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Computer System and Control of Biped "Johnnie"

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Abstract— **The biped robot "Johnnie" is designed to achieve a dynamically stable gait pattern, allowing for high walking velocities. Besides accurate and fast sensors, a powerful computer system is essential for the performance and stability of the machine. The control system requires hard real-time capabilities and low cycle times. With our new control concept and the new computer system, walking speeds of 2.4 km/h have been achieved in experiments.**

I. Introduction

In the past years, research on biped walking machines has become a growing field in the robotics society. Especially in Japan, more and more sophisticated humanoid robots have been designed [1]–[3].

The goal of our research project is the realization of a biped robot that is able to walk dynamically stable on even and uneven ground and around curves. For the future, it is also planned to realize a fast dynamically stable walking motion as well as "jogging" with flight phases. Up to now, a walking speed of 2.4 km/h has been reached in experiments, the robot can take turns and go up stairs as well (videos: http://www.amm.mw.tum.de/). The development of JOHNNIE is based on comprehensive experience in the development of two multi-legged walking machines [4] and general research in the area of robotic systems [5].

Fig. 1 shows the assembled robot "Johnnie". Its geometry corresponds to that of a male human with a body height of 1.8 m. The total weight is about 40 kg. The robot is equipped with 17 joints. Each leg is driven with 6 joints, three in the hip, one in the knee and two (pitch and roll) in the ankle. The upper body has one degree of freedom (DoF) about the vertical axis of the pelvis. To compensate for the overall moment of momentum, each shoulder incorporates 2 DoF. All joints are actuated by brush-DC motors with Harmonic-Drive gears, except for the ankle joints which are actuated by ballscrews. "Johnnie" is autonomous to a far extent, only the energy is supplied by cables. The sensor system mainly consists of internal joint sensors, force sensors that measure the interaction with the environment and an attitude sensor system that determines the orientation of the upper body with respect to the gravity vector [6], [7].

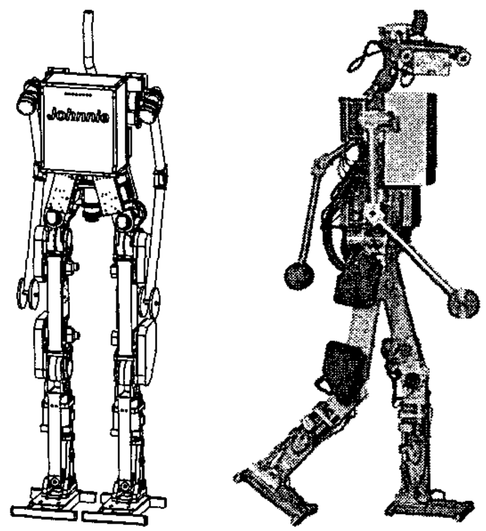

Fig. 1
Biped robot "Johnnie"

II. Control

A. Constraints

The main difficulties in the control of dynamically walking robots result from constraints that limit the applicability of conventional control concepts. Two groups of constraints need to be considered. Firstly, the workspaces of the joints $\boldsymbol{q}$, the maximum rotor velocities $\dot{\boldsymbol{q}}$ and the joint torques $\boldsymbol{\lambda}$ are limited:

$$\boldsymbol{q}_{min} \leq \quad \boldsymbol{q} \quad \leq \boldsymbol{q}_{max} \tag{1}$$

$$\dot{\boldsymbol{q}}_{min} \leq \quad \dot{\boldsymbol{q}} \quad \leq \dot{\boldsymbol{q}}_{max} \tag{2}$$

$$\boldsymbol{\lambda}_{min}(\dot{\boldsymbol{q}}, \boldsymbol{T}) \leq \quad \boldsymbol{\lambda} \quad \leq \boldsymbol{\lambda}_{max}(\dot{\boldsymbol{q}}, \boldsymbol{T}) \tag{3}$$

