Springer Tracts in Advanced Robotics

Volume 2

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Control of Single Wheel Robots
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472 p. 2005 [3-540-25728-4]

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224 p. 2005 [3-540-23956-1]

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595 p. 2005 [3-540-23214-1]

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Advances in Human-Robot Interaction
414 p. 2005 [3-540-23211-7]

Vol. 13: Chung, W.
Nonholonomic Manipulators
115 p. 2004 [3-540-22108-5]

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Mobile Robots in Rough Terrain – Estimation, Motion Planning, and Control with Application to Planetary Rovers
123 p. 2004 [3-540-21968-4]

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Soccer Robotics
353 p. 2004 [3-540-21859-9]

Vol. 10: Siciliano, B.; De Luca, A.; Melchiorri, C.; Casalino, G. (Eds.)
Advances in Control of Articulated and Mobile Robots
259 p. 2004 [3-540-20783-X]

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Simulating and Generating Motions of Human Figures
176 p. 2004 [3-540-20317-6]

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198 p. 2004 [3-540-40475-9]

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Algorithmic Foundations of Robotics V
577 p. 2004 [3-540-40476-7]

Vol. 6: Jarvis, R.A.; Zelinsky, A. (Eds.)
Robotics Research – The Tenth International Symposium
580 p. 2003 [3-540-00550-1]

Vol. 5: Siciliano, B.; Dario, P. (Eds.)
Experimental Robotics VIII
685 p. 2003 [3-540-00305-3]

Vol. 4: Bicchi, A.; Christensen, H.I.; Prattichizzo, D. (Eds.)
Control Problems in Robotics
296 p. 2003 [3-540-00251-0]

Vol. 3: Natale, C.
Interaction Control of Robot Manipulators – Six-degrees-of-freedom Tasks
120 p. 2003 [3-540-00159-X]

Vol. 2: Antonelli, G.
Underwater Robots – Motion and Force Control of Vehicle-Manipulator Systems
209 p. 2003 [3-540-00054-2]

Vol. 1: Caccavale, F.; Villani, L. (Eds.)
Fault Diagnosis and Fault Tolerance for Mechatronic Systems – Recent Advances
191 p. 2002 [3-540-44159-X]

Gianluca Antonelli

Underwater Robots

Motion and Force Control of Vehicle-Manipulator Systems

Second edition

With 95 Figures

Springer

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European ROBOTICS Research Network EURON

Ad Andrea e Giustina

E la locomotiva sembrava fosse un mostro strano
che l'uomo dominava con il pensiero e con la mano...
Francesco Guccini, La locomotiva, 1972.

Foreword

At the dawn of the new millennium, robotics is undergoing a major transformation in scope and dimension. From a largely dominant industrial focus, robotics is rapidly expanding into the challenges of unstructured environments. Interacting with, assisting, serving, and exploring with humans, the emerging robots will increasingly touch people and their lives.

The goal of the new series of *Springer Tracts in Advanced Robotics (STAR)* is to bring, in a timely fashion, the latest advances and developments in robotics on the basis of their significance and quality. It is our hope that the wider dissemination of research developments will stimulate more exchanges and collaborations among the research community and contribute to further advancement of this rapidly growing field.

The volume by Gianluca Antonelli is the second edition of a successful monograph, which was one of the first volumes to be published in the series. Being focused on an important class of robotic systems, namely underwater vehicle-manipulator systems, this volume improves the previous material while expanding the state-of-the-art in the field. New features deal with fault-tolerant control and coordinated control of autonomous underwater vehicles.

A well-balanced blend of theoretical and experimental results, this volume represents a fine confirmation in our STAR series!

Naples, Italy
October 2005

Bruno Siciliano,
STAR Editor

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The contributions of a quite large number of people were determinant for the realization of this monograph.

Prof. Stefano Chiaverini was my co-tutor during my PhD at the Università degli Studi di Napoli Federico II, he is now Full Professor at the Università degli Studi di Cassino. Since the beginning of the doctoral experience up to present all the research that I have done is shared with him. As a matter of fact, I consider myself as a co-author of this monograph. Furthermore, Stefano was, somehow, also *responsible* of my decision to join the academic career.

Prof. Lorenzo Sciavicco developed a productive, and friendly, research environment in Napoli that was important for my professional growing. Prof. Bruno Siciliano, my tutor both in the Master and PhD thesis, to whom goes my warmest acknowledgements.

