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DESIGN OF MECHANICAL AND CONTROL SYSTEM OF A WALKING MACHINE

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Authors describes design problems of currently being build six-legged walking machine. First mechanical structure is introduced, next hardware structure is described. Finally problems related to the synthesis of control system, gait planning and force, distance sensing are discussed. Same experimental results are given.

Key words: walking machines, mechanical and control system design, hexapods

1. Introduction

The robots of the future must be able to work interactively with people, learning the tasks in conjunction with their human partners. Such a property requires superior mobility, learning capability, a user interface which allows communication on the cognition level, and an autonomous operation capability to enable navigation and obstacle avoidance in the working environment. The sensing and navigation system of the autonomous walking machine should allow versatile perception of its environment. In addition, it is useful to transfer "cognitive" level information to the user through a virtual world description common to both the robot and its user. Research on walking machines has seen a rapid development in recent years, mainly due to the introduction of new generations of computers. Legged robots can be used as a means of transport over roadless terrain and for operation on sea or river bottoms or for operation in an environment harmful to man, and in rescue operations. They operate in diverse dynamic environments and so must be able to effectively utilize their limited resources. In comparison with industrial robots, the task to build such a robot is much more difficult. The requirements imposed on hardware and software systems are stricter than those associated with industrial manipulators.

To create an autonomous robot, five major problems must be solved:

- Choice and proper design of kinematics structure
- Design of actuating system
- Design of control system (hardware)
- Synthesis of control system (software)
- Choice of adequate set of internal and external sensors.

Every choice is related to the robot expected tasks, cost, reliability and expected degree of autonomy (independence for the operator). The authors are analyzing the above list of problems on the example of walking machine LAVA (currently being built in Robotics Research Centre, Nanyang Technological University).

2. State of knowledge

In the overview of the publications on the subject of multilegged walking machines, it can be noticed that the main attention is paid to:

- general (technical) descriptions of built prototypes, e.g. Pugh et al. (1990)
- methods of free gait planning, e.g. Hartikainen (1996), Pal and Jayarajan (1991)
- problems of gait synthesis using dynamics of quasi-dynamic modeling, (e.g. force distribution problems) – Debao et al. (1999), Gornievsky and Schneider (1990), Klein and Kittivatcharapong (1990), Manko (1992)
- problems of movement optimization – Nagy et al. (1994), Song and Waldron (1986)
- philosophy of control systems functional decomposition and mechanisms of machines adaptive behavior – Brooks and Stein (1994), Zielińska (1997).

There is a lack of description of the common design considerations on the mechanical and control system. Systematic approach to the mechanical and control system design can benefit in the flexibility for future development and modifications.

3. Design of kinematic structure

Mechanical structure of a walking machine should not only imitate the leg structure of living patterns (e.g. insects, spiders), but should also be designed considering the actuating systems properties (size and weight of motors) and limitations (size of body, power of motors, working volume).

The need for a general solution to robotics legs, one that is versatile for two, four or six legged vehicles is clear. However the ability to meet this need has been hampered by the lack of adequate joint mechanisms and controls. Joint technology is a key problem in the development of such vehicles, because hip and ankle joints require at a minimum pitch and yaw motion about a common center with remote location of drive sources analogous to muscles and joints. The lack of simple, compact, cost effective and reliable actuator packages has also been a major stumbling block in current designs. Ineffective joint designs lead to unwieldy vehicles that compensate for the instability of their simple joints by means of additional legs.

