

Motion Planning for Humanoid Robots Based on Virtual Constraints Extracted from Recorded Human Movements

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1 Introduction

Human movements are characterized by *synchronization of the individual body segments*. An analysis of recorded kinematic data allows to find geometric relations among the joint coordinates that are fairly consistent for ordinary motion patterns. Our investigation validates and supports the *wider and rigorous use of virtual holonomic constraints* for analyzing, planning and reproducing human-like motions based on mathematical tools previously utilized for very particular control problems.

2 Analysis of Recorded Human Movements

A qualitative analysis of recorded kinematic data allows to describe the evolution of various joint angles. Captures of human motions are typically given as depicted in Fig. 1.

A surprising fact is that *humans experience some underactuation* during motions involving single support, even though the overall level of actuation is very high. Consequently, the human body and thus the humanoid robot must be modeled as an underactuated mechanical system.

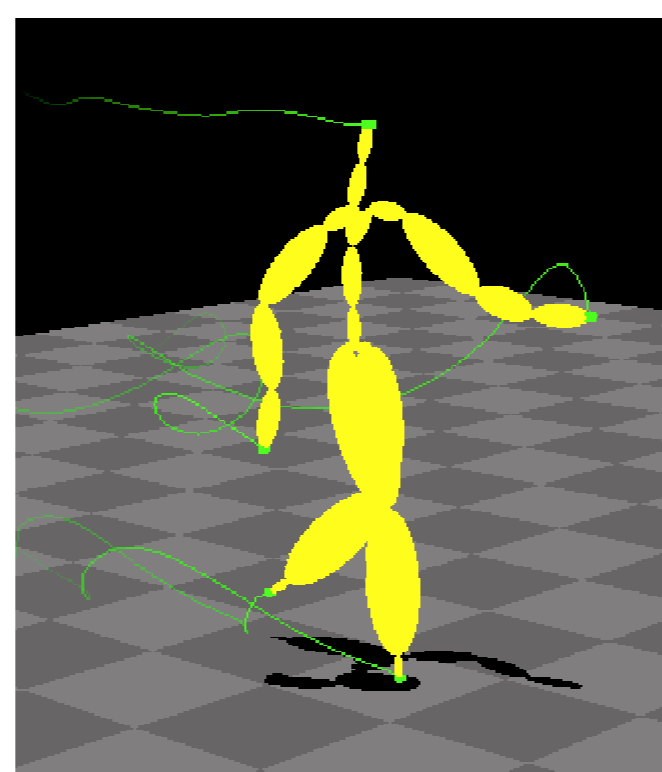
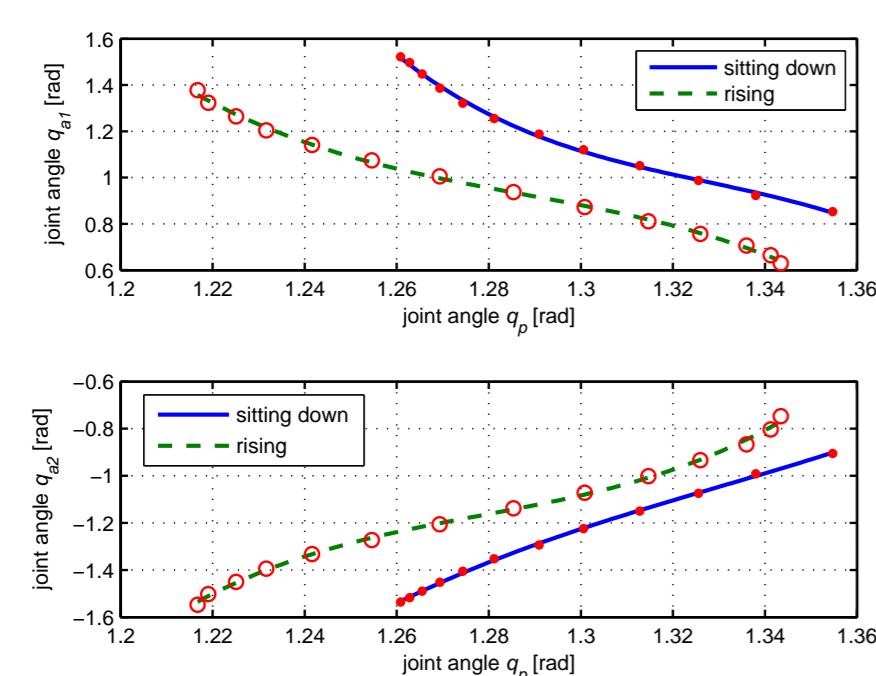
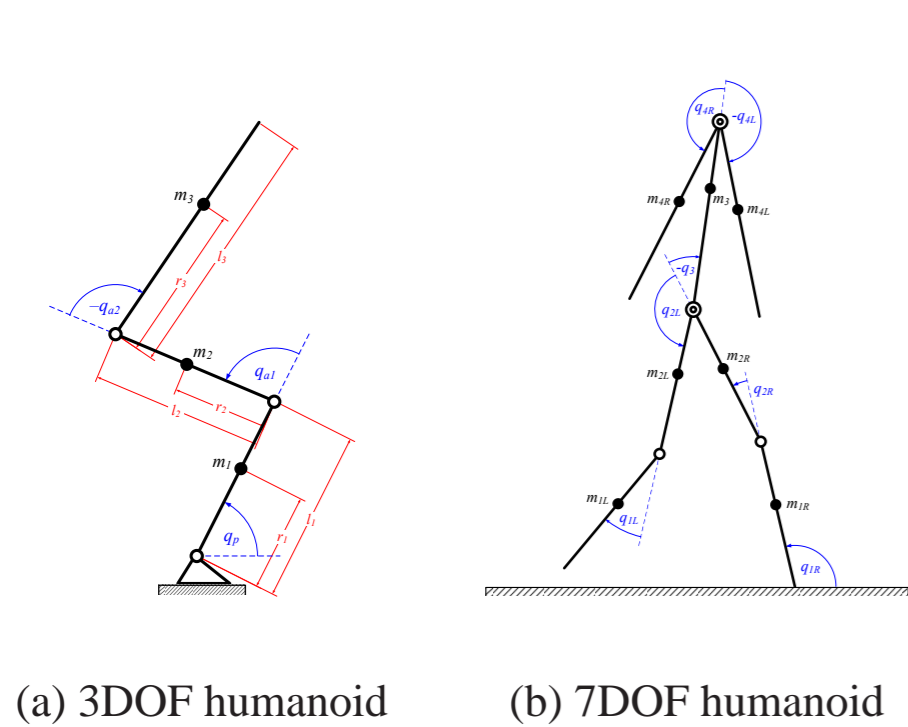
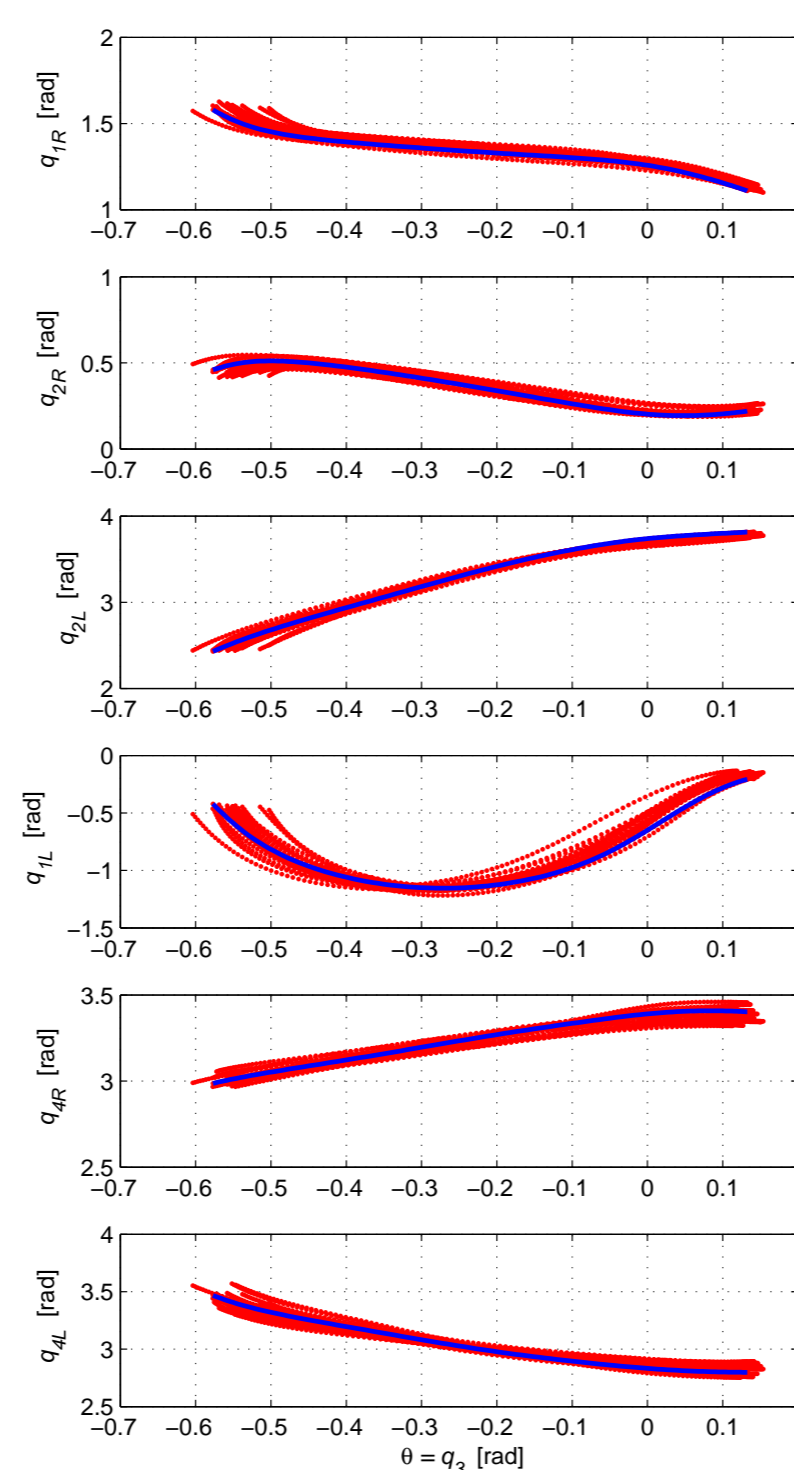


