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Biologically Inspired Reflex Based Stabilization Control of a Humanoid Robot with Artificial SMA Muscles

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***Abstract* - Suddenly occurring collisions or unintentional motions represent a high safety risk in robotics and must be prevented. Especially for humanoid robots, the influence of disturbances that occur unexpectedly during bipedal locomotion are difficult to compensate. A model based online control approach for stabilization of a humanoid robot with many degrees of freedom may require too much time for computing and implementing an adequate compensating motion. In addition, such a control approach usually requires accurate sensor information about the type and magnitude of the disturbance.**

The goal of the present paper is a reflex based online stabilization control of a humanoid robot actuator based on artificial SMA muscles. The design of a humanoid robot actuated with SMA muscles allows a lightweight robot design and simplifies the direct implementation of reflexes. The reflex that is integrated into the robot depends on an evaluation of the pressure distribution of the feet. An instable position of the center of mass of the robot leads to a known specific pressure disturbance that should be avoided.

The experiments show that the implementation of a reflex for the actuators in the calf leads to a stabilization of the entire robot. Additional reflexes are required when the strength or speed of disturbances are increased, such as in the upper leg or arms.

Index Terms – biologically inspired stabilization reflex, SMA wire bundle actuator, artificial muscle, humanoid robot

I. INTRODUCTION

Feedback control processes play an important role in both technical and biological systems. Due to the slow signal processing in biological systems to the brain, locally executed reflexes were evolved in animals and humans, in order to enable a fast reaction to a certain stimulus. This principle was often adopted for technical systems and is implemented in our new humanoid robot.

Shape memory alloy actuators that have a high power-to-weight ratio permitting a lightweight robot design actuate the new humanoid robot. Prestrained shape memory alloys (SMAs) change their length when they are heated by an electric current. The simplicity of their actuation principle with respect to the relatively large forces generated and their (bio)compatibility with other materials have made them attractive for miniaturized and micro-technical systems [1]. Prestrained SMAs like the used NiTinol change their lengths up to 8% when heated above their transformation temperature [2]. Based on this property various micro-technical actuators have been developed [3, 4]. In this paper, a novel SMA-actuator for a humanoid robot [5] is combined with a biologically inspired reflex based stabilization. This reflex is superior to the control from the software and is implemented in the hardware directly.

In general, the stabilization of a humanoid robot requires a complex control approach. The goal was to simplify this control process by integrating a reflex into the robot. This reflex should be independent of motion requests from the high-level control software. Whereas in many robots, the low level control runs on integrated circuits, the intention of our approach is to realize the reflex control purely on a hardware level.

II. BACKGROUND

A. *Biological Reflexes*

A fast, neurally mediated reaction to a certain stimulus is called reflex. Reflexes exist in different complexity stages, native, learned or trained [6]. A biological reflex action can be divided into three fundamental phases (cf. Fig. 1).

- The reflex is triggered by an adequate stimulus that is recognized by a receptor cell.
- The so generated neural activation is passed from the sensory nerves to the respective processing center in

the spinal cord.
In the spinal cord the signal will be transmitted through excitatory or inhibitory synapses to the motor nerves, which are connected to the descending nerves of higher control structures.

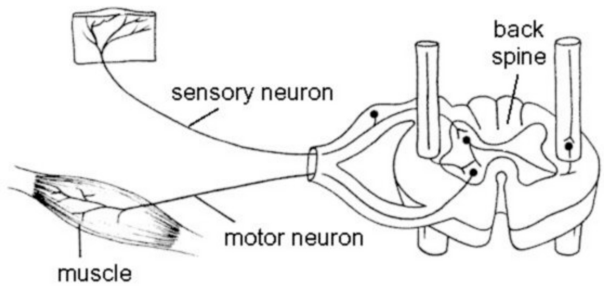

Fig. 1: A reflex action is a stereotyped response elicited by an adequate stimulus. The Figure from [17] shows the simple organisation of a reflex arc.

- The data processing of the stimulus happens completely locally without a possibility of an active control of the reflex.
- The motion caused by a reflex is just of short duration and has no lasting influence on the overall motion control.