3.1. Unique Differential Leg Mechanism

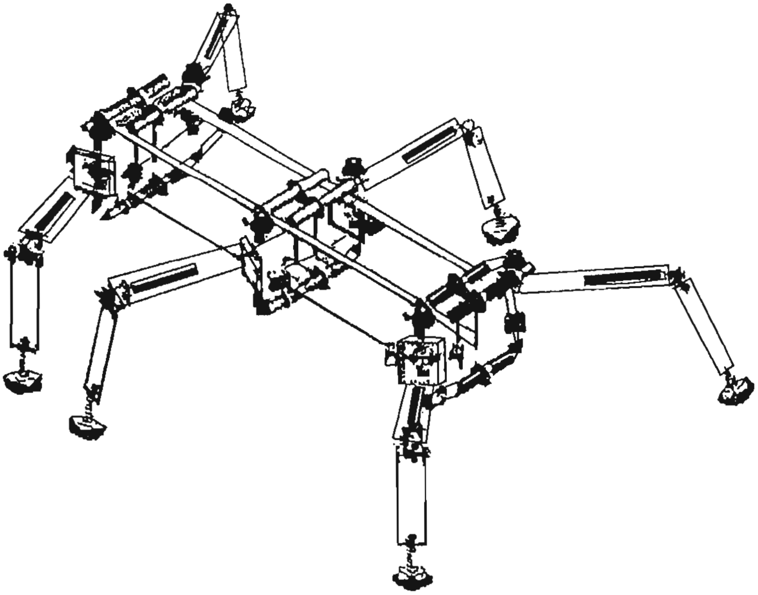

Fig. 1. Walking machine LAVA

The general structure of walking machine LAVA (Legged Autonomous Vehicular Agent) presented by Heng et al. (1999), Loh et al. (1998) is shown in Fig.1.

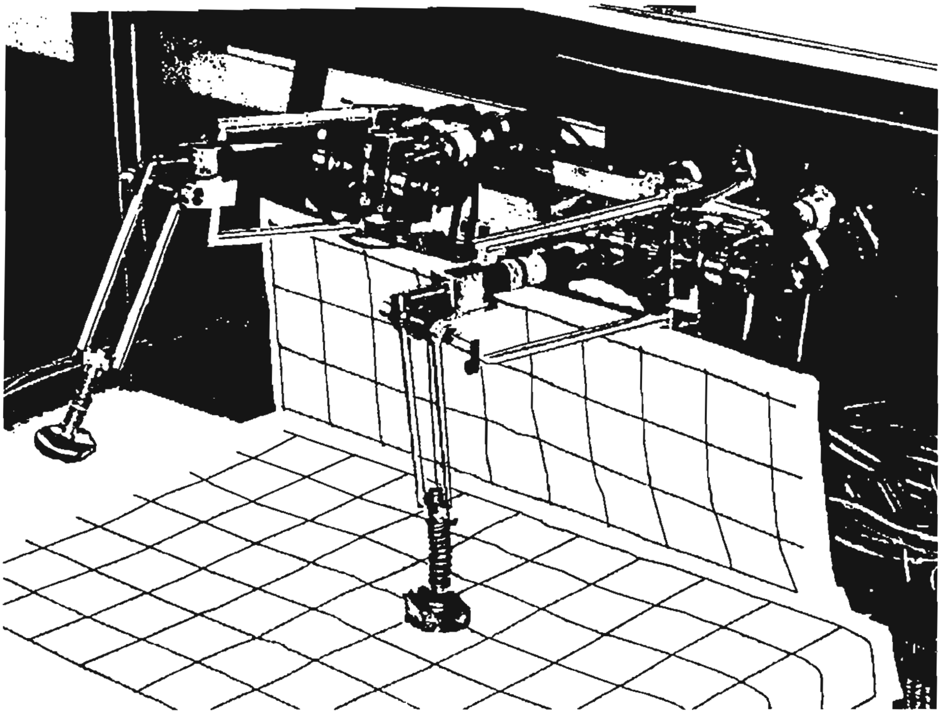

Fig. 2. Test rig

The thigh section employs a differential gear drive system to achieve both leg swing and leg lift functions (Fig.2). This drive system offers two distinct features that are superior to conventional leg design. Firstly, the leg lift and leg swing functions operate from a common geometrical pivot point. This feature will prove beneficial when performing workspace and kinematic modeling. Secondly, during the leg swing and leg lift motions, both motors are constantly working together to achieve the desired motion. No motor is left to idle and be carried around as a dead weight when only one particular leg motion is in use. The advantage would be that two smaller lighter motors could be utilized which can be combined to provide a cooperative effort instead of the conventional independent motor drive design.

