INITIATING NORMAL WALKING OF A DYNAMIC BIPED WITH A BIOLOGICALLY MOTIVATED CONTROL

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Two-legged locomotion is a much reseached topic in the robotics community since many decades. Nevertheless human walking and running is still unequaled. This paper introduces a biologically motivated approach of controlling bipeds that is based on recent results from neurological research on human walking. It features a hierarchical network of skills, motor patterns and reflexes that works locally and distributed and tries to exploit the natural dynamics of the system. The control concept is illustrated by the process of walking initiation.

Keywords: Biped Locomotion, Reflexes, Reactive Control, Behaviour-based Control, Passive Dynamics

1. Introduction

When controlling the locomotion of two-legged robots, two different approaches can be observed. The technical approach relies on concepts developed for industriel robotics and sound mathematical calculations, but several shortcomings can be observed:

- Mostly no exploitation of natural dynamics or elasticities
- No natural looking motions
- High energy costs and computational demands
- Low robustness and adaptability
- Dynamic model is necessary, which can never be exhaustive

On the other hand, the biological approach tries to transfer results from neurological or biomechanical reseach to technical systems. As nature's solution to biped walking still outclasses any technical solution of today, the authors suggest to follow the second, biologically motivated approach. Unfortunately the knowledge on nature's neuromechanical control concepts is far from being completely understood, so only part of them can be used as inspiration to a biped control system.

2. Related Work

Research results of the last years seem to support the assumption that neural motor control is of a hierarchical layout. Bizzi et al. found a spatial connection of stimulation of regions in the spinal cord of frogs and the kinematic reaction of its legs.[1] They suggested the existence of motor programs or modules creating activities of whole groups of muscles. Later results on the combination of such modules for movement show that the same modules are even used for different modes of locomotion.[2] Analysis of human motor control lead to similar finding. Ivanenko et al. used statistical methods like factor analysis or PCA to show that muscle activity patterns recorded using EMG during walking can be explained by the sum of only five basic temporal components. This holds true even for different walking speeds and on supporting body weight to various degrees.[3] A spatial mapping to the spinal cord could also be shown.[4] Further results imply that the same five motor patterns can account for both walking and running with only a phase shift of one of the temporal components.[5] Still there remains the question of a semantic interpretation of these basic patterns, and if a interpretation explains how the patterns evolved. While the observed motor patterns seem to be mostly of a feed-forward nature, one must ask how sensory feedback is incorporated. The reaction of reflexes must be combined with the muscle activation of motor patterns that are themselves modulated by various stimuli. Rossignol et al. discuss the dynamic sensorimotor interactions in the spinal cord and at supraspinal levels.[6] Zehr and Stein review research on the modulation of reflex responses during static tasks and locomotion.[7]

During the initiation of normal walking, the human body rotates about the ankles like a flexible inverted pendulum. This motion is created by stereotypical activation of the lower extremities' muscles.[8] The main action results from activity of the hip muscles.[9]

The following key aspects of natural motion control can be identified:

- Mechanics is optimized for the task by evolution ("intelligent mechanics")
- Heavily exploitation of natural dynamics and energy storage in elastic components
- Self-stabilizing properties of elastic elements

- Hierarchical control from brain via spinal cord to motor neurons
- Proprioceptive feedback triggers reflexes and modulates motor programs and CPGs
- Distributed subsystems reduce signal density and parameters
- High performance despite relatively slow signal transfer and computation units

There have been various attempts to control biped robots using methods inspired by biological insights as those just mentioned. Geng et al. implement a reflexive neural network for a small planar walker.[10] They show that fast walking is possible without planing of trajectories but rather by using local reflexes and by exploiting the passive dynamics of the mechanical system.[11] In can be demonstrated that a purely reactive sensorimotor neural network can produce a walking gait in a 8 DoF simulated biped.[12] Only a few works can be found on controlling fully articulated bipeds, let alone experiments on real hardware. Endo and his colleagues propose the use of a neural oscillator and feedback pathways similar to Kimura's work on quadrupeds.[13] They tested the approach on the QRIO robot, but used inverse kinematics of the legs to generate trajectories.

