Balanced walking and rapid movements in a biped robot by using a symmetric rotor and a brake

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***Abstract*— This work deals with a biped robot that is stabilized by a fast rotating, symmetric, heavy object (rotor). The rotor is directly connected to the motor, no gearhead is used. The rotor is completely enclosed in a box and interacts with its environment completely by the means of inertia principles. We present a conceptual framework for the control of such a system, and test it with ODE simulations. The dynamics of a such a rotor is different from that of a non-rotating solid body, e.g. in the case of small disturbances it tends to keep the axes the same. This circumstance is used and tested. In addition, the rotor is used as a reaction wheel by using a brake mechanism. Results show that such a robot is able to stand up without additional aid of other actuators. Some simple theoretical considerations give the necessary specifications e.g. the weight of the respective robot to stand up. Also other possible types of rapid movements are discussed.**

***Index Terms*— reaction wheel, inertia actuator, gyro actuator, gyro actuator with brakes, rapid movements**

I. Introduction

Walking with two legs is still one of the biggest challenges for the research in humanoid robots. This is mainly due to problems that are related to balancing. Classical approaches use trajectory-based control and/or the zero moment point for statically stable walking [1]. Robots using these approaches are slow and still consume several times more energy than humans of the same weight and size (cf. eg. the Honda Asimo specifications [2]). In the last years, approaches related to dynamic walking gained more and more attention in this field. The most pronounced examples are passive dynamic walkers (PDWs) [4]. The goal of passive dynamic walking is to exploit the natural dynamics of pendulum-like legs in order to achieve fast and economic walking in bipedal robots. There explicit methods of motion analysis like Poincaré Return Maps are applied in order to find the stable attractors of the physical motion dynamics and use those for a control that is least energy consuming or optimal with respect to other eligble criteria.

Two-dimensional walkers [3], [6]–[8] are an intermediate step in the development of passive-dynamic biped walking systems. Walkers such as those studied by McGeer and colleagues show a moderately stable gait at downhill slopes without using any control whatsoever. With respect to speed these walkers can compete with state-of-the art humanoid robots, provided the slope is sufficiently steep. The speed is, however, determined by the slope and payload, and cannot be changed for a given design.

Since the roll and yaw direction are stable by definition in 2D walkers, they are seen as a kind of standard test unit for the stability of the pitch balance dynamics. Still, the development of a real biped walker out of a 2D walker seems very difficult. It is a big technological challenge to control the balance in all three directions: pitch, roll, and yaw, simultaneously.

The starting consideration for the present work was to provide a unit in which the dynamic can be changed continuously from a quasi 2D walker state to a real biped by altering a single parameter that can be adjusted freely at each stage of the development.

The idea is to use a heavy fast rotating gyro for this purpose. The principle of the application of the gyro is outlined in [10]. In this way the roll and yaw are intended to be stabilized by the rotation.

Gyros are symmetric rotors that are used in many technical devices like satellites, artillery, navigation units etc. The most famous approach in robotics is the Gyrover robot [9], that is basically a wheel-shaped robot rotating on its own axis, driven by an asymmetric wheel. Approaches in biped robots have also been done in previous studies [11], [12]. However in both cases the rotor was implemented in a different way than in the present study. In these studies the axis of the rotor was set parallel to the direction of motion of the robot, whereas in the present study the axis of the gyro is set parallel to the hip.

The effect is well known, but of complex mathematics that may be not solvable analytically. The dynamics of the gyro can be described by the Euler equations.

Results from an investigation using a gyro to stabilize an – apart from the gyro – non-actuated passive dynamic walker are presented in the first part of the results of this paper.

Additionally, the gyro can be controlled in a way that the pitch is also balanced by accelerating and decelerating the rotation speed of the gyro.

