
A method used for PF is Sampling Importance Resampling (SIR) is presented in [22]. It consists in three steps: sampling, importance weight, and resampling.
The drawback of such a method is that it requires a high number of particles, and so a high computation capacity.
Algorithm 3 details the Particle Filter algorithm, where M represents the number of particles in a particle set χ_t and $w_t^{[m]}$ the weight of particle m.

Algorithm 3 Particle_Filter(χ_{t-1}, u_t, z_t)

$\bar{\chi}_t = \chi_t = \emptyset$
for $m = 1$ *to* M **do**
  sample $x_t^{[m]} \sim p(x_t \mid u_t, x_{t-1}^{[m]})$
  $w_t^{[m]} = p(z_t \mid x_t^{[m]})$
  $\bar{\chi}_t = \bar{\chi}_t + \langle x_t^{[m]}, w_t^{[m]} \rangle$
end for
for $m = 1$ *to* M **do**
  draw i *with probability* $\propto w_t^{[i]}$
  add $x_t^{[i]}$ *to* χ_t
end for
return χ_t

2.2.4 Methods

The previous methods explained in previous subsections are just general methods that need to be adapted to our problem. Bayesian Filters are widely used, as PF in [21]. EKF is used to estimate the position from range measurements and DR as in [13], [23] and [24]. Some previous works also use the KF with multiple GPS Intelligent Buoys (GIBs) [25][26], but what we want to achieve here is a method that is using one single ASV. A solution for that is to replace the multiple GIBs by an ASV turning around the target to perform multiple measurements [27]. This is also used for trilateration problems and Least Square Methods (LSM) [12], [13], [28] and [29].

2.3 Coordinated Motion

Keeping a good communication between the ROV and its co-pilot during wireless communication, or enabling the two robots moving while linked with a tether, will constraints the motions of the ROV. To do so, the ASV will have to follow the submerged one during all the operation. This part will focus on different methods of path following to permit the two robot to move coordinately.

2.3.1 Virtual Target approach

Knowing the planned trajectory of the ROV, the two robots can move coordinately by regulating their speed thanks to a Lyapunov-based virtual-target approach.
The method used in [30], using the previous work done in [31], aims to command the two robots to follow the same path, and adapt their speed to maintain their formation. The objective of the path-following part is to minimise the position and orientation error between the virtual and the real target.
To do so, the environment is assumed to be an horizontal plane. Based on the scheme on figure 2 we note, $\langle w \rangle$ the earth-fixed frame, $\langle v \rangle$ the Serret-Frenet frame that corresponds to the virtual target vehicle, and moves along the path to be followed by the vehicle.

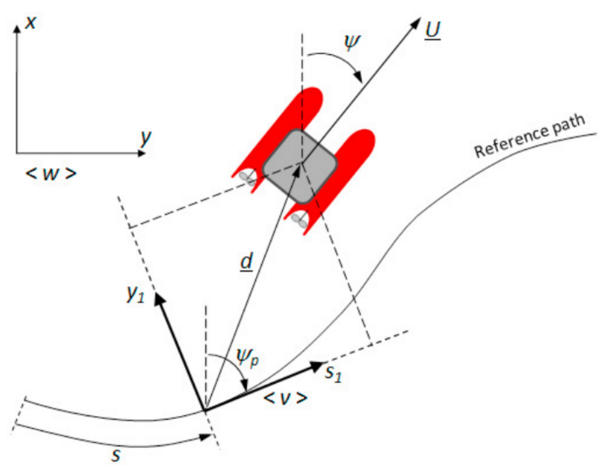


Figure 2: frame definition [30]

The kinematic error model is expressed, in frame $\langle v \rangle$: $\begin{cases} \dot{s}_1 &= -\dot{s}(1 - c_c\ y_1) + U\ cos(\beta) \\ \dot{y}_1 &= -c_c \dot{s} s_1 + U\ sin(\beta) \\ \dot{\beta} &= r - c_c \dot{s} \end{cases}$,

where $r = \dot{\psi}$ is the yaw rate of the vehicle, c_c the local path curvature, s the curvilinear abscissa, and U the norm of the vehicle's velocity.
The next step is to pose the Lyapunov function $V_e = \frac{1}{2}(s_1^2 + y_1^2)$ to find the right speed to control the vehicle, that will permit both vehicles to converge one to each other.