These are typical constraints for industrial robots and can be satisfied by an adequate design and an appropriate choice of the trajectories. However, critical control problems result from the second group of constraints that describe the unilateral contact between the feet and the ground. Depending on the normal force $F_{i,z}$ that is transmit from foot $i = 1, 2$ to the ground, the maximum transmissible torques $T_{i,x}$, $T_{i,y}$ and $T_{i,z}$, as well as the tangential forces $F_{i,x}$ and $F_{i,y}$ are limited by the size of the feet l_x, l_y and the coefficients of friction μ_t,

μ_d:

$$|T_x| \leq 0.5\ F_z l_y, \quad |T_y| \leq 0.5\ F_z l_x, \quad |T_z| \leq \mu_d F_z,$$
$$\sqrt{F_x^2 + F_y^2} \leq \mu_t F_z, \quad F_z \geq 0\,. \tag{4}$$

While practical experiments show that the robot usually does not start slipping, the limits of the torques in the lateral and frontal direction T_x and T_y lead to a small margin of stability. A lot of research has been spent on concepts to ensure that these constraints are satisfied throughout the entire gait cycle. The *Zero Moment Point* (ZMP) theory [8] is one of the most popular approaches to describe these constraints.

B. Trajectory Generation

The trajectories of the robot are defined in terms of Cartesian coordinates. These are the position of the center of gravity x_{cog}, the rotation of the upper body φ_U and the position and orientation of the foot that is swinging forward x_{Fs}, φ_{Fs}. Add to this the pelvis joint q_p and the joints of the arms q_a are controlled. Then

$$x_{ref} = \left(x_{cog}^T,\ \varphi_U^T,\ x_{Fs}^T,\ \varphi_{Fs}^T,\ q_p,\ q_a^T\right)^T \tag{5}$$

is the vector of controlled variables. Except for the horizontal motion of the center of gravity, the motion of these variables is defined in fifth order polynomials for each phase of the gait pattern.

The reference trajectories of the center of gravity (COG) are computed with a lumped mass model. These approximations are not completely exact, as the acceleration of the swinging foot does also influence the dynamics of the COG. However, practical experiments have shown that the reduced model is sufficient for walking speeds up to 2.4 km/h. In this model, it is assumed that the mass of the robot can be lumped to the COG. The motion of the COG in the frontal direction is independent of the lateral motion. When the COG is kept on a constant height, we obtain a particularly simple solution for its dynamics. For the lateral direction y_{cog} the acceleration is

$$\ddot{y}_{cog} = \frac{g_z}{z_{cog}}(y_{cog} - y_{zmp})\,. \tag{6}$$

Here, g_z is the vertical component of the gravity vector, z_{cog} is the height of the COG and y_{zmp} is the position of the ZMP. During walking, the COG is shifted periodically from one leg to the other such that the legs can alternately swing forward. During the single support phase the lateral position of the ZMP shall be constant with respect to the supporting foot. For maximum stability margins it can be selected to be in the middle of the foot area, for minimum lateral deviation of the COG it has to be on the inner edge of the supporting foot. The resulting equations for single support are

$$y_{cog} = c_1 \cosh(a(t - t_0)) + c_2 \sinh(a(t - t_0)) \tag{7}$$

with $a = \sqrt{\frac{g_z}{z_{cog}}}$. The coefficients c_1 and c_2 are computed such that $y_{cog}(t_0) = y_{cog}(t_1)$ and $\dot{y}_{cog}(t_0) = -\dot{y}_{cog}(t_1)$ with t_0 and t_1 being the beginning and the end of the single support phase. During double support the velocity of the COG shall be constant. The resulting motion of the COG is depicted in Fig. 2 (right).