This feature is easy to implement in simulations. In this

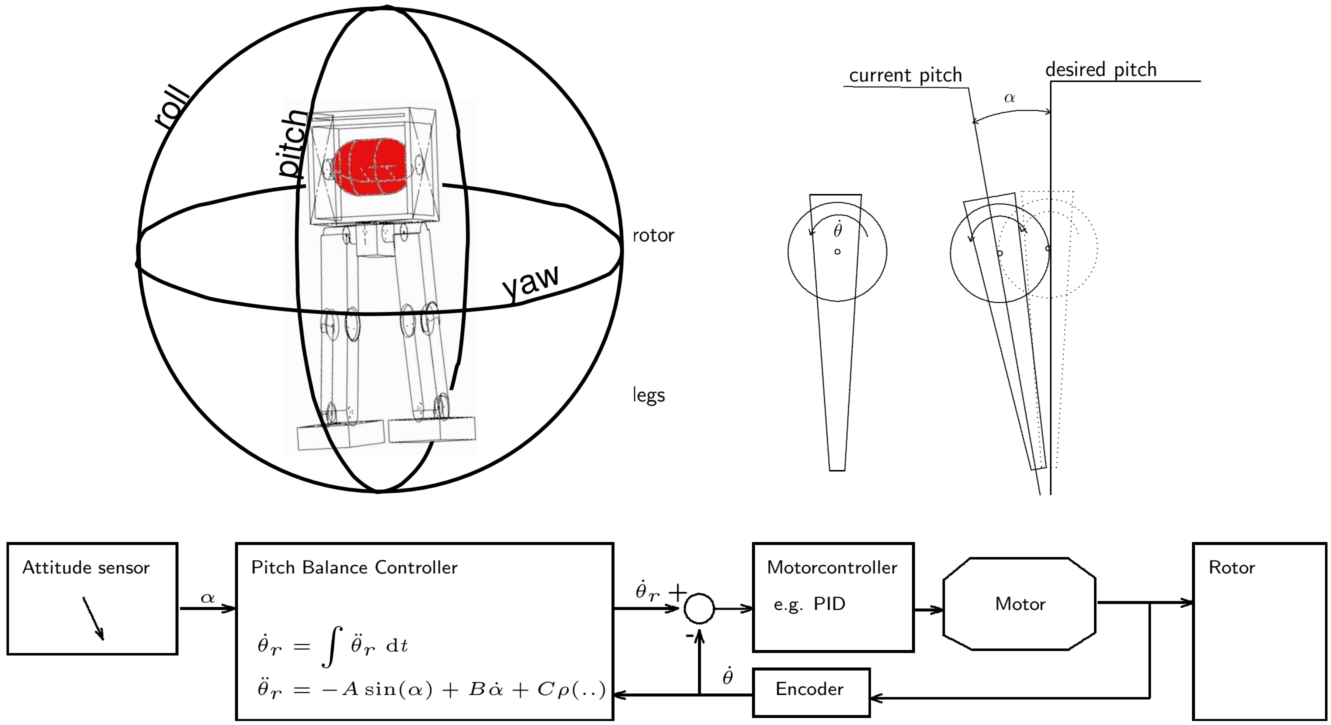

Fig. 1. Above left: Scheme for the proposed actuator in a biped robot. The rotor is marked bold. The rotor's axis is parallel to the hip. Above right: Schematic view from the left side of the robot. The pitch angle is α and the speed of the rotor $\dot{\theta}$. The positive values mean both the velocity and the pitch angle have the same direction. Below: Feedback loop for pitch balancing: The controller uses information about the attitude of the robot and the encoder values from the rotor as input, giving α as the output (e.g. gyroscope and gravity sensor combination). The parameters A, B, C have to be adapted to the properties of the robot.

way the gyro or rotor serves as a reaction wheel, which may also be called an inertia actuator.

Thus, this inertia actuator can influence the robot's movements in two ways:

- The roll and yaw are stabilized by the rotation of the rotor. The higher the speed of the rotor is, the slower the robot reacts to stability perturbations. However the movements of a gyro, also consist of undesirable precession and nutation movements. These can cause unusual and unexpected movements of the robot;
- Acceleration and deceleration make the rotor act as a reaction wheel. This is only useful in a closed loop control unit that uses sensory information of the pitch angle.

The control algorithm is outlined. Results of experiments with a second actuated robot that uses these mechanisms are discussed in detail. In a further section possibilities for control a robot with a brake mechanism for standing up are discussed.

