From Biomechanical Concepts Towards Fast And Robust Robots

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CLAWAR 2008 Special Session "Fast Biped Locomotion"

Robots of any kind, highly integrated mechatronic systems, are smart combinations of mechanics, electronics and information technology. The development of bipedal robots in particular, which perform human-like locomotion, challenges scientists on even higher levels.
Facing this challenge, this article presents a biomimetic bottom-up approach to use knowledge of biomechanical experiments on human walking and running, computer simulation and neuronal control concepts to sequentially design highly adaptable and compliant walking machines.

Keywords: biped walking, compliant actuator, neuronal control, biomimetic design

1. Introduction

Although human technology advances rapidly and demonstrates impressive power in special applications a short look into our environment shows a lot of more flexible, robust and advanced properties and behaviors in natural beings. In nature almost nothing is developed for high performance and specialised tasks, but technically seen animals are versatile, robust and adaptive, highly integrated systems. Locomotion is a major challenge in autonomous robotics as well as in animals. As the amount of energy is limited in mobile systems, energy efficiency is of high importance. Humans invented an efficient and high performance solution that cannot be found in nature – the wheel. Nevertheless it is limited to locomotion on even ground, across its boundaries, i.e. on unstructured terrain wheel-based systems will fast knock its limits. The alternative natural concept for fast and versatile movement on solid ground is legged locomotion.

2. Design Concepts for Legged Machines

Even while the concept of legged locomotion is inspired by nature the technical systems often did not exceed the stage of morphological biomimetics. Simple walking robots have been built already in the middle of the 20$^{\text{th}}$ century and advancing permanently. In the beginning machines with 4 and more legs were build to assure static stability. Drives in all joints ensure full controllability.[1] The biological inspiration was limited to the morphology of the leg, design and functional elements evolved from a purely technical toolbox to say stiff rotational drives, rigid mechanical chains and inflexible joints.
The development of biped walking machines was strongly motivated from prostethics and service robotics. New challenges for stability, mass distribution and light-weight elements appeared. An early biped walker was WAP-1 of Ichiro Kato,[2] that already used artificial rubber muscles and so was one of few elastic exceptions. On the other hand a lot of modern advanced biped robots which in tradition of mechanical engineering are built as stiff as possible. This leads to complex control tasks to avoid impacts that are typical for natural biped locomotion and may damage the structure and the joint drives. Static stability was an early and quite simple control paradigm that limited biped robots to square-cut movements and low speed. The more advanced control concept ZMP, that is still used by many up to date robots, was introduced in late 1970s.[3] This method requires permanent knowledge of system states namely precise joint-angle control, but is powerful in controlling biped machines to execute different tasks. The design and realisation process of Johnnie exemplarily shows, that ZMP-robot performance increases with computational power and battery capacity[4] and is still under-achieving in terms of efficiency, disturbance handling, and natural appearance compared to human walking.[5] Similar robots of this kind are ASIMO,[6] HRP-2[7] or REEM-2[a].
A promising, especially in energy efficiency, but mostly also stiff mechanics approach is the passive dynamic walker and its bipedal robot offsprings. The aim of passive dynamic walkers is to generate human-like movement with pure mechanics. The lack of control and energy supply does not per-

mit them to walk on level ground, but on shallow slopes they perform impressive dynamic gait.[8] The design once more was driven by engineering mechanics. The stability paradigm of this robot realises “limit cycle gait” for finding more efficient, natural, fast and robust walking motions.[9] On this basis actively driven robots were developed which consume remarkably low energy.[10] These concepts are not advanced enough today to fullfil complex motion task.
The presented approach will use functional biomimetics in addition to morphological biomimetics to bring technology closer to human running and walking skills.

3. Biomimetic Design Concept

Functional biomimetics as a scientific discipline systematically deals with a technical implementation of structures, methods and development processes of biological systems.[11] In a biomimetic bottom-up approach the technical development is inspired by biological findings. In a sequential process specific biological functionality is translated into functional components by means of a technical design process like simulation, CAD[b]and iteration.

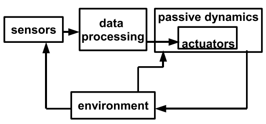

Fig. 1. Structural diagram of a biped robot as a mechatronic embodiment system

Most modern biped walking machines use stiff kinematic chains, a large number of different sensors and powerful computers for effective locomotion.[12] This is to keep themselves in balance, to avoid impacts and to react on external disturbance, e.g. obstacles. A biped walking robot is a complex mechatronic system that consists of sensors, actuators and data processing (Fig. 1). Compliant mechanisms are still difficult to handle and therefore not often used by engineers, but adaptable compliance like observed in human walking is just about to enter technical applications. To build a robust biped machine able to dynamically walk and even to run on different surfaces, it requires adaptive compliant mechanisms to handle impacts and thus reduce control effort.

