Gyro stabilized biped walking

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***Abstract*— We present here a concept and realization of a dynamic walker that is stabilized by using a fast and heavy rotor, a gyro. The dynamics of a symmetric, fast rotating gyro is different from that of a non-rotating solid body, e.g. in the case of small disturbances it tends to stabilize the axis. This property is used and tested in a passive dynamic walker. We investigate the stability of a knee-less walker that is stabilized by a gyro in a 3D environment, and present also simulations. As the result of this work we show that the rotor enhances the stability of the walking in the simulations. We also summarize some concepts and simulations of actuated robots with a gyro. Finally we give an overview of experiments and prototypes that are realized so far.**

I. Introduction

In recent years, approaches related to dynamic walking gained more and more attention in the field of biped and humanoid robots. 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. Explicit methods of motion analysis like Poincaré Return Maps are used in order to find the stable attractors of the physical dynamics. They are used for a control that is least energy consuming or optimal with respect to other eligible criteria. Dynamic walking placed earlier concepts of walking that base on static stability. These approaches use the zero moment point as a concept to guarantee the stability of biped during walking.

The most pronounced examples of dynamic approaches are passive dynamic walkers (PDWs) [4]. This type of walkers are merely able to walk down a slope. They use the gravitation to retrieve the energy for their motion. The earliest examples for passive dynamic walkers are toys from the 19th century have been rediscovered and used as examples for stable passive dynamic walking motion. Based on the analysis of the motion of these walkers, more complicated mechanical devices have been developed. The most advanced models are biped walkers with knees that are able two walk downhill with a considerable speed and with a remarkable low energy consumption [1].

Two-dimensional walkers [9], [7] are a special type of passive-dynamic biped walking systems. Typically these walkers consist of two pairs of legs. Each pair of legs are typically connected by a mechanical bond. Thus, the legs of each pair move synchronously and seem to have the same positions and velocities if an observer tracks them from a position perpendicular to the direction of motion.

From this perspective the motion resembles biped walking while at the same time stability in the roll and yaw direction is trivially guaranteed. By using this type of approach it is possible to investigate the problem of the balance of the pitch which is obviously a simpler problem then the stability of a real biped.

In addition, the dynamics of walking are easier to describe in two than in three dimensions. For this reason, much analytical work has been done about two dimensional walkers. The development of a 3D biped walker out of a 2D walker seems rather difficult. It is a big technological step to control the balance in all three directions: pitch, roll and yaw, simultaneously. A perspective to divide this step into smaller sections seems to be eligble.The first consideration for the present work was to provide a unit for walking systems, in which the dynamics 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.

We suggest for this purpose a gyro attached to a biped robot. The gyro is a symmetric object that can be rotated. Gyros are used in many technical devices like satellites, artillery, navigation units etc. The most famous approach in robotics is the Gyrover robot [2], that is basically a wheel-shaped robot rotating on its own axis, driven by an asymmetric wheel. Previous studies [5], [6] have also described a gyro or a reaction wheel that is attached to a biped walker. 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.

A high rotation speed gives high stability in the roll and jaw direction, whereas a stopped rotor results in a normal 3D biped. The degree of the stability can be varied continuously by using different speeds of the rotor. The rotor is in all designs presented within this work attached to the biped in that way that the axis of the rotation is parallel to the hip. The idea is here that in this way the axis of rotation, that is the direction of hinge joints in the hip, is stabilized. In the case of a complete stabilization of the hip, a walker should behave virtually like a two dimensional walker as described above.

At the same time it is well known that a gyro can have undesired effects like precession and nutation, that can disturb the walking process. The mathematics is well known, however often not simple enough for analytical approaches.

For this reason, we investigated possible designs numerically. The simulation was done by using the open dynamics engine (ODE), this is an open source tool package for simulating solid body dynamics and includes also a visualization tool basing on the open graphics library.

