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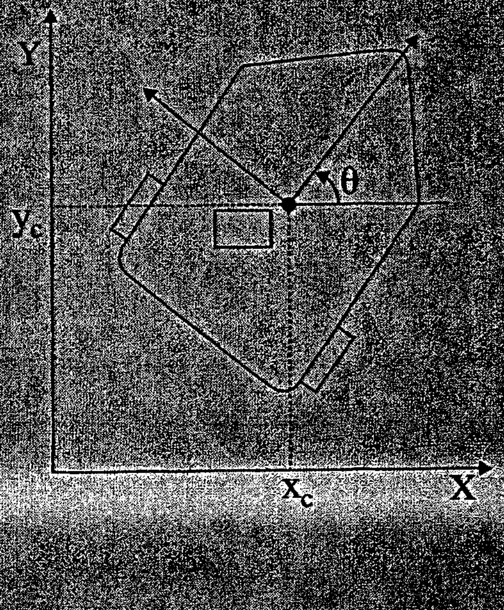
Warren E. Dixon, Darren M. Dawson,
Erkan Zergeroglu and Aman Behal

Nonlinear Control of Wheeled Mobile Robots



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With 52 Figures

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To My Wife, Lisa Dixon

W.E.D.

To My Wife, Kim Dawson

D. M. D.

To the Niblets, John and Pradeep

E.Z.

To Peter

A.B.

Preface

Wheeled mobile robots (WMRs) have been an active area of research and development over the past three decades. This long-term interest has been mainly fueled by the myriad of practical applications that can be uniquely addressed by mobile robots due to their ability to work in large (potentially unstructured and hazardous) domains. Specifically, WMRs have been employed for applications such as: *i)* mine excavation, *ii)* monitoring nuclear facilities and warehouses for material inspection and security objectives, *iii)* planetary exploration, *iv)* military tasks such as munitions handling, *v)* materials transportation, and *vi)* man-machine-interfaces for people with impaired mobility. Based on the wide range of applications described above, it is clear that WMR research is multidisciplinary by nature. That is, the aforementioned applications require accurate sensing of the environment, intelligent trajectory planning, and high precision control.

Due to the multidisciplinary nature of WMR research, most of the previous books have elected to present a broad overview of the different facets involved with WMR research, and hence, only provide a cursory overview of each of the research areas. In contrast, the intention of this book is to focus on the control problem for WMRs. To this end, in Sections 1.3 and 1.4 of Chapter 1, we present the design of a global asymptotic regulation controller and a global asymptotic tracking controller, respectively, originally proposed by C. Samson. These kinematic controllers are considered to be benchmarks in WMR control research because they represent a class of controllers that employ a differentiable, time-varying control strategy to overcome the technical obstacle presented by Brockett's condition. That is, due to the fact that the regulation problem cannot be solved via a differentiable, time-invariant state feedback law due to the implications of Brockett's condition, previous research efforts have focused on the development of discontinuous control laws, piecewise continuous control laws, or hybrid controllers to achieve setpoint regulation.

The kinematic controllers presented in Sections 1.3 and 1.4 of Chapter 1 are fundamental to WMR control research. However, due to the asymptotic nature of the transient performance (versus an exponential regulation or tracking result) and the fact that some applications may require the user to switch between a tracking controller and a regulation controller to perform a desired task, one is motivated to examine the design of alternative differentiable, time-varying control strategies. Based on this motivation, we illustrate how a global invertible transformation can be utilized to cast the governing differential equations into a form similar to Brockett's nonholonomic integrator. By utilizing the transformed open-loop system, we demonstrate how a dynamic oscillator can be used (instead of the explicit sinusoidal terms utilized in Samson's class of differentiable, time-varying controllers) to design a new class of unified controllers. The advantages of this new class of controllers are that: *i)* the regulation problem can be treated as a special case of the tracking problem (*i.e.*, one control law can be utilized to solve both problems simultaneously) and *ii)* the stability results tend to be global exponential versus global asymptotic. For example, in Section 1.6 of Chapter 1, we illustrate that one advantage of utilizing a differentiable kinematic control law is that standard backstepping techniques can be employed to incorporate the effects of the dynamic model in the overall control design.

In subsequent chapters, we utilize this new class of unified differentiable, time-varying kinematic controllers to address several theoretically interesting and practical control problems. For instance, in Chapter 2, we design a unified controller that is robust to parametric uncertainty and additive bounded disturbances in the dynamic model. In Chapter 3, we modify the structure of the kinematic controller to design a global exponential tracking and regulation controller (Note that the exponential tracking result is obtained provided a persistency of excitation condition on the reference trajectory is satisfied). Motivated by the fact that velocity measurements are often costly to obtain and are inherently noisy, we design an output feedback tracking and regulation controller in Chapter 4. In Chapter 5, we illustrate how an uncalibrated vision system can be utilized to overcome difficulties that are encountered in accurately obtaining the Cartesian position and orientation measurements. Specifically, in Chapter 5, we design a global asymptotic tracking controller despite uncertainty associated with the camera and the dynamic model of the WMR. In Chapter 6, we investigate robustness issues with regard to disturbances in the kinematic model. Specifically, we design tracking and regulation controllers that compensate for uncertainty or disturbances (*i.e.*, slipping and skidding) in the kinematic model. In Chapter 7, we illustrate how the new class of differentiable controllers can be applied to solve related problems. For example, we demonstrate how new types of controllers can be designed for underactuated surface vessels, twin rotor helicopters, and planar flexible joint manipulators.

All of the controllers that are developed in Chapters 1-7 are analyzed using Lyapunov-based stability proofs. A significant portion of the mathematical background that is required to follow the control designs and Lyapunov-based stability analyses are combined in Appendix A. Mathematical details that are specific to the control designs presented in subsequent chapters (*e.g.*, the boundedness of control terms, etc.) are included in Appendix B. The control designs that are presented in Chapters 2, 3, and 5 are implemented on a modified K2A manufactured by Cybermotion Inc. and a modified Pioneer II manufactured by ActivMedia. In Appendix C and Appendix D, details are given with regard to modifications made to the K2A and the Pioneer II, respectively.

The material contained in this book (unless noted otherwise) has resulted from the authors' research in robotic systems. The material is intended for audiences with an undergraduate background in robotics and control theory. Some knowledge of nonlinear systems theory may be helpful; however, we do not believe that it is necessary. As such, the book is mainly aimed at researchers and graduate students in the areas of robotics and control applications.

We would like to acknowledge and express our sincere gratitude to the following past and present graduate students of the Department of Electrical and Computer Engineering at Clemson University whose hard work made this book a reality: Nick Costescu, Bret Costic, Marcio de Queiroz, Matthew Feemster, John Hartranft, Markus Loffler, Aniket Malatpure, Siddharth P. Nagarkatti, Pradeep Setlur, Matthew Steel, and Fumin Zhang.

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