II. Gyro stabilized passive dynamic walker

For simulations we used the Open Dynamics Engine (ODE), which is an open source mechanics and dynamics simulator [13]. The value of the gravitation was set to 9.81 units in all simulations. Thus, one time unit in the simulation can be interpreted as one second and one distance unit can be interpreted as one meter. The slope was set to 3.0 degrees. The walker was not actuated except for a heavy gyro rotating with a constant speed. The walker with a fast rotating gyro was tested against a walker with a non-rotating gyro. In the simulations the walker with the rotating gyro could walk several more steps than the walker with the non-rotating gyro. The walker was designed simple. The hips and knees are hinge joints, the feet are fixed at the end of the lower legs. The rotor is connected with an additional hinge joint parallel to the hip axis, perpendicular to the direction of motion.

The masses of the parts are the following: Upper leg 0.07 kg, lower leg 0.012 kg, middle part (hip) 0.011 kg, rotor (heavy gyro) 0.565 kg. The speed of the gyro was 175 rad/s.

The joints of the knees stop at an angle of 0.23 rad, which allows a stable stance during walking. Except for the knee stop the joints are hinge joints without friction. The starting conditions are optimized manually.

For screen-shots of the simulated passive dynamic biped please cf. Fig. 3. The walker is able to walk up to five steps in the simulation with the rotating gyro. In the case of the non-rotating gyro the walker was not able to walk more than one or two steps.

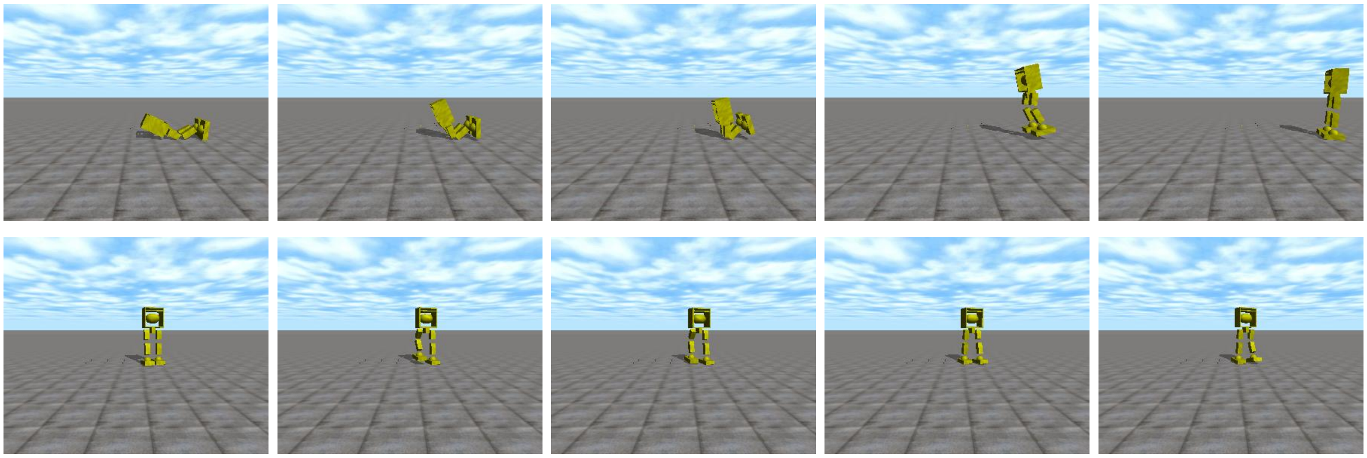

Fig. 3. Simulation results for three variant types of robots: First row shows an actuated biped robot with 3 degrees of freedom per leg and an acutated gyro (close loop control). The second row shows the same robot walking using an open loop control for the legs.

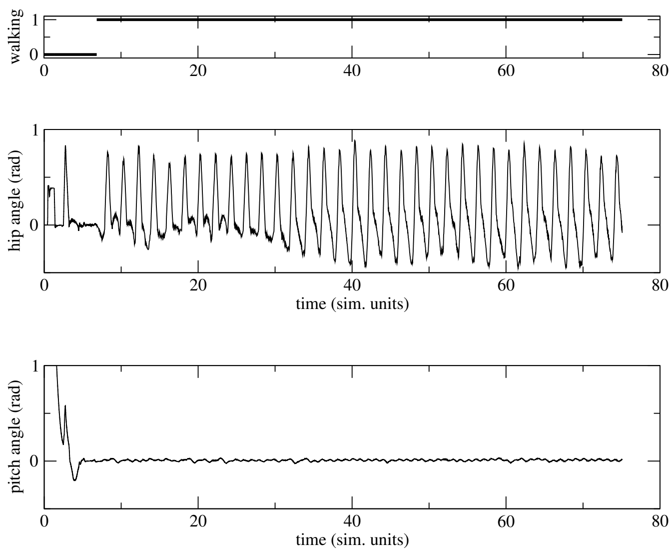

Fig. 2. Motion patterns of walking in the actuated biped robot. On top: the state of the waling behavior. Middle: Motion pattern of the left hip. The motion pattern is not entirely regular. Below: The state of the pitch value (α). A small oscillation can be seen.

