# Springer Tracts in Advanced Robotics Volume 2

Editors: Bruno Siciliano · Oussama Khatib · Frans Groen

#### Springer Tracts in Advanced Robotics

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# **Underwater Robots**

# Motion and Force Control of Vehicle-Manipulator Systems

**Second edition** 

With 95 Figures



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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 faulttolerant 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

#### Acknowledgements

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.

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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 January 2006  $Gianluca \ Antonelli$ 

#### 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), MA-RIUS 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 VOR-TEX, 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
$\Sigma_i, O - xyz$		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 $2.1$ )
${\rm I\!R}, {\rm I\!N}$		Real, Natural numbers
$\boldsymbol{\eta}_1 = [ egin{array}{ccc} x & y & z \ ]^{\mathrm{T}}$	$\in \mathbb{R}^3$	body (vehicle) position coordinates in the inertial frame (see Figure $2.1$ )
$\boldsymbol{\eta}_2 = [ \phi  \theta  \psi ]^{\mathrm{T}}$	$\in \mathbb{R}^3$	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) ori- entation with respect to the inertial frame
$oldsymbol{\eta} = \left[oldsymbol{\eta}_1^{\mathrm{T}}  oldsymbol{\eta}_2^{\mathrm{T}} ight]^{\mathrm{T}} \in$	$\mathbb{R}^6$	body(vehicle) position/orientation

$\boldsymbol{\eta}_q = \left[ oldsymbol{\eta}_1^{\mathrm{T}} \hspace{0.1 in} arepsilon^{\mathrm{T}} \hspace{0.1 in} \eta  ight]^{\mathrm{T}} \in {\rm I\!R}^7$	body (vehicle) position/orientation with the orientation expressed by quaternions
$\boldsymbol{\nu}_1 = [ u  v  w ]^{\mathrm{T}} \in \mathbb{R}^3$	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)
$\boldsymbol{ u}_2 = [p  q  r]^{\mathrm{T}} \in \mathbb{R}^3$	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)
$oldsymbol{ u} = egin{bmatrix} oldsymbol{ u}_1^{\mathrm{T}} & oldsymbol{ u}_2^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \in \mathbb{R}^6$	vector representing the linear/angular velocity in the body (vehicle)-fixed frame
$oldsymbol{R}^eta_lpha~\in {\rm I\!R}^{3 imes 3}$	rotation matrix expressing the transformation from frame $\alpha$ to frame $\beta$
$oldsymbol{J}_{k,o}(oldsymbol{\eta}_2) \ \in {\rm I\!R}^{3 imes 3}$	Jacobian matrix defined in $(2.2)$
$oldsymbol{J}_{k,oq}(\mathcal{Q}) \in {\rm I\!R}^{4 imes 3}$	Jacobian matrix defined in $(2.10)$
$\boldsymbol{J}_e(\boldsymbol{\eta}_2) \in {\rm I\!R}^{6 \times 6}$	Jacobian matrix defined in $(2.19)$
$\boldsymbol{J}_{e,q}(\mathcal{Q}) \in {\rm I\!R}^{7 \times 6}$	Jacobian matrix defined in $(2.23)$
$\boldsymbol{\tau}_1 = \begin{bmatrix} X & Y & Z \end{bmatrix}^{\mathrm{T}} \in \mathbb{R}^3$	vector representing the resultant forces acting on the rigid body(vehicle) expressed in the body(vehicle)-fixed frame
$\boldsymbol{\tau}_2 = \begin{bmatrix} K & M & N \end{bmatrix}^{\mathrm{T}} \in \mathrm{I\!R}^3$	vector representing the resultant moment acting on the rigid body (vehicle) expressed in the body (vehicle)-fixed frame to the pole ${\cal O}_b$
$oldsymbol{ au}_v = egin{bmatrix} oldsymbol{ au}_1^{\mathrm{T}} & oldsymbol{ au}_2^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}} \in \mathrm{I\!R}^6$	generalized forces: forces and moments acting on the vehicle
${oldsymbol{ au}}_v^\star \in {\rm I\!R}^6$	generalized forces in the earth-fixed-frame- based model defined in $(2.53)$
n	degrees of freedom of the manipulator
$oldsymbol{q} \in { m I\!R}^n$	joint positions
$\boldsymbol{\tau}_q \in {\rm I\!R}^n$	joint torques
$oldsymbol{ au} = \left[oldsymbol{ au}_v^{\mathrm{T}} \hspace{0.1 in} oldsymbol{ au}_q^{\mathrm{T}} ight]^{\mathrm{T}} \in \mathrm{I\!R}^{6+n}$	generalized forces: vehicle forces and moments and joint torques
$\boldsymbol{u} \in {\rm I\!R}^p$	control inputs, $\boldsymbol{\tau} = \boldsymbol{B}\boldsymbol{u}$ (see (2.72))