The result would provide savings in power consumption, weight penalty and size constraints. Other power saving features include using worm gears at a particular gear ratio to drive various appendages. This provides a self-lock feature, thus removing the need to keep the motors continuously powered when holding the walking machine in a particular orientation. To provide maximum foot placement flexibility with precise turning functions, full 3 DOF per leg was incorporated in the leg design.

3.2. Fully invertible walking machine platform with amphibious adaptability

The large leg lift and swing angle complements the symmetrical leg design, which enables the walking machine to be invertible. This feature is seen as being essential if the walking machine is to operate within the surf zone. The absence of exposed mechanical drive systems allows the walking machine to be "water proofed" and hence give an amphibious capability. The walking machine can be configured to walk on the seabed or spread its limbs to increase buoyancy and hence swim on the surface (Fig.3).

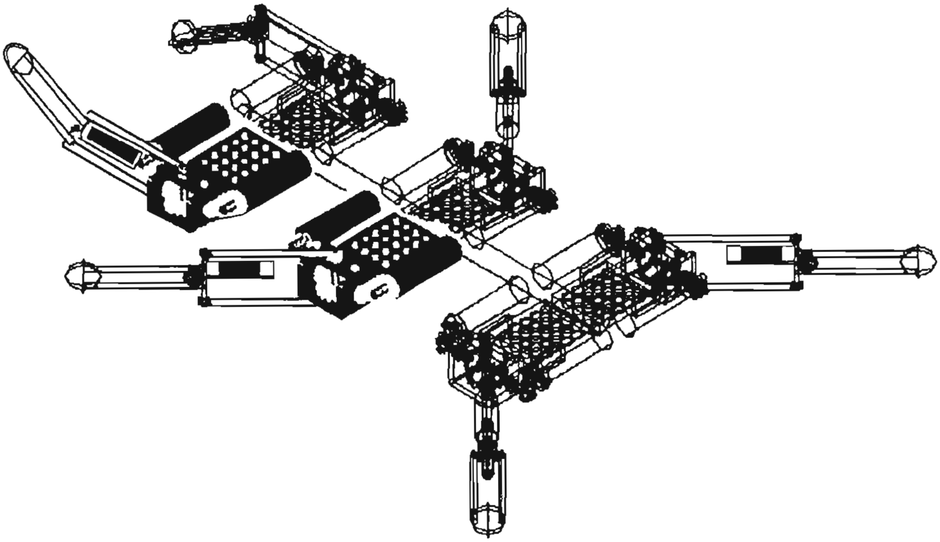

Fig. 3. LAVA in swimming configuration

4. Design of actuating system

In the design attention was paid to the calculation of motor powers and gear ratios.

To achieve the required load bearing capacity, motors with a high torque-to-weight ratio, in addition to gears with high reduction ratio and low weight are needed. In existing hexapod designs, motors and gears together make up for more than 50% of the total weight of a leg, and the motor-gear combination in the joints require detailed optimization to achieve maximum load capacity. Choice of motors has been done after theoretical study of expected energy consumption. The maximum and average joint torque has been calculated for the assumed gait type, body mass m, body speed v, step length s, and link lengths l_1, l_2. In these calculations (Zielińska, 2000), only the most energy consuming, leg-end support phase (body movement propelling phase), has been considered. The most representative shape (time history) of reaction forces (Pfeiffer et al., 1995) has been assumed for calculation of average torque demand. To quantify these results, it has been noted that the torque demand has an added factor (in order to deal with emergency purposes). On average, this factor is about 40%, but in the calculations of the motor power the ideal efficiency of the mechanical system has been considered. The energy (forces, torque) losses over the mechanical construction is normally rated at about $50 \div 60\%$. In all, the added factor in the torque demand will be overwhelmed by the limited efficiency of the mechanical system. The following parameters have been assumed:

- forward motion by tripod gait
- total mass of LAVA: $m = 40.0\,\mathrm{kg}$ (weight$= 392.4\,\mathrm{N}$)
- body speed: $v = 0.5\,\mathrm{m/s}$
- step length: $s = 0.3\,\mathrm{m}$
- length of leg links:
  - $l_1 = 0.320\,\mathrm{m}$
  - $l_2 = 0.400\,\mathrm{m}$
- leg reaction forces (average value):
  - f_z (vertical)$= 130.80\,\mathrm{N}$
  - f_y (motion direction)$= 68.67\,\mathrm{N}$
  - f_x (side)$= 68.67\,\mathrm{N}$.