III. A PITCH BALANCE CONTROLLER

As for the wished pitch it is better to have it as close as possible to the – possibly unstable – balance point. It is necessary for the controller to have a sensor which detects the pitch angle in relation to the whished pitch. In the following this angle shall be called α. The control equation is

$$\ddot{\theta}_r \;=\; -\,A\sin(\alpha)\;+B\dot{\alpha}\;+C\rho(\dot{\theta}) \tag{1}$$

Where $\dot{\theta}_r$ is the control signal for the motor speed that is sent to the motor controller, e.g. a PID controller. The constants A, B and C depend on the size, weight and current shape of the robot and have to be optimized similarly as in a PD controller. The angle of the pitch, α, is detected by sensors (e.g. a gyroscope).

The principle of the controller is the one of a reaction wheel. As in PD control we have parameters that have to be calculated analytically if the values of the inertia tensors of the controlled robot and the rotor are known, which is comparable to the P value in the PD controller paradigm. The parameter B prevents the overshoot and is thus analoguous to the D value of PD controller paradigm.

The parameter C and the the function $\rho(..)$ can be designed to keep the speed of the rotor wihin an operable range. The specific design of $\rho(..)$ depends in particular on the type of the balance point. For example if the balance point is unstable the following function $\rho(..)$ can be applied in the controller equation

$$\rho(\dot{\theta}) = H\left(\dot{\theta} - \dot{\theta}_{\mathrm{opt}}\right) \tag{2}$$

where $H(x)$ is a piecewise linear function, whose value is equal to x if within the limits of $|x| < H_{lim}$ or either of H_{lim} or $-H_{lim}$ for bigger or lower values of x, respectively. This design makes the robot move slightly ahead of its balance point if the rotor speed is low and behind it if the rotor speed is too high. This causes a continuous ingression – or degression, respecitvely – of the rotor speed in order to balance the robot. In case of a stable balance point just the inverse can be used

$$\rho(\dot{\theta}) = -H\left(\dot{\theta} - \dot{\theta}_{\mathrm{opt}}\right) \tag{3}$$

in order to control the rotor speed. The parameters C, H_{lim} should be chosen to be small enough not to interfere with the balancing, yet strong enough to keep the rotor speed in its limits and to let it converge against $\dot{\beta}_{opt}$.

