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Biped robot state estimation using compliant inverted pendulum model

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HIGHLIGHTS

- Humanoid robot has the flexibility feature and this disturbs the state estimation.
- A compliant inverted pendulum model is adopted to reflect the robot's key feature.
- The previously developed robust estimator is utilized to enhance the performance.
- Compliant model and robust estimator based state estimation framework is suggested.

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ABSTRACT

This study proposes a biped robot state estimation framework based on a compliant inverted pendulum model and a robust state estimator. A proper model that can express the key physical characteristics while considering limited computing power should be defined for the biped robot state estimation. A biped robot's limited structural stiffness and relatively long legs compared with the cross section of the body lead to undesired flexibility. However, the models used in previous research are either not suitable for state estimation or too simple to express the essential characteristics of the biped robot. A compliant inverted pendulum model is adopted herein to enhance the estimation accuracy. This model is made by adding a virtual spring and a damper to the conventional inverted pendulum. The additional elements represent the mechanical deformation and the undesired flexible movement. Adopting this model makes it possible to reflect the important characteristics of the biped robot while taking advantage of the merits of the single-mass model. In addition, a robust state estimator that we previously proposed is adopted to compensate for the estimation error caused by the modeling error. Using these two factors, the improved COM-kinematics estimate is obtained with respect to the existing simple-model-based biped state estimators.

1. Introduction

A variety of biped robots have been introduced in the recent years. It is a multi-body robot whose shape is similar to that of a human. Among the robot types, it is regarded as the most appropriate robot for collaborating with humans because its operating environment is already suited for human activities. Several institutes developed human-sized biped robots because of these advantages [1–5]. Such robots were previously only required to operate in limited environments. However, they are now required to take on various missions in diverse environments. To this end, robot hardware and control algorithms should be harmoniously developed. One of the key requirements is a technology for rapidly and accurately estimating the robot state. Accurate robot state estimation facilitates the use of greater sophistication in the design of feedback controllers and allows for greater controller gain, such that biped robots can more effectively respond to dynamic environments. Accordingly, many biped robots employ their own state estimators.

Linear estimators, such as the Kalman filter (KF) or its varieties, are usually used to construct the biped state estimator. Complex methods, such as quadratic programming (QP), can be used; however, the computational limitation of biped robots inhibits the use of a complex estimator framework. The model equations of the target system should be defined to configure the linear estimator. The system model can be a complex multi-dimensional expression or a simplified expression. For example, in the case of the biped robot, as described earlier, using a multi-dimensional system model can more accurately reflect the real physical characteristics

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of the robot because it is a complicated multi-joint/multi-body system. However, the inherent computation limitation of biped robots limits the use of such complex high-dimension models. Therefore, simplified system models, such as the linear inverted pendulum model (LIPM), are usually adopted to estimate the state of the biped robot.

The LIPM, which is sometimes referred to as the table-cart model, is an extremely simplified model, in which biped robot movements are represented as a point mass with a constant center of mass (COM) height [6,7]. Various studies performed biped state estimation using the LIPM and its modifications [8,9]. The LIPM is simple and intuitive; hence, it can be easily adopted. However, a modeling error will occur because the complex biped robot is oversimplified, eventually degrading the estimation performance. Some studies attempted to solve this problem while using the LIPM as it is. In [10], the effect of modeling errors and unknown forces on the estimation results was analyzed in the case of state estimation using a KF and the LIPM. Another study relaxed the problem by adding an extra term to the system input [11]. In that study, the difference between the desired and measured torques was considered to be the result of a modeling error, and was then modeled as an extra term of LIPM. The abovementioned studies were based on the LIPM and the KF. Some studies also used LIPM and the moving horizon estimator (MHE) [12].

The spring-loaded inverted pendulum (SLIP) is another simple model that simplifies the movement of biped robots. SLIP is a model for expressing the energy storage aspect of a biped robot by placing a virtual spring between the mass point and the pivot point of the general inverted pendulum. The SLIP model has been mainly used in biped-passive walking or biped-running fields rather than in state estimation fields because of these characteristics [13–16].

