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From Compliant Balancing to Dynamic Walking on Humanoid Robot: Integration of CNS and CPG

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Abstract— **We present our ongoing effort to achieve compliant balancing to dynamic walking on our torque-controlled, human-sized, biped humanoid robot. Inspired by human musculoskeletal systems, our approach integrates full-body task-space force controllers with joint-space pattern generators on the commanded joint torque output to facilitate robust control performance, as well as the efficient online learning. With this approach various compliant and stable motions have been created in a constructive manner. We demonstrate the effectiveness of our approach by two folds of experiments: 1) Compliant double / single-support balancing and quasi-static walking on uneven terrain, which do not require any joint patters, 2) Fast and stable squat and dynamic walking by introducing joint-space pattern generators.**

I. Introduction

It is widely accepted not only in robotics community, but also in neuroscience community that reproducing human-like behaviors on humanoid robots is indirect, but solid pathway to understand human motor control [1]. Although humanoid robots have been used to validate the new computational ideas based on neuroscience, past studies mainly focused on theoretical framework of learning algorithms, which have been implemented on the robots separately in different task contexts. Contrary to these studies, we focus on achieving *a flagship motor task of humans – biped locomotion* along to a *developmental manner* similar to that of humans. That is, we begin with fundamental full-body motor tasks, then move on to advanced control tasks *step by step*, where the acquired control modules or knowledge are utilized for further complex tasks, which lead to robust and energy-efficient biped locomotion. Although our approach does not directly reflect neuronal mechanism of human nervous systems, it retains solid engineering points of view; efficiency and flexibility in computation and learning, which we expect to highlight developmental aspects of human motor control and the associated neural mechanism.

Toward this goal, here we specifically address the integration of artificial central nervous system (CNS) and central pattern generator (CPG), inspired from human musculoskeletal systems, to explore robust control performance as well as efficient online learning, which is outlined in Section II. In Section III, we demonstrate the effectiveness of our approach by two folds of experiments on our robot (Fig. 1, left): 1) Compliant double / single-support balancing and quasi-static walking on uneven terrain, which do not require any joint patters, 2) Fast and stable squat and dynamic walking with joint-space pattern generators.

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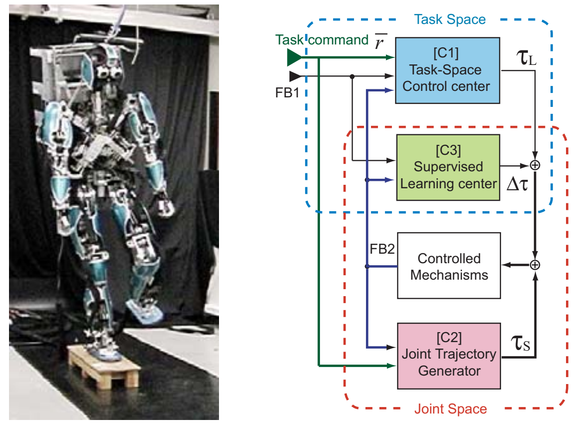

Fig. 1. (LEFT) Robot balancing on a step, (RIGHT) Learning framework

II. Framework

To provide an appropriate background to our work, here we review briefly our motor learning framework proposed in [2][3]. This is a new supervised learning and synthesis framework for fast and complex motor tasks as shown in Fig. 1(right) and outlined below:

1) **C1** achieves quasi-static motor task
2) **C2** learns the self-generated joint trajectories during motion into reference trajectories embedded in CPG having a motion phase
3) Superpose the control outputs of **C1** and **C2** with the increased speed of the phase evolution
4) **C3** learns dynamic compensation term around the joint trajectories based on the task-space tracking error, while modulating the stiffness (parameter of CPG) around the reference phase trajectories
5) **C2** learns the reference trajectory and compensation dynamics at once

The key aspect of this framework is to make the task-space controller act not only as a full-body motion control module, but also as a synergetic joint motion generator. As for **C1** we use a simple passivity-based task-space controller proposed in [4]. Although this passivity-based controller is simple and robust against modeling and sensing errors compared to inverse dynamics-based approaches, the method cannot achieve *fast and precise* dynamic tasks, when used alone, because of the simple dissipation term introduced to solve the redundancy. This is why we first generate motions in quasi-static situation. The generated trajectories helps to supress the internal motions for faster motion situations. With the self-generated joint trajectories, it is easy to learn the local dynamics around them via supervised learning schemes, which is necessary to achieve fast and precise motions. In the presentation below, however, we only address the step 1), 2) and 3), but not 4) and 5).

