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Neural network-based adaptive tracking control of mobile robots in the presence of wheel slip and external disturbance force

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ABSTRACT

In this paper, a novel adaptive tracking controller is proposed for mobile robots in presence of wheel slip and external disturbance force based on neural networks with online weight updating laws. The uncertainties due to the wheel slip and external force are compensated online by neural networks in order to achieve the desired tracking performance. The online weight updating laws are modified versions of the backpropagation with an e-modification term added for robustness. The global uniformly ultimately bounded stability of the system to an arbitrarily small neighborhood of the origin is proven using Lyapunov method. The validity of the proposed controller is confirmed by two simulation examples of tracking a straight line and a U-shape trajectory.

1. Introduction

In recent years, control of nonholonomic systems such as nonholonomic mobile robot has received wide attention and is a topic of great research interest due to the practical importance of its applications. The control researches for mobile robots have been centered on stabilization and tracking problems. Most proposed control algorithms have been proposed that rely on the kinematic model with nonholonomic assumptions such as backstepping [1], pure pursuit [2], neural networks [3], neural fuzzy [4], and linearization [5]. These algorithms completely neglect the robot dynamics. The control inputs, usually motor voltages, are assumed to instantaneously establish the desired robot velocities, known as *perfect velocity tracking*. In the case of heavy mobile robot with high speed, however, the above assumptions are not upheld in reality. In order to overcome this problem, some control schemes based on a full dynamic model have been proposed so far by taking into account the dynamic effects caused by mass, friction, and inertia [6]. Most of dynamic based controllers depend on the ideal of backstepping from kinematics into dynamics as proposed in [7]. Some control methods such as neural network [8,9], fuzzy [10], robust damping [11], sliding model [12] have been proposed to enhance the robustness of tracking control performance. Despite having a better performance can be achieved, these algorithms mainly rely on the assumptions of rolling contacts without sliding motions, known as *nonholonomic constraints*. In most real applications of mobile robots, slip between the ground and wheel cannot be avoided due to various reasons such as uneven terrain, robot high speed, ground conditions, slippery surface. The tracking performance of the mobile robot could be seriously reduced because of the sliding motions. In order to achieve the desired performance in the presence of slip, a controller which are robust to the slip between the wheel and the ground are significant.

The mobile robot freely moves in the ground based on the friction forces between the driving wheels and the ground, known as traction forces. Each traction force can be basically divided into two direction: longitudinal traction force and lateral traction force. The longitudinal traction force is proportional to the driving torque, which is usually supplied by electrical motor. Under the effect of that two forces, the wheel has ability to move forward or backward. In the acceleration or deceleration time, mobile robot always requires the high driving torque, which causes the high longitudinal traction force. If the longitudinal traction force exceeds the dynamic friction force, the sliding motion between the wheel and the ground in the longitudinal direction will occur, known as *wheel slipping*. The lateral traction force occurs under the effect of the centrifugal force generated when mobile robots tries to change its direction. If mobile robot with high speed suddenly changes its direction, the lateral traction force could not be enough to equalize the centrifugal force. Then the sliding

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motion in the lateral direction will occur, known as *wheel skidding*. In order to compensate only the effect of wheel slipping, an adaptive tracking controller is proposed and demonstrated via neural networks and wheel slip compensation in [13]. The slip ratios are assumed to be measurable using gyro-sensor and encoders. The approaches of using gyros and accelerometers to compensate for the slip in real time are also presented in [14,15]. A robust controller taking care both slip-kinematic and slip-dynamic models is proposed in [16] using the framework of differential flatness. The simulation and experimental results in the slip-kinematic case show the effect of the proposed robust controller when the sliding motion occurs. However, in the case of the slip-dynamic, the robust controller requires the measurements of robot accelerations, which are very difficult to obtain in reality. In [17], the longitudinal traction force is included in an omni-directional mobile robot model by externally measuring the magnitude of slip. However, the ideal mobile robot model is used in control design for simplicity. In order to achieve position control, the authors in [18] have modeled the overall wheeled mobile robot as a third order under-actuated dynamic system with a second order non-holonomic constraint. The measurements of wheel slip are still assumed to be available for the controller design. The disadvantage of this assumption is due to the requirement of extra sensors such as gyroscope, accelerometer.., to measure the wheel slip. In [19], a robust tracking controller is proposed in which the disturbance and state are estimated using a generalized extended state observer. The ideal of backstepping from kinematics into dynamics [7] is applied to find the required torque input. Another controller based on the estimate of the disturbance due to wheel slip can be found in [20]. In [21], the wheel slip and external loads are assumed to act as disturbances to the system. Then the sliding model control method [22,23] is employed to design a tracking controller of the mobile robot. Even the boundary layer method is also applied, the chattering problem is needed to be considered more. And the bound of the uncertainties, which is pre-defined based on the knowledge about robot system, are required to design the tracking controller. Too large bounded value can cause too much chattering in control effort or reduce the tracking performance. The disadvantages of measurable wheel slip or uncertainty bounded motive us to develop a new adaptive controller in which those information are no longer needed.

