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Control strategy switching for humanoid robots based on maximal output admissible set

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HIGHLIGHTS

- A novel framework for control strategy switching based on the maximal output admissible set (MOA) set is proposed.
- The formulation and computation procedure for the MOA set are presented for trajectory tracking control.
- The MOA set was applied to the falling prevention control. By switching between the regulator and trajectory tracking controller based on the MOA set, the robot can avoid falling with the COP constraint satisfied.
- An experimental computation method for the MOA set via identification of the macroscopic feedback gain is proposed. The validity of this framework was verified by the results of experiments.

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ABSTRACT

Human-like bipedal walking is a goal of humanoid robotics. It is especially important to provide a robust falling prevention capability by imitating the human ability to switch between control strategies in response to disturbances, e.g., standing balancing and stepping motion. However, the motion control of a humanoid robot is challenging because the contact forces are constrained. This paper proposes a novel framework for control strategy switching based on the maximal output admissible (MOA) set, which is a set of initial states that satisfy the constraints. This makes it possible to determine whether the robot might fall down due to a constraint violation. The MOA set is extended to a trajectory tracking controller with a time-variant reference and constraint. In this extension, the motion of the vertical center of gravity is also considered, which has often been neglected in previous studies. Utilizing the MOA set, an example is shown of the falling prevention control by switching the standing balance control and trajectory tracking control to a stepping and hopping motion. Moreover, a method is presented for applying the MOA set framework to a position-controlled humanoid robot. The validity of the MOA set framework is verified based on simulations and experimental results.

1. Introduction

One of the goals in humanoid robotics is to develop a humanoid robot system that can replace a human. To meet this goal, it is important to realize human-like bipedal walking. In particular, it is important to provide robust falling prevention capability by switching between various strategies because humans normally switch control strategies in response to disturbances, e.g., standing balancing and stepping motion. However, the motion control of a humanoid robot is challenging because the whole body dynamics includes large degrees of freedom (DOFs) and nonlinear characteristics. Moreover, there is a constraint on the contact forces because a humanoid is an under-actuated system, in which no link is connected to the environment. To overcome these problems, there have been numerous studies on control algorithms for biped locomotion. In many studies, a simple model focusing on the relationship between the center of gravity (COG) and center of pressure (COP) has been utilized. This macroscopic model can decrease the computation cost and make it easier to design a controller because the dynamics of this model is equivalent to that of an inverted pendulum. In addition, the constraints on the contact forces can be regarded as a constraint on the COP[1]: the COP exists inside the support polygon. Based on this property, numerous studies have been conducted on biped gait planning [2–6] and motion control [7–11].

To realize more robust motion control, studies have recently focused on falling prevention [12,13]. Because falling prevention requires a change in behavior, switching between multiple

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1 The COP constraint is also known as the zero moment point [1] constraint.

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control strategies has been investigated. Abdallah et al. [14] and Atkeson et al. [15] proposed *ankle/hip* strategies in which ankle and hip joints are automatically selected as the control input to maintain balance. Sugihara [16] and Stephens [17] proposed a *stabilizable* region for the COG state, in which it is possible to apply a regulator for standing balance without falling. In a similar way, the authors [18,19] applied the maximal output admissible (MOA) set[2] [20,21] to the standing balance control of a humanoid robot. The MOA set was originally proposed in the control engineering field to deal with a constrained system. The method proposed in [18] switched between multiple feedback gains for the standing balance control based on the MOA set, which improved the control performance. Then, the MOA set was used as a trigger to generate a stepping motion to prevent falling in [19]. In these studies, the MOA set was defined in a regulator for the standing balance with a constant support polygon. If we can extend the MOA set to other types of controllers such as the trajectory tracking controller or limit cycle controller, it is expected that we will be able to switch between multiple types of controllers based on the MOA set and improve the stability of the biped locomotion.

This paper proposes a novel framework for control strategy switching based on the MOA set. In particular, the author extends the MOA set to trajectory tracking control by changing the support polygon. Although Kogiso et al. [22] proposed an MOA set for a time-variant reference by parallel shifting the MOA set for a regulator, they assumed a constant constraint. In this paper, the author proposes a computation procedure for the MOA set that considers the time-varying constraint as the support polygon changes. Moreover, the vertical motion of the COG is also considered, even though it has often been neglected in previous studies. Then, the author proposes a method for applying the proposed MOA set framework to an actual robot system. Another challenging problem involves the development of a method for resolving the control input of the COG–COP model for the whole body humanoid system. In this paper, an experimental computation method for the MOA set is presented. The feedback gain in the COG–COP model is identified for a position-controlled humanoid robot by measuring the disturbance response. This identification can be regarded as an extraction of the *macroscopic feedback gain* in a way similar to the extraction of the macroscopic dynamics for the COG–COP model. The author reports the results of falling prevention experiments based on the MOA set obtained from identified feedback gain.