$\boldsymbol{\zeta} = \left[ oldsymbol{ u}_1^{\mathrm{T}}  oldsymbol{ u}_2^{\mathrm{T}}  \dot{oldsymbol{q}}^{\mathrm{T}}  ight]^{\mathrm{T}} \in \mathrm{I\!R}^{6+n}$	system velocity
$\boldsymbol{\Phi} \in R^{(6+n) \times n_{\theta}}$	UVMS regressor defined in $(2.73)$
$oldsymbol{ heta} \in R^{n_{ heta}}$	vector of the dynamic parameters of the UVMS regressor defined in $(2.73)$
$\boldsymbol{\varPhi}_{v} \in R^{6 \times n_{\theta,v}}$	vehicle regressor defined in $(2.54)$
$oldsymbol{ heta}_v \in R^{n_{ heta,v}}$	vector of the dynamic parameters of the vehicle regressor defined in $(2.54)$
$\boldsymbol{\eta}_{ee1} = [ x_E  y_E  z_E ]^{\mathrm{T}} \in \mathbb{R}^3$	position of the end effector in the inertial frame (denoted with $\boldsymbol{x} = [x_E \ y_E \ z_E]^{\mathrm{T}}$ in the interaction control sections)
$\boldsymbol{\eta}_{ee2} = \begin{bmatrix} \phi_E & \theta_E & \psi_E \end{bmatrix}^{\mathrm{T}} \in \mathbb{R}^3$	orientation of the end effector in the inertial frame expressed by Euler angles
$oldsymbol{ u}_{ee} \in { m I\!R}^6$	end-effector linear and angular velocities with respect to the inertial frame expressed in the end-effector frame
$\boldsymbol{J}_k(\boldsymbol{R}_B^I) \in {\rm I\!R}^{(6+n)  imes (6+n)}$	Jacobian matrix defined in $(2.58)$
$\boldsymbol{J}_w(\boldsymbol{R}_B^I,\boldsymbol{q}) \in {\rm I\!R}^{6\times(6+n)}$	Jacobian matrix defined in $(2.67)$
$\boldsymbol{J}(\boldsymbol{R}_B^I,\boldsymbol{q}) \in {\rm I\!R}^{6\times(6+n)}$	Jacobian matrix used in $(2.68)$
$oldsymbol{h}_{i}^{i}=\left[oldsymbol{f}_{i}^{i^{\mathrm{T}}} \hspace{0.1 in}oldsymbol{\mu}_{i}^{i^{\mathrm{T}}} ight]^{\mathrm{T}} \in \mathbb{R}^{6}$	forces and moments exerted by body $i-1$ on body $i$ (see Figure 2.4)
$oldsymbol{h}_{e} = \left[oldsymbol{f}_{e}^{\mathrm{T}} \mid oldsymbol{\mu}_{e}^{\mathrm{T}} ight]^{\mathrm{T}} \in \mathbb{R}^{6}$	forces and moments at the end effector (see Figure 2.5)
$t \in \mathbb{R}$	time
$\lambda_{\min(\max)}(oldsymbol{X})$	smallest (largest) eigenvalue of matrix $\boldsymbol{X}$
$\operatorname{diag}\{x_1,\ldots,x_n\}$	Diagonal matrix filled with $x_i$ in the <i>i</i> row, <i>i</i> column and zero in any other place
$ ext{blockdiag}\{oldsymbol{X}_1,\ldots,oldsymbol{X}_n\}$	Block diagonal matrix filled with matrices $X_1, \ldots, X_n$ in the main diagonal and zero in any other place
$\mathcal{R}(oldsymbol{X})$	range of matrix $\boldsymbol{X}$
$\dot{x}$	time derivative of the variable $x$
$\ m{x}\ $	2-norm of the vector $\boldsymbol{x}$
$\hat{oldsymbol{x}}\left(\hat{oldsymbol{X}} ight)$	estimate of the vector $\boldsymbol{x}$ (matrix $\boldsymbol{X}$ )
$x_d$	desired value of the variable $x$