In context with the reflex based control, mainly two aspects are of special interest. The holding reflex on one hand is responsible for stabilization of the body and the influence of reflexes on the execution of motions and their timing on the other.

1) Holding Reflexes: regulate the muscle tonus at trunk and extremities. By the tonic activation a certain posture can be maintained or can be recovered fast after disturbance. Locally it corresponds to the muscle stretch reflex which increases the muscle tension, triggered due to the own body weight. The generalized holding reflex modifies the entire body posture depending on the position of the head in space with regard to the macula (sense of balance) [7].

2) Influence on Motions: Reflexes can influence the execution of a motion in a way that it can adapt to current, unexpected situations without disturbing the basic motion pattern. This characteristic can be observed particularly in the reduced descending control from the brain, as shown in investigations at vertebrate and invertebrate [8]. Due to various, simultaneous sensory stimuli and interaction with higher motion commands, the effects of individual reflexes appear only weakly, if the connection to the higher control center is intact. However, under normal conditions they are responsible for the automatic regulation of motions [9].

B. Reflex Control for Robots

Suddenly occurring collisions or unintentional motions represent a high safety risk in robotics and must be prevented. Since disturbances occur unexpectedly, the robot may not have enough time to execute a compensatory action. If the dynamic model of the robot is high dimensional and highly nonlinear, there will be not enough time for the computing of an adequate compensatory motion. Furthermore, usually exact information is not given about the kind and magnitude of a disturbance. Under these conditions there are different approaches for control strategies which are based on the biological reflex, and which can also be found in industrial applications as in humanoid robots.

1) Impact Control: Although there are many approaches to handle impacts with standard control methods, most of them require either additional information about the environment or cannot deal with a wide range of environmental variations. The main advantage of reflex based control is that it can also handle unexpected collisions [10, 11]. Analogue to biological reflexes, the reflex control is inserted in a very fast, low level of the hierarchical control structure and intervenes only with the motion trajectory when necessary to prevent imminent danger.

2) Reflex Control in Humanoid Robots: Humanoid robots should be able to work in an environment, which was originally designed for human beings. Therfore, a biped robot must not only being able to walk in a known environment but also to adapt itself to real-world uncertainties. Therefore, a dual structure of precalculated walking trajectories and local feedback controls, based on biological reflexes, is often used in biped robots [12, 13]. The advantage of this approach is, that reflex actions enable a rapid response without requiring the exact model of robot dynamics, which would take to long to calculate for response. Similar to biology, the reflex control can be used to tune the walking motion in certain situations [14, 15].

C. SMA Actuator

To use SMAs for actuators of (humanoid) robots high forces are needed. But the cycle time highly increases with the wire's diameter which is directly proportional to the excerted force. To avoid this property the actuator/sensor design used for the humanoid robot in this paper combines many small SMA wires in a new way to one muscle-like actuator. By keeping a minimum distance between each single wire, a short cool-down time of the whole bundle of thin wires can be ensured for the entire actuator.

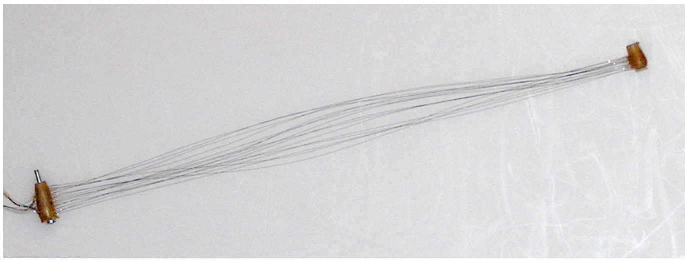

Fig. 2 Picture of the SMA wire bundle actuator.

The used actuator is made of Nickel-Titan-Oxide and scalable in pull-force and length and its resistance can be used as internal sensor for position control [5,16]. Thus there is no need for any additional sensors. Fig. 2 shows a picture of one actuator [16]. The actuator consists of 10 double laid SMA wires with 100µm diameter and a total pull force of 3.6kgf. The length of the actuator is 22cm.