[a]`http://www.pal-robotics.com/index.php`
[b]**C**omputer–**A**ided–**D**esign

4. Biological Investigation

Biomechanics of human gait was investigated in the Locomotion Laboratory. Probands walked and ran at different speeds on an instrumented treadmill and their joint motion was captured with a high speed optical system. Ground-reaction force (GRF) and center of pressure (CoP) were measured, center of mass (CoM) motion (Fig. 2), angular motion in joints

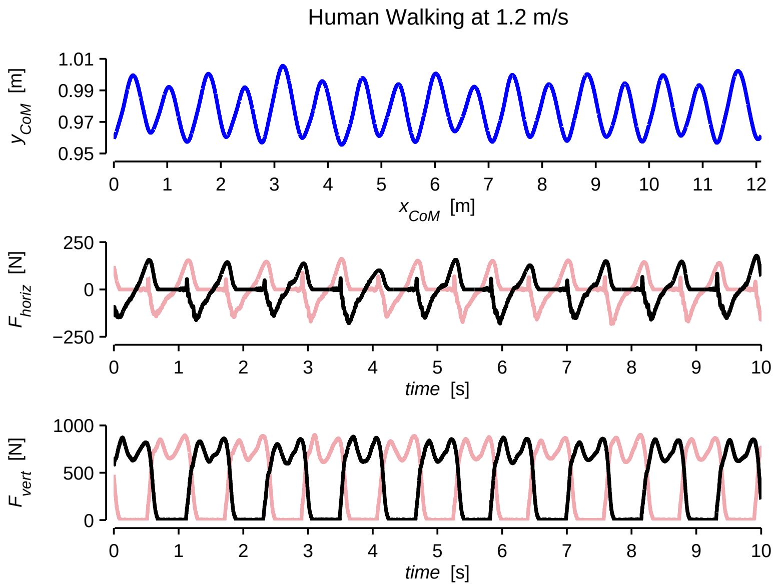

Fig. 2. Gait experiment on instrumented treadmill, CoM-motion, horizontal and vertical GRF

and joint torques were calculated from recorded motion capturing. These experiments on locomotion proofed that joint function in human legs does not correspond to any traditional technical actuator. Force–displacement and torque–angle–relation suggest spring–like properties with switchable or adaptable stiffness in joints. Besides impact avoidance elastic elements can store and release energy and increase energy efficiency.

Biological experiments furthermore discovered, that cyclic movements like walking or running may be driven by neural pattern generators[13] and only major disturbances are controlled on a higher level. This leads to the approach of designing mechanical parts and actuation robust enough to generate biped motion from simple patterns driving the actuators and to negotiate obstacles until higher level control intervenes. It becomes obvious, that joints behave like springs (displacement-force-relation) where compliance changes over time.

5. Problem Formulation

The aim is to build mechanical devices that can reproduce joint behavior observed in experiments. Starting on single joint level, mechanical characteristics of human joints in motion are implemented. Extending this to all joints and considering biarticular elastic connections the complete leg behavior will be mimiced. The compliant design should reduce impacts, energy consumption and high-level control effort. The mechanical structure will serve as an explanatory model to confirm biomechanical theories and form the basis of robust walking robots that in case of disturbances can be controlled by adaptive neural networks[14] that will actively adjust the compliance properties. This will enable these biped robots to adapt the gait to new situations.

A further question in this project is asymmetry in mechanical properties. This question addresses the requirement of mechanical precision of biped walking systems and will also arise new impulses for prostetics.

6. Methods

The design process for the envisioned biped robot will consist of several iterations. The aim of the first iteration stage is to build a knee joint with a clutching mechanism that can engage an extension spring in stance and disengage in swing. Biological data of the knee joint[15] show spring behaviour in stance phase and almost no internal force in swing phase. Different existing technical approaches to adjust compliance like fluidic muscles[16] or MACCEPA[17] were considered but these compliant systems may not reproduce the observed behaviour.

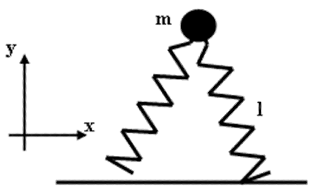

Fig. 3. basic spring mass model

Simultaneously a computer model is established based on the spring–mass model for walking and running[18] (Fig. 3). This model will guide the mechanical design and serve for defining mechanical parameters as well as for designing controllers and for testing control stragegies. The simulation results will be validated on robot testbeds derived from existing robotic platforms like JenaWalker[19] or RunBot.[14]

