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Control of a humanoid robot based on the ZMP method

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Abstract: Many biped walking robots are already introduced. Intelligent Handling and Robotics – IHRT at the Vienna University started developing a humanoid robot, which can be used as a servant at home. One part of the research works deals with the development of a method for controlling the stability of a biped robot in the stationary state based on the well known ZMP. This paper describes the control method of the angular momentum of walking robots through the manipulation of the zero moment point (ZMP).

1. INTRODUCTION

Most of the humanoid robots available today use the principle of Zero Moment Point for stabilizing the robot (Hirai, 1998). It was proposed for the first time by Vukobratovic in 1968, and many control algorithms were proposed based on this principle. The ZMP is a stability indicator, other indicators are the center of pressure, the projection of mass center, etc. The "Zero Moment Point – ZMP" is a point located on the ground surface where the sums of all moments of the robot with respect to this point are equal to zero. If this point is inside the stability area the robot is stable - will not fall down - during walking. The stability area depends on the walking phase and is bounded by the points where feet contact the ground, defining the shape of a polygon. When the ZMP is inside of this polygon, it coincides with the Center of Pressure (CoP) and can be computed directly, using the pressure sensors mounted on the foot.

There are methods that use the ZMP concept or sometimes they combine this indicator with others, for examples most frequently with the projection of the center of mass. But the most of them need accurate trajectories of the robot and adjust the pattern generator.

Towards an example, the condition of the ZMP can be satisfied using the concept of fuzzy logic, which provides satisfactory results for a simple robot (Park, 2003). First the fuzzy rules are generated, after an attentive study of a human gait and practical results the fuzzy motion can just follow a pre-established trajectory. Based on the robot's complexity there are immense number of practical results. Therefore the generation of the fuzzy rules is difficult.

Another example is the use of the genetic algorithm for obtaining an optimum result in control and motion synthesis of the biped robot. The genetic algorithms usually generate configurations of the robots to minimize the energy. Because of the long optimization process, for the real-time application genetic algorithms can be hardly implemented.

As next the components of a humanoid robot will be described which is developing at IHRT. A method for the control of the stability of a robot in stationary state as well as the way in which it was implemented will be reported.

2. NEW CONCEPT

A new biped humanoid robot called **ARCHIE** is developing**.** The goal is to build up a humanoid robot, which can simulate in some situations a human being. Therefore ARCHIE needs a head, a torso, two arms, two hands and two legs and will have the following features:

1. Height: 80 - 100 cm
2. Weight: less than 40kg
3. Operation time: minimum 2hrs
4. Walking speed: minimum 1m/s
5. Degrees of freedom minimum 24
6. "On board" intelligence
7. Hands with three fingers (one fixed, two with three DOFs)
8. Capable to cooperate with other robots to form a humanoid Multi Agent System (MAS) or a "Robot Swarm".
9. Reasonable low Selling Price – using commercially available standard components.

Technical details – according to the currently available technologies:

Sensors: Proximity for measuring distances and to create primitive maps, temperature, acceleration, pressure and force for feeling and social behaviour, two CMOS-camera-modules for stereoscopic looking, two small microphones for stereoscopic hearing and one loud speaker to communicate with humans in natural language.

The control system is realised by a network of processing nodes (distributed system), each consisting of relative simple and cheap microcontrollers with the necessary interface elements. According to the currently available technologies the main CPU is for example a PDA module, one processor for image processing and audio control and one microcontroller for each structural component, e.g.: a Basic Stamp from Parallax.

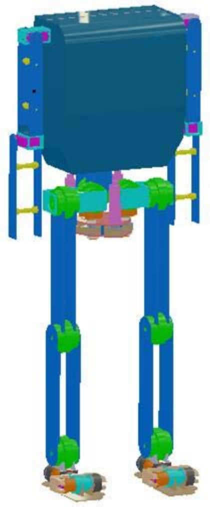

Fig. 1 Design concept of ARCHIE

3. STABILITY CONTROL

There are various sources for control problems in humanoid, biped robots. The structure and selection of control algorithms are responsible to fulfil various criteria such as energy efficiency, energy distribution along the time cycle, stability, velocity, comfort, mobility and environment impact. In addition some other limit conditions have to be taken into account like capability of mechanical implementation due to the physical limitations of joint actuators, coping with complex highly-nonlinear dynamics and uncertainties in the model based approach, complex nature of periodic and rhythmic gait, inclusion of learning and adaptation capabilities, computation issues ……

One of the major control problems is biped walking because of the high-order, highly- coupled nonlinear dynamics and furthermore the discrete changes in the dynamic phenomena due to the nature of the gait.