According to the calculations the maximum torque in the hip joint amounts to $121.938\,\mathrm{Nm}$ and in the knee joint – to $63.404\,\mathrm{Nm}$. The average torque consumption is equal to $111.90\,\mathrm{Nm}$ for the hip joint and equal to $42.62\,\mathrm{Nm}$ for the knee joint. Reduction factors calculated for the given vehicle speed demand are: hip reduction $r_h = 515.374$, knee reduction $r_k = 950.302$.

From that, the approximation of the power required for each hip motor was 56.843 W and for knee motor is 23.4834 W. Those results have been used for the final choice of motors power.

5. Design of hardware

The hardware structure of the control system (Fig.4) includes: PC host (leg CPU), motion control cards (PID controllers) connected to the amplifiers powering the leg motors. To provide a position feedback, 16 lines digital encoders are used. Leg-end 3-components KISTLER piezoelectric force sensor coupled through a 4-channel charge amplifier passing through an A/D converter delivers the data to the PC host. The control program is written in C language and is implemented in the PC host.

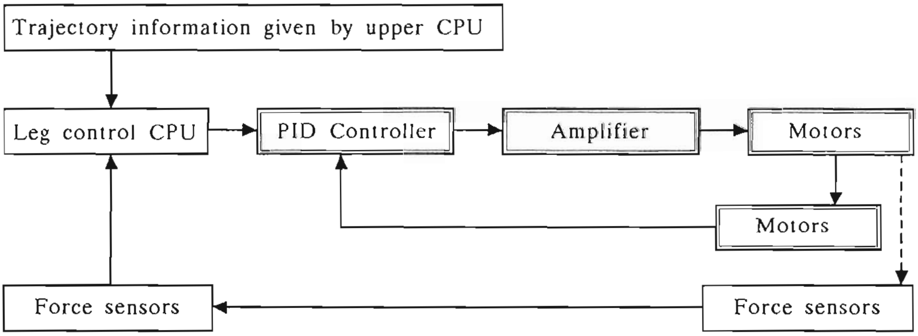

Fig. 4. General hardware structure

The control cards uses National Semiconductor LM680 dedicated motion-control processors. The host computer must program the controllers as the bus peripherals. Sampling rate (one close of feedback loop together with encoder reading) slightly depends on the motor control method (PWM or current/voltage control) and in our case of current control is in the range of 400μs. The time of one control step on the leg level depends on properties of the motion. It was found from by various experiments, that this time could not be shorter than 0.03 s for the smooth leg-end movement. The controllers use trapezoidal velocity profile of the motor motion (so-called position mode). Adequate procedures are responsible for calculating the maximum velocity and acceleration for each control step. During trajectory following movement, the acceleration must be constant which prevents the leg-end from vibrations. Proper values of the acceleration were obtained by experiments for each motor separately (see Zielińska et al., 1999).

6. Synthesis of control system

6.1. Structure

The real time QNX system and Watcom C are being used in the development of the control software. The inter-process cooperation is according to the typical client-server pattern. Currently, three processes have been developed into software: *leg* process, *driver* process and *sensor* process. The *leg* process is the client while both the *sensor* and *driver* processes are the servers. The *leg* process is responsible for generation of motion trajectories according to the rules given by a programmer and the data received from the *sensor* process. The *sensor* process serves the force sensor. The *driver* process is responsible for cooperation with hardware. It receives command and data from the *leg process*, transforms that data to the format acceptable by the hardware (motion controllers) and communicates with the hardware. The back-paths (from servers to clients) includes transmission of: sensor data (from *sensor* process), confirmations of the end of movement (from *driver* process) and, information about the errors which can be hardware or software type (Fig.5). In the *leg* process the user (programmer) defines different shapes of the leg-end trajectory for "continuos path" motion or sends only the coordinates of the final position (position of leg-end or angular joint position) for the "point-to-point" motion. The programmer is responsible for manual synchronization of the legs (from PC host keyboard). In the design of control software it has been assumed that, in the future, the control program would be implemented in an autonomous on-board control computer.