7. Simulation Results

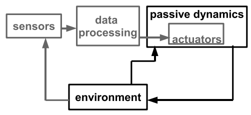

Fig. 4. Passive dynamic setup in first iteration

The first iteration addresses the interaction between the mechanical setup and the environment (Fig. 4). The corresponding model consists of a simple point mass with two spring-like, mass-less legs programmed in Matlab and Simulink. Its dimensions are equal to average humans (mass 80 kg). The model is *conservative* and runs without actuation on flat ground. Spring stiffness, angle of attack and leg length are adjustable parameters. In first simulations self–stability was approved and experimental data matched (compare Figs. 2 and 5). To demonstrate the ability for self-stabilisation of this passive compliant walker model, the parameters were set to leg length

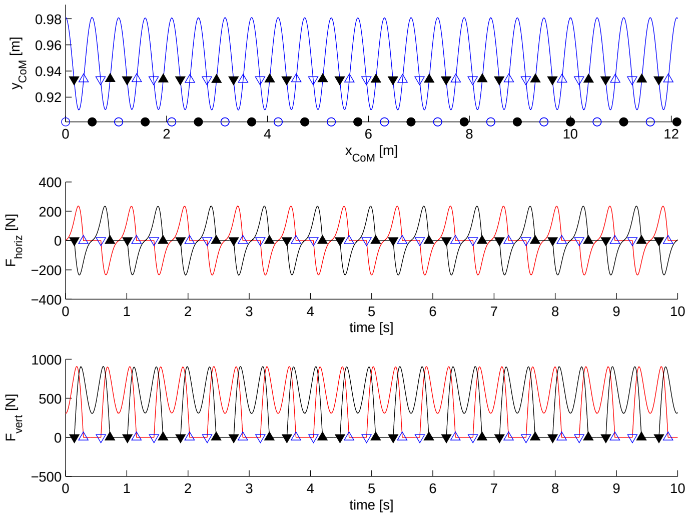

Fig. 5. Simulation results of a walking biped spring mass model (x_0=0 m, y_0=0.981 m, v_{x0}=1.1 m/s, v_{y0}=0 m/s, c_1=16 kN/m, c_2=16 kN/m) show displacement ($y_{CoM}(x_{CoM})$, above) and GRF ($F_{horiz}(t)$ center, $F_{vert}(t)$ below). Touch-down (triangle down) and take-off (triangle up) of left (empty markers) and right (filled markers) legs as well as footpoints (circles) are depicted.

1 m, angle of attack 69°and spring stiffness c_1=16 kN/m. Simulation re-

sults are shown in Fig. 5. In a second simulation the spring constants were changed asymmetrically to c_1=16 kN/m and c_2=18 kN/m for left and right leg respectively. The results are shown in Fig. 6. These simulations will be validated in experiments later and help to explain biomechanical theories of human walking and running.

8. Discussion

As a result, even with asymmetric springs the model is able to stabilize passively in a very short time with appropriate initial conditions. This first result leads to some important conclusions: (1) compliant walkers are able to generate stable gait pattern, (2) certain asymmetry in design may be compensated, (3) control strategies could be derived to minimize asymmetry by tuning stiffness. As asymmetry is a common feature in simple robots and also in locomotor dysfunctions, e.g. due to amputation, further investigations may help to understand human gait far more than today.
The next steps are to set up modules for a new biped robot using adaptable compliant mechanisms and to test their ability to reproduce the required force and torque characteristics for dynamic walking and running, to compare the robot results with experimental data and to introduce obstacles into the simulation for stability testing.

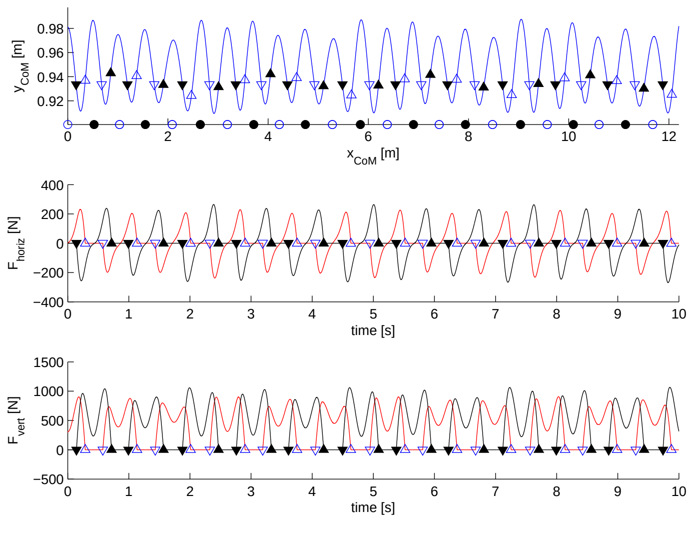

Fig. 6. Simulation results of a walking asymmetric biped spring mass model with similar initial conditions (compare Fig. 5) c_r=18 kN/m, c_l=16 kN/m

Acknowledgments

This work is supported by the German Research Foundation (DFG, SE1042/05). The authors would like to appreciate Susanne Lipfert and our other collaborators for providing us the experimental results of human locomotion.

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