Preface

Recently, many robotic systems designed with wheeled inverted pendulum (WIP), such as the Segway PT and Segway type system based Robonauts (NASA robot astronauts), have been quite popular in the robotic community. In fact, WIP based robots are able to provide effective physical assistance to humans in various activities such as delivery and touring. The design with WIP guarantees high work capabilities, e.g., high speed, convenience without sacrifice of safety. The simple structure of the robot on the WIP contributes to reducing the weight of the system compared to a wheeled mobile robot and it ensures high safety against overturn when unpredictable collision occurs, because it is always controlled to maintain dynamic stability. The two coaxial wheels configuration as well as the small foot-print makes it able to achieve high mobility, to do stationary U-turns on dime, to navigate on various terrains and traverse small steps or curbs. These properties would definitely give the operator greater maneuverability and thus access to places most able-body people take for granted.

However, the control of the self unstable WIP system is a challenge. First of all, the kinematics of the system have been proved to be uncontrollable and therefore balancing of the pendulum is only achieved by dynamic effects. Active control must be applied to drive the wheels in the direction the upper part of the robot is falling to maintain the balance. In addition, WIP systems are different from either the conventional cart and pendulum systems or the conventional non-holonomic systems, many previous developed control approaches for these two kinds of systems are not applicable directly to the WIP systems.

Compared with other non-holonomic systems, the WIP systems are subject to (i) only kinematic constraints which geometrically restrict the direction of mobility, i.e., wheeled mobile robot; (ii) only dynamic constraints due to dynamic balance at passive degrees of freedom where no force or torque is applied, i.e., the robotic manipulator with passive link. It belongs to (iii) not only kinematic constraints but also dynamic constraints. While compared with cart and pendulum systems, the cart of WIP is no longer constrained to the guide rail but moves in its terrain while balancing the pendulum and the motors driving the wheels are directly mounted on the body of the pendulum. Therefore, many available control design approaches are not applicable to the WIP systems. Moreover, another notable control challenge of WIP lies in multiple under-actuated configurations, i.e., the number of the control inputs is less than the number of the degrees of freedom to be stabilized.

Although modeling and control of WIP systems have attracted much research attention in last decade, many fundamental problems are still either unexplored or less well understood. In particular, there still lacks a comprehensive framework that can cope with all the core issues in a systematic way. This motivated us to write the current monograph.

The book presents theoretical explorations on several fundamental problems for the modeling, motion planning, control and identification of the WIP systems. By integrating fresh concepts and state-of-the-art results to form a systematic approach for the motion control and identification, a fundamental theoretical framework is formed towards WIP systems.

The book is primarily intended for researchers and engineers in the robotics and control community. It can also serve as complementary reading for nonlinear system theory at the post-graduate level.

The book starts with a brief summary of the useful mathematical concepts and tools from operator, matrix and sign function, stability theory, as well as other stability results in Chap. 2. They are the tools used for stability analysis of the controllers presented later. Then, a detailed overview of the kinematics and dynamics of the WIP systems is presented in Chap. 3. To make the book self-content, we start from the basic Newton–Euler and Lagrange–Euler equation to derive the dynamics equation governing the general robotic systems, and then we focus on the expression and analysis of the WIP system dynamics.

In Chap. 4, we investigate control design approaches based on the linearized WIP dynamical model. Self-tuning PID controller is first studied, and then the optimal LQR control is designed, finally H_∞ control and backstepping are investigated. The corresponding simulation results of the proposed controls have been well compared.

In Chap. 5, we further develop nonlinear control for the WIP systems. First, we investigate the nonlinear feedback linearization approach. Then, taking advantage of the physical model properties, the system is decomposed into three sub-systems and model-based control and stability analysis have been studied for each of the sub-system.

In Chap. 6, both adaptive and robust motion control designs have been studied. Then control design is proceeded with on-line parameters estimation strategy and introduced to compensate for dynamics uncertainties and external disturbances. Then, hybrid motion/force adaptive robust control has been thoroughly studied. The unmodeled dynamics have been compensated by both online learning of the uncertain parameters and robust approach.

In Chap. 7, a number of intelligent control approaches have been investigated. First, the modeling and control method using the Least Squares Support Vector Machine (LS-SVM) have been utilized to design efficient model free control. Then, we further study the universal functional approximation of fuzzy logic and neural networks. All these intelligent control methods employ a systematic online adaptation mechanism without prepared off line learning.

In Chap. 8, aiming at shaping the controlled vehicle angular motion dynamics to be of minimized motion tracking errors and accelerations, we employ the linear quadratic regulation (LQR) optimization technique to obtain an optimal reference model. Adaptive control has then been developed using variable structure to ensure the reference model can be matched within a prescribed finite time horizon, in the presence of various uncertainties. The property of the optimized reference model as well as the minimized yaw and tilt angle accelerations guarantee rider's comfort.

In Chap. 9, the model reference control proposed in Chap. 8 has been further developed using neural network (NN) for the fully actuated angular motion subsystem. Same as in Chap. 8, we exploit the fact that the forward velocity can be indirectly affected by the reference trajectory of tilt angle, and design an NN based reference trajectory generator that guarantee the desired forward velocity is achieved.

Acknowledgments

For the creation of the book, we are very fortunate to have many helpful suggestions from our colleagues, friends and coworkers, through many stimulating and fruitful discussions. First of all, we would like to express our sincere gratitude to the careful scrutiny. We would also like to express our sincere appreciation to our coworkers who have contributed to the collaborative studies of Robotics.

We are greatly indebted to our parents and families for their love, support and sacrifice over the years. It is our pleasure to dedicate the book to them for their invisible yet invaluable contribution.

This work is supported by the National Natural Science Foundation of China (Nos. 60804003, 61174045, and 60935001) and International Science & Technology Cooperation Program of China (No. 2011DFA10950).

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Springer
http://www.springer.com/978-1-4471-2962-2

Advanced Control of Wheeled Inverted Pendulum Systems
Li, Z.; Yang, C.; Fan, L.
2013, XIV, 218 p., Hardcover
ISBN: 978-1-4471-2962-2