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During the PhD I have been visiting researcher at the Autonomous Systems Laboratory of the University of Hawaii where I carried out some experiments on dynamic control of autonomous underwater vehicles and worked on the interaction control chapter. I would like to acknowledge Prof. Nilanjan Sarkar and Prof. Junku Yuh, my guests during the staying.

For this second edition several colleagues provide me with their illustrative material, I would like to thank Eng. Massimo Caccia, Prof. Giuseppe Casalino, Prof. Tom McLain, Prof. Daniel Stilwell, Eng. Gianmarco Veruggio and Prof. Junku Yuh.

My mother, my father, my brothers Marco and Fabrizio, my wife Giustina and, recently, my son Andrea, they all tolerated, and will have to tolerate for longtime, my *engineeringness*.

About the Author

Gianluca Antonelli was born in Roma, Italy, on December 19, 1970. He received the “Laurea” degree in Electronic Engineering and the “Research Doctorate” degree in Electronic Engineering and Computer Science from the Università degli Studi di Napoli Federico II in 1995 and 2000, respectively. From January 2000 he is with the Università degli Studi di Cassino where he currently is an Associate Professor. He has published more than 60 journals and conference papers; he was awarded with the “EURON Georges Giralt PhD Award”, First Edition for the thesis published in the years 1999-2000. From September, 2005 he is an *Associate Editor* of the *IEEE Transactions on Robotics*. His research interests include simulation and control of underwater robotic systems, force/motion control of robot manipulators, path planning and obstacle avoidance for autonomous vehicles, identification, multi-robot systems.

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Preface to the Second Edition

The purpose of this Second Edition is to add material not covered in the First Edition as well as streamline and improve the previous material.

The organization of the book has been substantially modified, an introductory Chapter containing the state of the art has been considered; the modeling Chapter is substantially unmodified. In Chapter 3 the problem of controlling a 6-Degrees-Of-Freedoms (DOFs) Autonomous Underwater Vehicle (AUV) is investigated. Chapter 4 is a new Chapter devoted at a survey of fault detection/tolerant strategies for ROVs/AUVs, it is mainly based on the Chapter published in [10]. The following Chapter (Chapter 5) reports experimental results obtained with the vehicle ODIN. The following 3 Chapters, from Chapter 6 to Chapter 8 are devoted at presenting kinematic, dynamic and interaction control strategies for Underwater Vehicle Manipulator Systems (UVMSs); new material has been added thanks also to several colleagues who provided me with valuable material, I warmly thank all of them. The content of Chapter 9 is new in this Second Edition and reports preliminary results on the emerging topic of coordinated control of platoon of AUVs. Finally, the bibliography has been updated.

The reader might be interested in knowing what she/he will not find in this book. Since the core of the book is the coordinated control of manipulators mounted on underwater vehicles, control of non-holonomic vehicles is not dealt with; this is an important topic also in view of the large number of existing *torpedo*-like vehicles. Another important aspect concerns the sensorial apparatus, both from the technological point of view and from the algorithmic aspect; most of the AUVs are equipped with redundant sensorial systems required both for localization/navigation purposes and for fault detection/tolerant capabilities. Actuation is mainly obtained by means of thrusters; those are still object of research for the modeling characteristics and might be the object of improvement in terms of dynamic response.

Cassino, Italy *Gianluca Antonelli*
January 2006

Preface to the First Edition

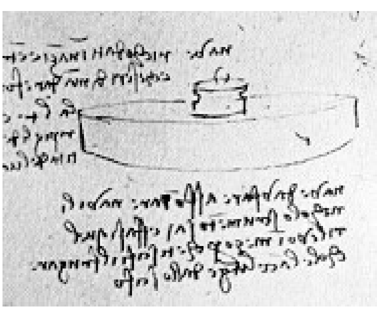
Underwater Robotics have known in the last years an increasing interest from research and industry. Currently, it is common the use of manned underwater robotics systems to accomplish missions as sea bottom and pipeline survey, cable maintenance, off-shore structures' monitoring and maintenance, collect/release of biological surveys. The strong limit of the use of manned vehicles is the enormous cost and risk in working in such an hostile environment. The aim of the research is to progressively make it possible to perform such missions in a completely autonomous way.