III. DESIGN OF THE HUMANOID ROBOT

The reflex is integrated into a biologically inspired humanoid robot. First, simulation models of the new actuator and of the multi-body dynamics of the robot legs that consist of 6 actuated joints, have been established as well as the prototype of the bipedal robot. At first a skeleton of two legs and a hip has been built in order to provide the needed degrees of freedom for bipedal walking. Hence, thirteen actuators haven been arranged in each leg for this purpose.

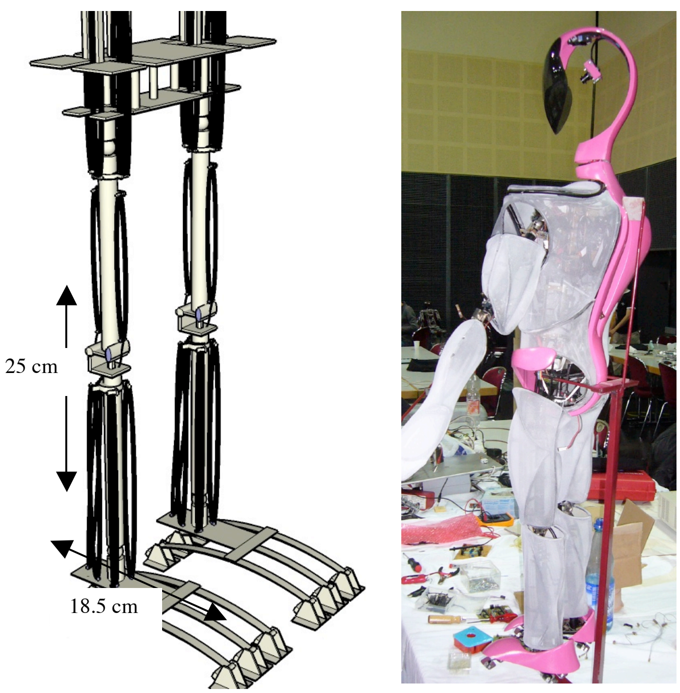

Fig. 3 Picture of the humanoid robot Lara actuated by SMA muscles and CAD-model of the legs.

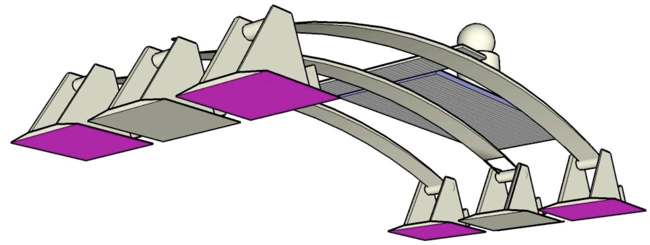

Fig. 4 Foot design with force sensors colored

The arrangement of the points of actuation has more freedom for the new SMA actuator than for rotary electric motors that are placed in the actuated joints in almost all currently successfully walking humanoid robots.

The next development step was the construction of the upper body, the head and arms of the robot. The upper body is static and provides space for the microelectronics and the batteries. 6 actuators that provide 3 degrees of freedom actuate each of the two arms. The head motion and control is realized with two servomotors. One servomotor is used for rotating the head horizontally, and one for the vertical motions of the head-camera. The robot has a total height of 130cm. The novel actuator system enables a more lightweight robot design and therefore the robot has an overall weight of 6.5kg including electronics and batteries and the outer design cover (Fig 3).

B. *Foot Design*

The main interaction of a biped robot with the environment happens with its two feet. Obviously unevenness in the ground influences the robot’s balance. The goal of the foot design is the possibility of a passive adaptation of the foot to the ground. The foot contains therefore three springs fixed at a base plate to get a defined contact to ground. Each spring has two swiveling brass plates with force sensor films at the outer springs (colored). To prevent the twist of the springs a spacer is adjusted between them (Fig. 4).