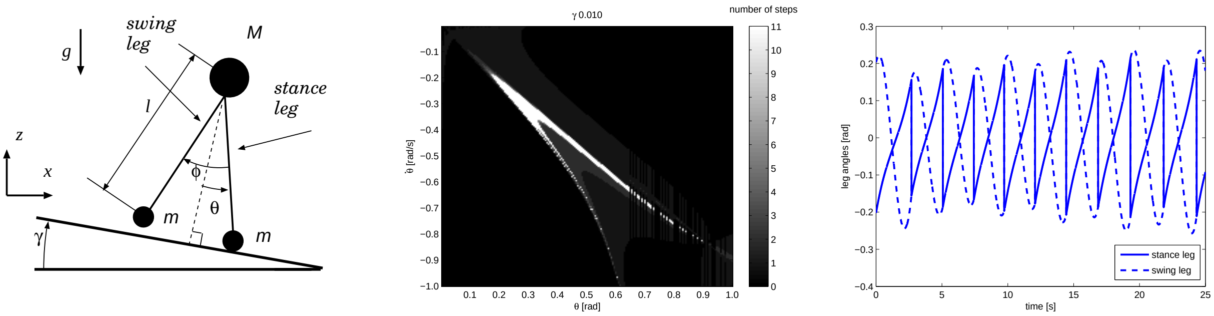


Fig. 1. Left: Knee-less walking model. Middle: stability of the knee-less walker in a noise-free 3D simulation environment. The simulation is started with a starting condition that only depends on the two parameters θ and $\dot{\theta}$. The color of each pixel in the graph indicates how many steps the walker walks before falling. White means 11 steps, black 0 steps. The simulation was stopped after 11 steps. Right: Walking pattern of the leg angles as a function of time.

We also briefly summarize approaches for actuated robots and control approach for the pitch balance that uses the gyro also as a reaction wheel. Also a rotor brake system is presented.

Finally, we present the design of a real walker that is currently being build.

II. Knee-less walking model

The approach discussed here is based on an analysis of a knee-less two dimensional walking model that has been described as the *simplest walking model* [3], [11]. We briefly review this approach:

There a semi analytic motion analysis in two dimensions revealed a stable attractor of a cyclic walking pattern that can be realized under certain initial conditions.

The knee-less walker is shown in Fig. 1. It consists of two rigid legs with length l, connected by a frictionless hinge at the hip. The mass is distributed over three point masses; one with mass M at the hip, and two with mass m at the feet. The foot mass shall be negligible in comparison with the hip mass, β=m/M $\rightarrow$ 0. Then, the motion of the walker can be described as

$$\begin{bmatrix} \ddot{\theta} \\ \ddot{\phi} \end{bmatrix} = \begin{bmatrix} \sin(\theta-\gamma) \\ \sin(\phi)(\dot{\theta}^2 - \cos(\theta-\gamma)) + \sin(\theta-\gamma) \end{bmatrix}, \quad (1)$$

World		
gravity	g	1 m/s^2
slope angle	γ	0.01 rad
Model		
leg length	l	1 m
foot radius	r	0.04 m
hip mass	M	1 kg
leg mass	m	0.001 kg
Gyro		
gyro mass	M	1 kg
gyro inertia	Ix	0.1 kgm^2
	Iy	0.2 kgm^2
	Iz	0.1 kgm^2

TABLE I

Design parameters values in ODE

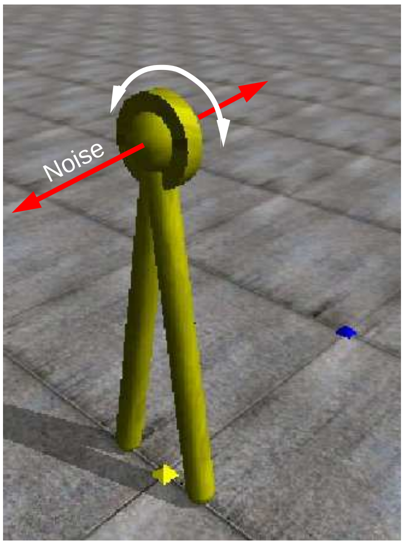
where θ is the angle of the stance leg with respect to the slope normal, ϕ is the angle between the two legs and γ is the slope of the ground. Walking with two straight legs of same length is impossible in a two dimensional model and on plain ground[10]. However, for this theoretical approach we use the following constraint for the heel-strike: The first time the tip of the foot can cross the line of the ground and leave the ground again. The heel-strike is then assumed to be the second time when the foot is hits the ground. After the heel-strike the step is finished. Stance leg and swing leg are swapped and the next step starts. The heel strike is described as an inelastic hit. The equations are