One of the difficulties until now was the realization of the coordinated movements on the legs and other links in a coordinated way that the robot reaches a distinct goal and not falling down. Important parameters are the method of balance, actors, construction of the body as well as the necessary speed and the walking environment.

For biped walking if the centre of inertia is not in a vertical line over the contact area the robot gets instable and is falling down. Therefore the centre of inertia must be always moved over the leg prior the other one is moving. Another possibility is the quasi dynamic balance, in that case the centre of inertia is moving during the swing face in that way that the moment for falling down is compensated by the putting on the ground again of the second leg. In that case the control problem could be divided in one for the frontal and the second one for the back area. This simple stability control could be realized very easy. The main disadvantage is the low movement and the sensitivity to disturbance variable.

The stability issues are the most crucial problem and can be divided according to three different types of robots.

A. Static walkers: Their motion is very slow so that the system stability is completely described by the normal projection of the centre of gravity which depends only from the positions of the joints.

B. Dynamic walkers: The stability depends in addition on joint velocities and accelerations. These walkers are able to move in a static way provided they have large enough feet and the motion is reasonably slow.

C. Purely dynamic walkers: Usually they are much faster but the control is very complex. In the walk with dynamic balance the projected centre of mass is allowed outside of the area inscribed by the feet.

Stability control has to compensate the disturbance variables like rough terrain, error of tracking the reference, measurements errors and external forces and moments. A method to minimise these unexpected effects is based on the relations between forces and moments which appear in different regions of the robot. The attempt to control the moment of robot joint with respect to a reference point is a solution hereto problem.

For example, let us to consider a simple body with mass *m*. that rotates with an angular speed ω around the point O (Fig. 1). By definition, the angular momentum of the body with respect to point *P* is defined by the following equations:

$$\boldsymbol{M} = \boldsymbol{I} \cdot \omega \quad (1)$$

$$\boldsymbol{M} = \boldsymbol{r} \times \boldsymbol{L} \quad (2)$$

where *I* is the moment of inertia, *r* the distance from the center of mass of the body to the center of rotation O and *L* the linear momentum of the body. Supposing that the center of pressure is situated in point D, and the pressure is *Fn* which is measured by pressure sensors.

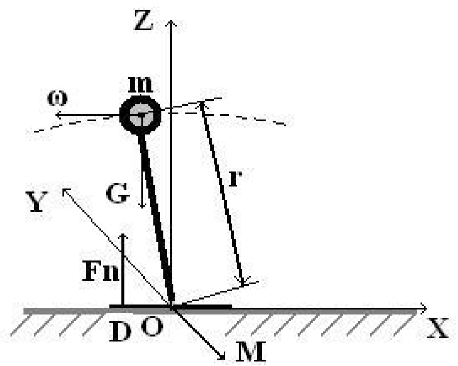

Fig. 2 . Angular momentum of a simple body

In this case, if we want that the angular momentum of the body with respect to point *P* has to be zero, a solution will be to move his center of pressure, so that he tally with point P, or to maintain as much as possible near to this point (and the angular velocities caused by gravitational acceleration tends to zero, in this case). Therefore, if the torques applied in the point *P* are the side and the fit size, the angular moment tends to the reference. Let consider that the new center of coordinates is point *P*, and *X, Y* are the coordinates of the center of mass of the body, in the new coordinates system. The new point $D(d^d_{zmp})$ can be computed by using next relation:

$$\delta^d_{ZMP} = \frac{1}{\sum_{i=1}^{n} m_i(\ddot{y}_i - g)} \left(\sum_{i=0}^{n} m_i x_i g + K_Y - K_{ref} \right). \quad (3)$$

where *g* is the gravitational acceleration and *Mref* the reference value for angular moment *M*.

