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 *Springer Tracts in Advanced Robotics (STAR)* series 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 monograph written by Karl Iagnemma and Steve Dubowsky is an evolution of the first Author's Ph.D. dissertation. Mobile robotic systems have lately been receiving a great deal of attention, thanks to their increased use in unstructured environments, such as rugged fields, mines, forests, disaster sites and, last but not least, planetary surfaces after the recent success of the Mars exploration rover missions. This volume addresses several critical problems associated with estimation, motion planning, and control of wheeled mobile robots operating in rough terrain. The unique feature of the work lies in its comprehensive treatment of the problem from the theoretical development of the various schemes to simulation and experimental results for a number of outdoor applications.

The first monograph based on a US doctoral thesis to make the series, this title constitutes a fine addition to STAR!

Naples, Italy
March 2004

Bruno Siciliano
STAR Editor

Preface

New and exciting applications continue to be found for mobile robotic systems. One of the most important trends of the past decade has been the increased use of mobile robots in rough, unstructured terrain, such as underground mines, forests, disaster sites, and planetary surfaces. The extremely successful Sojourner and Mars Exploration Rover missions in 1997 and 2004, respectively, are highly-publicized examples of this trend. Many lesser-known systems have also been developed and successfully deployed.

Unstructured environments are often harsh, dangerous, or inaccessible to humans, and thus motivate the use of robotic systems. For example, planetary surface exploration is hazardous to humans due to high levels of radiation, extreme temperatures, and other environmental factors. Underground mines have traditionally been associated with health hazards caused by poor air quality. These dangers have spurred many robotics researchers to shift their focus from developing robots that operate in indoor, laboratory settings, to those that can successfully overcome the real-world challenges associated with rough terrain operation.

Developing mobile robots for outdoor applications is difficult for several reasons. These operating environments require robots to travel over rugged terrain without becoming entrapped or tipping over. This requires a robot to accurately assess its mobility characteristics over various terrain types and adapt its control strategy accordingly. Outdoor applications also require a robot to depend on simple, on-board sensors to perceive the environment. Such sensors can be noisy, miscalibrated, or unreliable. Finally, outdoor applications often require a robot to possess some degree of autonomy to operate effectively. Specifically, robots often must plan their route through difficult terrain without human supervision.

This monograph addresses several critical problems associated with estimation, motion planning, and control of robotic systems in rough terrain. All of these areas have been studied by various researchers over the past twenty years; however, much of the research has been developed for robots operating in indoor, structured environments. Thus the work in this monograph represents a new view of several "traditional" robotics research areas.

This monograph is composed of five chapters. The first chapter serves as an introduction and overview of the work, and summarizes related research. Chap. 2 addresses the issues of rough terrain modeling and estimation. A novel method for on-line estimation of important terrain physical parameters is presented, as is a novel method for estimating wheel-terrain contact angles. Chap. 3 addresses the problem of rough terrain motion planning by presenting two motion planning algorithms. The goal of the first planning method is to find a safe, direct path from the rover's current position to a distant goal position. The goal of the second planning method is to determine the optimal configuration of an actively articulated suspension rover, to improve tipover stability during travel in rough terrain. Chap. 4 addresses the problem of rough terrain control by presenting a servo-level control method for improved wheel traction or reduced power consumption in rough terrain. Chap. 5 summarizes the contributions of this monograph and presents suggestions for future work. For all of the work, simulation and experimental results are presented for wheeled mobile robots operating in rough, outdoor environments. These results demonstrate the effectiveness of the proposed methods.

The concepts presented in this monograph were initially developed in the first author's 2001 Ph.D. thesis at the Massachusetts Institute of Technology. Much of the work, however, has been updated and expanded for this volume. This work was supported by the NASA Jet Propulsion Laboratory (JPL). The authors would like to acknowledge the assistance and encouragement of Drs. Paul Schenker, Samaad Hayati, and Rich Volpe of JPL.

It is the authors' hope that this monograph will be of interest to robotics researchers and engineers who study and develop robotic systems designed for the outdoor world. As mobile robots become more advanced and their use more widespread, we feel that this subject area can only grow in importance.

Cambridge, Karl Iagnemma
March 2004

Mobile Robots in Rough Terrain
Estimation, Motion Planning, and Control with Application to Planetary Rovers

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2004, XII, 111 p., Hardcover
ISBN: 978-3-540-21968-2