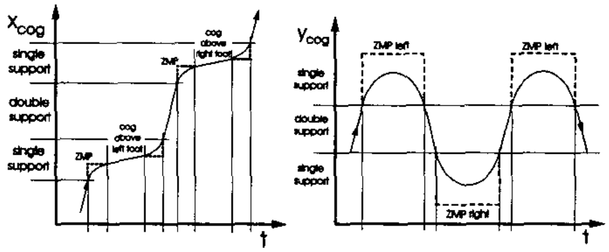

Fig. 2
COG FRONTAL (LEFT) AND LATERAL (RIGHT)

The velocity of the COG in walking direction is computed according to the same principle. During the single support phase the ZMP moves from the rear edge of the supporting foot to the front edge. This way the velocity of the COG can be kept constant while it is above the supporting foot. The corresponding motion of the COG in the frontal direction is depicted in Fig. 2 (left). The simplified model has the advantage that the trajectories can be computed online. So it is possible to compensate model inaccuracies as well as external disturbances by an adaptation of the trajectories.

C. Control of the Robot

The presented trajectories satisfy the dynamical constraints of the system, therefore the robot is in balance as long as the joint angles follow these trajectories exactly. However, this is only possible at very low walking speeds. In reality even small disturbances or modeling errors lead to instability within a few steps. Therefore an online adaptation of the trajectories is necessary to control the overall posture of the robot.

In a first approach, the control system had a three-layered structure, where the lowest level was based on a Feedback Linearization system [9]. The robot was performing well, however, experiments with a fast decentral torque control were not promising. Even though the foot torques could be tracked very fast, the overall system bandwidth was limited due to a considerable time delay of the orientation sensor. The current control scheme is structured in two layers according to Fig. 3; if the robot is vision-controlled we get a higher-ranking third layer of vision evaluation and global task-planning.

The first level takes on the global gait coordination including the transition between different gait patterns. Also the computation of the reference trajectories and the adaption on the orientation of the robot and the forces that act on the feet occurs on this layer. Finally, the Cartesian trajectories are mapped onto joint space. The second level consists of the joint controllers that control the position and velocity of each degree of freedom.

Similar concepts are used to control most of the existing biped robots that can perform a stable walking motion [1], [10], [11]. The implementations differ in terms of the variables

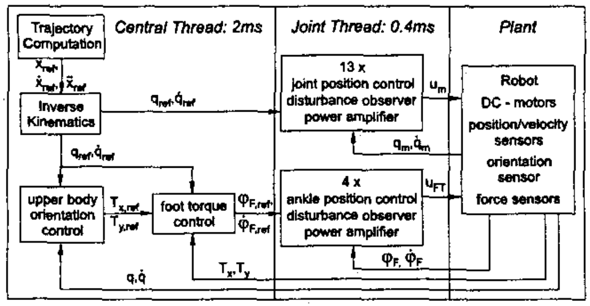

Fig. 3
TRAJECTORY CONTROL

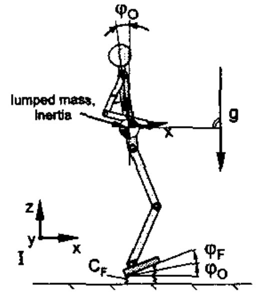

Fig. 4
INVERTED PENDULUM

that are used to adapt the trajectories. In most cases the orientation of the supporting foot i.e. the ankle joint is used to control the foot torques in order to stabilize the robot. Add to this it is possible to accelerate the upper body horizontally to keep an upright posture. A very popular approach is also to vary the step length in sagittal and lateral direction. Variations of these two parameters strongly affect the motion of the robot, however, the implementation is limited by the workspace of the joints. In order to reduce impacts when the swinging foot hits the ground, it is possible to introduce some impedance in the vertical position of the feet, i.e. to vary the vertical position of the feet with respect to the upper body.

In our robot we have investigated all approaches experimentally, but in the following only the control of the ankle joints will be discussed, since it is the most important control parameter.

The dynamics of the robot are linearized around the motion on the reference trajectories. This is possible since the deviations from the reference are assumed to be small. In particular the inclination of the foot plates differs from the reference position by small angles $\varphi_F = (\varphi_{Fx}\ \varphi_{Fy})^T$, while the remaining degrees of freedom of the robot are moving according to the reference trajectories. For a given state of the system, the mass and inertia of the robot are summed together such that we obtain an inverted pendulum model according to Fig. 4.