This objective is challenging from the technological as well as from the theoretical aspects since it implies a wide range of technical and research topics. Sending an autonomous vehicle in an unknown and unstructured environment, with limited on-line communication, requires some on board *intelligence* and the ability of the vehicle to react in a reliable way to unexpected situations. Techniques as artificial intelligence, neural network, discrete events, fuzzy logic can be useful in this *high* level mission control. The sensory system of the vehicle must deal with a noisy and unstructured environment; moreover, technologies as GPS are not applicable due to the impossibility to underwater electromagnetic transmission; vision based systems are not fully reliable due to the generally poor visibility. The actuating system is usually composed of thrusters and control surfaces; all of them have a non-linear dynamics and are strongly affected by the hydrodynamic effects.

In this framework the use of a manipulator mounted on a autonomous vehicle plays an important role. From the control point of view, underwater robotics is much more challenging with respect to ground robotics since the former deal with unstructured environments, mobile base, significant external disturbance, low bandwidth of sensory and actuating systems, difficulty in the estimation of the dynamic parameters, highly non-linear dynamics.

Referring to Autonomous Underwater Vehicles (AUVs), i.e., unthetered, unmanned vehicles to be used mainly in survey missions, [294, 321] present the state of the art of several existing AUVs and their control architecture. Currently, there are more than 46 AUV models [321], among others: *ABE* of the Woods Hole Oceanographic Institution (MA, USA), *MARIUS* developed under the Marine Science and Technology Programme of the IV framework of European Commission (Lisbon, Portugal), *ODIN* designed at the Autonomous Systems Laboratory of the University of Hawaii (Honolulu, HI, USA), *OTTER* from the Monterey Bay Acquarium and Stanford University (CA, USA), *Phoenix* and *ARIES* belonging to the Naval Postgraduate School (Monterey, CA, USA), *Twin Burgers* developed at the University of Tokyo (Tokyo, Japan), *Theseus* belonging to ISE Research Ltd (Canada). Reference [92] shows the control architecture of *VORTEX*, a vehicle developed by Inria and Ifremer (France), and *OTTER*. Focusing on the low level motion control of AUVs, most of the proposed control schemes take into account the uncertainty in the model by resorting to an adaptive strategy [83, 91, 126, 130, 138, 314] or a robust approach [90, 93, 145, 201, 259, 310, 311]. In [145] an estimation of the dynamic parameters of the vehicle NPS AUV *Phoenix* is also provided. An overview of control techniques for AUVs is reported in [127].

As a curiosity, in the Figure below there is a draw of one of the first *manned* underwater vehicles. It was found in the *Codice Atlantico* (Codex Atlanticus), written by Leonardo Da Vinci between 1480 and 1518, together with the development of some diver's devices. Legends say that Leonardo worked on the idea of an underwater military machine that he further destroyed by himself the results judged too dangerous. Maybe the first idea of an underwater machine is from Aristotle; following the legend he built a machine: *skaphe andros* (boat-man) that allowed Alexander the Great to stay in deep for at least half a day during the war of Tiro in 325 b. C. This is unrealistic, of course, also considering that the Archimedes's law was still to become a reality (around 250 b. C.).



Draw of the manned underwater vehicle developed by Leonardo Da Vinci

The current technology in control of underwater manipulation is limited to the use of a master/slave approach in which a skilled operator has to move a master manipulator that works as *joystick* for the slave manipulator that is performing the task [56, 287]. The limitations of such a technique are evident: the operator must be well trained, underwater communication is hard and a significant delay in the control is experienced. Moreover, if the task has to be performed in deep waters, a manned underwater vehicle close to the unmanned vehicle with the manipulator need to be considered to overcome the communication problems thus leading to enormous cost increasing. Few research centers are equipped with an autonomous Underwater Vehicle-Manipulator System. Among the others:

- *ODIN* and *OTTER* can be provided with a one/two link manipulator to study the interaction of the manipulator and the vehicle in order to execute automatic retrieval tasks [297];
- on *VORTEX* a 7-link manipulator (*PA10*) can be mounted with a large inertia with respect to the vehicle that implies a strong interaction between them;
- *SAUVIM*, a semi-autonomous vehicle with an *Ansaldo* 7-link manipulator is under development at the Autonomous Systems Laboratory of the University of Hawaii; this vehicle, in the final version, will be able to operate at the depth of 4000 m.
- *AMADEUS*, an acronym for Advanced MAnipulation for DEep Underwater Sampling, funded by the European Commission, that involved the Heriot-Watt University (UK), the Università di Genova (Italy), CNR Istituto Automazione Navale, (Italy), the Universitat de Barcelona (Spain), the Institute of Marine Biology of Crete (Greece). The project focused on the co-ordinated control of two tele-operated underwater *Ansaldo* 7-link manipulators and the development of an underwater hand equipped with a slip sensor.