This foot design is able to compensate unevenness of about 10 mm without a tilt of the base plate as has been demonstrated in experiments, e.g., conducted in a demonstration of the technical challenge of passing a rough terrain with another humanoid robot called Bruno at RoboCup 2006. Therefore the robot maintains balance more easily in case of disturbances from the ground, but the stabilization in general is more difficult.

There are four SMA wire bundle actuators placed at each foot in an angle of 90° to generate the motions (Fig. 5).

IV. REFLEX ELECTRONICS

A reflex-based control necessitates a short time between an event and the reaction. The reflex is directly implemented in the robot's hardware. The basic idea for integration of a reflex was to superpose for example the walking algorithm of the software directly by the superior hardware reflex if the robot is getting instable.

In contrast to conventional humanoid leg design using decentralized, independent control of rotary electric servo-motors the advantage for integrating reflexes lies in the principle of the SMA actuators. The actuators are controlled by a pulse-width modulation and the current heats up the actuators thus so that they contract. The total contraction time of the SMA actuator varies with the load between 0.1 and 1 second. Although the speed of the SMA actuator is not very high, the reaction of the robot is the fastest possible for this type of actuator, because no model-based dynamics has to be calculated. The reflex is directly implemented into the most basic control loop. A circuit limits the maximum current, thus superposing the pulse-width signal by a reflex can be realized by an OR-gate easily.

To implement the reflex into the robot the pressure disturbance of the feet must be transferred into a reflex superposing the "controlled" motion. The point and the strength of the reflexes are pre-defined on the reflex board.

A board was developed to compare the contact force between the toes. If the measured pressure difference gets too high the reflex is triggered by the stimulus, which is recognized by a comparator circuit. The point of activation and their strength can be defined at the hardware with potentiometers directly. The activation is coupled with a scalable hysteresis to avoid a jitter of the robot caused by a too short reflex. The so generated control signal is passed from the reflex board directly to the actuators and leads to a contraction of the actuators. The duration of the reflex can also be defined with hysteresis.

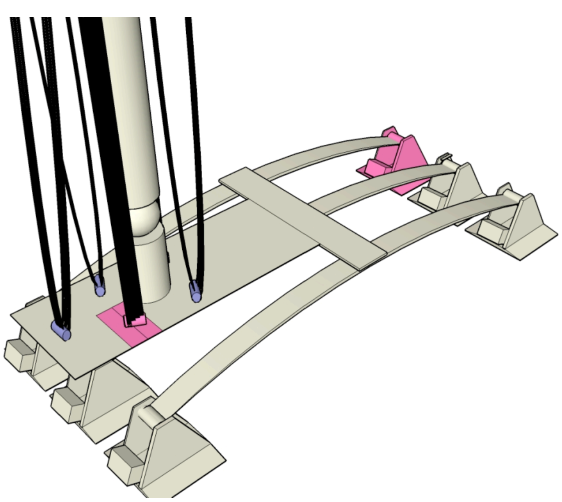

Fig. 5 Principle of the reflex: direct coupling of contact force sensor and superposed pulse-width modulation for the corresponding SMA muscle.

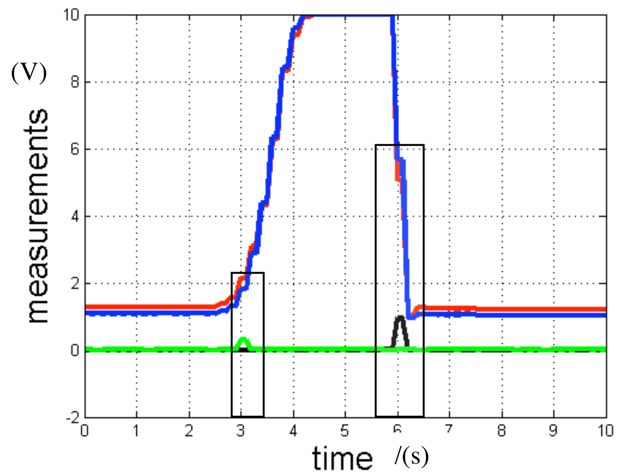

Fig. 6 Rising pressure with a constant pressure disturbance. Contact force of the left front toe (red line), right back toe (blue line) and resulting current (black and green).

