Research on Intelligent Manufacturing

Jian Huang · Mengshi Zhang ·
Toshio Fukuda

# Robust and Intelligent Control of a Typical Underactuated Robot

## Mobile Wheeled Inverted Pendulum

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# Preface

Cities all over the world are gradually implementing plans to ban gasoline and diesel-powered vehicles within the next decade or so. To achieve this goal, the concept of last mile is one of the key problems that should be addressed in various measures taken by administrators. The last mile is that distance traveled between the termination of public transport and one's destination. For example, your office might be as far as a mile away from the nearest bus stop. Even taking the bus to and from work, you have to conquer the final mile with portable urban transportation if you don't want to walk.

The mobile wheeled inverted pendulum (MWIP) is a typical underactuated robotic system, which is widely used in modern urban transportation vehicles aiming at solving the last mile problem. This kind of urban transportation vehicle includes the Segway PT, Toyota Winglet, Honda U3-X, and so on. In the real-world application scenarios, the MWIP suffers from many internal/external uncertainties, e.g., different road conditions, the random user, or wind load. Besides, the system identification of MWIP parameters is also difficult due to the complex structure and multiple degrees-of-freedom (DOFs). The conventional model-based control method is thus hard to fulfill the high-performance control tasks of MWIP. Therefore, the advanced robust and intelligent control of MWIP is vital, and this motivates us to write the current monograph.

Since the dynamic model of MWIP is the prerequisite for its control design, this book firstly introduces the modeling procedure of MWIP, in both two-dimensional and three-dimensional cases. Second, to deal with the internal/external uncertainties, we lumped the uncertainties into a single disturbance term and designed a novel high-order disturbance observer (HODO) to online estimate this disturbance term. With the compensation of disturbance, a new high-order disturbance observer-based sliding mode control (HODOSMC) strategy is proposed. Third, considering the chattering problem in sliding mode control (SMC), this book introduces two approaches for the MWIP. One is the adaptive super-twisting algorithm, which is a second-order SMC strategy and able to efficiently alleviate the chattering phenomenon. The other is the terminal sliding mode control (TSMC), which can ensure that all variables converge to the expected value in a limited time. Next, to better model and cope with uncertainties, the interval type-2 fuzzy sets (IT2 FSs) are introduced to design a new fuzzy controller for the MWIP system. The proposed controller can control its balance, position, and direction simultaneously. Finally, all the proposed control approaches are implemented in a physical MWIP platform. Various experiments are conducted, and the results demonstrate that these approaches are effective to solve the uncertainty problems in controlling MWIP.

This book mainly presents theoretical explorations for controlling MWIP systems. Readers can systematically study the MWIP system, including its modeling, controller design, stability analysis, numerical simulation, and experimental platform construction. 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 and underactuated robotic control techniques at the postgraduate level.

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# Contents

# Symbols

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|---|---|
| $\psi_l$ | Rotation angle of the left wheel |
| $\psi_r$ | Rotation angle of the right wheel |
| $\alpha$ | Yaw angle of the MWIP system |
| $\theta$ | Inclination angle of the body |
| $m_b$ | Mass of the body |
| $m_w$ | Mass of a wheel |
| $I_{by}$ | Moment of inertia of the body about Y-axis |
| $I_{bz}$ | Moment of inertia of the body about Z-axis |
| $I_{wa}$ | Moment of inertia of a wheel about Y-axis |
| $I_{wd}$ | Moment of inertia of a wheel about Z-axis |
| $l$ | Length between the wheel axle and the center of gravity of the body |
| $r$ | Radius of the wheel |
| $2b$ | Distance between two wheels |
| $D_b$ | Viscous resistance in the driving system |
| $D_w$ | Viscous resistance of the ground |
| $u_r$ | Rotation torque of the left motor |
| $u_l$ | Rotation torque of the right motor |
| $\tau_{ext}$ | External disturbances |
| $\tau_d^*$ | Lumped model uncertainties and external disturbances |
| $(x_b, y_b)$ | Position of the MWIP body in two-dimensional model |
| $(x_w, y_w)$ | Position of the MWIP wheel in two-dimensional model |
| $\mathbf{q_{2D}}$ | Configurational vector of two-dimensional model |
| $(x_1, y_1, z_1)$ | Position of the MWIP body in three-dimensional model |
| $\mathbf{q_f}$ | Full state vector of three-dimensional model |
| $\mathbf{q_{3D}}$ | Configurational vector of three-dimensional model |
| $T_b$ | Translational kinetic energy of the MWIP body |
| $T_w$ | Translational kinetic energy of the MWIP wheels |
| $R_b$ | Rotational kinetic energy of the MWIP body |
| $R_w$ | Rotational kinetic energy of the MWIP wheels |
| $U$ | Potential energy of the MWIP system |
| $D$ | Dissipated energy of the MWIP system |

| | |
|---|---|
| $L$ | Lagrange function |
| $\hat{\tau}_d$ | Estimation of the lumped disturbances |
| $\hat{\tau}_d^i$ | Estimation of the lumped disturbances of the i-th-order disturbance observer |
| $e$ | Estimation error of the disturbance observer |
| $L_i$ | Gain matrices of the high-order disturbance observer |
| $\bar{d}_i$ | Bound of the estimation error |
| $S_1$ | The first sliding surface |
| $S_2$ | The second sliding surface |
| $K_1$ | Switching coefficient of the first sliding surface |
| $K_2$ | Switching coefficient of the second sliding surface |
| $\lambda_i$ | Parameters of the sliding surface |

# Chapter 1
# Introduction

## 1.1 An Overview of MWIP Robots

As early as 1987, Kazuo Yamafuji, professor of the University of Electro Communications, began to study the two-wheeled balance control technology, which is considered as the ideological origin of two-wheeled self-balancing robot [1]. As shown in Fig. 1.1, the small lever on the wheel acted as a sensor to detect the inclination of the car body, and the rectangular control motor drives the inverted pendulum to maintain the overall balance of the robot itself. However, due to the low technology of computer and sensor at that time, this technology did not receive much attention.

Grasser et al. [2] of the Swiss Federal University of Technology have developed a two-wheeled self-balancing car named as JOE, as shown in Fig. 1.2. This self-balancing car can realize zero radius and U-shaped rotation; furthermore, remote control of the movement speed and direction also has been achieved.

American scientist David P. Anderson developed a two-wheeled self-balancing vehicle model nBOT based on inverted pendulum, as shown in Fig. 1.3 [3]. By measuring the tilt angle and angular speed of the inverted pendulum and the position and speed of the chassis, the controller outputs the torque which is directly proportional to the motor voltage, so as to realize the self-balance and movement of the car. nBOT can not only realize zero radius rotation, move indoors and outdoors, but also choose the route to bypass the obstacles and continue to move after encountering obstacles.

In 2001, Segway company of the USA invented a new type of convenient two-wheeled vehicle Segway [4]. After several improvements, Segway Pt has become a practical, mature, and self-balancing modern transportation technology product, as shown in Fig. 1.4. Segway users can start, accelerate, decelerate, and stop the vehicle by regulating the position of the gravity center. Under the condition of keeping balance, the users can drive conveniently on various roads. Its appearance fully demonstrates the flexibility and practicability of two-wheeled self-balancing mobile robot and arouses people's attention to the future traffic.

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