Advanced AUV Motion Control and Terrain Following for Automatic Seabed Inspection

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Declaration of Originality

I, Fabio Guelfi, hereby declare that this thesis is my own work and all sources of information and ideas have been acknowledged appropriately. This work has not been submitted for any other degree or academic qualification. I understand that any act of plagiarism, reproduction, or use of the whole or any part of this thesis without proper acknowledgment may result in severe academic penalties.

Acknowledgements

This is an optional section, where you can write acknowledgments. Don't forget to acknowledge your supervisor!

This is a short, optional, dedication. To all the Master and PhD students of Robotics Engineering at the University of Genova.

Abstract

The abstract should be a concise report of what the thesis is about. Do not use citations here, and avoid the use of abbreviations. It should not exceed one page of length.

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Introduction

1.1 Content

In the introduction, please state clearly the context your work is framed within, and the motivations of your work. Furthermore, it is important to clarify your contribution (and not those of the group you work in - it is still an exam after all). Provide an outline of the thesis.

1.2 Basic commands

This is a citation: Caccia *et al.* (1999). Make sure to correctly enter all the bibliographic details. It is important that you double check them when retrieving the bibtex file from a source such as Google Scholar. Consistency in the references is valued by the Committee.

This is an emphasized word: *global*.

This is a reference to another part of the thesis: Chapter 2.

This is an enumerated list:

1. first item.

2. second item.

This is an in-line equation: $x-$.

This is a word in quotes: “regular”.

1.3 Equation

This is an equation:

$$\mathcal{U}_k(s_k) = \frac{P_k}{C_k}. \tag{1.1}$$

Equations follow the punctuation rules, as if they were inline with the text. This is an equation split over multiple lines:

$$\begin{aligned} x_k &= \mathcal{F}(x_{k-1}, u_k, w_{k-1}), \\ z_k &= \mathcal{H}(x_k, v_k). \end{aligned} \tag{1.2}$$

This is an example of equation with matrices:

$$\mathcal{Q}_l = \frac{d_l^2 \sigma_\phi^2}{2} \begin{bmatrix} 2\sin^2\phi_l & -\sin 2\phi_l \\ -\sin 2\phi_l & 2\cos^2\phi_l \end{bmatrix} \begin{bmatrix} cc\frac{\sigma_d^2}{2} & 2\cos^2\phi_l & \sin 2\phi_l \\ & \sin 2\phi_l & 2\sin^2\phi_l \end{bmatrix}. \tag{1.3}$$

This is a reference to the Equation 1.2. Avoid using unnumbered equations as it makes it difficult to reference them during a discussion. Also, be consistent in the use of matrix or vector notation. For example, $\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$ or $\boldsymbol{y} = \alpha\boldsymbol{x}$, where the α is a scalar. You can change the corresponding definitions in the class file, as long as you remain consistent.

1.4 Figure

I add a figure.

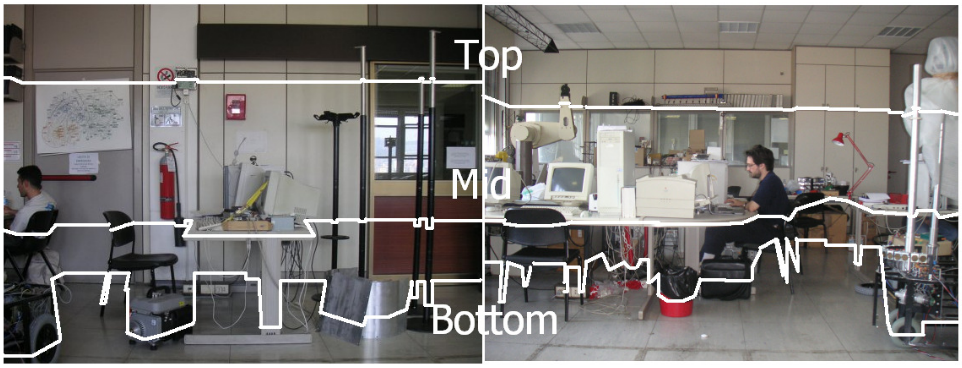

Figure 1.1: Scan profiles: *bottom*, *mid* and *top view*.

Make sure that figures axis are readable. Make sure to label all the units on both axes. The width of the lines should be also crosschecked for readability (the typical MATLAB plot might need higher line width). Double check that legends are present. Figures' captions should allow the reader to fully understand the figure.