$$\begin{split} & \tilde{x} \\ & \boldsymbol{x}^{\mathrm{T}} \left( \boldsymbol{X}^{\mathrm{T}} 
ight) \\ & x_{i} \\ & X_{i,j} \\ & \boldsymbol{X}^{\dagger} \end{split}$$

error variable defined as  $\tilde{x} = x_d - x$ 

transpose of the vector  $\boldsymbol{x}$  (matrix  $\boldsymbol{X}$ )

 $i\,\mathrm{th}$  element of the vector  $\boldsymbol{x}$ 

element at row i, column j of the matrix  $\boldsymbol{X}$ 

Moore-Penrose inversion (pseudoinversion) of matrix X

If  $\boldsymbol{X}$  is low rectangular it is

$$oldsymbol{X}^{\dagger} = oldsymbol{X}^{\mathrm{T}} \left(oldsymbol{X}oldsymbol{X}^{\mathrm{T}}
ight)^{-1}$$

If X is high rectangular it is

$$oldsymbol{X}^{\dagger} = \left(oldsymbol{X}^{\mathrm{T}}oldsymbol{X}
ight)^{-1}oldsymbol{X}^{\mathrm{T}}$$

 $I_r$  $(r \times r)$  identity matrix  $O_{r_1 \times r_2}$  $(r_1 \times r_2)$  null matrix  $\boldsymbol{S}(\cdot) \in \mathbb{R}^{3 \times 3}$ matrix performing the cross product between two  $(3 \times 1)$  vectors defined in (2.6) $\rho^3$ water density  $\mu$ fluid dynamic viscosity Reynolds number  $R_n$  $g^I$ gravity acceleration expressed in the inertial frame

## Contents

1.	Intr	oduction	1
	1.1	Underwater Vehicles	3
	1.2	Sensorial Systems	5
	1.3	Actuation	5
	1.4	Localization	7
	1.5	AUVs' Control	9
		1.5.1 Fault Detection/Tolerance for UUVs	11
	1.6	UVMS' Coordinated Control	11
	1.7	Future Perspectives	11
2.	Moo	delling of Underwater Robots	15
	2.1	Introduction	15
	2.2	Rigid Body's Kinematics	15
		2.2.1 Attitude Representation by Euler Angles	16
		2.2.2 Attitude Representation by Quaternion	17
		2.2.3 Attitude Error Representation	19
		2.2.4 6-DOFs Kinematics	21
	2.3	Rigid Body's Dynamics	22
		2.3.1 Rigid Body's Dynamics in Matrix Form	24
	2.4	Hydrodynamic Effects	25
		2.4.1 Added Mass and Inertia	26
		2.4.2 Damping Effects	28
		2.4.3 Current Effects	29
	2.5	Gravity and Buoyancy	31
	2.6	Thrusters' Dynamics	32
	2.7	Underwater Vehicles' Dynamics in Matrix Form	34
		2.7.1 Linearity in the Parameters	35
	2.8	Kinematics of Manipulators with Mobile Base	36
	2.9	Dynamics of Underwater Vehicle-Manipulator Systems	39
		2.9.1 Linearity in the Parameters	42
	2.10	Contact with the Environment	42
	2.11	Identification	43

