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Robotic manipulators and vehicles: control, estimation and filtering

An integrated approach

Springer

To the memory of my father George Rigatos
(1933-2017)

Foreword

The aim of the monograph is to solve control, estimation and filtering problems in advanced models of robotic manipulators and vehicles. The methods to be developed are generic and applicable to a wide range of robotic systems. The methods are of assured stability and of proven robustness thus confirming the reliable function of robotic manipulators and vehicles under variable operating conditions, model uncertainty and external disturbances. The following types of robotic manipulators are examined: multi-DOF rigid-link robots, manipulators subject to input/output delays, underactuated robots and redundant manipulators, closed-chain robotic systems, and flexible-link robots. Moreover, the following types of robotic vehicles are examined: automatic ground vehicles (AGVs), unmanned aerial vehicles (UAVs), unmanned surface vessels (USVs) , autonomous underwater vessels (AUVs) and various types of cooperating autonomous vehicles.

Robotic manipulators and vehicles exhibit complicated dynamics and kinematics. As a consequence the solution of the associated problems of nonlinear control, nonlinear estimation and nonlinear filtering is still an open research problem. Despite progress in developing advanced robotic mechanisms and elaborated robotic vehicles, control schemes for robots lack often a global stability proof and may be based on heuristically tuned PID controllers that allow functioning only around local operating points. Moreover, estimation and filtering schemes for robots may lack convergence proof (as for instance in the case of neural modelling approaches or in the case of state estimation with the Extended Kalman Filter). Due to the aforementioned reasons, the precision of robots in tasks execution is hindered while their safe and uninterrupted functioning may be also risked. To overcome these shortfalls the monograph presents nonlinear control methods for robotic manipulators and vehicles which are globally asymptotically stable, while also exhibiting sufficient robustness to external perturbations. Moreover, the monograph presents nonlinear estimation methods for robots which are of proven convergence thus allowing the real-time identification of the manipulators' and vehicles' unknown dynamics. Finally the monograph presents optimal and convergent filtering methods for robotic manipulators and vehicles which allow for their reliable functioning through the processing of measurements of a small number of sensors.

In the area of robotic manipulators (including industrial robots) one can distinguish between two main problems: (i) robots operating in a free working space, with indicative application examples in robotic welding, painting, or laser and plasma cutting and (ii) robots performing compliance tasks, with indicative application examples in assembling, finishing of metal surfaces and polishing. When the robotic manipulators operate in a free environment then kinematic and dynamic analysis provide the means for designing a control law that will move appropriately their effector and will enable the completion of the scheduled tasks. (ii) In the case of compliance (force-control) tasks, the objective is not only to control the end effector's position but also to regulate the force developed due to contact with a surface. The monograph's results in this field aim at treating also the simultaneous position and force control problem of robotic manipulators.

In the area of mobile robots and autonomous vehicles one has to handle nonholonomic constraints and to avoid potential singularities in the design of the control law. Again the kinematic and dynamic models of the mobile robots provide the basis for deriving a controller that will enable tracking of desirable trajectories. Several applications can be noted such as path tracking by autonomous mobile robots and automatic ground vehicles (AGVs), motion control of articulated and off-road land vehicles, trajectory tracking and dynamic positioning of surface and underwater vessels (USVs and AUVs) and flight control of unmanned aerial vehicles (UAVs). Apart from controller's design, path planning and motion planning are problems to solve. The monograph's results in this area aim particularly at handling problems of advanced difficulty for autonomous vehicles e.g. when the unmanned vehicle operates in an unknown environment with moving obstacles and stochastic uncertainties in the measurements provided by its sensors.

The monograph is primarily addressed to the academic community.The contents of the monograph offer a useful insight to researchers in the areas of robotics and automation about key problems on nonlinear control estimation and filtering. On the other side the monograph offers the knowhow about the handling of uncertainty in the dynamics or in the kinematic model of robotic manipulators and vehicles It also analyzes the implementation stages of new estimation and filtering techniques and demonstrates their use in the modelling of robotic manipulators and autonomous vehicles. The aforementioned topics cover a large research area including robotic arms and mobile robots or drones of various types.The contents of the monograph can be used as the basis for late undergraduate and of post-graduate courses in robotics, in several engineering departments. Moreover, the monograph is addressed to engineers working on robotics applications and on industrial automation. The methods developed in it are applicable in industry and in several manufacturing tasks as well as in intelligent transportation systems Therefore, the monograph's approach to the problems of control, estimation and filtering for robotic manipulators and autonomous vehicles can be of use by engineers treating practical robotic applications.

