Robotics and Autonomous Systems 83 (2016) 287–298

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

A novel approach for the generation of complex humanoid walking sequences based on a combination of optimal control and learning of movement primitives

Debora Clever [a,*], Monika Harant [a], Henning Koch [a], Katja Mombaur [a], Dominik Endres [b]

[a] *Interdisciplinary Center for Scientific Computing (IWR), Optimization in Robotics & Biomechanics (ORB), University of Heidelberg, Germany*

[b] *Theoretical Neuroscience Group, Department Psychology, Philipps-University Marburg, Germany*

ARTICLE INFO

Article history:
Available online 21 June 2016

Keywords:
Optimal control
Movement primitives
Learning
Humanoid gait generation
HRP-2

ABSTRACT

We combine optimal control and movement primitive learning in a novel way for the fast generation of humanoid walking movements and demonstrate our approach at the example of the humanoid robot HRP-2 with 36 degrees of freedom. The present framework allows for an efficient computation of long walking sequences consisting of feasible steps of different kind: starting steps from a static posture, cyclic steps or steps with varying step lengths, and stopping motions back to a static posture. Together with appropriate sensors and high level decision strategies this approach provides an excellent basis for an adaptive walking generation on challenging terrain. Our framework comprises a movement primitive model learned from a small number of example steps that are dynamically feasible and minimize an integral mean of squared torques. These training steps are computed by solving three different kinds of optimal control problems that are restricted by the whole-body dynamics of the robot and the gait cycle. The movement primitive model decomposes the joint angles, pelvis orientation and ZMP trajectories in the example data into a small number of primitives, which effectively deals with the redundancy inherent in highly articulated motion. New steps can be composed by weighted combinations of these primitives. The mappings from step parameters to weights are learned with a Gaussian process approach, the contiguity of subsequent steps is promoted by conditioning the beginning of a new step on the end of the current one. Each step can be generated in less than a second, because the expensive optimal control computations, which take several hours per step, are shifted to the precomputational off-line phase. We validate our approach in the virtual robot simulation environment OpenHRP and study the effects of different kernels and different numbers of primitives. We show that the robot can execute long walking sequences with varying step lengths without falling, and hence that feasibility is transferred from optimized to generated motions. Furthermore, we demonstrate that the generated motions are close to torque optimality on the interior parts of the steps but have higher torques than their optimized counterparts on the steps boundaries. Having passed the validation in the robot simulator, we plan to tackle the transfer of this approach to the real platform HRP-2 as a next step.

1. Introduction

Animals in general and humans in particular are able to control, adapt and recognize the movements of their bodies seemingly without much effort, even though biological motion is a continuous dynamical process in space–time encompassing a large number of degrees of freedom. Movement primitives (MP) have been proposed as a way of simplifying this control problem, thereby facilitating the planning and execution of movements [1,2]. MPs form the link between the observable, continuous motor output and a (hypothetical) discrete internal movement representation. Another prominent hypothesis for human movement generation is based on optimal control (OC). This hypothesis posits that the human motor system is optimal (or near optimal) in its choice of movements, given the sensory input and goal specifications [3,4].

* Corresponding author.
E-mail address: debora.clever@iwr.uni-heidelberg.de (D. Clever).

http://dx.doi.org/10.1016/j.robot.2016.06.001
0921-8890/

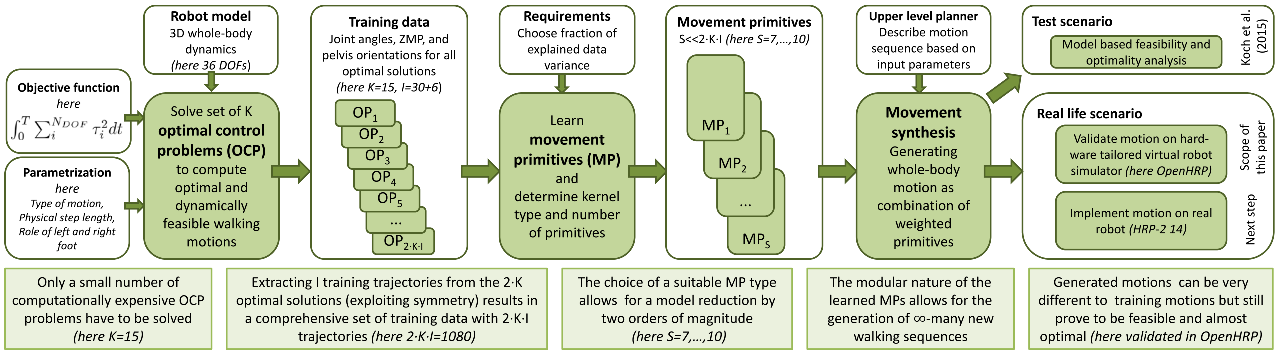

Fig. 1. Methodology. Optimal and dynamically feasible motion trajectories are computed by an optimal control approach. Movement primitives are learned in a Gaussian process framework. New motions are generated by using a small number of primitives. The resulting motions prove to be sufficiently close to optimality and dynamic feasibility, validated in the virtual robot simulator OpenHRP. A corresponding video is available online: http://orb.iwr.uni-heidelberg.de/ftp/CleverEtAl_OCMP_OpenHRP (see also Appendix A).