Some studies described biped robots as multi-body/multi-dimension models. In [17], a five-link planar model was used for the COM-kinematics estimation. It showed a slightly improved estimation performance compared to the LIPM-based method. Simplified multibody dynamics was used in [18]. In [19–21], high-dimensional multi-link models were used for the biped robot control algorithms; however, they did not extend their models to state estimation algorithms. These high-dimensional complex models are advantageous in that they can improve the performance of the state estimation by more accurately reflecting the physical characteristics of the biped robot. However, they have a disadvantage of being difficult to implement because of complicated formulas, and are limited by computing power depending on the complexity.

All these models are either unsuitable for state estimation or too simple to express the essential characteristics of a biped robot. This study introduces the state estimation framework using a compliant inverted pendulum model, which can reflect the key characteristics of the biped robot. Biped robots must be light to maximize robot mobility, but this complicates the design of the high-stiffness mechanical structure. In addition, long legs relative to the cross-section of the robot render the robot more flexible. This un-modeled flexibility causes an undesired motion that disturbs the accurate state estimation. The distortion of each joint and the presence of a force–torque (F/T) sensor in each ankle make this problem worse. The adopted compliant inverted pendulum model reflects this flexibility feature. Compliant or flexible inverted pendulum model-based biped humanoid motion descriptions have already been studied in previous studies [22–26]. Although each of them described flexibility in slightly different forms, the basic concepts are similar. As with the compliant models, most of them concentrated on the walking pattern generation algorithms or control strategies and did not actively extend their compliant model to the biped state estimation problems. We adopt herein their model concept for our proposed biped robot state estimation framework. The model is made by adding a virtual spring and a damper to the conventional inverted pendulum model. The attached spring and damper represent the mechanical deformation and the undesired-flexible movement of the robot, respectively. Adopting this model makes it possible to reflect the important characteristics of the biped robot while taking advantage of the merits of the single-mass model.

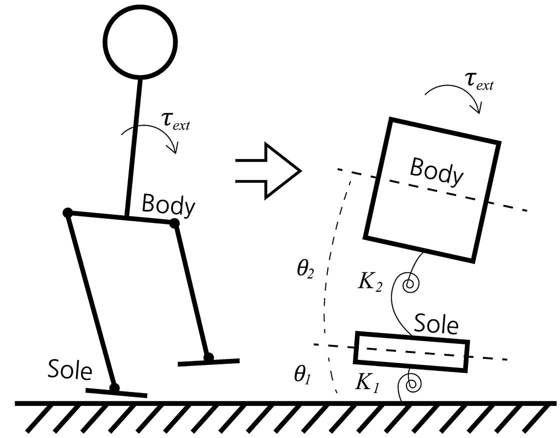

Fig. 1. Low stiffness and undesired structural deformation make the robot flexible. This undesired flexibility appears as an unexpected motion, which ultimately hinders the state estimation of the biped robot.

The robust state estimation framework is employed in addition to the compliant inverted pendulum model. A modeling error is inevitably generated when a complex robot system is represented by a model equation; hence, a robust estimator scheme that can compensate for the error is required. This study uses the dual-loop Kalman filter (DLKF) [27], which we previously proposed, as a robust state estimator. Using these two factors, the improved COM-kinematics estimate can be obtained with respect to the existing simple-model-based biped state estimators. The superiority will be demonstrated through simulations.

Section 2 introduces the structure, equation description, and characteristics of the compliant inverted pendulum model. Section 3 briefly reviews the pre-developed dual loop KF. Sections 4 and 5 present the composition of the biped robot state estimator based on the compliant inverted pendulum model and the DLKF. Its performance is then compared with the existing biped robot estimators. Finally, Section 6 concludes the paper and briefly explores some directions for future work.

2. Inverted pendulum model with compliant joint

This section describes the characteristics of biped robots and the compliant inverted pendulum model. Unlike industrial robots, mobile robots, such as biped humanoid robots, must be lightweight because of the limitations of weight and volume. Therefore, there is a limitation to increase the stiffness of the mechanical structure. Biped humanoid robots have long legs relative to the cross-section of the robot. Leg structures can be beam deflected because of this structural feature. In addition, the F/T sensor in each ankle and the shock-absorber in each sole have their own deformation. In some cases, the position tracking performance of each joint also affects the undesired deformation. Fig. 1 shows these characteristics. The adverse effects of these factors can also be found in [22,25], and [26]. An undesired flexibility appears as an unexpected motion, which ultimately hinders the state estimation of the biped robot.

Although the low stiffness and the undesired structural deformation problems are important key features of biped humanoid robots, many of the existing simplified biped models do not consider them. The most commonly used simplified models for control