$$\begin{aligned} \theta_{n+1} &= -\theta_n^- \\ \phi_{n+1} &= -2\theta_n^- \\ \dot{\theta}_{n+1} &= cos(2\theta^-)\dot{\theta}_n^- \\ \dot{\phi}_{n+1} &= cos(2\theta^-)(1-cos(2\theta^-))\dot{\theta}_n^- . \end{aligned} \quad (2)$$

for the transition from step n to step $n+1$, where the index $-$ indicates the state of the variable before the impact. The equations show that the following step is only dependent on the values of the previous step's θ_n^- and $\dot{\theta}_n^-$. Thus, in spite of the fact that the complete dynamics can only be described with a minimum information of four scalar values (ϕ , $\dot{\phi}$, θ , $\dot{\theta}$). The information of ϕ and $\dot{\phi}$ is lost during heel-strike. As a consequence, the next state and the complete future of the walking pattern is only dependent on θ^- and $\dot{\theta}^-$. Therefore the basin of attraction of a walking pattern can be described as the function of the two scalar variables θ_n^- and $\dot{\theta}_n^-$. Schwab and Wisse [11] derive this basin of attraction for various slopes in their work.

Based on these results we investigated the walking behavior of a walking model in the ODE simulation environment. The idea here is to work in two steps:

- Reproduce the theoretical results derived for a two dimensional walker model. In the case of the knee-less walkers we use the results mentioned above. In addition, theoretical results exist for two dimensional kneed walker[3].



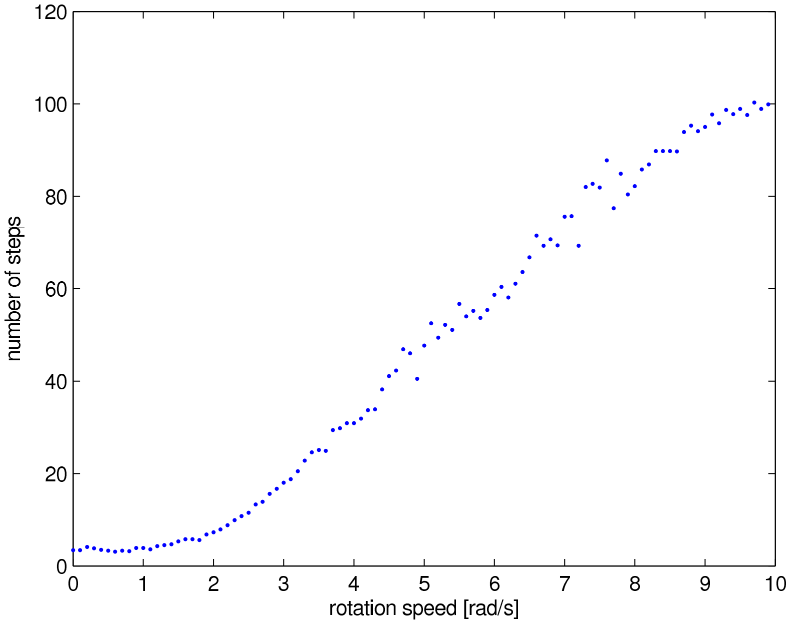


Fig. 2. Left: Knee-less walking model in a ODE simulation the arrow indicate the direction in which the noise was applied to the model, right: stability of the knee-less walker to an environment that consisted of constant noise. The graph depicts the average number of steps of the walker until falling in relation to the rotor speed. The number of steps increases when the speed of the rotor increases.

Both approaches can be used as a starting point for a gyro stabilized biped passive dynamic walker.

- In a second step the walker is embedded in three dimensional environment. Here, the dynamics should be the same as in the two dimensional approach, merely the stabilization in the roll and yaw direction depends on the speed of the rotor. In addition, the walker should have a narrow hip in order to keep the forces resulting from the asymmetry between the steps as small as possible.

In the case of the knee-less walker we investigated the three dimensional environment in conditions that are as close as possible to conditions described by Schwab and Wisse[11]. The ODE environment however requires finite inertia tensors and finite dimensions of the walkers geometries, which results in some inevitable differences between their model and the ODE model of this work. Thus, we used the parameters as described in Table I for the simulated walker. Since the simulation in this stage were completely free of noise the walker could walk an infinite number of steps although the walker is unstable in roll and yaw direction. Adding noise to the model results in immediate falling of the walker.

