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Observer-based dynamic walking control for biped robots

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ABSTRACT

This article presents a novel observer-based control system to achieve reactive motion generation for dynamic biped walking. The proposed approach combines a feedback controller with an online generated feet pattern to assure a stable gait. Using the desired speed of the robot, a preview control system derives the dynamics of the robot's body, and thereby the trajectory of its center of mass, to ensure a zero moment point (ZMP) movement, which results in a stable execution of the calculated step pattern. Extending the control system by an observer, based on this knowledge and the measured sensor values, compensates for errors in the model parameters and disturbances encountering while walking.

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1. Introduction

The trend in robotics is currently shifting from traditional fixed-base manipulator arms in assembly line production to autonomous mobile robots capable of performing more complex tasks, such as search and rescue or military operations, and also performing service and entertainment activities. To fulfill tasks in the latter two areas of application, these robots must be capable of navigating in and interacting with environments made for humans, and of communicating with people naturally. Environments designed for humans are particularly challenging for the movement of conventional wheeled autonomous robots. Normal stairs or small objects lying on the floor become insurmountable barriers. For these reasons the design of such robots tends to mimic human appearance in respect of body design, capability of gestures and facial expressions [1].

As a consequence, humanoid robots are one of the major topics of robotics research and are believed to have a high potential for future applications. Despite this, the present humanoid robots have a substantial lack of mobility. Even basic tasks such as walking on even ground without an external disturbance are not a trivial challenge. The humanoid shaped form of a two-legged robot ends up with a relatively high center of mass (CoM) of its body while standing upright. As a result the stance of a humanoid robot is quite unstable, making it likely to tip over. Therefore research on stable biped walking is one of the central problems in this area at the moment. Gait planning for humanoid robots is fundamentally different from the path planning for simple robotic arms. The robots center of mass is in motion all the time while the feet periodically interact with the ground in an unilateral way, meaning that there are only repulsive but no attractive forces between the feet and the ground. Therefore the movement of the center of mass cannot be controlled directly, but is governed by its momentum and the eventual contact forces arising from ground interaction. These have to be carefully planned in order not to suffer from postural instability.

2. Stability

A robot's posture is called balanced and its gait is called statically stable, if the projection of the robot's center of mass on the ground lies within the convex hull of the foot support area (the support polygon). This kind of gait however results in relatively low walking speeds. Similarly natural human gaits are normally not statically stable. Instead they typically consist of phases in which the projection of the center of mass leaves the support polygon, but in which the dynamics and the momentum of the body are used to keep the gait stable. Those gaits are called dynamically stable.

The concept of the zero moment point (ZMP) is useful for understanding dynamic stability and also for monitoring and controlling a walking robot [2]. The ZMP is the point on the ground where the tipping moment acting on the robot, due to gravity and inertia forces, equals zero. The tipping moment is defined as the component of the moment that is tangential to the supporting surface, i.e. the ground. The moment's component perpendicular to the ground may also cause the robot to rotate, but only in a way to change the robot's direction without affecting its stability, and is therefore ignored. For a stable posture, the ZMP has to be inside the support polygon. In the case when it leaves the polygon, the vertical reaction force necessary to keep the robot from tipping

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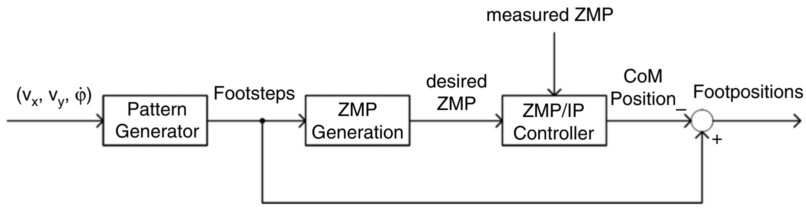

Fig. 1. Pipeline visualization of the walking pattern generation process.

over cannot be exerted by the ground any longer, thus causing it to become instable and fall.

In fact, following Vukobratovic's classical notation [3], the ZMP is only defined inside the support polygon. This coincides with the equivalence of this ZMP definition to the center of pressure (CoP), which naturally is not defined outside the boundaries of the robot's foot. If the ZMP is at the support polygon's edge, any additional moment would cause the robot to rotate around that edge, i.e. to tip over. Nevertheless, applying the criteria of zero tipping moment, results in a point outside the support polygon in this case. Such a point has been proposed as the foot rotation indicator (FRI) point [4] or the fictitious ZMP (FZMP) [3]. In this so-called fictitious case the distance to the support polygon is an indicator for the magnitude of the unbalanced moment that causes the instability and therefore is a useful measure for controlling the gait.