The rest of this paper is organized as follows. In Section 2, the author reviews related works and explains the difference between them and the MOA set framework. In Section 3, the author formulates a state equation and the COP constraint for the COG–COP model. Then, the MOA set in a regulator for the standing balance is presented in Section 4. In Section 5, the author proposes a computational procedure for the MOA set for trajectory tracking control, and presents computation examples for a bipedal walking and hopping motions. The MOA set is applied to the falling prevention control, and a simulation result is shown in Section 6. In Section 7, the experimental computation of the MOA set is explained, and the validity of the MOA set framework is verified based on the results of experiments. Finally, Section 9 provides a summary and discussion. The main part of this paper was published in international conferences [23–25]. The author has added the detailed formulation and analysis of the MOA set in Section 4.3 and Appendix B, respectively.

[2] It is also called the *maximal constraint positively invariant (CPI) set*.

2. Related works

2.1. Classification of biped locomotion control

Biped locomotion control can be divided into (A) tracking control with a time-variant referential trajectory and (B) autonomous control without a referential trajectory. In (A) trajectory tracking control, many researchers have proposed biped gait planning methods [2–6]. In these studies, a biped gait is planned so that the COP constraint is satisfied. While the planned gait is used as a reference, a robot is controlled by compensating for modeling errors (e.g., modification of the foot landing position, leg impedance control for uneven terrain, or body attitude compensation). These controllers allow a robot to track the referential trajectory as precisely as possible. Therefore, it is difficult to absorb a large disturbance by drastically changing its behaviors. Although a motion database [26] was proposed to generate various motions, connecting different motions requires dynamic filtering [27].

(B) Autonomous control includes (B1) standing balance control in the upright position [7,8], (B2) limit cycle control for steady walking [9,10], and (B3) the optimal control scheme [11] or model predictive control (MPC) [28].

In B1, the standing balance control is realized by a regulator. The ankle/hip strategies [14,15] and switching controllers based on the MOA set [18] can be regarded as a control strategy switching methods in this type of controller. Stephens et al. [29] and Sugihara [30] proposed a method to switch between B1 and B2.

The MOA set framework proposed in this paper makes it possible to switch between (A) a trajectory tracking controller and (B1) standing balance controller. Theoretically, the MOA set can be defined in (B2) the limit cycle controller and (B3) the MPC. Therefore, the MOA set can be applied to a unified framework to switch between various types of controllers. As an extension of the MOA set, the computation procedure for the trajectory tracking controller is presented in this paper.

2.2. Falling prevention control

Falling prevention control has recently received greater attention. For example, Urata et al. [13] proposed an on-line generation method for foot placement to prevent a robot from falling. In that studies, a stepping motion was triggered by a threshold, which was given by trial and error, and there was no discussion on how to appropriately switch between the control strategies.

Wieber [31] proposed the concept of *viability*. According to this concept, the viability kernel provides a set in which it is guaranteed that the robot will never fall if the initial state is included. However, it is extremely difficult to derive a closed form of the viability kernel; switching control strategies require a closed form of a set.

Pratt et al. [32] proposed the concept of *capture point*, which is a feasible foot landing position to make a robot stop. This concept was further extended to *capturability*, which is applied to multiple stepping motions and to the COG–COP model involving a foot sole with finite size [12]. The MOA set resembles the concept of N-step capturability. In particular, the 0-step capturability has a close relationship with the MOA set in the standing balance controller. Capturability, however, does not explicitly take into consideration how the COP moves inside the foot sole. In contrast, in the MOA set, state feedback explicitly indicates the motion of the COP, thereby offering clear guidelines designing a controller. Section 8 compares capturability with the MOA set in detail.

2.3. Resolving from COG–COP model to whole body motion

Most of the above-mentioned studies utilized the COG–COP model. However, how to resolve the control input in the COG–COP model for the whole body control is another issue. The COG