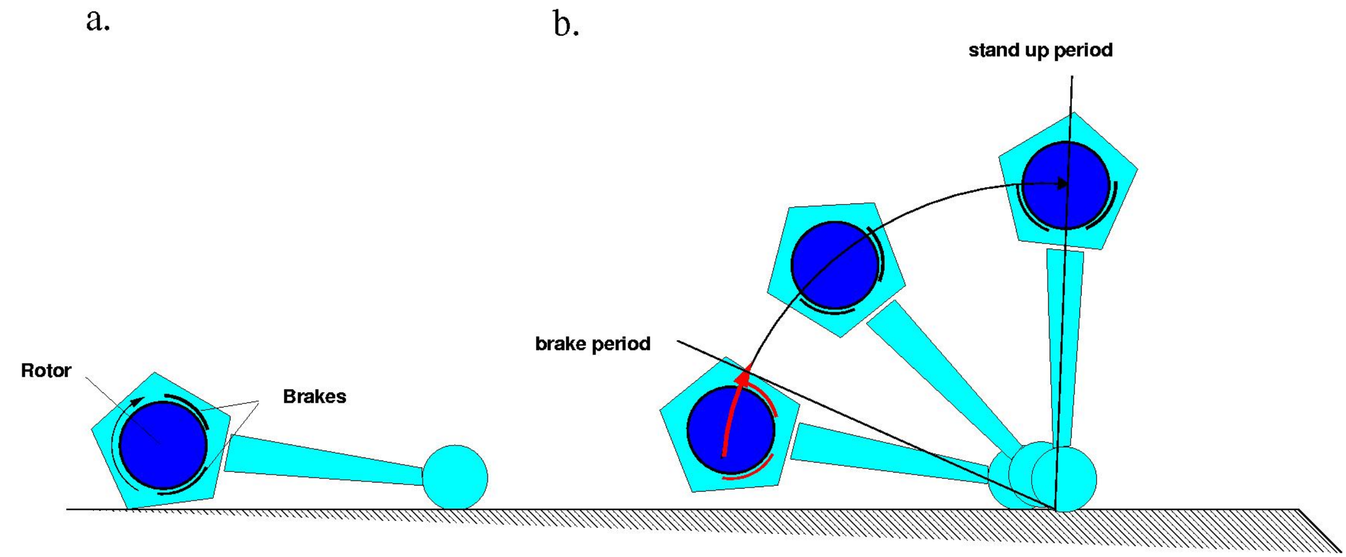

Fig. 4. A robot during standup: a. The robot is prepared by accelerating the rotor in the direction of the desired movement of the robot. In this way the needed momentum is stored in the rotor. b. The rotor is stopped by braking and the robot stands up.

IV. Results for an actuated walker with gyro reaction wheel

The pitch balance controller was tested on a biped robot with 3 degrees of freedom in each leg. The simulation resulting in standing up, walking and in jumping was done with the following parameters:

Body width	1.0 u	rotor radius	0.25 u
Body height	1.3 u	foot length	0.80 u
Body depth	0.6 u	foot height	0.20 u
upper leg length	0.5 u	foot width	0.50 u
lower leg length	0.6 u	Dist. betw. legs	0.35 u

The values are given in units of the simulation program which might be thought as Metric Units since Gravitation was set to 9.81 units.

In the simulations the walker control was able to perform the following three functions: Stand up, walk and jump. For walking the step length was variant and had a maximum of about 0.4 units per step. The robot was able to walk for a long period without falling down. However, the speed of the rotor tended to go out of its boundaries, so that the robot had to stop once in a while and recover the optimal speed of the rotor. The reason for this is that phases of stable and unstable balance occur during the walking, and thus the optimal control (i.e. leaning forward and backward) interchanges eventually driving the rotor speed out of its boundaries. The graph in Fig. 2 shows that the walking (indicated by the regular pattern of hip movements) is anticipated by an oscillation of the pitch angle (α). This happened because the constant A was set such as to make the pitch controller have a moderated suboptimal control. Experiments showed that less strict pitch control resulted in better walking patterns than the more strict ones. So it turned out to be useful that the walking is anticipated elastically by the hip movement. In addition, the swinging leg is moving downward before it hits the ground. During jumping the robots attitude could be controlled while it was completely in the air.

The design outlined here differs from previous approaches that use gyros and/or reaction wheels in the way that the axis of the gyro is parallel to the hip, thus allowing the robot's attitude to be controlled. The hip was allowed to pend forward and backward. This was not possible in previous approaches where the axis of the rotor was positioned vertical [11], or parallel to the direction of motion [12].

V. Considering and simulating a robot with a rotor and brake mechanism under realistic conditions

A robot of the size of Sony's Qrio needs roughly a torque of 5-10 Nm in order to move as described in the simulations. The problem is here that the torque is anticipated by the acceleration of the rotor, such that the motor has to produce such a torque for a wide speed range. At the same time the rotor is a gyro and stabilizes the yaw and roll. The higher the speed of the rotor, the higher is this effect. This also needs to be considered.

Thus, the designer of the actuator faces a trade off between speed and torque which is a fundamental problem of the design described above.

One possible solution is to build a rotor which implements a mechanical brake (cf. Fig. 4). In this way the negative acceleration of the brake can produce torques that are about the range that is outlined above.