6.2. Generation of body motion and leg-end trajectories

Every shape of the body path can be generated using straight line and circular segments. Generation of gait for a straight-line motion is very simple and will be not commented by the authors (related works were discussed by Shaoping et al. (1999)). A circular motion can be generated in several ways. The authors proposed a method which is simple in implementation because it is limited to "discretised" changes of the body orientation in the world non-moving coordinate frame, and the leg-end trajectories related to the body

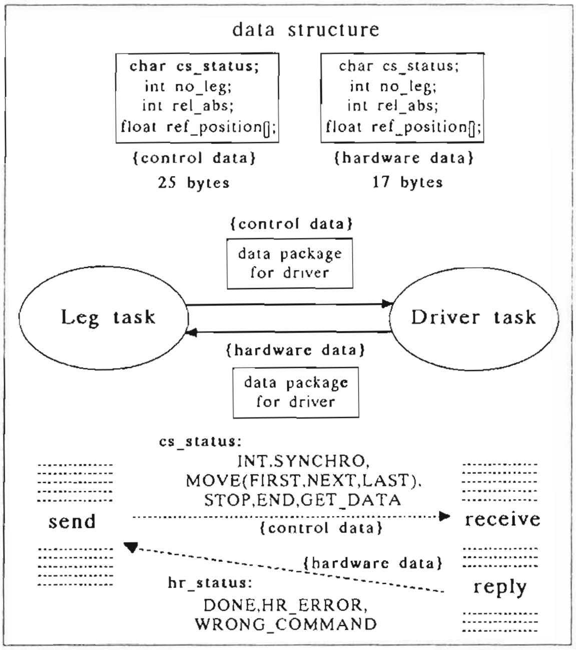

Fig. 5. Inter-process communication

fixed frame are parts of straight lines (not circles). Turning motion results from the "discrete" (not along the circle) change of the body orientation in one walking step. Assuming that this change is equal to α, the expected change of motion direction equal to $n\alpha$ will be realized in n walking steps. The minimum absolute value of α is equal to zero which results in a straight line body motion. The maximum absolute value of α, the change of orientation in one step of walk, is limited by the leg kinematic structure, length of the leg links and body dimensions what is related to the stability conditions of motion and the leg-end work space. Analysis of all that factors showed that the change of body orientation (turn) equal to 5° is easy to obtain in one step during a movement on flat terrain. For description of the leg-end coordinates in turning motion the coordinate frame attached to the center of the body has been defined. This frame is translated and rotated accordingly to the body motion.

Fig.6a shows the body initial position (beginning of one walking step). The small circles are marking the leg-end position. The localization of the body fixed coordinate frame in this state is described by OX_AY_A. The leg-ends position for the control system purpose are expressed in the hip-attached

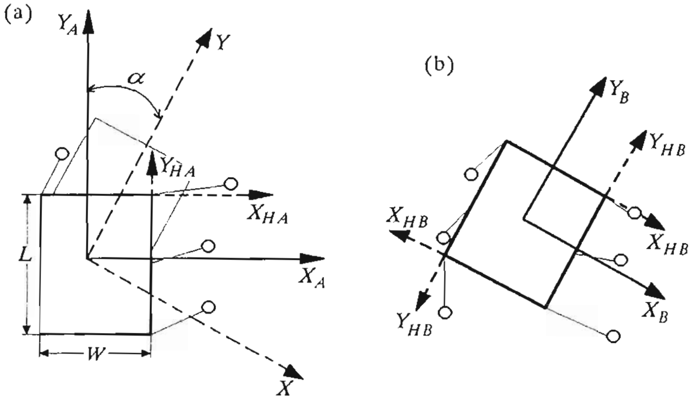

Fig. 6. Turning motion – coordinate frames in: (a) initial state, (b) final state of one walking step

frames which are only translated in relation to the body fixed frame. Fig.6b shows the body final position (end of one walking step). During one step the leg-ends supporting the ground are non-moving in relation to the support surface, and are moving in relation to the body (and hips) frame/frames.