Focusing on the motion control of UVMSs, [56, 159] present a telemanipulated arm; in [192] an *intelligent* underwater manipulator prototype is experimentally validated; [67, 68, 69] present some simulation results on a Composite Dynamics approach for *VORTEX/PA10*; [106] evaluates the dynamic coupling for a specific UVMS; adaptive approaches are presented in [124, 197, 198]. Reference [206] reports some interesting experiments of coordinated control. Very few papers investigated the redundancy resolution of UVMSs by applying inverse kinematics algorithm with different secondary tasks [20, 24, 25, 249, 250].

This book deals with the main control aspects in underwater manipulation tasks and dynamic control of AUVs. First, the mathematical model is discussed; the aspects with significant impact on the control strategy will be remarked. In Chap. 6, kinematic control for underwater manipulation is presented. Kinematic control plays a significant role in unstructured robotics where off-line trajectory planning is not a reliable approach; moreover, the vehicle-manipulator system is often kinematically redundant with respect to the most common tasks and redundancy resolution algorithms can then be applied to exploit such characteristic. Dynamic control is then discussed in Chap. 7; several motion control schemes are analyzed and presented in this book. Some experimental results with the autonomous vehicle *ODIN* (without manipulator) are presented, moreover some theoretical results on adaptive control of AUVs are discussed. In Chap. 8, the interaction with the environment is detailed. Such kind of operation is critical in underwater manipulation for several reasons that do not allow direct implementation of the force control strategies developed for ground robotics. Finally, after having developed some conclusions, a simulation tool for multi-body systems is presented. This software package, developed for testing the control strategies studied along the book, has been designed according to modular requirements that make it possible to generate generic robotic systems in any desired environment.

Napoli, August 2002 *Gianluca Antonelli*

Notation

In this Chapter, the main acronyms and the notation that will be used in the work are listed.

AUV	Autonomous Underwater Vehicle
CLIK	Closed Loop Inverse Kinematics
DOF	Degree Of Freedom
EKF	Extended Kalman Filter
FD	Fault Detection
FIS	Fuzzy Inference System
FTC	Fault Tolerant Controller
KF	Kalman Filter
ROV	Remotely Operated Vehicle
TCM	Thruster Control Matrix
UUV	Unmanned Underwater Vehicle
UVMS	Underwater Vehicle-Manipulator System
$\Sigma_i, O - \boldsymbol{xyz}$	inertial frame (see Figure 2.1)
$\Sigma_b, O_b - \boldsymbol{x}_b\boldsymbol{y}_b\boldsymbol{z}_b$	body(vehicle)-fixed frame (see Figure 2.1)
$\mathbb{R}$, $\mathbb{N}$	Real, Natural numbers
$\boldsymbol{\eta}_1 = [\, x \quad y \quad z \,]^{\mathrm{T}} \in \mathbb{R}^3$	body(vehicle) position coordinates in the inertial frame (see Figure 2.1)
$\boldsymbol{\eta}_2 = [\, \phi \quad \theta \quad \psi \,]^{\mathrm{T}} \in \mathbb{R}^3$	body(vehicle) Euler-angle coordinates in the inertial frame (see Figure 2.1)
$\mathcal{Q} = \{\boldsymbol{\varepsilon} \in \mathbb{R}^3, \eta \in \mathbb{R}\}$	quaternion expressing the body(vehicle) orientation with respect to the inertial frame
$\boldsymbol{\eta} = [\, \boldsymbol{\eta}_1^{\mathrm{T}} \quad \boldsymbol{\eta}_2^{\mathrm{T}} \,]^{\mathrm{T}} \in \mathbb{R}^6$	body(vehicle) position/orientation