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Preface

The monograph treats problems of (i) nonlinear control, estimation and filtering for robotic manipulators (multi-DOF rigid-link robots, robots subject to input-output delays, underactuated manipulators, redundant manipulators, and closed-chain robotic mechanisms) and (ii) nonlinear control, estimation and filtering for robotic manipulators (automatic ground vehicles, unmanned aerial vehicles, unmanned surface vessels, autonomous underwater vessels, cooperating mobile robots) The monograph attempts a thorough coverage of the entire range of applications of robotic manipulators and autonomous vehicles. The nonlinear control and estimation methods it develops are of generic use and suitable for a wide range of robotic systems. Such methods can improve robustness, precision and fault tolerance in robotic manipulators and vehicles while they also enable the reliable functioning of these systems under variable conditions, model uncertainty and external perturbations. Through a balance between the theoretical and the applications part the monograph's results and methods can be assimilated and used by both researchers or members of the academic community and by engineers. The monograph can be a useful contribution to robotics research and a reference guide for engineers working on practical robotic applications.

The content of the monograph's chapters is outlined in the following:

Chapter 1: Rigid-link manipulators and model-based control. The chapter analyzes the model-based nonlinear control approaches for multi-DOF rigid-link robots, that is (i) control based on global linearization methods, and (ii) control based on approximate linearization methods. As far as approach (i) is concerned, that is methods based on global linearization, these are techniques for the transformation of the nonlinear dynamics of the robotic system to equivalent linear state-space descriptions for which one can design state feedback controllers and can also solve the associated state estimation (filtering) problem. One can classify here methods mainly based on the theory of differentially flat systems. Differentially flat systems form the widest class of systems to which global linearization-based nonlinear control can be applied. Control of rigid-link robotic manipulators becomes of elevated difficulty when the robot is subject to input-output time-delays. However, global linearization methods can offer efficient solution even in the latter case. As far as approach (ii) is concerned. solutions are pursued to the problem of nonlinear control of robots with the use of local linear models (defined around local equilibria). For such local linear models, feedback controllers of proven stability can be developed. One can select the parameters of such local controllers in a manner that assures the robustness of the control loop to both external perturbations and to model's parametric uncertainty.

Chapter 2: Underactuated robotic manipulators. Control of underactuated robots has received significant attention and its application areas comprise several types of industrial and service robotic manipulators. The purpose of research in this area is to design of robotic mechanisms that can be controlled despite having a number of actuators that is smaller than their degrees of freedom. This approach can reduce the cost and weight of robots or can provide robotic systems with tolerance to actuators failures. Again the control problem for such robots is treated with (i) global linearization methods, (ii) approximate linearization approaches and (iii) Lyapunov methods. To achieve model-free control of underactuated manipulators, improved esstimation approaches are developed.,allowing the real-time identification of their unknown dynamics or kinematics. Moreover, to implement feedback control of underactuated robots through the measurement of a limited number of the robot's state variables nonlinear filtering methods of proven convergence are developed.

Chapter 3: Rigid-Link manipulators and model-free control. The chapter analyzes model-free nonlinear control approaches for multi-DOF rigid-link robots, based on Lyapunov methods. There, one comes against problems of minimization of Lyapunov functions so as to assure the asymptotic stability of the control loop. Model-free control takes often the form of indirect adaptive control. In such a case the design of the controller is not based on prior knowledge of the robot's dynamics. With the use of adaptive algorithms and elaborated estimation methods it is possible to identify in real-time the unknown dynamics of the robots and subsequently to use this information in the control loop, thus arriving at indirect adaptive control schemes. Finally, the development of nonlinear filtering methods for robotic manipulators allows the implementation of feedback control through measuring of only a small number of the robot's state variables. Global stability is proven for the control loop that comprises both the nonlinear controller of the robot's dynamics nonlinear filters that estimate the robot's state vector from indirect measurements.

Chapter 4: Closed-chain robotic systems and mechanisms. Control of closed-chain robots is a non-trivial problem because it is often associated with complicated dynamic and kinematics models exhibiting nonlinearities. Unlike robotic manipulators with a free end-effector, closed-chain robotic mechanisms include actuators which are usually placed on a fixed base. On the one side this enables to develop mechatronic systems with low moving inertia and fast motion control. On the other side this may incur underactuation problems. Comparing to open-chain robots, closed-chain robotic mechanisms have many advantages such as high stiffness, high accuracy, and high payload-to-weight ratio To solve the nonlinear control problem of closed-chain robotic systems the following approaches are proposed (i) nonlinear control based on global linearization methods, (ii) nonlinear control based on approximate linearization methods and (iii) nonlinear control based on Lyapunov methods. Besides to apply model-free control for such a type of robotic manipulators, online estimation algorithms of the unknown dynamics of the robot can be considered once again. The global asymptotic stability of the control which is based on the real-time estimation of the robot's dynamics is proven. Moreover, as in the previously analysed closed-chain manipulator models, to implement feedback control through the measurement of a limited number of the closed-chain robot's state vector, nonlinear filtering methods of proven convergence are developed.