The principle of the reflex is quite simple. If the pressure of the left front toe compared with the right back toe is getting too high, the actuator at the left back toe is contracting until the pressure difference is reduced to the desired level The strength of the reflex is exponential with a free scalable coefficient. The used coefficient in the experiments is 2. (Fig. 5).

V. EXPERIMENTS

To demonstrate the impact of the reflex various experiments are conducted. A practical problem is the direct measurement of the motions caused by the reflex, thus the impact can currently only be measured indirectly by the change in the pressure disturbance.

A. Robot Standing on a Horizontal Plate

At first it had to be improved that a symmetric load of the robot will not lead to an activation of the reflex. Therefore the robot was placed on a horizontal plate and loaded with additional weights to get a rising pressure. Fig. 6 shows that a constant increase of the pressure disturbance leads to a higher voltage of the sensors of the front right toe and the back left toe, however, it is not resulting in a stimulus for the actuators. To constantly increase the pressure lead was filled into a container placed on the body of the robot.

This is important due to the use of the reflex in respect to the walking ability. While walking, the robot will have changing loads at the feet and this would lead to a stimulus otherwise. The reflex is activated at the marked small ranges only, nonetheless, this is caused by the manual loading/unloading of additional weights

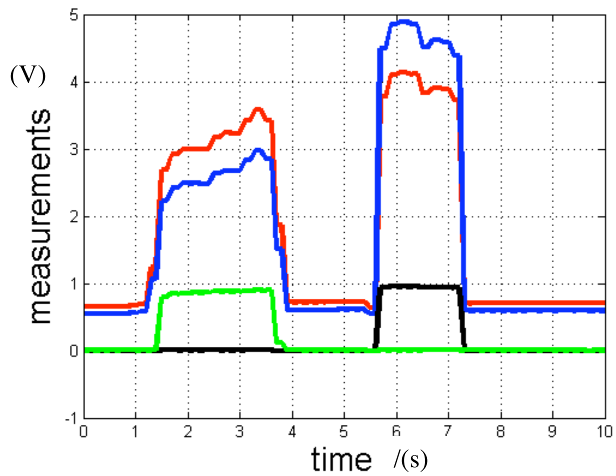

Fig. 7 Asymmetrical load of the robot: Contact force of the left front toe (red line), right back toe (blue line) and resulting current (green line back right toe, black line left front toe).

B. *Robot Loaded Asymmetrically*

In the second experiment, the robot was loaded with different weights outside its center of mass to test the impact of the reflex to an unintentional pressure disturbance. The weights were placed at a height of 100cm and shifted 25cm outside the robot with a stick fixed at the body of the robot. The load varied between 250gf and 1.5kgf. Fig. 7 shows the rising pressure measured at the feet. At first a load of 1kgf was placed at the front of the robot. These results in the measured pressure difference and leads to the current. Afterwards the robot was loaded with 1.5kgf at the back. As shown in the measurement the resulting current leads to a contraction of the actuators and thus to the stabilization of the robot in terms that the measured contact forces are almost equalized. Without the reflexes no current is provided for the SMA actuators and therefore the robot will collapse. With the reflexes the robot is able to stand without any help of a software control.

C. *Various Strengths of the Reflex*

One of the goals was to determine the maximum strength of the reflex. A too soft reflex will not lead to an adequate compensational motion, a too strong reflex to an overreaction and to a swinging of the robot. A high current leads to a faster heating of the actuator, thus it contracts faster and with a higher force. To get the optimal current for the reflex response the current of the reflex was varied between 0.5A and 2.5A in steps of 250mA. Fig. 8 shows the compensation motion of the reflex with a current of 2.5A. A load of 1kgf at the front of the robot results in a pressure difference and in a current for the back left actuator. The actuator contracts fast and moves the robot too far backwards thus it swings back to the front (marked in the measurement). Again a pressure difference stimulates the reflex, but the lower difference leads to a lower current and to a stabilization of the robot thus it does not collapse.