For a real robot the contact to the ground has always some compliance. It results from the stiffness of the links, the elasticity of the foot elements and the compliance of the ground surface. In the model all of these elasticities are combined to a contact stiffness C_F. Typically the damping of the contact is relatively low, and it increases the robustness of the controller. We can therefore neglect the damping without loosing the applicability of our approach. The torques that are transmit from the foot to the ground are:

$$T_F = -C_F(\varphi_O + \varphi_F) \tag{8}$$

Here the angles φ_O and φ_F denote only the differences of the orientation of the upper body and the foot from the reference trajectory. Also the torque T_F is the part of the foot torques that results from deviations from the reference trajectory.

Without moving the ankle joints, the dynamics of the system are denoted:

$$J\ddot{\varphi}_O + C_F(\varphi_O + \varphi_F) = 0 \tag{9}$$

When the motion of the joints is independent of the orientation of the upper body ($\varphi_F = 0$), the system is obviously marginally stable. Please note that even without additional control there is a feedback of the position φ_O resulting from the compliance of the ground contact. In order to obtain an asymptotically stable system, we have to introduce damping to the system.

For the linearized system sagittal and lateral dynamics are decoupled. For each direction we obtain the state equations:

$$\begin{pmatrix} \ddot{\varphi}_O \\ \dot{\varphi}_O \\ \ddot{\varphi}_F \\ \dot{\varphi}_F \end{pmatrix} = \begin{pmatrix} 0 & -\frac{C_F}{J} & 0 & -\frac{C_F}{J} \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \dot{\varphi}_O \\ \varphi_O \\ \dot{\varphi}_F \\ \varphi_F \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ u \\ 0 \end{pmatrix} \tag{10}$$

The orientation and rotational velocity of the upper body and the position of the foot can be measured such that we can feed back the entire state:

$$u = (K_3\ K_4\ K_1\ K_2)(\dot{\varphi}_O\ \varphi_O\ \dot{\varphi}_F\ \varphi_F)^T \tag{11}$$

A block diagram of the system is depicted in Fig. 5. Obviously the system is controllable and we can place the poles arbitrarily by choosing $K_1 \ldots K_4$.

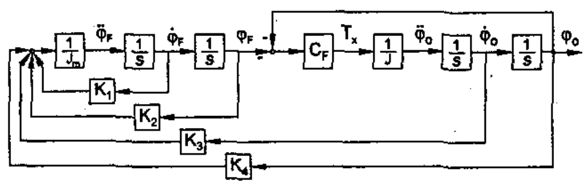

Fig. 5
CONTROL OF INVERTED PENDULUM MODEL

In this diagram the limitation of the foot torques due to the length and width of the feet are not considered. It is assumed that the maximum torques are sufficient during normal walking. However, the limits have to be taken into account in case of major disturbances such that the feet do not tilt. Therefore a cascaded control structure is used to consider the torque limits according to Fig. 6. The inner loop (feedback K_1 and K_2) consists of a PD-control of the joint angles. Here the transfer function of the motor-gear system and the controller are replaced by a simplified system for conciseness. In the real robot the joint control is augmented with friction observers to obtain a zero steady state error.

In the outer loop the orientation of the upper body is controlled with the torques of the ankle joint. For this loop the desired torque is computed from the orientation and rotational velocity of the upper body (gains K_4 and K_5). It is limited to the maximum possible value, that depends on the normal force and the size of the feet. The desired value is compared with the measured torque (T_x) and serves as input to the ankle position control (gain K_6). An integral term K_7 allows to compensate the steady state error.