This is a reference to Figure 1.1.

1.5 Table

The suggested packages for tables is tabular. There are many examples on the Internet. In general, avoid vertical lines, and use horizontal lines sparingly. Here S allows to align to the decimal point.

m	$\Re\{\underline{\mathfrak{X}}(m)\}$	$-\Im\{\underline{\mathfrak{X}}(m)\}$	$\mathfrak{X}(m)$	$\frac{\mathfrak{X}(m)}{23}$	A_m	$\varphi(m)$ / °	φ_m / °
1	16.128	8.872	16.128	1.402	1.373	−146.6	−137.6
2	3.442	−2.509	3.442	0.299	0.343	133.2	152.4
3	1.826	−0.363	1.826	0.159	0.119	168.5	−161.1
4	0.993	−0.429	0.993	0.086	0.08	25.6	90
5	1.29	0.099	1.29	0.112	0.097	−175.6	−114.7
6	0.483	−0.183	0.483	0.042	0.063	22.3	122.5
7	0.766	−0.475	0.766	0.067	0.039	141.6	−122
8	0.624	0.365	0.624	0.054	0.04	−35.7	90
9	0.641	−0.466	0.641	0.056	0.045	133.3	−106.3
10	0.45	0.421	0.45	0.039	0.034	−69.4	110.9
11	0.598	−0.597	0.598	0.052	0.025	92.3	−109.3

1.6 Algorithm

This is an algorithm:

Algorithm 1 Split & Merge [& Split]

Require: A scan s. A stack $\mathcal{L}$. A counter j. A threshold τ

Ensure: $\lambda \leftarrow \mathcal{M}(s)$, $j = 1, ..., |\lambda|$

$\mathcal{L}$ = `push`(s)
$j \leftarrow 1$
while $\mathcal{L} \neq \varnothing$ **do**
  $\mathcal{L}$ = `pop`(s_{top})
  $l_j \leftarrow$ `fitting`(s_{top})
  $q_k = \text{argmax}_q$ `dist(`l_j`,q)`
  if `dist(`l_j`,`q_k`)` $< \tau$ **then**
    $j \leftarrow j + 1$
    `continue`
  else
    $s_a \leftarrow$ `sub`$(s_{top}, 1, k)$
    $s_b \leftarrow$ `sub`$(s_{top}, k + 1, |s|)$
    $\mathcal{L}$ = `push`(s_a)
    $\mathcal{L}$ = `push`(s_b)
  end if
end while
$\{l_j\} \leftarrow$ `merge`$(\{l_j\})$
$\{l_j\} \leftarrow$ `split`$(\{l_j\})$

1.7 Historical background

The first real underwater explorations date back to the Phoenicians, Greeks, and Romans, who, through diving and free diving, recovered corals, sponges, and objects from the seabed, in addition to defenses Erodoto (V sec. a.C.). Many years later, in 1535, Guglielmo de Lorena designed the first underwater bell for underwater inspections, but only at shallow depths Eliav (2015). It was not until 1934 that the first real exploratory expedition took place with William Beebe and Otis Barton's bathyscaphe to a depth of about 923 meters, and in 1960, Auguste Piccard's bathyscaphe, the Trieste, reached a depth of 10,916 meters in the Mariana Trench Jacques Piccard (1961).

1.7.1 Marine robotics

With the advent of technology, remotely operated vehicles (ROVs) emerged, allowing for deeper and more complex underwater exploration without putting human divers at risk. The most complex challenge was the communication between the

ROV and the surface vessels. The solution was to build tethered systems that could maintain a constant connection. The CURV, Cable Controlled Undersea Recovery Vehicle, was the first ROV to be used in underwater missions.

1.7.2 Autonomous navigation

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Chapter 2

AUV Dynamic

This chapter introduces the equations that describe the dynamics of an underwater vehicle. As a first step, it is essential to present the conventions used to define reference frames in marine robotics. This makes it possible to describe the general equations of dynamics Fossen (2011) for any marine robot in 6-DOF, degrees of freedom, and subsequently conduct a more in-depth analysis for the BlueRov2 class and the parameters used in the simulation.

The study begins with the fundamental equation for underwater dynamics. The simplifications due to low-speed conditions, together with the most relevant parameters, will be illustrated in detail. Finally, the parameters adopted in the BlueRov simulation are derived from an identification study Berg (2012).