Figure 1: A typical human motion capture.

3 Invariant Geometric Relations



(c) Geometric relations for sitting/rising



(d) Geometric relations for walking in single support

Figure 2: Geometric relations obtained from human motions and corresponding humanoid model

An analysis of human motion patterns gives evidence for geometric relations that describe the synchronization of joint angles. Such relations are depicted in Fig. 2 for

- sitting down motion and chair-rise Fig. 2(a,c), and
- single support phase of the walking gait Fig. 2(b,d).

The fact that the obtained geometric relations are fairly consistent motivates the application of the virtual constraints approach.

4 Virtual Holonomic Constraints and Reduced Dynamics

Consider the underactuated controlled Euler-Lagrange system

$$\frac{d}{dt} \left[\frac{\partial \mathcal{L}(q, \dot{q})}{\partial \dot{q}} \right] - \frac{\partial \mathcal{L}(q, \dot{q})}{\partial q} = B(q)u \quad (1)$$

with the Lagrangian given by $\mathcal{L}(q, \dot{q}) = \frac{1}{2} \dot{q}^T M(q) \dot{q} - V(q)$ subject to underactuation degree one, i.e. $\dim q - \dim u = 1$. $M(q)$ is a positive definite matrix of inertia, $V(q)$ represents potential energy of the system, and $B(q)$ is a full rank input matrix. Suppose there exists a control law u_* that imposes the *virtual holonomic constraint*

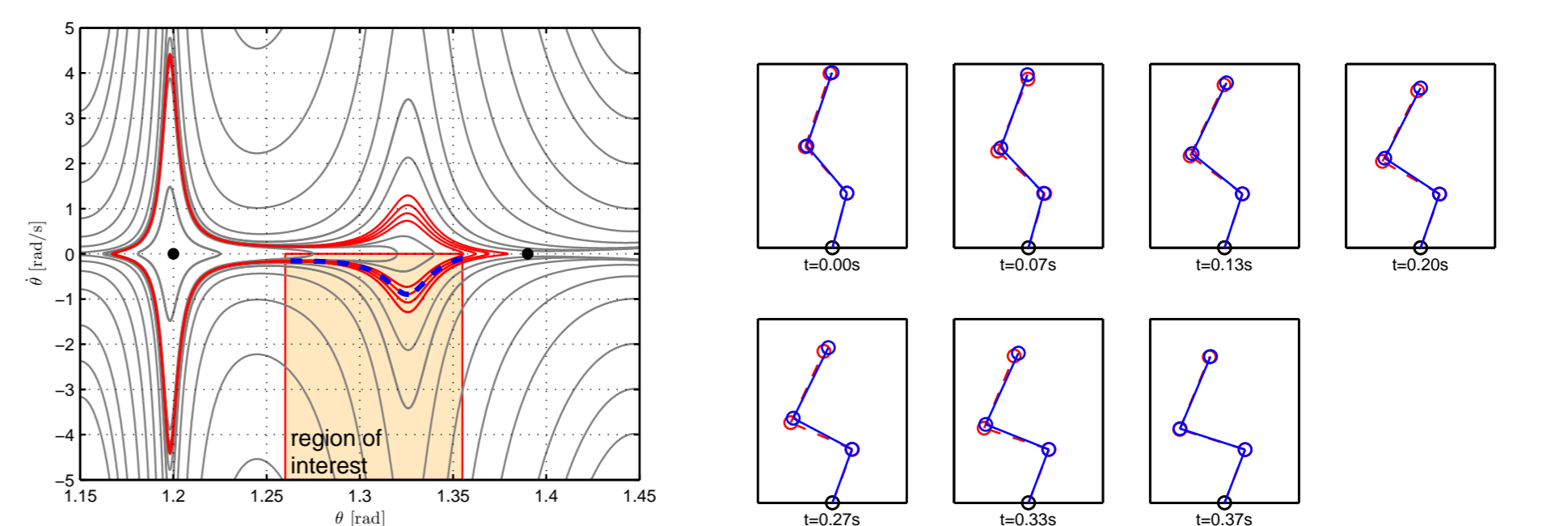
$$\{q_1 = \phi_1(\theta), \quad q_2 = \phi_2(\theta), \quad \dots, \quad q_n = \phi_n(\theta)\} \quad (2)$$