$\boldsymbol{\eta}_q = [\,\boldsymbol{\eta}_1^{\mathrm{T}} \quad \boldsymbol{\varepsilon}^{\mathrm{T}} \quad \eta\,]^{\mathrm{T}} \in \mathrm{I\!R}^7$	body(vehicle) position/orientation with the orientation expressed by quaternions
$\boldsymbol{\nu}_1 = [\,u \quad v \quad w\,]^{\mathrm{T}} \in \mathrm{I\!R}^3$	vector representing the linear velocity of the origin of the body(vehicle)-fixed frame with respect to the origin of the inertial frame expressed in the body(vehicle)-fixed frame (see Figure 2.1)
$\boldsymbol{\nu}_2 = [\,p \quad q \quad r\,]^{\mathrm{T}} \in \mathrm{I\!R}^3$	vector representing the angular velocity of the body(vehicle)-fixed frame with respect to the inertial frame expressed in the body(vehicle)-fixed frame (see Figure 2.1)
$\boldsymbol{\nu} = [\,\boldsymbol{\nu}_1^{\mathrm{T}} \quad \boldsymbol{\nu}_2^{\mathrm{T}}\,]^{\mathrm{T}} \in \mathrm{I\!R}^6$	vector representing the linear/angular velocity in the body(vehicle)-fixed frame
$\boldsymbol{R}_\alpha^\beta \in \mathrm{I\!R}^{3\times 3}$	rotation matrix expressing the transformation from frame α to frame β
$\boldsymbol{J}_{k,o}(\boldsymbol{\eta}_2) \in \mathrm{I\!R}^{3\times 3}$	Jacobian matrix defined in (2.2)
$\boldsymbol{J}_{k,oq}(\mathcal{Q}) \in \mathrm{I\!R}^{4\times 3}$	Jacobian matrix defined in (2.10)
$\boldsymbol{J}_e(\boldsymbol{\eta}_2) \in \mathrm{I\!R}^{6\times 6}$	Jacobian matrix defined in (2.19)
$\boldsymbol{J}_{e,q}(\mathcal{Q}) \in \mathrm{I\!R}^{7\times 6}$	Jacobian matrix defined in (2.23)
$\boldsymbol{\tau}_1 = [\,X \quad Y \quad Z\,]^{\mathrm{T}} \in \mathrm{I\!R}^3$	vector representing the resultant forces acting on the rigid body(vehicle) expressed in the body(vehicle)-fixed frame
$\boldsymbol{\tau}_2 = [\,K \quad M \quad N\,]^{\mathrm{T}} \in \mathrm{I\!R}^3$	vector representing the resultant moment acting on the rigid body(vehicle) expressed in the body(vehicle)-fixed frame to the pole O_b
$\boldsymbol{\tau}_v = [\,\boldsymbol{\tau}_1^{\mathrm{T}} \quad \boldsymbol{\tau}_2^{\mathrm{T}}\,]^{\mathrm{T}} \in \mathrm{I\!R}^6$	generalized forces: forces and moments acting on the vehicle
$\boldsymbol{\tau}_v^\star \in \mathrm{I\!R}^6$	generalized forces in the earth-fixed-frame-based model defined in (2.53)
n	degrees of freedom of the manipulator
$\boldsymbol{q} \in \mathrm{I\!R}^n$	joint positions
$\boldsymbol{\tau}_q \in \mathrm{I\!R}^n$	joint torques
$\boldsymbol{\tau} = [\,\boldsymbol{\tau}_v^{\mathrm{T}} \quad \boldsymbol{\tau}_q^{\mathrm{T}}\,]^{\mathrm{T}} \in \mathrm{I\!R}^{6+n}$	generalized forces: vehicle forces and moments and joint torques
$\boldsymbol{u} \in \mathrm{I\!R}^p$	control inputs, $\boldsymbol{\tau} = \boldsymbol{B}\boldsymbol{u}$ (see (2.72))