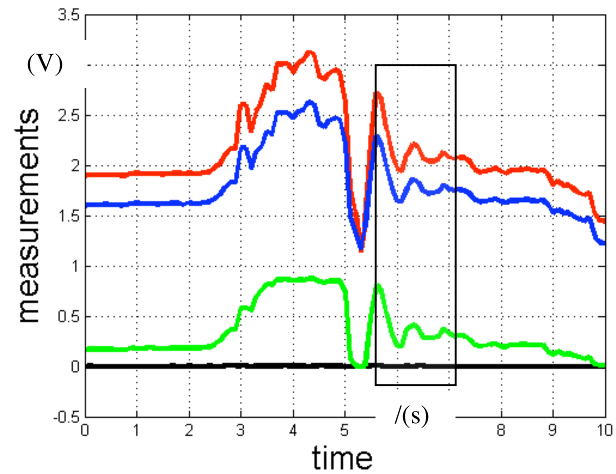

Fig. 8 High power reflex: Contact force of the left front toe (red line) right back toe (blue line), and resulting current (green line back right toe, black line left front toe).

The experiments show that for the described robot the optimal current is 1.5A to generate a fast but not too strong stimulus for the actuator.

D. *Robot Balancing*

To test the reflexes in principle the robot was placed on an even plate and pushed at random. This experiment should prove the ability of the reflex to stabilize the robot if suddenly occurring collisions happen. The measurement shows that the robot can compensate a random push. The maximum current was limited to 1.5A. As shown in Fig. 9 the reflex is stimulated by the changing pressure disturbance. Even if the robot has to deal with random forces the resulting motions stabilize the robot. Without implementing the reflex the robot is getting instable and falls down in the experiment.

VI. CONCLUSIONS AND OUTLOOK

The experiments demonstrate that the integration of a biologically inspired reflex into a humanoid robot with artificial SMA muscles is possible and can lead to a stabilization of the robot's posture. The reflex is superior to any model-based computational control method of the robot's motion or pose with respect to reaction time. The stimulus of the reflex leads to a contraction of the actuator and to a direct motion of the robot. This is possible with respect to the novel robot design with SMA actuators instead of servomotors. The level of activation of the stimuli for the reflex can be defined directly at the hardware, just as well as the maximum force and the range of the hysteresis.

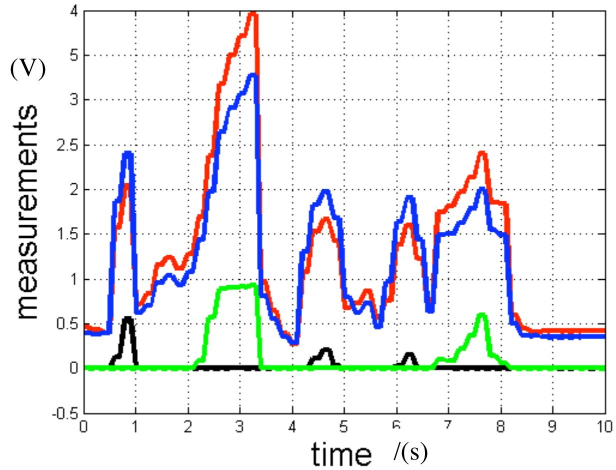

Fig. 9 Pushing of the robot: Contact force of the left front toe (red line) right back toe (blue line), and resulting current (green line back right toe, black line left front toe).

However, it is difficult to measure the influence of the reflex on the whole robot. Therefore the next development step will be the integration of a sensor system to measure the position of the center of mass.

Further research aims at the combination of the walking algorithm and the reflex based stabilization. A simple walking gait can be generated by a pattern generator in combination with reflexes and a suitable compliant leg design. However, for a high quality walking incorporating, e.g., the capability of active balancing, more complex control structures must be included corresponding, e.g., to the macula organ in animals and humans. Therefore a gyroscope will be implemented also into the robot to compare the position and inertial motion of the upper body with respect to random disturbances.

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