The torque T applied in *P,* is computed using the next relation:

$$T = - Fn \cdot d^d_{zmp} \quad (4)$$

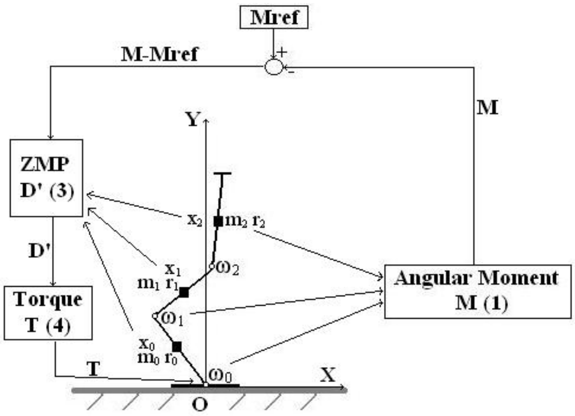

Fig. 3. Control Method Scheme

For the implementation the following steps are necessary:

- The computation of the angular moment of the robot with respect to an exterior point, depending on the mathematical model of robot, using the angular speeds of each joint (Eq. 2);
- Calculation of the desired ZMP point, as a function of the error (which is equal to the difference between angular momentum and reference value) and the sinusoidal positions (Eq. 3);
- The computation of the ankle joint torque in function of the ZMP and foot pressure, value returned back to the simulator (Eq. 4).

The method presents the advantage that not require a high performance from hardware point to view, or from position controllers point to view, allowing the control of a low cost biped robot, but, it is very important the synchronization between the data transmission speed and the execution speed of each part of the robot. The results show that this method can adjust properly the variables of the robot in case of the appearance of the disturbances, so it can be used in combination with other methods, to obtain a better result.

4. SIMULATION

For the simulation of the correctness of method, firstly a simple model in Matlab was built. This simulation shows as the angular moment checked up tends to reference. Afterwards, the tests used a simulation software of a robot foot. (Khao, 2006) shows the utility of using of a RT (Real Time) module, implemented below with the help of the operating system Linux. The simulation system is presented in Fig. 4 and contains of 3 modules for the communication:

- TCP/IP (Transmission Control Protocol / Internet Protocol),
- FIFO (First In, First Out) and
- COM (Component Object Model).

The interface TCP/IP is used for communication among the other modules, the results given were satisfactory concerning the time of transmission, and excellently concerning the independence of the used platforms. Using a communication protocol of our own (represented *D#1* and *D#2* in Fig. 4) the variables of robot are transmitted that contain angular velocities, angles, positions of joints, distances among couple etc., These values are used for control. This module succeeds in transmitting in the real time the messages.

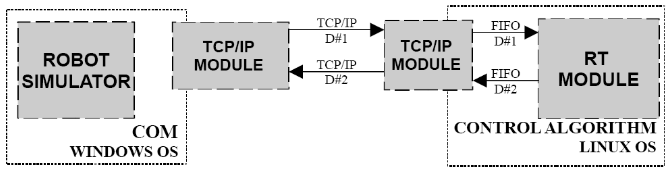

Fig. 4 Stability Control System

The inputs and the outputs of the control algorithm implemented in C++, below RTAI (Real Time Application Interface) put at command of the operating system Linux, are transmitted to the TCP/IP module through a message queue, this ways of transmission being optimum. These options were selected because of a very good processing time, this thing being very important in the control of such a system which requires a minimum answer time.

The COM technology is well-known in the communication among the application of the Windows operating system. Through this the inclusion of the robot simulator software in the application developed under the developmental environment .NET, was possible, which transmits the dates from the control module to this simulator and vice versa.

2.2. Control Method

The relations between forces and moments which react on the robot are, how is showed antecedently, the fundamentals of the implementation of these control methods. The control of moments is better than the control of angular speed or positions.

At this stage the configuration of the robot (positions of each joint, in this case, without ankle joint) is necessary. This can be got from the pattern generator. Because this isn't still implemented, a sinusoidal generation is used for the positions. For this method the position of each joint of the robot and its accuracy don't play an important role because this method does not adjust a position, but the angular momentum of the robot. For this controller the controlled variable is the angular momentum, and the command value is the ZMP point in the stability domain. Basically, on every iteration, it is chosen from all the points in the stability domain of the ZMP, a point which makes the angular momentum to be closer to the reference (to minimize the error), and in conformity with this desired ZMP. A torque which leads the robot to the desired ZMP is calculated. In the last iteration the ZMP will be found to achieve the angular momentum equal or very close to the reference. The method accomplishes the adjustment in small steps, and influences the angular momentum through the ankle joint torque value.