There are different approaches to generating dynamically stable walking motions for biped robots. One method is the periodical replaying of trajectories for the joint motions recorded in advance, which are then modified during the walk according to sensor measurements [5]. This strategy explicitly divides the problem into subproblems of planning and control. Another method is the realtime generation of trajectories, based on the present state of the kinematic system and a given goal of the motion, where planning and control are managed in a unified system. Implementations of this approach differ in the kinematic models being used and the way the sensor feedback is handled. One group requires precise knowledge of the robot's dynamics, mass distribution and inertias of each link to generate motion patterns, mainly relying on the accuracy of the model for motion pattern generation [6–8]. A second group uses limited knowledge about a simplified model (total center of mass, total angular momentum, etc.) and relies on feedback control to achieve a stable motion [9, 10]. The model used for this is often called the inverted pendulum model.

This paper describes the generation of walking patterns based on a simple inverted pendulum model, using a sophisticated preview controller to generate motions, resulting in a desired future ZMP movement and the ablity to compensate small disturbances or unforeseen forces. The motion generation process can be regarded as stages in a pipeline process, which will be described in the next section.

3. Generating the walking patterns

The general problem of walking can be seen as an appropriate placement of the feet and a movement of the rest of the body, both of these must satisfy the condition to keep the overall resulting motion stable. The generation of such motion patterns can be divided into separate tasks with one depending on the results of another, thereby forming a pipeline (Fig. 1).

The goal of the desired walk is a certain translational and rotational speed of the robot which might change over time, either smoothly i.e. when the robot is slowing down while approaching an object, or rapidly i.e. when the robot's high-level objective changes. The translational and rotational speed vector is taken as

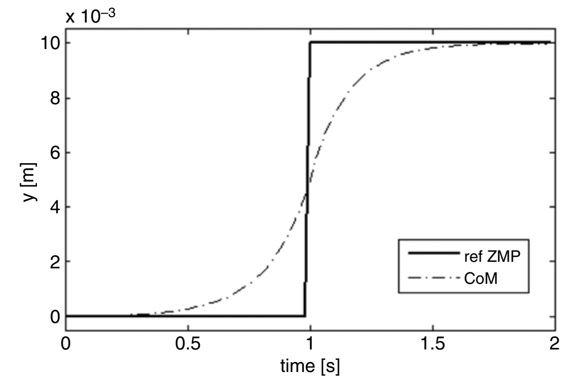

Fig. 2. CoM motion required to achieve a given ZMP trajectory.

the input of the motion generation pipeline. This speed vector is the desired speed of the robot, which does not translate into its CoM speed directly, for obvious stability reasons, but merely to its desired average. Thus a path is specified that the robot intends to follow at this point of time. The feet of the robot have to be placed along this path to ensure the correct overall motion of the robot. Alternatively, in scenarios with uneven ground, the feet placement at safe positions must be prioritized, resulting in an irregular gait dictating different changes of speed.

Once the step patterns are set, these define a region for possible ZMP trajectories to result in stable gaits, namely the support polygon at every given time. A gait can be divided into two phases, a double support phase where both feet are on the ground and a single support phase where only one foot has contact with the ground. During each single support phase the ZMP should be positioned at the center of the ground foot. Consequently in the double support phase the ZMP has to be shifted from one foot to the other. While these restrictions are sufficient to specify the stability of a gait, there is some freedom left in the specification of the exact ZMP trajectory. Jerky ZMP movement tends to result in high peak accelerations of the robot's body necessary to achieve this. So in this implementation the ZMP trajectory during the double support phase is described by a Bezier curve to guarantee smooth ZMP movement, therefore smooth acceleration changes the robot's center of mass avoiding jerks in its motion.

The next stage of the process is the generation of a CoM trajectory in which kinematics result in the desired ZMP trajectory. As can be seen in Fig. 2, it is not sufficient to shift the CoM at the same time as the ZMP. Instead the CoM has to start moving before the ZMP does. This is realized using a preview control described in more detail in the following section. Its output is a CoM trajectory as shown in Fig. 1.

All trajectories and positions calculated so far are given in a global world coordinate frame. From the step pattern the feet positions are known, and so is the position of the center of mass at a given time. If the robot's CoM relative to its coordinate frame is known (or assumed to be constant in a simple model), the difference between these directly provides the foot positions in a robot centered coordinate frame. Those can subsequently be transformed into leg joint angles using inverse kinematics.

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