Chapter 5: Flexible-link robots. Control for flexible-link robots is a non-trivial problem that has increased difficulty comparing to the control of rigid-link manipulators. This is because the dynamic model of the flexible-link robot contains the non-linear rigid-link motion coupled with the distributed effects of the links flexibility. This coupling depends on the inertia matrix of the flexible manipulator while the vibration characteristics are determined by structural properties of the links such as the damping and stiffness parameters. Moreover, in contrast to rigid-link robots the dynamic model of flexible-link robots is an infinite dimensional one. The model exhibits a certain number of mechanical degrees of freedom associated to the rotational motion of the robots joints and has also an infinite number of degrees of freedom associated to the vibration modes in which the deformation of the flexible link is decomposed The controller of a flexible manipulator must achieve the same motion objectives as in the case of a rigid manipulator, i.e. tracking of specific joints position and velocity setpoints. Additionally, it must also stabilize and asymptotically eliminate the vibrations of the flexible-links that are naturally excited by the joints' rotational motion. A first approach for the control of flexible-link robots is to consider the vibration modes as additional state variables and to develop stabilizing feedback controller for the extended state-space model of the flexible manipulator. To this end, one can use again (i) control based on global linearization methods, (ii) control based on Lyapunov methods (energy-based control). Again global asymptotic stability for this control approach can be demonstrated. On the other side, nonlinear filtering methods can be used for implementing state feedback control of the manipulator's state vector through the measurement of a limited number of elements from the flexible robot's state vector.

Chapter 6: Micro-manipulators, Microrobots can be used in the manipulation and procise positioning of micro-objects, as well as in several microelectronics applications. Microrobotics is primarily concerned with control problems of micro electromechanical systems (MEMS). Specific problems one comes against in the development of microrobotic systems and MEMS is the imprecision about the microrobot's dynamic model and the inability to measure specific state vector elements in it. This in turn signifies that the design of feedback controllers for such systems has to be sufficiently robust to compensate for unmodelled dynamics or for parametric uncertainty. To this end one can consider either model-free control methods of proven stability (such as adaptive neurofuzzy control schemes), or model-based control methods capable of eliminating the effects of modelling errors, parametric inconsistency and external perturbations (such as H-infinity control). Moreover, one has to implement state estimation-based feedback control methods, making use of robust state observers, that will allow for estimation of the entire state vector of the microrobot or MEMS through the processing of measurements from a small number of sensors.

Chapter 7: Unicycles and two-wheel autonomous ground vehicles. Models of unicycles and two-wheel autonomous vehicles can be used to describe the driving behaviour of autonomous ground vehicles in several cases. Robotization of such vehicles requires that several of their functionalities and driving tasks, are automatically performed. To achieve this objective, the need of developing and using elaborated control and estimation methods for motorcycles has become apparent. To this end, several results have been developed aiming at solving the stabilization and path tracking problems for autonomous or semi-autonomous motorcycles. Due to underactuation in the motorcycles model and the strong nonlinearities characterizing its state-space description, the solution of the associated motion problem is a difficult and challenging endeavour. To achieve a satisfactory solution of the problem of autonomous motorcycles driving, different nonlinear control methods can be considered such as global linearization-based control, as well as approximate linearization-based control approaches jointly with optimal control methods. To implement state estimation-based control for two-wheel autonomous vehicles,without the need to process measurements from a large number of on-board sensors, robust state estimation and filtering methods are proposed.

Chapter 8: Four-wheel autonomous ground vehicles. In the recent years there has been significant effort in the design of intelligent four-wheel autonomous vehicles capable of operating in variable conditions. The precise modeling of the vehicles dynamics improves the efficiency of vehicles controllers in adverse cases, for example in high velocity, when performing abrupt maneuvers, under mass and loads changes or when moving on rough terrain. Using model-based control approaches it is possible to design a nonlinear controller that maintains the vehicle's motion characteristics according to given specifications. When the vehicle's dynamics is subject to modeling uncertainties or when there are unknown forces and torques exerted on the vehicle it is important to be in position to estimate in real-time disturbances and unknown dynamics so as to compensate for them. In this direction, estimation for the unknown dynamics of the vehicle and state estimation-based control schemes have been developed. Feedback control of robotic ground vehicles can be primarily based on (i) global linearization approaches, (ii) approximate linearization approaches and (iii) Lyapunov methods. The control is applied to (a) 4-wheel vehicles, and (b) articulated vehicles. Finally to implement control of the ground vehicles through the measurement of a small number of its state variables, elaborated nonlinear filtering approaches are developed.