with $n = \dim q$, then the resulting closed-loop dynamics can be represented by the following *scalar second order differential equation*

$$\alpha(\theta) \ddot{\theta} + \beta(\theta) \dot{\theta}^2 + \gamma(\theta) = 0 \quad (3)$$

describing the evolution of the new independent variable $\theta(t)$. All degrees of freedom will be geometrically related to it, i.e. the whole motion is parameterized by the chosen configuration variable according to (2).

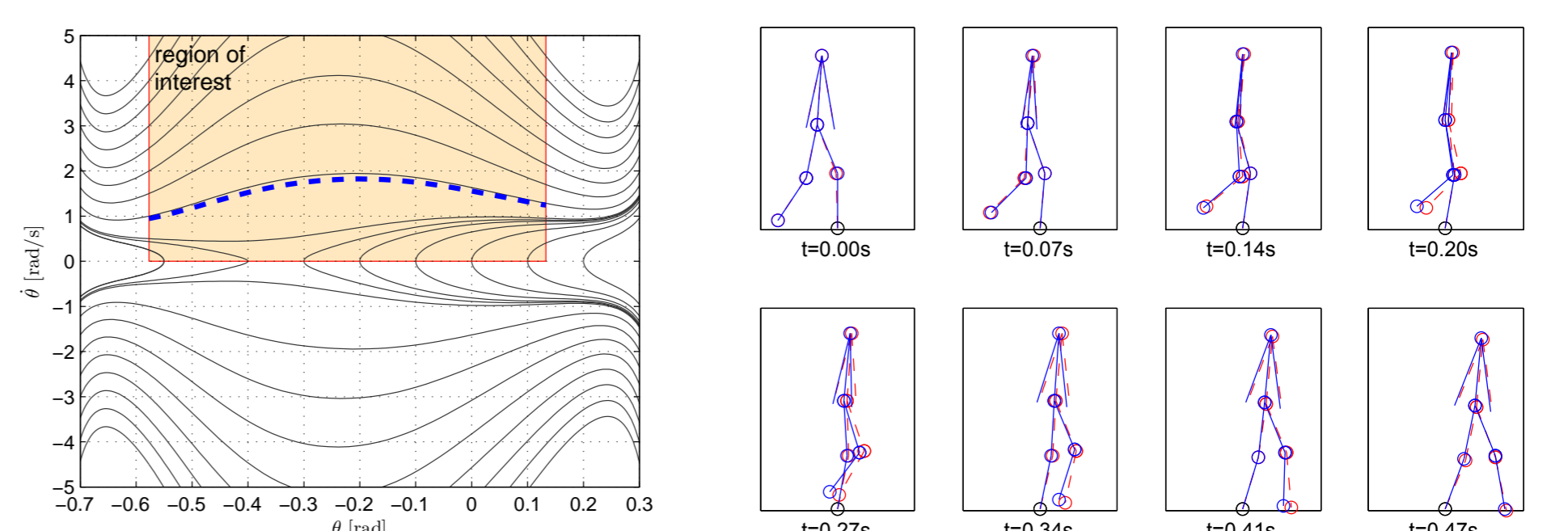
Main result: Fig. 3 and Fig. 4 show that the reduced order dynamics reproduce the studied human motions with respect to the evolution of the chosen configuration variable.



(a) Phase portrait of reduced dynamics with $\theta := q_1$.

(b) Virtually constrained motion superimposed on the recorded human motion.

Figure 3: Sitting down to a chair.



(a) Phase portrait of reduced dynamics with $\theta := q_3$.

(b) Virtually constrained motion superimposed on the recorded human motion.

Figure 4: Single support phase of the walking gait.