2.3.2 Fisher Information Matrix

An other, widely used, method uses the Fisher Information Matrix (FIM). It is used to optimise the trajectory when measurements are subject to noise [32]. "Consider the problem of estimating an unknown but fixed parameter $\theta \in \mathbb{R}^n$ using a sequence of measurements z_k"[11], the FIM is defined by:

$$FIM(\theta) = \mathbb{E}_\theta \left[(\nabla_\theta(log\mathcal{L}_\theta(z)))(\nabla_\theta(log\mathcal{L}_\theta(z))^T) \right] \in \mathbb{R}^{n \times n}$$

with $FIM(\theta)$ the FIM that is symmetric and positive semi-definite, $\mathcal{L}_\theta(z)$ the likelihood of measurement vector z with respect to the parameter θ and $\mathbb{E}$ the expectation operator.
In order to obtain the path to follow, we search for the trajectory that will maximise the scalar function $J(U) = ln\ det(FIM_U(\theta)$, which is equivalent to minimising $-J(U) = ln\ det((FIM_U(\theta))^{-1})$ [27][33].
This statistical tool is used to find the next position that will minimise the variance. To do so, the parameter will be tested for different position until $J(U)$ is maximised.

2.4 Simulation Tools

In order to fulfil this project, it is important to select the appropriate simulation engine. In this case, using ROS kinetic, there are two simulators that could be used: UUV Simulator and UWSim.

2.4.1 UWSim

UWSim [34] is a simulation and visualisation tool for underwater robotics. It permits to visualise the output computed by external programs, but many control algorithms permit to permit to use this software as a good and reliable simulation.
These programs that can be added to work with UWSim can permit to have an easy configurable environment, different sensors, manage the physics and dynamics, and support multi-robot operations.

2.4.2 UUV Simulator

UUV Simulator [35] is a Gazebo-based package also used for multiple UUV simulation. The advantage of using a Gazebo-based simulator is for the low complexity to setup new scenarios and models. UUV Simulator propose a good management of dynamics and underwater environment forces. Also, different modules can be added to add more precise functionality.

3 Project Plan

In this project, I will try to compare and evaluate different methods for ASV-assisted ROV localisation using a range-only measurement. For localisation, EKF and trilateration methods will be explored, while virtual target and FIM approaches will be explored to enable a coordinated motion. All this work will be performed in simulation only, as due to special circumstances - COVID-19 - no access to the lab will be granted.
This project will take place from the 27^{th} of april to the 24^{th} of july 2020, and will supervised thanks to a weekly videoconference meeting. The time unit used for planing tasks is expressed in days of 6 to 8 working hours with regular breaks to prevent health problem due to a prolonged time spent in front of a laptop screen. Weekends have been considered as non-working days.

3.1 List of Tasks

The different tasks that will be performed are detailed after the following table. They include 12 days of report writing distributed after each work package. Table 3 lists all work packages, that ware more detailed in the gantt chart in section 3.2 - figure 3.

Work packages	**Time (day)**
WP1 - Environment Setup	5
WP2 - Communication	7
WP3 - Localisation, sensor-based estimation	5
WP4 - Localisation, EKF-based	6
WP5 - Localisation, Trilateration-based	12
WP6 - Coordinated Motion	31
Report Writing	12

Table 3: List of work packages, and time associated.

WP1 - Environment Setup - the fist week of this project will be dedicated to setting up all required tools. It will consist in making the simulation tools and the robots work all together with their sensors. Also, this week will permit to learn how to use properly the simulator. - *M1:* Environment setup complete on laptop and all necessary code to run simulation installed and validated. - *D1:* Github with all necessary code to replicate experiments set up.

WP2 - Communication - the key element for this project, is to simulate correctly the communication, first with tether, and then acoustic. It is important to create a reliable model as it will not be possible to test the work on real robots. - *M2:* Necessary code to simulate the communication between the 2 robots, with their constraints, done. - *D2:* A ROS-service that will simulate each of the communication way.