III. Experiments (video)

A. Joint torque control

To show that our robot has compliancy and precise joint torque controllability, first we included the movie of the gravity compensation for the limbs.

B. Double-support balancing / motion with CNS and CPG

In the second movie, the robot maintains its balance on randomly changing incline. The global terrain adaptation is innate in our full-body force control as discussed in [6]. In the third movie, the robot performs fast squat motion with CPG. The joint motion patterns are learned during the slow squat motion, which are shown in the subsequent video (with the sway motion). The biological understanding of the superposition and its experimental validation are presented in [5]. Without CPG, the robot could not perform fast squats.

The video on the push-recovery with under-actuated model (hip strategy) shows additional integration of upper-layer control module. Here we superposed the hip torque computed from the under-actuated double pendulum model onto the original hip torque [7]. The stepping has been taken when the disturbance is too large. Here we adopted "Symmetric Walking Control" (SWC) shown in [8], but the target swinging leg trajectory is transformed into the parameters of CPG (see Section III-E) via inverse kinematics. Otherwise, the quick foot placement was not achieved. The next movie shows the balancing ability during high-speed upper body motions, where the local joint stiffness around the fixed initial posture has been applied to overcome the sensory delay. With the joint stiffness around the specified posture, the steady stability increased a lot.

C. Single-support balancing and transition

The robot can transit from double support (DS) to single support (SS) by shifting the desired CoM position. Here we used a sinusoidal target CoM trajectory and made the contact switching. Specifically, when the CoM velocity exceeds the threshold determined by the saddle condition of the inverted pendulum model, we removed the contact from one foot. Since the robot is gravity compensated, not only the swinging leg, but also the supporting leg has compliance during the one-foot balancing. The transition from SS to DS (touchdown) is naturally done by *feedforward* manner; the robot simply switches its controller from SS balancing to DS balancing, regardless of the actual touchdown, once the decision of the phase transition has been made (hence the prediction is important). The swinging leg trajectory is not given at all. This is a powerful strategy that compliant robots only can take. Thanks to the innate terrain adaptability of our controller, the robot can land or even stand on wooden blocks of the moderate size.

D. Quasi-static walking

Almost the same controller described in Section III-C is applied for quasi-static walking too. The only exception here is that the operator commands the foot position by key inputs. With this simple scheme, climbing stairs, forward/backward walking have been achieved without any difficulty (except for the low torque capacity of the hip and knee joint). The desired CoM position is fixed to the center of the supporting foot, which is the definition of static walking.

E. Dynamic stepping and walking with CNS and CPG

So far, we are not successful in dynamic walking or stepping *only with* CNS control due to the tracking errors and delays. On the other hand, simple periodic joint motions superposed onto full-body gravity compensation works to some extent, and, more importantly, it is simple. We imposed simple sinusoidal trajectories which are determined according to the preferred step length, step height and step frequency. If we tune the parameters, the robot can take step without difficulty. However, the stability of such gaits is poor in general. Combining active balancing controller is a logical way to overcome the instability.

However, still one need to design CoM trajectories according to the walking parameters, which makes the controller design careful. Instead of designing CoM trajectories, we left it constant (zero), and tried to modulate the speed of the gait pattern. The idea of the speed modulation is to achieve synchronization between the swinging motion and the global robot dynamics – inverted pendulum. This has been the main issue of CPG-based walking. Among many similar methods, here we adopted a continuous version proposed by Morimoto in [9]. We combined SWC to determine the foot placement for forward / backward walking. Currently, we are trying to embed the self-experienced joint trajectory into CPG as in the squat example.

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