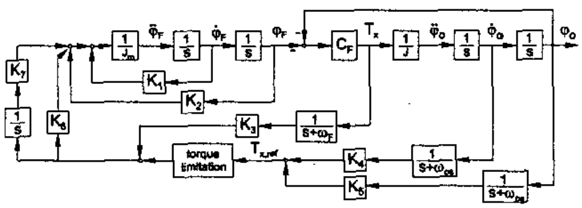

Fig. 6
CONTROL WITH TORQUE LIMITATION

In order to get a useful design of the control gains, the transfer functions of the sensors have to be considered. The orientation sensor is approximated by a PT-1 filter, the force sensors are filtered with a cross over frequency of 250 Hz. Using standard design methods, the poles of the closed loop system can be placed to achieve a high system bandwidth.

III. COMPUTER SYSTEM

The computer system plays an essential role in the performance of a walking machine. It has to read in all sensor data, compute the motor torques and put out the pulse width signals:

- Each joint requires one evaluation unit for the incremental encoder, one pulse width modulated output for motor control including one direction bit and one digital input for the light barrier that is used for referencing purposes.
- 24 A/D channels for the force/torque sensors and the attitude sensor.
- Six digital outputs to drive the D/A converters that are used to calibrate the force/torque sensors.

A. Decentral Computer System

In a first approach, a decentral computer system was implemented. Its structure is based on the hardware concept of two previous robots that were built at our institute. The solution had been implemented successfully in our six-legged walking machine [12] and our pipe crawling robot [13], [14]. It consists of six microcontrollers (Infineon C167CS) on the robot and an external host system (dual Pentium III). The microcontrollers communicate with the host PC via six parallel CAN bus lines. In order to achieve a high sampling rate, the computation of the trajectories and the control of the system dynamics are performed on the host PC. On the other hand, the low level motor control and the data acquisition are handled by the microcontrollers. The sensor signals and the joint control are distributed on the microcontrollers according to the structure of the robot. For example the control of the ankle joint and the evaluation of the force/torque sensor are assigned to the same controller. This allows for a decentral control of the ankle joint torques.

With this computer system, a minimum cycle time of 4 msec has been achieved. However, experiments have shown that this cycle time is too slow for the implementation of faster gait patterns. Add to this, it is difficult to implement complex control algorithms on the microcontrollers since they are optimized for 16-bit integer mathematics. Another drawback of the decentral computer system is the fact that the host PC cannot be mounted on the robot due to lag of space.

B. On-board PC System

As stated above, decentralized control concepts have been implemented successfully in multi-legged walking machines, but they are not suitable for a biped robot. Its highly coupled kinematics and dynamics suggest the use of a centralized on-board system. With our new PC-based system, the problems have been solved. Now the robot is completely controlled by an on-board PC which is connected to an external computer via Ethernet. The external PC is just used for basic operating commands and monitoring purposes.

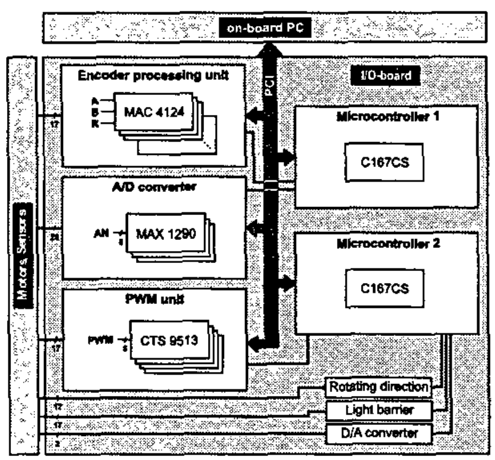

Fig. 7
ARCHITECTURE OF THE I/O BOARD

1) Realization: Different hardware solutions have been investigated for the central control system. Due to the rapid development of the PC-market, the use of standard PC-boards turned out to be the most efficient solution. These systems provide a very high computational power and can be upgraded easily. When the hardware was selected for our robot, processors with 2.8 GHz maximum clock rate were available.