WP3 - Localisation, sensor-based estimation - dead reckoning for the ROV and GPS localisation for the ASV has to be done as a first and fast way to localise the two robots. These sensors will have to be correctly set so the data received by the robot could correspond to the reality. Then, the ROV will have to treat its information to draw a trajectory using the DVL and the IMU. At the end, these data will be shared through a ROS-message. - *M3:* The two robots are able to localise themselves using dead reckoning. Data from the GPS and DVL are computed for this task. - *D3:* A topic for DR-localisation for the ASV and the ROV.

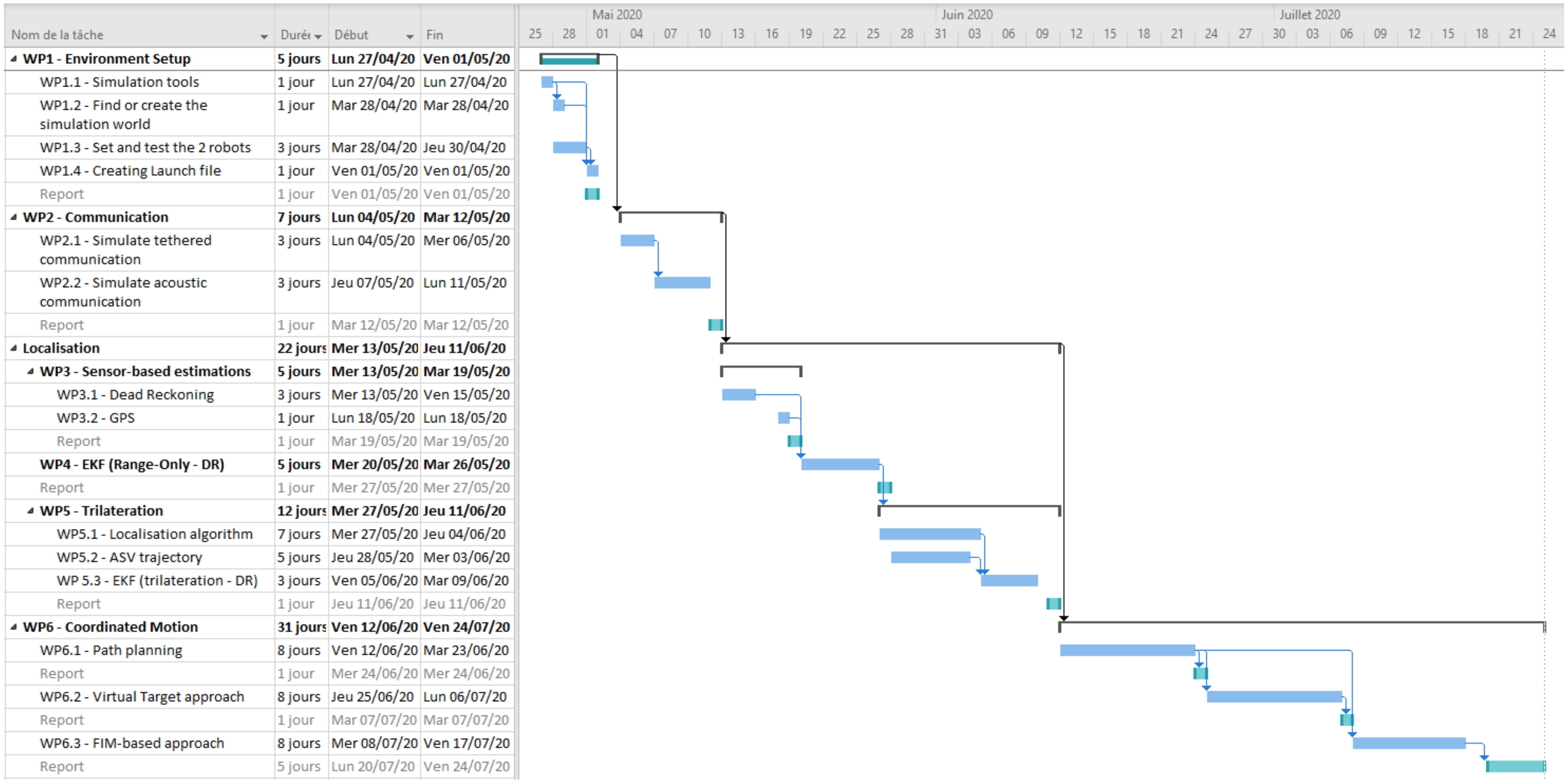
WP4 - Localisation, EKF-based - the first localisation approach that will be implemented is the EKF-based approach. For this, estimations from range-only measurements and dead reckoning will be fused to obtain one more accurate estimated position. Then, the estimation will be compared to the groundtruth position given by the simulator. - *M4:* The EKF-based approach for localisation is implemented and the accuracy will be evaluated. - *D4:* ROS topic with the robot position using this method.