3. Controlling Dynamic Motions of Bipeds with Reflexes and Motor Patterns

The approach described in this paper tries to incorporate features of natural locomotion control as those described above into a robotics control architecture:

(1) The system is structured as a hierarchical network of control modules. This way it is possible to represent different levels of neural motor control like reflexes or motor patterns. The layout of the control system is shown in figure 1.
(2) The control components are local and distributed. No elaborate models of the robot or its environment are necessary and no explicit trajectories are includes. The complexitys is reduced.
(3) Reflexes introduce a tight sensor/actor coupling for fast responses to stimuli. Reflexes can be inhibited or react different depending of the phase or mode of locomotion as it is the case in biological control.
(4) Motor patterns allow for temporal synergies of a few cooperating joints. The patterns can be modulated by descending pathways or proprioceptive inputs, i.e. by high-level modules, sensors like inertial system or

load cells, or measurement of joint torques and angles. Torque impulses instead of trajectories do not force robot into unsuitable motions.

(5) The passive dynamics of the mechanical system and its interaction with the environment are allowed to contribute to the overall motions. This leads to low energy consumption and natural motions.

(6) Easy and transparent fusion of different control unit's outputs for similar actuators is possible, so no additional work on arbitration is necessary.

The system is based on a behavior-based control framework that was successfully used before on various robots by the authors and others (e.g. Ref. 14) and allows to implement the characteristics just mentioned[a].

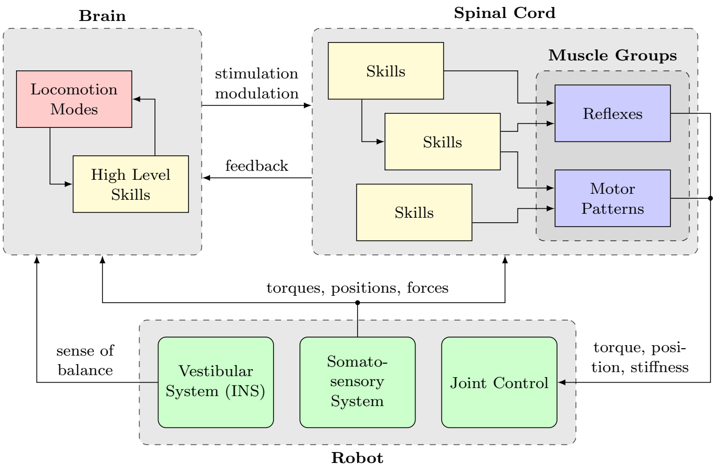


Fig. 1: Structural layout of the control scheme

Designing an architecture supporting the features just mentioned is not sufficient. There still remains the difficult part of finding the proper reflexes and motor patterns for the control network to do the aspired job. One of the ways proposed here is the analysis of muscle activities and temporal basic components appearing in human motor control. For parts of this data there already exists a semantic interpretation by biological research, e.g. there exists common agreement on the existence of several reflexes involved

[a]The behavior-based control framework iB2C can be downloaded at `http://rrlib.cs.uni-kl.de`

in locomotion and posture regulation. Other reflexes or motor patterns are designed to match certain muscle activities or to handle remaining control issues. One of the common design guidelines for control units is to prefer torque control over position control to incorporate the passive dynamics of the robot and the environment. Instead of biological data, results from numerical optimization calculations can also give similar insights that are closely fitted to the technical system. This technique has also been used by the authors.[15]

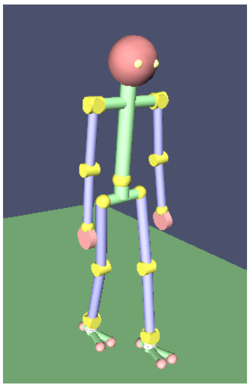


Fig. 2: The simulated biped featuring 21 degrees of freedom

In contrast to most approaches using a more biologically inspired control, the proposed method is applied to a highly complex biped robot. The fully articulated humanoid features six degrees of freedom (DoF) per leg, a three DoF spine and three DoF arms, 21 DoF in total (Fig. 2). The robot is dynamically simulated and includes mechanical properties like elasticity as those found in the biological example. A control network for the simulated biped is developed using the proposed methodology. It enables the robot to walk and to keep balance on moving ground and against other disturbances like external forces.

4. Initiation of Walking

To illustrate the features and the design procedure of the proposed approach, the initiation of normal walking is presented. The process of initializing the first step is examined in biomechnical research,[8,9] but is seldom in the focus of robot control.