With this method, the robot's angular momentum is adjusted in order to find an appropriate value which guarantees the stability of the robot. The value depends on the phase of walking.

The method shows the advantage that from hardware point to view, or from position controllers point to view a high performance is not necessary to control a low cost biped robot. But the synchronization between the data transmission speed and the execution speed of each part of the robot is important. The results show that this method can adjust properly the variables of the robot in case of the appearance of the disturbances. Also in order to get better results it can be used in combination with other methods.

5. IMPLEMENTATION

Computer simulation is an essential step in the design and construction of biped robots, because it enables rapid testing and virtual prototyping during the construction phase. The Robot Simulator (Fig. 5) shows the simulation results of the calculated ZMP and measuered ZMP.

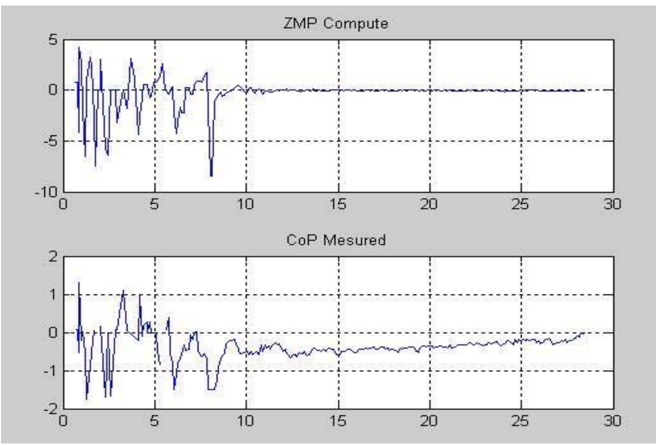

Fig. 5 ZMP computed and ZMP measured

6. CONCLUSIONS AND OUTLOOKS

A control algorithm for the stability of a biped robot is presented. This method can be used to fulfill the condition of stability. With the algorithm the movement of a biped robot will be possible. As future research, the pattern generator must be implemented. Usually, this gives pre-established trajectories (for each joint) for the gait of the robot.

There are many problems involving the walking control of a humanoid robot. The method presented is able to control the stability of a humanoid robot in stationary position. The method can be used in combination with other methods for improving the stability, fields for possible future projects be:

- Orientation measurement –Sensing with a high accuracy the positions, orientation and displacement of three-dimensional (3D) or two-dimensional surfaces is a very powerful trump for improving the stability and walking control of a humanoid robot.
- Intelligent control – all control techniques that use various AI (Artificial Intelligence) approaches like neural networks, Bayesian probabilistic, fuzzy logic, machine learning, evolutionary computation and genetic algorithms can be put into the class of intelligent control. New control techniques are created continuously as new models of intelligent behavior and computational methods.
- Path planning – the art of deciding which route to be taken, based on and expressed in terms of the current internal representation of the terrain.
- Reinforcement learning - the idea that we learn by interacting with our environment is probably the first to occur to us when we think about the nature of learning. When an infant plays, waves its arms, or looks about, it has no explicit teacher, but it does have a direct sensor-motor connection to its environment. Exercising this connection produces a wealth of information about cause and effect, about the consequences of actions, and about what to do in order to achieve goals. Throughout our lives, such interactions are undoubtedly a major source of knowledge about our environment and ourselves. Whether we are learning to drive a car or to hold a conversation, we are acutely aware of how our environment responds to what we do, and we seek to influence what happens through our behavior. Learning from interaction is a foundational idea underlying nearly all theories of learning and intelligence.
- Gyroscopes – can be used in different axis to draw feedback from the system and adjust the parameters in order to synchronize the dynamic balance period with the bipedal waking algorithm. Integration with the gyros reading can give an estimation of the orientation and we can use the gyros for reinforcement learning to correct abnormal behavior for different surfaces.

- Image processing with two cameras can provide 3D information for the environment and we can use it for path planning and intelligent control.

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