WP5 - Localisation, Trilateration-based - the second localisation approach is using trilateration. This will be tested first with a static-ROV as the ASV will have to move around it, and then the dynamic parameter will be added. This workpackage will lead to a comparison with the groundtruth position, and with the WP4 results. - *M5:* The robot is able to localise using trilateration method. The two last methods are compared in terms of accuracy. - *D5:* ROS topic with the robot position using trilateration.

WP6 - Coordinated Motion - after selecting the more accurate localisation approach, the two robots will have to move coordinately. WP6.1 will focus on drawing the path that will be followed by the ROV, then the virtual-target approach will be tested in WP6.2, and FIM-based approach in WP6.3. At the end, the two approaches implemented in WP6.2 and WP6.3 will be compared. - *M6:* The two methods for coordinated motion are implemented, tested and compared. - *D6:* A ROS package that contains everything needed to have the two robot moving coordinately and knowing their position.

Report Writing - 12 days of report writing, including 1 day after each work package and 5 days at the end of the project.

3.2 Gantt Chart



Nom de la tâche	Durée	Début	Fin
WP1 - Environment Setup	**5 jours**	**Lun 27/04/20**	**Ven 01/05/20**
WP1.1 - Simulation tools	1 jour	Lun 27/04/20	Lun 27/04/20
WP1.2 - Find or create the simulation world	1 jour	Mar 28/04/20	Mar 28/04/20
WP1.3 - Set and test the 2 robots	3 jours	Mar 28/04/20	Jeu 30/04/20
WP1.4 - Creating Launch file	1 jour	Ven 01/05/20	Ven 01/05/20
Report	1 jour	Ven 01/05/20	Ven 01/05/20
WP2 - Communication	**7 jours**	**Lun 04/05/20**	**Mar 12/05/20**
WP2.1 - Simulate tethered communication	3 jours	Lun 04/05/20	Mer 06/05/20
WP2.2 - Simulate acoustic communication	3 jours	Jeu 07/05/20	Lun 11/05/20
Report	1 jour	Mar 12/05/20	Mar 12/05/20
Localisation	**22 jours**	**Mer 13/05/20**	**Jeu 11/06/20**
WP3 - Sensor-based estimations	**5 jours**	**Mer 13/05/20**	**Mar 19/05/20**
WP3.1 - Dead Reckoning	3 jours	Mer 13/05/20	Ven 15/05/20
WP3.2 - GPS	1 jour	Lun 18/05/20	Lun 18/05/20
Report	1 jour	Mar 19/05/20	Mar 19/05/20
WP4 - EKF (Range-Only - DR)	**5 jours**	**Mer 20/05/20**	**Mar 26/05/20**
Report	1 jour	Mer 27/05/20	Mer 27/05/20
WP5 - Trilateration	**12 jours**	**Mer 27/05/20**	**Jeu 11/06/20**
WP5.1 - Localisation algorithm	7 jours	Mer 27/05/20	Jeu 04/06/20
WP5.2 - ASV trajectory	5 jours	Jeu 28/05/20	Mer 03/06/20
WP 5.3 - EKF (trilateration - DR)	3 jours	Ven 05/06/20	Mar 09/06/20
Report	1 jour	Jeu 11/06/20	Jeu 11/06/20
WP6 - Coordinated Motion	**31 jours**	**Ven 12/06/20**	**Ven 24/07/20**
WP6.1 - Path planning	8 jours	Ven 12/06/20	Mar 23/06/20
Report	1 jour	Mer 24/06/20	Mer 24/06/20
WP6.2 - Virtual Target approach	8 jours	Jeu 25/06/20	Lun 06/07/20
Report	1 jour	Mar 07/07/20	Mar 07/07/20
WP6.3 - FIM-based approach	8 jours	Mer 08/07/20	Ven 17/07/20
Report	5 jours	Lun 20/07/20	Ven 24/07/20

Figure 3: Project Gantt chart

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