The interface to the sensors and the motor electronics consists of a PCI extension board that has been developed at our institute. It is based on a PCI prototype board (manufacturer: *HK-Messsysteme, Berlin/Germany*) and a sophisticated I/O board, which is equipped with the following components:

- 2 microcontrollers (Infineon C167CS),
- 3 fast A/D converters with 8 channels each (Max 1290),
- 17 encoder processing units (Mazet MAC 4124),
- 4 pulse width modulation devices (Celeritous CTS 9513).

Right now, the microcontrollers are just used to manage the data flow between the PCI bus and the components of the I/O board. The data ports of all sensor modules are directly connected to the PCI bus, but they are inactive by default. In a read cycle the microcontrollers activate the sensor modules subsequently such that their data can be read in one by one. The setup of the I/O board is shown schematically in Fig. 7.

2) Software structure: The control of the robot has to satisfy hard real-time conditions. In order to meet these requirements, the control software is structured according to Fig. 8. The real-time Linux derivative RT-Linux is used as operating system for the on-board PC.

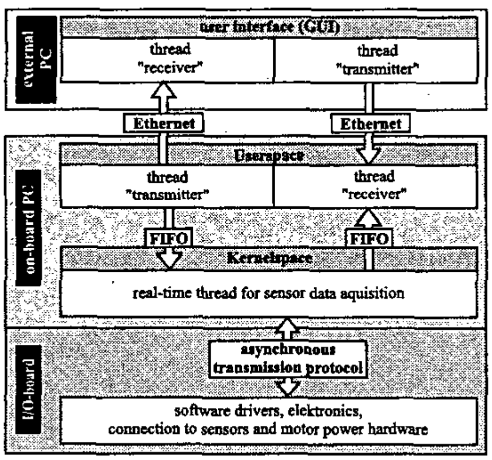

Fig. 8
SOFTWARE STRUCTURE OF THE ON-BOARD COMPUTER SYSTEM

3) Asynchronous PCI Transfer Protocol: As shown in Fig. 8, the real-time control loop can directly access the I/O board over the PCI bus and exchange the sensor data and PWM values. However, the fast bus access is very sensitive to time delays. RT Linux task latency jitter due to high CPU load may disturb the data exchange. During development, accidental transmission errors were noticed if the RT Linux system was loaded with significant user space tasks.

Therefore a reliable bidirectional communication protocol has been developed. In the beginning of each transmission, both microcontrollers are in idle state. The data sampling cycle is initiated by a control word triggered by the on-board PC. This control word is handled by the microcontrollers and the desired module is addressed. If there are valid data on the PCI bus, a signal („data valid" bit) is sent to the PC and the data gets accepted. Fig. 9 shows the procedure of reading three consecutive values; the transmission of PWM-values is done similarly. A checksum is transferred to detect errors. However, the transmission protocol slows down the data exchange such that the transfer of all data takes about 250 μsec. A possible solution is to provide all data via direct memory access (DMA), which could be supported by our PCI card.

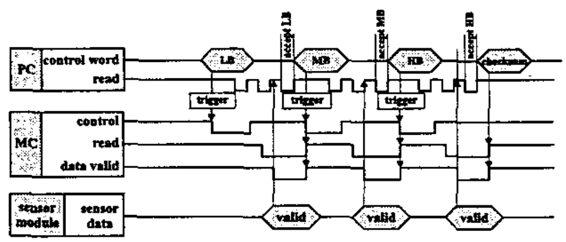

Fig. 9
ASYNCHRONOUS PCI DATA TRANSFER

4) Mechanical design: Fig. 10 shows the mechanical assembly of the on-board PC system. The PC mainboard is very compact (Micro-ATX) and is equipped with a 2.8 GHz Pentium IV processor and on-board Ethernet. For data storage, a lightweight 2,5" hard disk is used, which is mounted elastically to reduce shocks. The PCI card described above is connected to the mainboard by a flexible bus extender, which allows for a highly integrated design. All electronic components are protected in an aluminum box to avoid electromagnetic interference. The ATX-power supply (DC/DC converter) is mounted on the back of the robot.