Chapter 9: Unmanned aerial vehicles. The multi-DOF dynamic model of unmanned aerial vehicles (UAVs) is a highly nonlinear one and its control can be performed again with (i) global linearization control methods, (ii) local inearization control methods and (iii) Lyapunov analysis-based methods. In approach (i) the dynamic model of the UAV is transformed into an equivalent linear description through the application of a change of variables (diffeomorphisms). In (ii) the nonlinear model of the UAV is decomposed into local linear models for which linear feedback controllers are designed and next the aim is to select the feedback control gains so as to assure the global asymptotic stability of the control loop. In (iii) the objective is to define an energy function for the UAV (Lyapunov function) and to demonstrate that through suitable selection of the feedback control the first derivative of the energy function is always negative and thus the global stability of the control loop is assured. The latter approach is particularly suitable for model-free control of UAVs and takes the form of adaptive control methods.This chapter analyzes the aforementioned control approaches for UAVs and proves global asymptotic stability for the aforementioned control approaches. The robustness of the developed control methods against model uncertainty and external perturbations is confirmed. Besides elaborated nonlinear filtering approaches are developed that allow for accurate estimation of the state vector of the UAVs through the processing of measurements coming from a limited number of sensors.

Chapter 10: The problem of control and trajectory tracking for unmanned surface vessels (of the ship or hovercraft type) is non-trivial because the associated dynamic and kinematic models are complex nonlinear onea. A first problem that arises in controller design for unmanned surface vessels is that trajectory tracking has to be achieved despite modelling uncertainty and external perturbations and thus the control loop must exhibit sufficient robustness. Another problem that has to be dealt with is that the vessel's model is often underactuated (the propulsion system consists of less actuators than the vessel's degrees of freedom). The present chapter treats the problem of control of unmanned surface vessels. Solution to the associated control problem is provided through (i) global linearization methods, (ii) approximate linearization methods and (iii) Lyapunov methods. Moreover, for the accurate localization of the vessel and for precise computation of its motion characteristics advanced (and precisely validated) nonlinear filtering and distributed filtering are applied. These enable to perform fusion of the measurements of heterogeneous sensors and of state estimates provided by individual distributed filters that track the vessel's motion.

Chapter 11. Autonomous underwater vessels. The control of multi-DOF autonomous underwater vessels (AUVs) exhibits particular difficulties which are due to the complicated nonlinear model of the submersible vessels, the coupling between the systems control inputs and outputs, and the uncertainty about the values of their dynamic and kinematic models parameters. Moreover, the AUVs' dynamic model is subject to external perturbations which are caused by variable sea conditions and sea currents. Consequently, an efficient control scheme for AUVs should not only compensate for the nonlinearities of the associated dynamic model, but should also exhibit robustness to model parameter variations in its model and to external disturbances. To this end, the present chapter provides results on robust control of AUVs, as well as on adaptive control of such submersible vessels Thus the control problem for autonomous underwater vessels is treated with (i) global linearization methods (ii) approximate linearization methods and (iii) Lyapunov methods. The solution of the control problem requires a more elaborated procedure when the AUVs' dynamic model is underactuated. which means that the number of actuators included in its propulsion system is less than the number of its degrees of freedom.The methods developed in this chapter treat also the case of underactuated AUVs. Moreover, advanced estimation methods are used to identify in real-time the unknown dynamics of the underwater vessels or disturbance forces and torques that affect them. This allows for the implementation of indirect control schemes for the AUVs. Additionally,for the precise localization of the AUVs and their safe navigation elaborated nonlinear filtering methods are developed. These permit to solve problems of multi-sensor fusion as well as problems of decentralized state estimation with the use of spatially distributed nonlinear filters that track the AUVs motion.

