Direct torque control for cable conduit mechanisms for the robotic foot for footwear testing

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**Abstract**

As the shoe durability is affected directly by the dynamic force/pressure between the shoe and its working environments (i.e., the contact ground and the human foot), a footwear testing system should replicate correctly this interaction force profile during gait cycles. Thus, in developing a robotic foot for footwear testing, it is important to power multiple foot joints and to control their output torque to produce correct dynamic effects on footwear. The cable conduit mechanism (CCM) offers great advantages for designing this robotic foot. It not only eliminates the cumbersome actuators and significant inertial effects from the fast-moving robotic foot but also allows a large amount of energy/force to be transmitted/propagated to the compact robotic foot. However, CCMs cause nonlinearities and hysteresis effects to the system performance. Recent studies on CCMs and hysteresis systems mostly addressed the position control. This paper introduces a new approach for modelling the torque transmission and controlling the output torque of a pair of CCMs, which are used to actuate the robotic foot for footwear testing. The proximal torque is used as the input signal for the Bouc–Wen hysteresis model to portray the torque transmission profile while a new robust adaptive control scheme is developed to online estimate and compensate for the nonlinearities and hysteresis effects. Both theoretical proof of stability and experimental validation of the new torque controller have been carried out and reported in this paper. Control experiments of other closed-loop control algorithms have been also conducted to compare their performance with the new controller effectiveness. Qualitative and quantitative results show that the new control approach significantly enhances the torque tracking performance for the system preceded by CCMs.

1. Introduction

Flexible transmission mechanisms such as cable-conduit mechanism (CCM) and tendon-sheath mechanism (TSM) have been widely adopted and developed in many types of applications from surgical robots [1–4] to robotic hands [5,6], wearable robots [7], and soft exosuits [8,9]. A CCM (or a TSM) consists of a cable/tendon which goes through a flexible conduit/sheath and connects an actuator with the robotic joint. One end of the cable/tendon attaches to a proximal pulley which is controlled by an actuator, while its other end connects to a distal pulley, which attaches to the robotic joint. The conduit/sheath is a flexible tube which lets the cable/tendon go through and can hold constant length so that the force/motion can be propagated from the proximal pulley to the distal pulley. Thus, these mechanisms allow designers to install the output joints away from the actuators and therefore are the preferred solutions for those systems requiring narrow working environments and tortuous transmission routes. They are also very suitable for those applications which require high payload, compact design, and small weight and inertia such as for rehabilitation [10], exoskeletons [11,12], and ankle-foot prosthesis [13]. Utilizing these advantages, Nguyen et al. [14,15] adopted the CCMs to develop a robotic foot for footwear testing.

This robotic foot was designed to simulate the wear conditions that the footwear encounters in different walking, running, and other sports gaits with various ground conditions so that the system can automatically evaluate the footwear designs in a realistic testing manner. It consists of three primary segments (i.e., the shank, the foot, and the toe) and two controlled joints (i.e., the ankle joint and the metatarsophalangeal (MTP) joint). To simulate correctly the wear conditions caused by the human foot, the robotic foot should have similar capacity to mimic the human foot biomechanics during gaits. In high dynamic gaits (e.g., high running gaits), the human foot's joints convey a very high
amount of torque/energy during gait cycles [16–18]. Also, the robotic foot must have the same shape, size, and appearance of the human foot. Thus, available robotic feet with traditional transmissions [19–22] cannot afford adequate power to mimic high dynamic gaits. On the other hand, CCMs, which can tether-transmit the force/motion to the joints from remote actuators and have compact designs, are very suitable to develop a powered robotic foot. CCMs not only offer great power for the foot joints but also eliminate the high inertial effects caused by cumbersome motors and actuators out of the fast-moving robotic foot.

However, the other natural characteristics of CCMs and TSMs such as nonlinear friction and backlash hysteresis limit the system performances. These drawbacks are the results of the interactions between the cables and the conduits in operation, especially when the conduit configurations randomly change along with the movement of the output joint location. In those scenarios, high accuracy tracking control results are much more difficult to accomplish. There are two primary approaches to compensate the friction and backlash hysteresis effects of CCMs including (i) the feedforward friction compensation based on model parameters and off-line identification results without any real-time feedback during the operations, and (ii) the closed-loop compensation in real-time with the aids of indirect sensors (because traditional sensors such as encoders and force transducers are often not applicable for applications of CCMs).