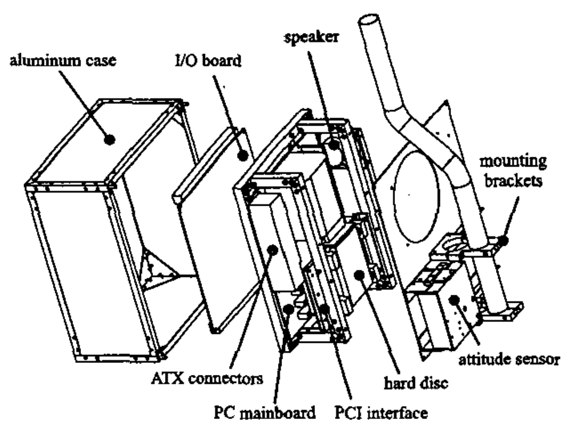

Fig. 10
MECHANICAL DESIGN OF THE ON-BOARD PC SYSTEM

IV. Conclusion

The presented control scheme has been verified in experiments, Fig. 11 shows JOHNNIE walking on a conveyor belt. Presently, stable walking can be realized with up to 2.4 km/h and step lengths of 55 cm.

In the upcoming project, we are going to redesign JOHNNIE's lightweight structure and its sensor system. Secondly, we are going to revise the control scheme in order to reach more flexible gait patterns at higher walking speeds.

Acknowledgment

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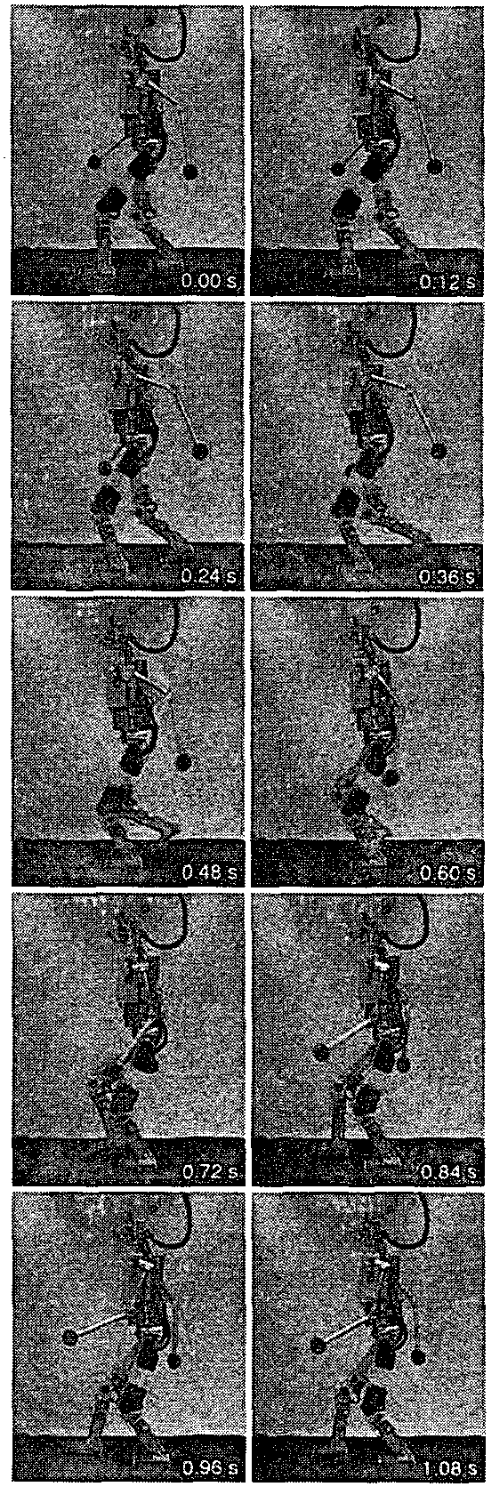

Fig. 11
JOHNNIE walking on a conveyor belt