See Fig. 1 for a diagram of the number of walked steps in dependence of the initial θ and $\dot{\theta}$. The noise was simulated by adding at each time step an equally distributed random value between -0.05 to $0.05 m/s^2$ to the gravity. The direction of the noise was parallel to the axis of the rotor. The dynamics of the walker did not depend on the speed of the rotor, since the rotor has only an effect in roll and yaw direction the dynamics of the walker is like the dynamics of the two dimensional walker. Thus, the basin of attraction remains independent of the speed of the rotor. The simulation was interrupted after 11 steps. White color indicates that the walker walked 11 steps and then the simulation of the walker was interrupted. The shape of the white area in ODE simulation roughly resembles the structure of the basin of attraction retrieved by Schwab and Wisse[11]; we also assumed that the description of the initial state by varying the free variables θ and $\dot{\theta}$ is sufficient for describing the state of the walker at the begin of a step, while the others variable were initialized according to the approach of Schwab and Wisse[11].

We investigated how the walking behavior is affected by noise and how the walker can be stabilized by rotating the mass of the hip with a constant speed. In these simulations the noise was simulated by random vectors in the direction parallel to the axis of the rotor, i.e. perpendicular to the gravity vector and the direction of the motion. The results are depicted in Fig. 2. For a constant level of noise the number of steps varies dependent on the speed of the rotor. The higher the speed of the rotor the less is the device sensitive to noise.

III. Passive Dynamic Walker with Knees

In analogous approach to the knee-less walker the two dimensional kneed walker has been investigated. The two dimensional approach has been studied earlier[3]. The dynamics of the 2D kneed walker apparently depend highly on the shape of the feet and on mass distributions of each foot and shank. The ODE environment is slightly different that the assumed environment of the above mentioned publication, e.g. the ODE environment requires a non-singular metric tensor, i.e. does not accept point masses. Though it was possible to produce periodic walking patterns over several steps it could not be clarified if the patterns are indeed on a stable attractor of motion. However, the stabilizing effect of the rotor with

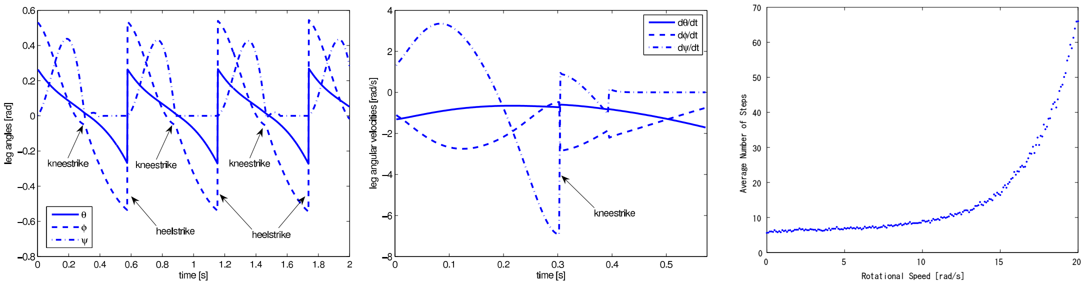


Fig. 3. Periodic walking patterns of a kneed PDW with knees: Left: The pattern of motion of three dynamic angles of the walker as a function of time, i.e. θ the angle of the stance leg with respect to the gravity vector, ϕ the angle between the legs and ψ the knee angle (straight knee $= 0$). Middle: Derivatives in time of the variables of the picture of the left side. Right: Simulation with noise the stability of the walker plotted against the speed of the rotor.

respect to the roll and yaw direction in case of noise could be shown. Up to now we could not produce a stable pattern of motion for the kneed walker according to this approach. This is caused by a different foot shape in our model from the above mentioned approach. However, it was possible to produce a configuration and starting conditions in which those walkers were able to walk several steps. This type of motion, however, highly depends on the speed of the rotor and the exact simulation conditions. Fig. 3, left and middle side shows an example of the resulting walking pattern. Depending on the step-size of the simulation, the walker is falling after 14 to an infinite number of steps. This may be an indication that the studied walking cycle is not stable. For better simulation conditions the vulnerability of the walker against noise was tested. Fig. 3, right shows the number of steps in relation to the rotation speed of the rotor and noise. The noise was simulated by adding at each time step of the simulation an equally distributed random value between $-0.0005m/s^2$ and $0.0005m/s^2$ of to the gravity. The direction of the noise was parallel to the axis of the rotor.