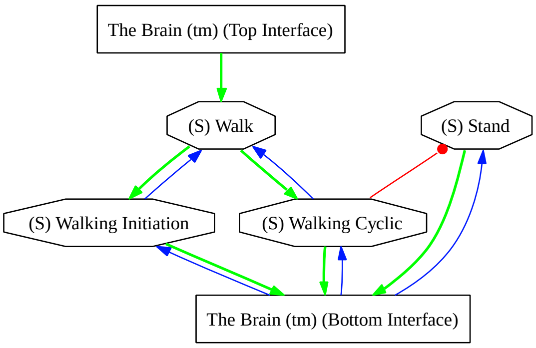


Fig. 3: Interaction of locomotion behaviours in the brain group

Figure 3 gives an overview on the high level locomotion behaviours. When stimulating the walking skill, it will first enable the walking initiation. When this behaviour is content, the cyclic walking behaviour will become active and inhibit the standing skill (inhibiting connection with the dotted end).

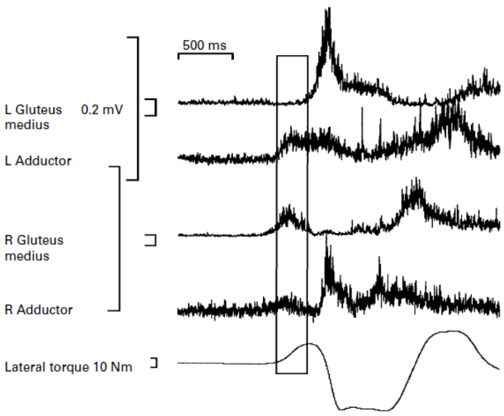
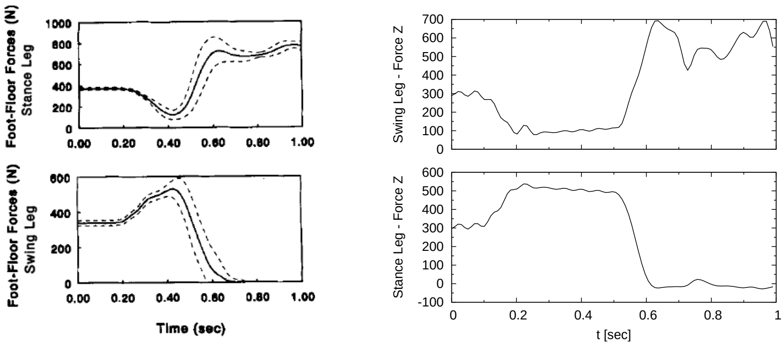


Fig. 4: EMG measurements during human walking initiation[9]

The walking initiation process consists of a forward motion of the whole body by adding torque to the ankle joints, taking the load of the first swing leg and starting the first step. For moving the body's center of gravity in direction of the stance leg, a motor pattern is stimulated. This pattern is derived from EMG measurements during human walking initiation (Fig. 4).

It can be seen that the adductor muscle of the stance leg and the glueteus medius muscle of the swing leg is active. This is translated into a motor pattern producing torques in the hip joints. It must be noticed that the rest of the body joints remain passive except a certain elasticity, so the whole body movement results from passive dynamics.

The foot contact forces in simulation (Fig. 5b) can be compared to the ground reaction forces measured in human initiation of normal walking (Fig. 5a). It can be seen that the characteristics of force progression are the same. Most noticable the load of the designated swing foot first increases as reaction to the hip movement, but than decreases to zero as the natural body dynamics moves the centre of gravity over the stance leg. The swing leg is than free to take the first step.



(a) Human contact forces[8]   (b) Simulation results

Fig. 5: Comparing foot forces during walking initiation

5. Conclusion and Outlook

A control concept for dynamical biped motions has been suggested. Based on the findings in biomechanical and neural research, a hierarchical network of skills, reflexes and motor patterns is designed. Those control units are derived e.g. from motion and muscle activity analysis, but can also be found by mathematical optimization. A network for stable standing, walking initiation and walking has been created. Future work will focus on walking robustness by adding further reflexes modulating the walking motion. Standing stability will be increased by adding a stepping strategy besides the ankle and hip strategies. The construction of a biped prototype will continue to test the control concept on a real robot.

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