3.	Dyı	namic Control of 6-DOF AUVs	45
	3.1	Introduction	45
	3.2	Earth-Fixed-Frame-Based, Model-Based Controller	47
	3.3	Earth-Fixed-Frame-Based, Non-model-Based Controller	49
	3.4	Vehicle-Fixed-Frame-Based, Model-Based Controller	51
	3.5	Model-Based Controller Plus Current Compensation	53
	3.6	Mixed Earth/Vehicle-Fixed-Frame-Based, Model-Based Con-	
		troller	55
		3.6.1 Stability Analysis	56
	3.7	Jacobian-Transpose-Based Controller	57
	3.8	Comparison Among Controllers	59
		3.8.1 Compensation of the Restoring Generalized Forces	59
		3.8.2 Compensation of the Ocean Current	60
	3.9	Numerical Comparison Among the Reduced Controllers	60
		3.9.1 Results	63
		3.9.2 Conclusions and Extension to UVMSs	77
4.	Fau	It Detection/Tolerance Strategies for AUVs and ROVs	79
	4.1	Introduction	79
	4.2	Experienced Failures	80
	4.3	Fault Detection Schemes	82
	4.4	Fault Tolerant Schemes	86
	4.5	Experiments	88
	4.6	Conclusions	91
5.	Exp	periments of Dynamic Control of a 6-DOF AUV	93
	5.1	Introduction	93
	5.2	Experimental Set-Up	93
	5.3	Experiments of Dynamic Control	94
	5.4	Experiments of Fault Tolerance to Thrusters' Fault	101
6.	Kin	ematic Control of UVMSs	105
	6.1	Introduction 1	105
	6.2	Kinematic Control 1	106
	6.3	The Drag Minimization Algorithm 1	112
	6.4	The Joint Limits Constraints 1	112
	6.5	Singularity-Robust Task Priority 1	113
	6.6	Fuzzy Inverse Kinematics 1	121
	6.7	Conclusions 1	139
7.	Dyı	namic Control of UVMSs 1	141
	7.1	Introduction	141
	7.2	Feedforward Decoupling Control	143
	7.3	Feedback Linearization 1	146
	7.4	Nonlinear Control for UVMSs with Composite Dynamics 1	146

	7.5	Non-regressor-Based Adaptive Control 149
	7.6	Sliding Mode Control 151
		7.6.1 Stability Analysis 152
		7.6.2 Simulations 154
	7.7	Adaptive Control 157
		7.7.1 Stability Analysis 158
		7.7.2 Simulations 160
	7.8	Output Feedback Control 162
		7.8.1 Stability Analysis
		7.8.2 Simulations
	7.9	Virtual Decomposition Based Control 181
		7.9.1 Stability Analysis
		7.9.2 Simulations
		7.9.3 Virtual Decomposition with the Proper Adapting Action194
	7.10	Conclusions
Q	Into	reaction Control of UVMSc 201
0.	8 1	Introduction to Interaction Control of Robots 201
	8.2	Devterous Cooperating Underwater 7 DOF Manipulators 203
	0.2 8 3	Impedance Control 203
	8.4	External Force Control 205
	0.4	8/1 Inverse Kinematics 206
		8.4.2 Stability Analysis $207$
		8.4.3 Bobustness 208
		8.4.4 Loss of Contact 200
		845 Implementation Issues 209
		846 Simulations 210
	85	Explicit Force Control 213
	0.0	8.5.1 Robustness 217
		8.5.2 Simulations
	8.6	Conclusions
0	C	
9.	C00	rdinated Control of Platoons of AUVS
	9.1	Introduction
	9.2	Kinematic Control of AUVS
	0.9	9.2.1 Simulations
	9.3 0.4	Experimental Set-Up at the Virginia Tech
	9.4	Conclusions
10.	Con	cluding Remarks

Α.	Mat	thematical models 2	39
	A.1	Introduction	39
	A.2	Phoenix	39
	A.3	Phoenix+6DOF SMART 3S	41
	A.4	ODIN	42
	A.5	9-DOF UVMS	43
Ref	feren	<b>ces</b>	47