To generate movements for humanoid robots, both approaches are very interesting. Their advantages and disadvantages can be found in two fundamentally opposite directions. Movement generation with MPs is a fast and efficient approach, applicable in the framework of on-line control. However, these primitives often model kinematics only, chosen to be safely feasible for the robot. Especially in the context of walking motions, this approach results in a conservative and generally slow motion. On the other hand, motion generation by solving optimal control problems allows for movements which exploit the limits of the robot, are dynamically feasible because they are constrained by the robot mechanics and can be optimal with respect to a variety of criteria: speed, stability, integrated torques, etc. Another benefit of OC is that it offers a natural way to solve the redundancy issue in highly articulated motions. The major drawback of this approach is the fact that it requires a high computational simulation effort and hence is only feasible for off-line use.

We aim to combine the advantages of both approaches: the fast movement generation ability of movement primitives, and the optimality and dynamical feasibility of the optimal control approach, see Fig. 1. This paper substantially extends our own previous work presented at the IEEE Humanoids conference [5]: there, we demonstrated that individual movements in form of cyclic steps based on OC can be represented in a compressed form by a simple MP model, and that novel movements can be generated by interpolation in this model. Here, we extend the MP model to allow for concatenations of steps with varying step lengths into longer walking sequences. A further novelty is the augmentation of the training data set. Whereas in [5] it exclusively consists of periodic steps with an initial velocity, here it also includes starting steps (from a static posture) and stopping steps (back to a static posture). This augmentation is essential to transfer the motions to a real robot. Furthermore, we demonstrate that the sequences thus generated can be executed by the robot (simulated by the virtual robot OpenHRP) and that the resulting movements are near-optimal most of the time. One of the most remarkable achievements of the present approach is the reduction in on-line computing time. The generation of almost optimal and feasible motions, which are executable in OpenHRP takes less than a second instead of hours (as for the pure OC based approach).

This paper is structured as follows: in Section 2, we give an overview of common MP models and OC approaches. We introduce our optimal control movement generation framework in Section 3.1, and describe the morphable MP model for novel movement production in Section 3.2. The results obtained with this combination of approaches are described in Section 4, focusing on feasibility, optimality and model comparison between MP models of different complexity. Conclusion and outlook are offered in Section 5.

2. Related work

2.1. Movement primitives

A plethora of movement primitive (MP) definitions have been proposed already. In an earlier paper [6], we argued that kinematic MPs could be grouped into temporal [7–9], spatial [10,11], and spatio-temporal primitives [2]. *Temporal* MPs are the ones which we use in this paper. They are stereotypical time-courses of degrees of freedom (DOF), e.g. joint angles. To generate complex movements, such as different human gait patterns, these time-courses are usually superimposed linearly. Modularity is an advantage of these kinematic primitives [2]: new movements can be obtained by a weighted recombination of previously learned MPs. This modularity accounts for the observed variability of human movement in the theory of MPs. It can e.g. be used to produce movements with differing styles from a small number of MPs, which has been demonstrated in computer graphics applications [12]. Movement primitives are also an important tool for efficient humanoid gait generation. In robotics, MPs are often learned from human motions and transferred to the robot (see e.g. [13]). Due to the different dynamics of human and humanoids, this approach usually is not directly applicable in the context of walking motions. Dynamical movement primitives (DMP) [14], which generate trajectories by transforming the output of a canonical dynamical system via a learned kinematics mapping onto the robot, have become popular tools for motion generation recently. DMPs can be easily modulated by task demands. The dynamical systems approach facilitates sequencing of primitives into complex actions [15]. Also, it was demonstrated in [16] that individual DMPs can encode both transient and rhythmic components of a movement. However, they are not (yet) modular (but see [17,18]), i.e. one DMP drives all relevant degrees of freedom. Thus, it remains to be shown how learned DMPs can be recombined into novel motions. Non-modular kinematic primitives were used by [19,20] for robotic gait generation. The lack of modularity results in rather large databases of MPs, containing all possible combinations of walking movements and transients which one might want to generate. This is in contrast to our modular approach, which leads to a very compact representation, as shown below.

2.2. Optimal control

Optimal control problems (OCP) restricted by multi-body dynamics are an alternative tool for off-line motion generation in humanoid robotics. They solve the redundancy issue of the underlying multi body dynamics in an elegant and beneficial way and allow to include a wide range of complicated constraints on