2.1 Reference frames and naming conventions

To tackle the study of AUV dynamics, it is essential to define the main reference frames in accordance with marine robotics conventions, namely the body-fixed frame, where the dynamic of the vehicle is described, and an earth-fixed frame, with respect to the position and the orientation of the vehicle are described.

The body-fixed frame $\{B\}$ is a right-handed coordinate system, it is rigidly attached to the vehicle, with its origin O_B located at the center of gravity (CG). The axes $\{x_B, y_B, z_B\}$ are defined following the "SNAME" notation The Society of Naval Architects and Marine Engineers (SNAME) (1950), so:

- the x_B axis points towards the head of the vehicle (longitudinal axis);
- the y_B axis points to the right side of the vehicle (transverse axis);
- the z_B axis points downwards (normal axis).

Having defined the robot's frame of reference, we now need to define a fixed observation reference to estimate the position and movement of the AUV. We can therefore assume the rotation and curvature of the Earth as zero, given the low-speed and small variations in latitude and longitude operating conditions. Based on these considerations, we define a earth-fixed-frame $\{I\}$ at a point on the sea surface within the vehicle's area of operation. Following convention, the frame will be a local NED (North-East-Down) frame, then a right-handed coordinate system, with the axes pointing respectively:

- the x_I axis pointing towards the North;
- the y_I axis pointing towards the East;
- the z_I axis pointing downwards.

Given the assumption stated earlier, $\{I\}$ can be considered an inertial frame, so Newton's laws of motion are valid.

Having defined the two reference frames, it is possible to introduce the SNAME notation for all parameters essential for determining the position, orientation and velocity of the AUV, considering external forces and moments applied to it. The position of the origin of the body-fixed frame with respect to the inertial frame is defined through the vector $\eta_1 = [x, y, z]^T$, while the orientation of $\{B\}$ with respect to $\{I\}$ is given by the rotation matrix ${}^I_B R$ defined by the Euler angles contained in the vector $\eta_2 = [\phi, \theta, \psi]^T$. The velocity of $\{B\}$ with respect to $\{I\}$, on the other hand, is divided into linear $\nu_1 = [u, v, w]^T$ and angular $\nu_2 = [p, q, r]^T$ components, while the external forces and moments are expressed in $\{B\}$ and are described by the vector $\tau = [\tau_1, \tau_2]^T$, where $\tau_1 = [X, Y, Z]^T$ for forces and by the vector $\tau_2 = [K, M, N]^T$ for moments.

This notation is more easily visible in the table 2.1, where the parameters that will be widely used in this thesis are defined in the 6 degrees of freedom.

DOF	Direction	Position and Euler angles	Velocity	Force and Moment
1	along x_B	x	surge speed u	X
2	along y_B	y	sway speed v	Y
3	along z_B	z	heave speed w	Z
4	rotation about x_B	roll angle ϕ	roll rate p	K
5	rotation about y_B	pitch angle θ	pitch rate q	M
6	rotation about z_B	yaw angle ψ	yaw rate r	N

Table 2.1: SNAME nomenclature and symbols Abreu (2014).

2.2 Dynamics

The dynamic equations of motion describe how forces and torques affect the movement of the vehicle. These equations are commonly expressed in the body-fixed reference frame, as this formulation keeps the inertia tensor constant and allows external forces (weight, buoyancy, hydrodynamic effects) to be represented more conveniently.

The derivation of the rigid-body dynamics follows Newton-Euler laws for both translational and rotational motion Fossen (2011):

$$\begin{cases} \sum F_{RB} = m[\nu_2 \times \nu_1 + \dot{\nu}_1] \\ \sum N_{RB} = I_{RB}\dot{\nu}_2 + \nu_2 \times I_{RB}\nu_2 \end{cases} \tag{2.1}$$

where m is the mass of the vehicle, I_{RB} is the inertia tensor, $\sum F_{RB}$ are the external forces and $\sum N_{RB}$ are the external moments acting on the vehicle.
The equations 2.1 can be rewritten in a more compact matrix form as:

$$M_{RB}\dot{\nu} + C_{RB}(\nu)\nu = \tau \tag{2.2}$$

M_{RB} is the rigid body inertia matrix, while C_{RB} contains the Coriolis, centripetal and gyroscopic terms. These matrices satisfy some key properties:

- $\dot{M}_{RB} = 0$: the inertia matrix is constant in the body-fixed frame;
- $\dot{M}_{RB}^T = \dot{M}_{RB}$: the inertia matrix is symmetric and positive-definite. Moreover, when the body-fixed frame is centered at the center of gravity and aligned with the principal axes of inertia, M_{RB} is diagonal;
- $C_{RB}(\nu) = -C_{RB}(\nu)^T$: the Coriolis and centripetal matrix can be parameterized to be skew-symmetric.

