# Human Walking Imitation based on Quadratic Programming

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***Abstract*— This work presents a procedure of imitating human walking motion online for a humanoid robot. Two aspects are essential for a successful walking imitation: stable footprints and motion similarity. The human footprints are recognized from the captured motion data and imitated by the robot through conventional zero-moment point (ZMP) control scheme. For the motion similarity we focus on similar knee joint trajectories, which are related to knee stretching and swing leg motion. After human motion capturing and preprocessing, the walking imitation problem is formulated as a quadratic programming (QP) problem with inequality constraints and dynamic equality constraints. The continuity of the control law is ensured by introducing a task activation buffer and position dependent velocity limit. Finally we evaluate the effectiveness of the proposed approach on the DLR humanoid robot TORO in dynamics simulation.**

## I. INTRODUCTION

Based on the well established ZMP control scheme, some researchers have worked on mapping the human locomotion to the humanoid robot. Several offline procedures [1], [2], [3], [4] focused on extracting human walking features from human motion data, such as knee stretching, toe-off and heel-down motions. These features are then applied to a ZMP-based pattern generator to realize human-like locomotion, which requires intensive optimization or careful setup of the parametrization. Online footprint imitation was realized on the MAHRU-R robot by recognizing and parameterizing the human footprints during the walking [5]. The recognized human footprints are adapted for the robot and corresponding robot walking pattern is generated. However the footprint parameters contain no information about the motion similarity.

In this research we propose an online walking imitation algorithm for a humanoid robot from human motion capturing. We consider the walking imitation problem as two essential parts: stable footprints imitation and motion similarity. The human footprints are recognized from the captured motion data and imitated by the robot through conventional ZMP control scheme. Since human and humanoid robot have similar kinematics, it is reasonable to evaluate the motion similarity in joint space, which is similar to the joint space imitation of the upper body [6]. Especially we focus on similar knee joint trajectories, which are related to knee stretching and swing leg motion. The walking imitation problem is formulated as a quadratic programming (QP) problem with inequality constraints and dynamic equality constraints. The continuity of the control law is ensured by introducing a task activation buffer and position dependent velocity limit. Finally we evaluate the effectiveness of the proposed approach on the DLR humanoid robot TORO in dynamics simulation (Fig. 1).

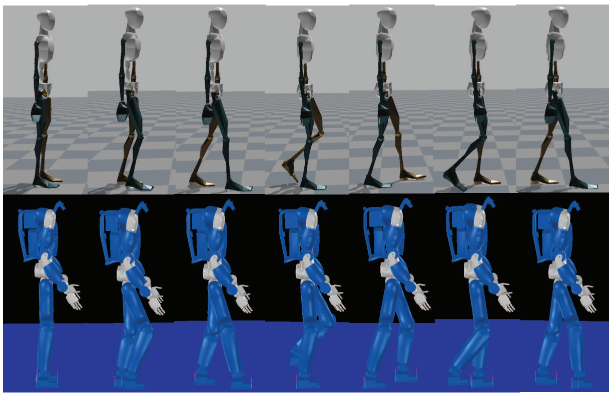

Fig. 1. Snapshots of the simulation results. Top: Recorded human walking motion in MVN Moven Studio: The walking frequency is around 0.8sec/step and the human stride length is around 70cm; bottom: TORO robot imitates the human walking. The dynamics simulation is carried out in OpenHRP [7].

## II. WALKING MOTION RECOGNITION AND PATTERN GENERATION

Online human motion data are acquired by the MVN inertial motion capture system from Xsens Technologies[1]. Human motion data consist of position and orientation of 23 body parts are available through network streaming in real-time. Human joint angle trajectories are calculated from orientation data and adapted according to the robot joint limit and joint velocity limit.

### A. Foot Support Event and Footprint Extraction

In order to extract suitable footprint trajectory for the robot, we control the humanoid robot as a marionette by feeding the corresponding adapted human joint angles into the robot forward kinematics model. Different foot support event are determined by examining the feet position and velocity data and the transitions between different support states are modeled as a finite state machine. The next supporting foot position is then determined by extracting the relative feet position at the time of stance changes and adding it to the current supporting foot position.

