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Research paper

Nonsingular fast terminal sliding mode posture control for six-legged walking robots with redundant actuation☆

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ABSTRACT

The posture changing ability of multi-legged walking robots is significant for walking in rough terrains. Six-legged walking robots are nonlinear and redundant systems with uncertainties and disturbances. The rabidity, accuracy, and robustness of posture control are important for enhancing the posture changing ability. In this study, a new nonsingular fast terminal sliding mode (NFTSM) is proposed for the posture control of six-legged walking robots. The NFTSM controller is designed with a nonsingular terminal sliding manifold and a fast terminal sliding-type reaching law based on the posture control model of six-legged walking robots. The stability, rapidity, and robustness of the controller are analyzed. Simulation and experiment results show that fast, accurate, and robust performance is obtained for the posture control of six-legged walking robots using the NFTSM controller.

1. Introduction

Multi-legged walking robots present superior mobility in natural terrains compared with wheeled and tacked robots because of the discrete footholds used for each foot [1,2]. These robots can change their postures to obtain stability and appropriate footholds for walking in rough terrains [3,4]. For example, a six-legged walking robot walks in three different environments which are with obstacles, steps, and slopes as shown in Fig. 1(a), (b), and (c). In Fig. 1(a), the body of the six-legged walking robot turns an angle to avoid an obstacle [5,6]. In the environment with steps as shown in Fig. 1(b) [7], the robot walks forward with the body keeping level or rolling an angle. The robot's feet can obtain more space to put down when the body rolls an angle. As shown in Fig. 1(c) [8,9], the robot pitches its body with an angle to walk up a slope. In Fig. 1, the robot changes its attitude to walk in rough terrains. The attitude of the body in this study is called as the posture of the robot, and yaw, roll, and pitch angles are generally used to describe the posture of the robot.

Therefore, the posture changing ability is significant for multi-legged walking robots [10]. Furthermore, the accuracy and robustness of the posture control are important aspects to guarantee the posture changing ability of multi-legged walking robots; they determine whether the robots can obtain accurate posture to succeed walking through irregular terrains and accomplish the corresponding work. This paper focuses on the good accuracy and robustness study of the posture control of multi-legged walking robots.

Only a few papers have discussed the posture control of six-legged or other multi-legged robots. In the posture control of multi-legged robots, PID control method is widely adopted. The heading angle of the six-legged walking robot, SILO-6, is manipulated by a heading controller, which uses a simple proportional control law [11]. The posture of LittleDog is also controlled by an integral controller to maintain itself stability despite small slips at the stance feet [12]. A proportional controller is used in the posture control of the hybrid wheeled-legged robot (Hylos) for high stability and traction performance [13,14]. The similar proportional controller is applied for the posture control in the robots (MHT [15] and eQuad [16]). The authors also applied a proportional controller to implement a closed-loop control on the position and posture of the ZJU Walker to solve the position-posture deviation problem caused by its semi-round rigid feet [17]. The PID method is simple and has good performance [18]. It verifies the validity in the posture control of multi-legged robots. However, the PID method is not effective and robust in certain circumstances [19], such as in responding to nonlinearities and disturbances. The six-legged walking robot is exactly a nonlinear, coupled, and redundant system, whose posture control is affected by uncertainties and disturbances, which

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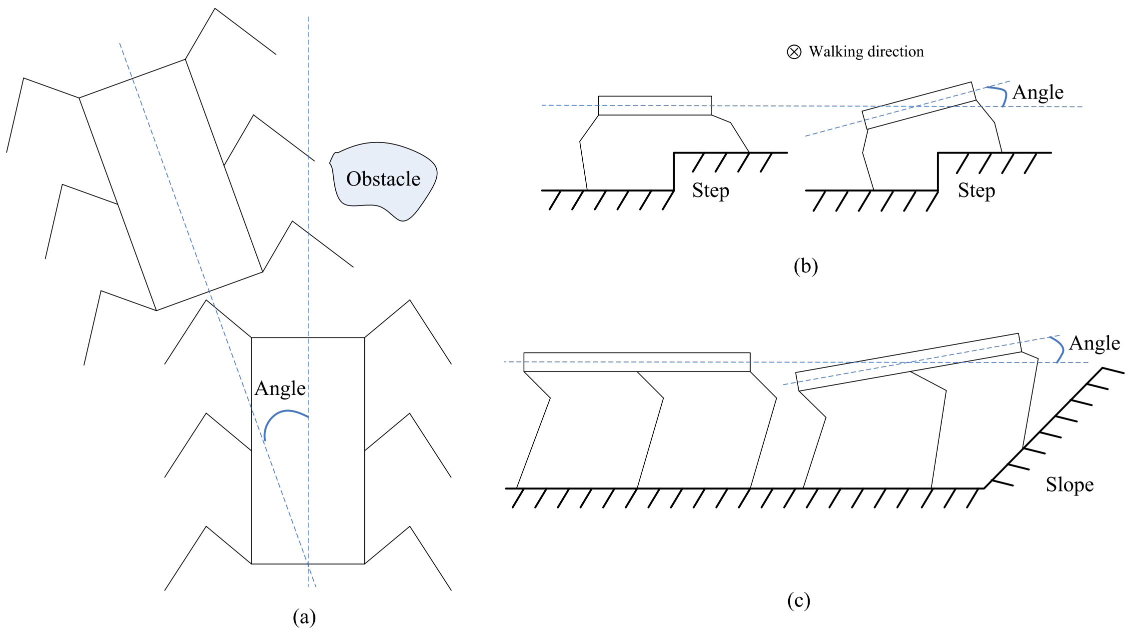