Chapter 12: Cooperating autonomous vehicles. Distributed and coordinated control of autonomous vehicles (automatic ground vehicles, unmanned aerial vehicles, unmanned surface and underwater vessels) has received significant attention during the last years. In this chapter a solution is developed first for the problem of distributed control of cooperating unmanned surface vessels (USVs) which chase a target. The distributed control aims at achieving the synchronized convergence of the autonomous vessels towards the target and at maintaining the cohesion of the vessels' team, while also avoiding collisions between the individuals vessels and collisions between them and obstacles in their motion plane. To estimate the motion characteristics of the target, distributed filtering is performed. To treat the distributed control problem for the cooperating unmanned surface vessels a Lyapunov theory-based method is introduced. To treat the distributed filtering and state estimation in the multi-vehicle system one can apply established methods for decentralized state estimation. The proposed distributed control and filtering method can be used for surveillance and security tasks executed by multi-robot systems and in particular by multi-USV systems. The method for coordinated control of USVs is a generic one and thus applicable to various types of autonomous robots, such as automatic ground vehicles. A second part of the chapter is concerned with distributed control and cooperation of automatic ground vehicles (such as agricultural robotic vehicles). A global linearization approach is used to transform the nonlinear kinematic model of the vehicle into an equivalent linear form. In this linear description, both the control and state estimation problems of the individual vehicles can be solved, while it is also ascertained that the control loop is globally stable. Moreover, distributed filtering is performed for accomplishing multi-sensor fusion and distributed state estimates fusion. It is shown that the method assures the vehicles' precisely synchronized motion.

The problems of nonlinear control, estimation and filtering for robotic manipulators and for autonomous vehicles are nontrivial ones and the present monograph offers efficient solutions about them. Thus the monograph is anticipated to have a significant impact to members of the academic and research community, as well as to engineers working on practical robotics problems. The benefits from the application of the monograph's results are as follows: (i) the stability of the control loop for robotic manipulators and autonomous vehicles is assured, (ii) convergence of estimation and filtering methods for the aforementioned robotic systems is also ascertained, (iii) the robotic control loops exhibit robustness to modelling uncertainty and external perturbations (iv) the implementation of feedback control does not have as a prerequisite the precise knowledge of the robots' dynamic or kinematic model. Actually, by following the monograph's results one can develop adaptive control methods which are entirely model-free (v) the presented methods are not constrained by any assumption about the form and structure of the controlled robotic system (vi) the implementation of feedback control does require measurement of the entire state vector of the robots and can be performed through the processing of the readings of a limited number of sensors. All these reasons indicate that the technical and scientific impact of the present monograph will be noteworthy.

The monograph can be a reference for researchers working on elaborated robotic systems. Moreover, the content of the monograph can be exploited for teaching undergraduate or postgraduate courses on advanced robotic systems. Therefore it can be used by both academic tutors and students as a reference source for such a course. Almost all departments of electrical, industrial and mechanical engineering, include in their curriculum robotics courses. and nonlinear control courses. This means that the academic audience that will bear interest for such a monograph is very wide. Moreover, since studies on robotics and control theory and applications thereof are gaining importance, one should expect that in the following years the number of engineers that will use the monograph's methods on robotics and nonlinear control will also grow.

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October 2017

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Acknowledgements

The authors of the monograph would like to thank reviewers of this manuscript, coming from the research and academic community, who have contributed to the improvement of this research work through their constructive comments.

Acronyms

AC motor	Alternate Current Motor
AGV	Automatic Ground Vehicle
ARE	Algebraic Riccati Equation
ARMAX	Auto-Regressive Moving Average system with Noise
AUV	Autonomous Underwater Vessel
CRLB	Cramer-Rao Lower Bound
CT	Computed Torque Method
DEIF	Derivative-free Extended Information Filter
DGPS	(Differential Global Positioning System)
DH	Denavit-Hartneberg
DKF	Derivative-free nonlinear Kalman Filter
DOF	Degrees of Freedom
EIF	Extended Information Filter
EKF	Extended Kalman Filter
FDI	Fault Detection and Isolation
FKF	Fuzzy Kalman Filter
GLR	Generalized Likelihood Ratio
GPS	Global Positioning System)
H_∞ control	H-infinity Control
H_∞ KF	H-infinity Kalman Filter
IF	Information Filter
IMU	Inertial Measurement Uni)
KF	Kalman Filter
LMI	Linear Matrix Inequalities
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
MEMS	Micro-electromechanical Systems)
MIMO	Multi-Input Multi-Output
MPC	Model Predictive Control
MSE	Mean Square Error
NES	Normalized Error Square

NME	Normalized Mean Error
NMPC	Nonlinear Model Predictive Control
PD	Proportional Derivative Control
PF	Particle Filter
PID	Proportional Integral Derivative Control
RMSE	Root Mean Square Error
RTK-GPS	Real-Time Kinematic GPS
SISO	Single-Input Single-Output
SMC	Sliding Model Control
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UIF	Unscented Information Filter
UKF	Unscented Kalman Filter
USV	Unmanned Surface Vessel
4WS	4 Wheel Steering
4WD	4 Wheel Drive

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