The same principle can be implemented on a actuated robot. The next section discusses actuated robots that use a gyro also as a reaction wheel.

IV. Simulations of an Actuated Robot Using the Rotor as a Reaction Wheel for Pitch Balance

Additionally, the gyro can be controlled in such a way that the pitch is also balanced by accelerating and decelerating the rotation speed of the gyro. The approach has been discussed in detail in an earlier publication [8]. We briefly outline here the approach and the results, For details please see the above mentioned publication.

This feature is easy to implement in simulations. In this 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.

In an ODE simulation a biped robot could easily balanced by using the rotor as an reaction wheel, an open loop control algorithm could handle the walking. Since the necessary acceleration of the rotor is too high it seems that the design can not be realized in this form. 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.

V. Rotor–Brake System for Rapid Movements

Theoretically the gyro/reaction wheel can also be used for rapidly changing the attitude of the robot and thus creating rapid movements, like standing up from ground. The above mentioned design constraints seem to make such an approach infeasible.

One possible solution however is to build a rotor which can be stopped by a mechanical brake (see Fig. V). In this way the negative deceleration of the brake can produce torques that are about the range that is outlined above.

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:
$$M > g \times m \times r, \tag{3}$$
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 gravitational constant $9.81m/s^2$.
- The second condition is that the angular momentum that sums up over the braking time and is transferred to the robot has to be sufficient enough to bring the robot up.

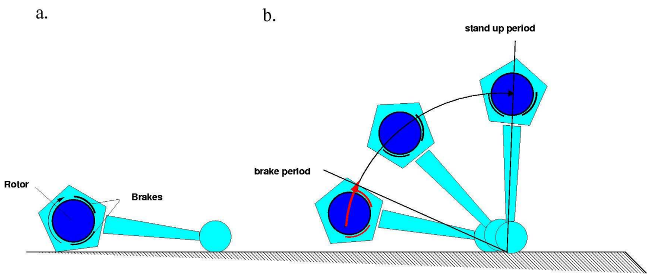


Fig. 4. A rotor–brake system during stand-up: a. The robot is prepared by accelerating the rotor in the direction of the desired movement of the robot. In this way the needed momentum is stored in the rotor. b. The rotor is stopped by braking and the robot stands up.

In the following we assume that the time that the rotor needs to be stopped 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 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:

$$0.5 \times m \times \dot{\alpha}^2 \times r^2 = r \times m \times g, \tag{4}$$

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

$$I \approx \dot{\alpha} \times m \times r \tag{5}$$

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

$$I > \sqrt{2gr} \times m. \tag{6}$$

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

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

Other rapid movements are also possible. For details see [8].

VI. Real robots

Based on the outlined considerations several test equipments and robot prototypes have been realized:

- The robot Jumping Joe has been demonstrated at Aichi Expo as part of the NEDO robot project for this event. Among other things the robot included a reaction wheel/brake system. The design was done at the Kyushu Institute of Technology.
- A test rotor with a balance controller has been designed (at the University of Freiburg)
- A passive dynamic walker that is stabilized by a gyro is currently constructed at Osaka university (see Fig.5).

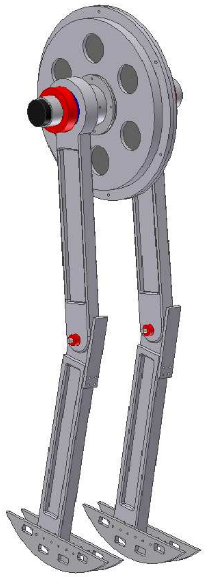


Fig. 5. A passive dynamic walker that is currently being build at Osaka University.

VII. Summary and Discussion

We outline in this work how a biped robot can be stabilized by a gyro. The work bases on earlier work on two dimensional workers and shows how the considerations can be extended to a biped by using the gyro. We present results from ODE simulations from several types of biped robots:

- A knee-less passive dynamic walker
- A passive dynamic walker with knees

We investigate the stability for various values of the speed of the rotor. The main result of this work is that the stability in the roll an yaw direction increases as the rotor speed increases. Thus, the rotor may be used at different speeds to construct intermediate steps between a two dimensional walker and a full biped approach and in this way ease the challenge to develop such a device. Further we briefly summarize ideas for an actuated gyro that can be used as a pitch balance controller.

VIII. Acknowledgments

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