$\boldsymbol{\zeta} = [\,\boldsymbol{\nu}_1^{\mathrm{T}} \quad \boldsymbol{\nu}_2^{\mathrm{T}} \quad \dot{\boldsymbol{q}}^{\mathrm{T}}\,]^{\mathrm{T}} \in \mathrm{I\!R}^{6+n}$	*system* velocity
$\boldsymbol{\Phi} \in R^{(6+n)\times n_\theta}$	UVMS regressor defined in (2.73)
$\boldsymbol{\theta} \in R^{n_\theta}$	vector of the dynamic parameters of the UVMS regressor defined in (2.73)
$\boldsymbol{\Phi}_v \in R^{6\times n_{\theta,v}}$	vehicle regressor defined in (2.54)
$\boldsymbol{\theta}_v \in R^{n_{\theta,v}}$	vector of the dynamic parameters of the vehicle regressor defined in (2.54)
$\boldsymbol{\eta}_{ee1} = [\,x_E \quad y_E \quad z_E\,]^{\mathrm{T}} \in \mathrm{I\!R}^3$	position of the end effector in the inertial frame (denoted with $\boldsymbol{x} = [\,x_E \quad y_E \quad z_E\,]^{\mathrm{T}}$ in the interaction control sections)
$\boldsymbol{\eta}_{ee2} = [\,\phi_E \quad \theta_E \quad \psi_E\,]^{\mathrm{T}} \in \mathrm{I\!R}^3$	orientation of the end effector in the inertial frame expressed by Euler angles
$\boldsymbol{\nu}_{ee} \in \mathrm{I\!R}^6$	end-effector linear and angular velocities with respect to the inertial frame expressed in the end-effector frame
$\boldsymbol{J}_k(\boldsymbol{R}_B^I) \in \mathrm{I\!R}^{(6+n)\times(6+n)}$	Jacobian matrix defined in (2.58)
$\boldsymbol{J}_w(\boldsymbol{R}_B^I, \boldsymbol{q}) \in \mathrm{I\!R}^{6\times(6+n)}$	Jacobian matrix defined in (2.67)
$\boldsymbol{J}(\boldsymbol{R}_B^I, \boldsymbol{q}) \in \mathrm{I\!R}^{6\times(6+n)}$	Jacobian matrix used in (2.68)
$\boldsymbol{h}_i^i = \left[\,\boldsymbol{f}_i^{i\,\mathrm{T}} \quad \boldsymbol{\mu}_i^{i\,\mathrm{T}}\,\right]^{\mathrm{T}} \in \mathrm{I\!R}^6$	forces and moments exerted by body $i-1$ on body i (see Figure 2.4)
$\boldsymbol{h}_e = [\,\boldsymbol{f}_e^{\mathrm{T}} \quad \boldsymbol{\mu}_e^{\mathrm{T}}\,]^{\mathrm{T}} \in \mathrm{I\!R}^6$	forces and moments at the end effector (see Figure 2.5)
$t \in \mathrm{I\!R}$	time
$\lambda_{\min(\max)}(\boldsymbol{X})$	smallest(largest) eigenvalue of matrix $\boldsymbol{X}$
$\mathrm{diag}\{x_1, \ldots, x_n\}$	Diagonal matrix filled with x_i in the i row, i column and zero in any other place
$\mathrm{blockdiag}\{\boldsymbol{X}_1, \ldots, \boldsymbol{X}_n\}$	Block diagonal matrix filled with matrices $\boldsymbol{X}_1, \ldots, \boldsymbol{X}_n$ in the main diagonal and zero in any other place
$\mathcal{R}(\boldsymbol{X})$	range of matrix $\boldsymbol{X}$
$\dot{x}$	time derivative of the variable x
$\\|\boldsymbol{x}\\|$	2-norm of the vector $\boldsymbol{x}$
$\hat{\boldsymbol{x}}\left(\hat{\boldsymbol{X}}\right)$	estimate of the vector $\boldsymbol{x}$ (matrix $\boldsymbol{X}$)
x_d	desired value of the variable x

$\tilde{x}$	error variable defined as $\tilde{x} = x_d - x$
$\boldsymbol{x}^{\mathrm{T}} \left(\boldsymbol{X}^{\mathrm{T}}\right)$	transpose of the vector $\boldsymbol{x}$ (matrix $\boldsymbol{X}$)
x_i	i th element of the vector $\boldsymbol{x}$
$X_{i,j}$	element at row i, column j of the matrix $\boldsymbol{X}$
$\boldsymbol{X}^{\dagger}$	Moore-Penrose inversion (pseudoinversion) of matrix $\boldsymbol{X}$ If $\boldsymbol{X}$ is low rectangular it is $$\boldsymbol{X}^{\dagger} = \boldsymbol{X}^{\mathrm{T}} \left(\boldsymbol{X}\boldsymbol{X}^{\mathrm{T}}\right)^{-1}$$ If $\boldsymbol{X}$ is high rectangular it is $$\boldsymbol{X}^{\dagger} = \left(\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X}\right)^{-1} \boldsymbol{X}^{\mathrm{T}}$$
$\boldsymbol{I}_r$	$(r \times r)$ identity matrix
$\boldsymbol{O}_{r_1 \times r_2}$	$(r_1 \times r_2)$ null matrix
$\boldsymbol{S}(\cdot) \in \mathbb{R}^{3\times 3}$	matrix performing the cross product between two (3×1) vectors defined in (2.6)
ρ^3	water density
μ	fluid dynamic viscosity
R_n	Reynolds number
$\boldsymbol{g}^I$	gravity acceleration expressed in the inertial frame

Contents