Fig. 1. A six-legged walking robot walking through different environments with different postures.

cannot be described easily. Thus, an effective, accurate, and robust method should be urgently developed for the posture control of multi-legged walking robots.

Sliding mode control (SMC) has been widely applied for its fine robustness against uncertainties and disturbances [20]. It adopts the linear sliding mode manifold and thus requires infinite time when the system states converge to the equilibrium point [21]. Terminal sliding mode (TSM) has been proposed to guarantee a finite time convergence [22,23]. The TSM uses a nonlinear sliding mode manifold to provide a faster convergence than the SMC [23,24]. However, the TSM has a singularity problem [25]. To address singularity problem, nonsingular TSM (NTSM) control was proposed and used [26]. NTSM control has good tracking precision, fast convergence, and a singularity avoidance property [27,28]. Thus, NTSM is widely used in nonlinear dynamic systems, of which robotic manipulators are the representatives. Yu et al. proposed a continuous finite-time control scheme for rigid robotic manipulators by using a new form of TSM [29,30]. Zhao et al. used a new TSM for robotic manipulator control based on the finite-time stability theory and the differential inequality principle [31]. Jin et al. also adopted a practical NTSM tracking control design for robot manipulators using time-delay estimation [21]. Yang et al. proposed the nonsingular fast terminal sliding mode (NFTSM) control for nonlinear dynamical systems [32].

The NTSM control method is valid for dynamic systems [33]. However, few studies on the NTSM control for multi-legged walking robots are available [34]. The performance of the NTSM control can also be improved. In this study, the authors proposed the NFTSM controller for the posture control of a six-legged walking robot (ZJU Walker) with redundant actuation. A new fast terminal sliding-type reaching law was proposed. This method has a faster convergence speed than the existing reaching law of the NFTSM posture control. The robustness of the NFTSM posture controller is analyzed with disturbances in the control.

The rest of this paper is organized as follows. A six-legged walking robot with redundant actuation is described and its kinematic is analyzed in Section 2. Then, the posture control model of six-legged walking robots with redundant actuation is analyzed in Section 3. Subsequently, the design of the NFTSM posture controller is presented in Section 4. The simulations and experiments conducted to verify the effectiveness of the proposed method are discussed in Section 5. Finally, conclusions are discussed in Section 6.

2. A six-legged walking robot with redundant actuation and its kinematic analysis

A six-legged walking robot (ZJU Walker) was designed as depicted in Fig. 2 [35]. The ZJU Walker has a body and six legs, and each leg has three joints. The six legs are distributed on two sides of the body. Each joint is actuated by a servomotor. All joints are regulated by a control system [36]. The ZJU Walker is 595.2 mm long and 395 mm wide, and the thigh and shank legs are 150 mm and 149.1 mm respectively. The specifications of the six-legged walking robot are listed in Table 1.

The control system is used to control the robot, which is shown in Fig. 3(a). It contains upper computer, lower computer, and joint execution system. The communication interval between the upper computer and the lower computer is 0.1 s. The communication interval between the lower computer and the joint execution system is also 0.1 s. The posture of the robot measured by ADIS16355 is updated every 1 ms. The posture control algorithm runs in the upper computer which communicates with the lower computer through wireless communication mode, and the interface of the upper computer is presented in Fig. 3(b). The lower computer is constructed based on LPC2132, and its work has three parts. The first part work is sending the joint data obtained from the upper computer to the joint execution system with specific instructions, and receiving the feedback joint data; the second part one is to receive and process the data from the posture sensor; the

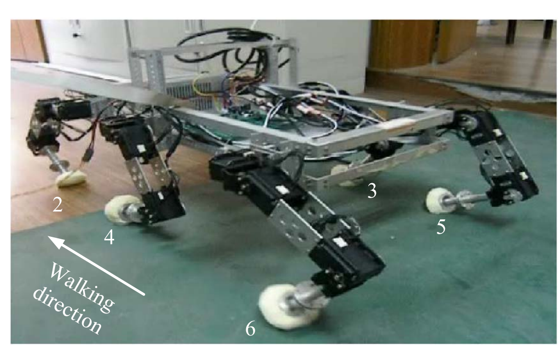

Fig. 2. Six-legged walking robot (ZJU Walker).