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### B. Pattern Generation

Mapping human's ZMP to the robot is difficult because there is a big gap of the dynamics properties between the two subjects. Two principles are utilized to design the desired ZMP trajectory for the robot:

- Single Support: The ZMP moves along the main axis of the supporting foot forward with a predefined velocity. The maximal ZMP displacement is bounded by the foot size.
- Double Support: The ZMP jumps to the middle of the new supporting foot position at the beginning of the double support phase.

The reference COM trajectory are then generated through ZMP preview controller proposed in [8] based on the linear inverted pendulum model.

## III. Walking Imitation Control

Compared with the human walking behavior, the conventional ZMP-based walking control scheme has several factors which make the resulted motion quite different. In order to avoid the knee stretching singularity, the COM/pelvis height is usually set to be relatively low. Human however walks with almost stretched knees and small vertical COM motion [9]. The robot upper body orientation is usually fixed because the LIPM neglects the angular momentum. During the human walking the whole-body angular momentum is highly regulated but the body orientation is not strictly fixed. Based on the above two observations we can release these strict constraints and make the biped system redundant. The redundancy is resolved by designing suitable cost function, which achieves a compromise between the dynamic stability and human motion similarity.

### A. Problem Formulation

We formulate the walking control problem as following quadratic programming problem:

$$\begin{aligned}
\arg\min_{\dot{\boldsymbol{q}}} \quad & f(\dot{\boldsymbol{q}}) = \omega_1 f_1 + \omega_2 f_2 + \omega_3 f_3 \\
& f_1 = \left\| \dot{\boldsymbol{x}}_{feet,xy,ori} - J_{feet,xy,ori}\dot{\boldsymbol{q}} \right\|^2 \\
& f_2 = \left\| \dot{\boldsymbol{x}}_{body,ori} - J_{body,ori}\dot{\boldsymbol{q}} \right\|^2 \\
& f_3 = \| \dot{\boldsymbol{q}} - \dot{\boldsymbol{q}}_{human} \|^2 \\
\text{subject to} \quad & \boldsymbol{J}_{com,xy}\dot{\boldsymbol{q}} = \dot{\boldsymbol{x}}_{com,xy} \\
& \boldsymbol{A}_{knee}\dot{\boldsymbol{q}} \leq \boldsymbol{b}_{knee} \\
& \dot{\boldsymbol{q}}_{min} \leq \dot{\boldsymbol{q}} \leq \dot{\boldsymbol{q}}_{max} \\
& \boldsymbol{J}_{feet,z}\dot{\boldsymbol{q}} = \dot{\boldsymbol{x}}_{feet,z} \quad \text{(dynamic).}
\end{aligned}$$

The quadratic cost function consists of three terms: the foot horizontal position error and orientation error, the body orientation error and the human joint knee trajectory tracking error. And $\{\omega_i | i = 1,2,3\}$ are weighting factors of each term respectively. They are selected according to the task importance. The horizontal COM trajectory is treated as equality constraints. Additionally we have the knee minimal position constraint to prevent knee stretching singularities. Since the human knee tracking task is conflicting with the foot height control task, we treat the foot height control as a dynamic equality constraint whose activation and deactivation depend on the walking states.

### B. State-dependent Foot Height Control

During single support phase we want to track the human knee trajectory and achieve a human like walking. Therefore we deactivate the foot height constraint. In order to achieve a stable foot contact we design a foot landing trajectory from the current foot states and activate the foot height constraint. For smooth transition of the task activation, an activation buffer is introduced:

$$\boldsymbol{J}_{feet,z}\dot{\boldsymbol{q}} = h\dot{\boldsymbol{x}}_2 + (1-h)\boldsymbol{J}_{feet,z}\dot{\boldsymbol{q}}_{static} \tag{1}$$

in which $h$ is activation parameter changes smoothly from 0 to 1 during task activation and 1 to 0 during task deactivation and $\dot{\boldsymbol{q}}_{static}$ represents the inverse kinematics solution with only static constraints.

## IV. CONCLUSIONS

We propose to use quadratic programming to solve the walking imitation problem. Stable footprints are imitated through the conventional ZMP control scheme. Knee singularity problem can be solved easily by adding inequality constraints explicitly. The lower priority tasks are formulated as soft constraints in the cost function conveniently. A state-depend foot height controller is designed to achieve human-like walking motions, finding compromise between walking stability and motion similarity. Continuous control law of task activation and deactivation is achieved by introducing an activation buffer.

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