To improve the system performance without the output sensors (i.e., the off-line compensation methods), many research groups such as Tian and Wang [23], Phee et al. [24], Pali et al. [5], Chen et al. [25], and Wu et al. [26] have been developing the lumped mass element methods with Coulomb friction model to characterize the force/motion transmission of the TSMs. Subsequently, inverse models and control signals were derived to compensate the friction. Nevertheless, these approaches often require in advance the cable-conduit configurations and assume the uniform distribution of the cable pretension. These conditions are either difficult to achieve or not practical. Other limitations in these methods include the dramatic increase of computation when the users increase the number of lumped elements and the discontinuity phenomenon in control due to the use of the static Coulomb friction model. Furthermore, by employing a set of partial derivative equations, Agrawal et al. [27] are able to describe the TSM transmission characteristics without the assumption of constant pretension and the knowledge of sheath configuration. However, complex model parameters, computational burden, and discontinuity are still the common limitations of this approach. Another major approach in modeling the TSM and CCM transmission characteristics is the use of either the backlash models [28,29] or the backlash-like hysteresis models [30–32] to capture the transmission profile. Subsequently, inverse models and feedforward control signal are derived to compensate the friction and backlash effects. Although the off-line compensation approaches do not require output feedback and thus suitable for those systems which cannot install any sensor at the joints, they cannot cope with the dramatic changes of the transmission characteristics when the pretension and cable-conduit configurations vary in operation. Therefore, they limit the tracking control performance. In addition, few studies on torque tracking control were found. Although Wu et al. [26] and Jeong et al. [33] carried out some experiments on torque tracking control, however, fixed configuration assumption and limited tracking performance are still their drawbacks.

Alternatively, by employing non-traditional and indirect sensors (e.g., image processing systems) to feed back the output, researchers can adopt closed-loop control algorithms to enhance the position tracking performance. Recently, Do et al. [34–36] adopted the Bouc–Wen model [37,38] to describe the motion transmission with displacement input and developed adaptive control schemes to cope with the changes of the conduit configuration and track to the position reference. However, no force/torque control algorithm was proposed. In addition, in the art of control theory for systems with hysteresis and nonlinearities (e.g., mechanical actuators, electromagnetic fields, and electronic relay circuits), many studies [39–43] have developed various control schemes to compensate for the backlash-like hysteresis effects. Nonetheless, few experimental validations have been conducted [43] and no force/torque control scheme was proposed.

On the other hand, to develop the robotic foot for footwear testing, it is crucial to control the output torque at the foot's joints in order to replicate correctly the wear conditions that the footwear endures during the gaits. Thus, our prime objective is to address the challenges of output torque tracking control. The database search on Elsevier's Scopus and ISI Web of Science with keywords such as cable conduit mechanism, tendon sheath mechanism, Bowden cable mechanism, and cable-driven control found few studies on force/torque control for those mechanisms. Although the cable-driven rotary series elastic actuator (RSEA) developed by Kong et al. [44] operates in torque mode control, the system only uses the position feedbacks and derived cable tensions to compensate the friction in four cases of the cable curvature. Similarly, Lu et al. [45] used the derived output torque from the distortion of the torsional spring, the off-line estimations of the geared motor's inertia and damping, and a disturbance observer (DOB) to control the zero output torque for a human assistive joint actuated by a cable-driven RSEA. In addition, for the system actuated by a single CCM, Zhang et al. [46] carried out a case study of nine low-level controllers and three high-level controllers in torque mode control to find the best control schemes for driving an ankle exoskeleton to assist the human ankle in walking. However, this system also used the feedback extension of the elastic element (i.e., the series spring) to derive the output torque and the none-modeled control laws to track to the reference torque profile regardless of the nonlinear transmission characteristics of the CCM. By installing four vertical load cells at four corners and one horizontal load cell in front of the contact floor of the robotic footwear testing system, the authors can monitor the ground reaction forces and calculate the output torque at the foot’s joints. Therefore, in this paper, we design a new robust adaptive control scheme for torque tracking with the availability of output torque feedback. A torque transmission model developed from Bouc–Wen hysteresis model and proximal input torque is used to compensate for hysteresis effect of the CCMs. Three conventional closed-loop controllers are also implemented and assessed their torque tracking performances.

The first novelty of this paper is a method of modeling the torque transmission of a pair of CCMs. Instead of using the proximal displacement as an input and then calculating friction forces on the CCMs in the well-known Bouc–Wen hysteresis model, this paper uses a measured proximal torque as the input for the Bouc–Wen model. Then, the output distal torque is expressed directly in term of the input proximal torque by the Bouc–Wen hysteresis model. This modeling method reduces the order of the system time-derivative equations and allows the authors to control the output torque which is independent of proximal displacement.

The second novelty is a new adaptive control design. In this design, an accumulative error is chosen as the variable of interest. Then, followed the design process, this accumulative error, the tracking error, and its first time-derivative are added to the torque control signal. This means that this adaptive controller does account for the tracking error, its changing speed, and its accumulation. Similar to the PID controller, this controller helps reduce steady-state error and overshoot while it can also estimate and compensate for system hysteresis to improve torque tracking performance. In addition, with the proposed Lyapunov function, the authors can prove analytically that the torque tracking error converges to a small constant (in a robust adaptive control design with leakage offset modifications).

2. Experimental system and problem formulation

2.1. Experimental system

To investigate the torque transmission characteristics of the CCMs
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