The subscript RB highlights that the formulation includes only rigid-body dynamics, with all external forces and moments grouped in the generalized vector $\tau_{RB} = [X, Y, Z, K, M, N]^T$. In order to account for different contributions, this term can be decomposed as:

$$\tau_{RB} = \tau + \tau_A + \tau_D + \tau_R + \tau_{dist} \tag{2.3}$$

where:

- τ represents control inputs given by the thrusters;
- τ_A accounts for added mass and added Coriolis effects, described by the matrices M_A and $C_A(\nu)$ respectively. It can be studied by computing the kinetic energy imparted by the vehicle to the surrounding displaced fluid (even for inviscid fluid);

- τ_D models drag forces and moments, including contributions from skin friction and pressure;
- τ_R represents restoring forces and moments arising from buoyancy and weight imbalance;
- τ_{dist} includes unmodeled external disturbances such as waves (not important in my application) and currents.

So, the equation 2.2 can be rewritten as:

$$\tau_{RB} = \tau - M_A\dot{\nu} - C_A(\nu)\nu - D(\nu)\nu - \mathbf{g}(\eta) + \tau_{dist} \tag{2.4}$$

The complete dynamic model, neglecting the disturbances, becomes:

$$(M_{RB} + M_A)\dot{\nu} + (C_{RB}(\nu) + C_A(\nu))\nu + D(\nu)\nu + \mathbf{g}(\eta) = \tau, \tag{2.5}$$

Or more compactly:

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + \mathbf{g}(\eta) = \tau, \tag{2.6}$$

By assuming that the origin of the body-fixed reference frame coincides with the vehicle's center of gravity, that the body axes are aligned with the principal axes of inertia, that the added mass matrix M_A is symmetric and positive definite, and that hydrostatic stability conditions hold, the overall inertia matrix M is symmetric and positive definite. Furthermore, the damping matrix $D(\nu)$ is positive definite, while the Coriolis-centripetal matrix $C(\nu)$ can be parameterized to be skew-symmetric.

2.3 BlueRov2 AUV

The equation 2.6 represents the complete 6-DOF dynamic model of an underwater vehicle neglecting the disturbances, but ...

Although the BlueROV2 is originally designed as a Remotely Operated Vehicle (ROV), in this work it is modeled and employed as an Autonomous Underwater Vehicle (AUV). This choice is justified by the fact that the platform is fully actuated in all six degrees of freedom, with independent thrusters for each motion, making it a suitable candidate for testing the proposed control and estimation algorithms in simulation. In the following sections, the BlueROV2 will therefore be analyzed as an AUV, even though it is not one in practice. The possible hardware and software modifications required to achieve such a transformation in reality are beyond the scope of this work and will not be addressed.

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Write the results here...

Chapter 9

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Write the conclusions here...

Appendix A

Extra

Write here...

Write here...

References

ABREU, P.C. (2014). Sensor-based Formation Control of Autonomous Underwater Vehicles. 7

BERG, V. (2012). *Development and Commissioning of a DP System for ROV SF 30k*. Ph.D. thesis, Norwegian University. 6

CACCIA, M., BRUZZONE, G. & VERUGGIO, G. (1999). Active sonar-based bottom-following for unmanned underwater vehicles. *Control Engineering Practice*, **7**, 459–468. 1

ELIAV, J. (2015). Guglielmo's Secret: The Enigma of the First Diving Bell Used in Underwater Archaeology. *The International Journal for the History of Engineering & Technology*, **85**, 60–69. 4

ERODOTO (V sec. a.C.). Storie. 4

FOSSEN, T.I. (2011). *Handbook of Marine Craft Hydrodynamics and Motion Control*. Wiley, 1st edn. 6, 8

JACQUES PICCARD, R.S.D. (1961). Seven Miles Down. 4

THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS (SNAME) (1950). Nomenclature for treating the motion of a submerged body through a fluid. 6