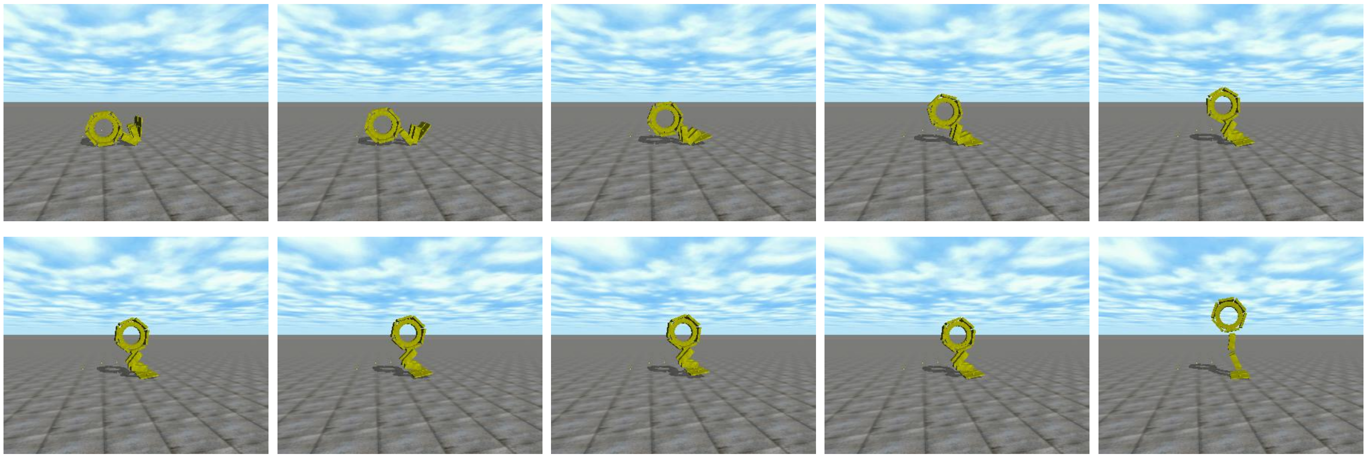

Fig. 5. Biped with realistic specifications of a motor/brake combination standing up.

Theoretical considerations show that robot has to meet two requirements in order to stand up:

- The initial moment of a torque has to overcome the gravity. Simple theoretical considerations show that this means:

$$M > g \times m \times r, \tag{4}$$

where M is the moment of a torque produced by the brake, m is the point of mass of the robot. It is assumed that the mass of the robot is concentrated on one point at the end of the legs of the robot. The legs have the length r. g is the graviational constant $9.81 m/s^2$.

- The second condition is that the angular momentum that sums up over the braking time and is transferred to the robot has to be just about enough to bring the robot up. In the following we assume that the time that brakes need to stop the rotor is significantly shorter than the time that the robot needs to stand up. This means the complete momentum from the rotor is transferred to the robot. The initial momentum of the rotor, i.e. equivalent to its speed can be calculated from the following equations. On one hand the kinetic energy has to be sufficient to bring the robot in to the vertical position:

$$0.5 \times m \times \dot{\alpha}^2 \times r^2 = r \times m \times g, \tag{5}$$

where $\dot{\alpha}$ is the necessary pitch angle velocity. On the other hand, the value of $\dot{\alpha}$ can be calculated from the angular momentum of the robot. After a very hard and short braking almost the complete angular momentum I of the rotor should be transferred to the robot's body and thus

$$I \approx \dot{\alpha} \times m \times r \tag{6}$$

The second condition can be given easily from this, as:

$$I > \sqrt{2gr} \times m. \tag{7}$$

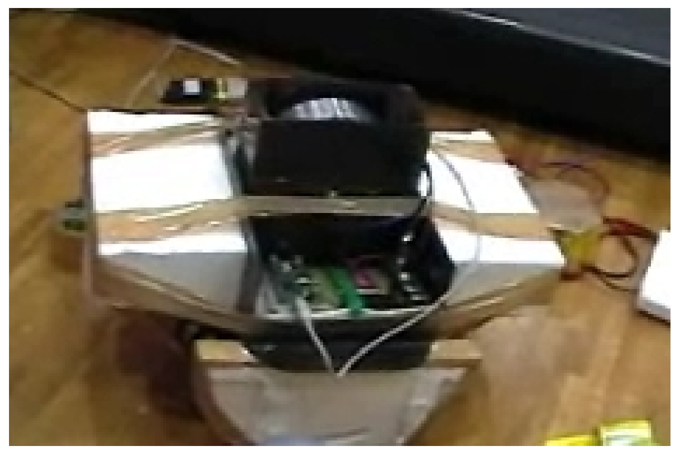

Fig. 6. First experiments with a real rotor at Freiburg University May 2004

For sufficient short brake times the robot stops close to the vertical point if

$$I \approx \sqrt{2gr} \times m. \tag{8}$$

Additional simulations (cf. Fig. 5) with ODE show that the rotor/brake design is possible if the system can produce sufficient torque. Fig. 5 shows a motion pattern for standing up for a real world robot. The simulated brake can produce 2 Nm; the rotor speed is about 4000 rpm. By using an appropriate leg control the robot was able to stand up.