Recently, neural networks are increasingly recognized as a powerful tool for controlling many complex dynamic systems thanks to the advantages such as learning ability, adaptation, flexibility [24–27]. In this paper, we propose a new adaptive controller using an online tuning neural network to deal with the mobile robot uncertainties due to the wheel slip and external disturbance forces. First, the detail of dynamic model of mobile robot subject to wheel slip and external disturbance load is developed [21]. The friction forces are simply divided into two forces: lateral and longitudinal forces, which are generated due to the slip angle and the tire slip, respectively. The equation motion of the mobile robot can be obtained by the summation of the external forces and moments in the body centered reference frame based on Newton's Law. In order to reduce the harmful effect of the external loads and wheel slip on the control performance, an online learning neural networks, which does not require preliminary offline tuning, is implemented. The neural network weights are updated based on the backpropagation plus an e-modification term to guarantee its robustness. It is noted that the proposed controller does not require the assumption of uncertainty bounded or measurement of wheel slip. Finally, two simulation examples of tracking a straight line and a U-shape trajectory are performed to confirm the effectiveness of the proposed algorithm.

This paper is organized as follows: In Section 2, the kinematic and dynamic model of mobile robots in presence of wheel slips and external disturbance forces are described. In Section 3, the proposed adaptive tracking controller using online tuning neural networks is presented in details and the stability of the closed-loop system is proven. Two simulation examples of tracking a straight line and a U-shape trajectory are presented in Section 4. Finally, the research conclusions are given in Section 5.

2. Kinematic and dynamic model of mobile robot with wheel slip and external disturbance forces

In this section, we derive the kinematic and dynamic model of a differentially driven wheeled mobile robot shown in Fig. 1. o-XY is the global coordinate system. G-xy is the coordinate system fixed to the mobile platform. G is the center of mass of the mobile robot. u and v are the longitudinal and lateral velocities at the center gravity of the mobile robot, respectively, and r denotes the yaw rate. ω_r and ω_l are the wheel angular velocities of right and left wheel, respectively.

The mobile robot is controlled through the velocities or torques of the driving wheels. The kinematic equations are derived based on the constraints of the velocity components. With the wheel velocities ω_r and ω_l are given, the longitudinal and lateral velocities u, v and the yaw rate r are given as follows

$$u = \frac{1}{2}(u_l + u_r) \tag{1}$$

$$v = \frac{d}{2b}(u_l - u_r) + v^s \tag{2}$$

$$r = \frac{1}{2b}(u_l - u_r) \tag{3}$$

$$u_l = R\omega_l - u_l^s \tag{4}$$

$$u_r = R\omega_r - u_r^s \tag{5}$$

where u_r and u_l are the longitudinal speeds of the right and left wheel centers, respectively. v^s is the wheel skidding. u_r^s and u_l^s are the wheel slipping of the right and left wheel centers, respectively. b is the distance from the wheel center to the geometrical center line of the platform. d is the distance from the wheel center line to the mass center of the platform. R is the wheel radius. The wheel slip model is considered by adding the three velocity components:

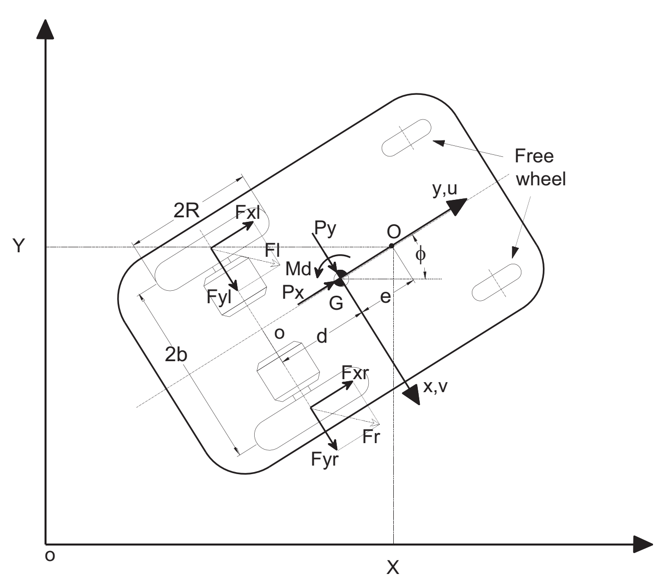

Fig. 1. Mobile robot.