VI. Conclusion and Outlook

We investigated the applicability of a combined reaction wheel/gyro actuator to a biped walker by using numerical simulations. We use the open dynamics engine (ODE) realistic mechanic simulator [13]. Intention was to design an applicable control for balancing the robot (a) by using the rotor as a gyro and in this way stabilizing yaw and roll and

(b) by using the rotor at the same time as a gyro and as a reaction wheel. One additional design (c) includes a brake in order to produce high torques.

Case (a) was simulated on top of a passive dynamic walker, case (b) was simulated by using a robot that was actuated and had three degrees of freedom in each leg. Finally in case (c) the control for a brake/actuator mechanism was given. The virtues of this type of actuator were demonstrated by testing under what conditions this robot is able to stand up. Also, an ODE simulation was done with a robot that had 3 degrees of freedom in each leg.

One important point of this work is balancing: The robot was balanced by a control algorithm that contains three free scalar variables that have to be adapted according to the mechanical properties of the robot. By optimizing these parameters the duration of the transient phase and the consumed energy consumption can be minimized.

In case (a) the simulated robot was able to walk more steps in the case of the rotating rotor than in the case of the non-rotating rotor. The simulation shows that the axis is stabilized.

In case (b) it was possible to make the robot stand up, walk, and jump. Apart from the balancing the robot used open loop control for all three behaviors.

In case (c) a concept for performing rapid movments is demonstrated for the case of standing up. Other movement patterns seem to be applicable as outlined in Fig. 5. Movements like a somersault seem possible because the necessary momentum should be less than for standing up. Still, it seem to be a challenge for the control mechanism.

High torque is necessary in order to make certain movements (like standing up)possible. Even balancing is demanding.

Some experiments with testsets for real rotors have been done earlier (cf. Fig. 6. The preliminary results seem to be promising, still further work has to be done.

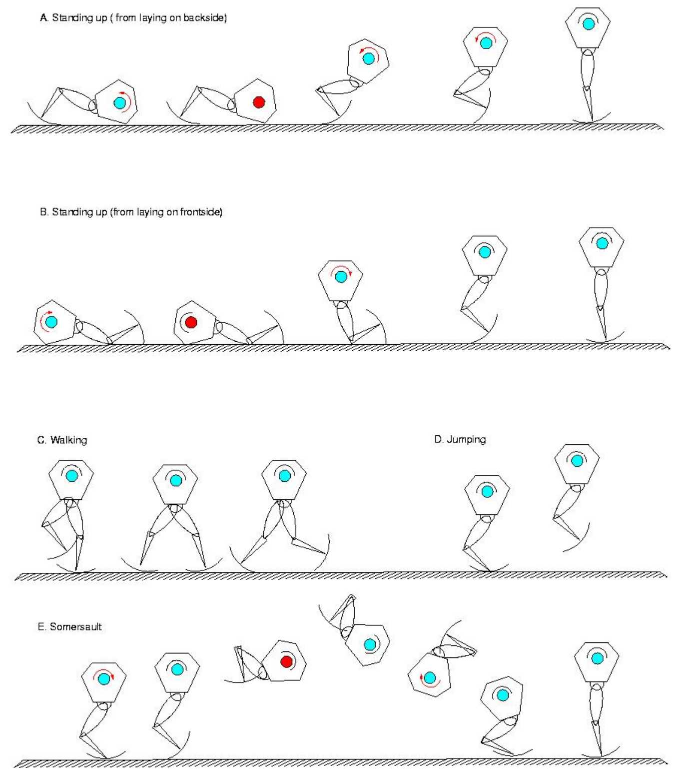

Fig. 7. Hypthetical actions that can be controlled with the rotor/ brake mechanism. A red rotor indicates that the brake is activated.

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