This movement is the body driving movement and results in the body translation and rotation in relation to the ground (in non-moving reference frame). By the of description of the leg-ends position in the body (or hips) frame during the support phase we will obtain description of the turning motion which can be utilized by the control system. The final leg-end position (in hip frame, for each leg separately) is a position typical for the end of the support phase of the tripod gait. Such an assumption allows an easy transfer to the straight line tripod gait in the next walking step. Continuation of the turning gait means only a repetition from step to step the described method. Only the leg-end positions at the beginning of the support phase (i.e. points of placement of the legs on the ground on the end of transfer phase) must be modified and compared with the straight line body motion. That starting position will be calculated knowing that, after the assumed body translation and rotation in one support phase, the leg-end positions expressed in the hip (or body) frames must be shifted to the positions typical for the end of the support phase. The leg indexes are: leg 1 – front right, 2 – middle left, 3 – hind right, 4 – front left, 5 – hind left, 6 – middle right. W is the width of the body and L is its length (see Fig.6).

The following variables are defined:

- ${}^{HB}y_{min}$, ${}^{HB}y_{min}$ – leg-end coordinates at the end of the support phase expressed in the hip frames (see Fig.6b), those coordinates are known (leg-end positions at the end of the support phase of the tripod gait),
- the leg coordinates (at the end of the support phase) expressed in the body frame OX_BY_B attached to the final body position are equal to:

$$\begin{aligned}
\text{leg } 1: \quad & {}^{B}y_1 = 0.5L + {}^{HB}y_{min} \\
& {}^{B}x_1 = 0.5W + {}^{HB}x_{min} \\
\text{leg } 2: \quad & {}^{B}y_2 = {}^{HB}y_{min} \\
& {}^{B}x_2 = -0.5W - {}^{HB}x_{min} \\
\text{leg } 3: \quad & {}^{B}y_3 = -0.5L + {}^{HB}y_{min} \\
& {}^{B}x_3 = 0.5W + {}^{HB}x_{min} \\
\text{leg } 4: \quad & {}^{B}y_4 = 0.5L + {}^{HB}y_{min} \\
& {}^{B}x_4 = -0.5W - {}^{HB}x_{min} \\
\text{leg } 5: \quad & {}^{B}y_5 = -0.5L + {}^{HB}y_{min} \\
& {}^{B}x_5 = -0.5W - {}^{HB}x_{min} \\
\text{leg } 6: \quad & {}^{B}y_6 = {}^{HB}y_{min} \\
& {}^{B}x_6 = 0.5W + {}^{HB}x_{min}
\end{aligned}$$

- ${}^{A}x_i$, ${}^{A}y_i$ – leg-end coordinates at the beginning of the support phase expressed in the body initial frame OX_AY_A (see Fig.6). The supporting legs are fixed to the ground, therefore the leg-end positions described by ${}^{A}x_i$, ${}^{A}y_i$ coordinates are equal to the leg-end positions at the end of the support state.

During one step, the body undergoes a translation by the distance s (this distance is equal to the step length) and rotation by the angle α (positive angle is for the clockwise rotation), the leg-end coordinates ${}^{A}x_i{}^{A}y_i$ can be easily obtained by making use of the homogeneous matrix

$$
{}^{A}_{B}\mathbf{T} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 & s\sin\alpha \\ \sin\alpha & \cos\alpha & 0 & s\cos\alpha \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

The vector of coordinates of the ith leg-end in the B frame is

$$^{B}\boldsymbol{X}_i = \begin{bmatrix} ^{B}x_i \\ ^{B}y_i \\ ^{B}z_i \\ 1 \end{bmatrix}$$

The leg-end coordinates in the frame A are

$$^{A}\boldsymbol{X}_i = ^{A}_{B}\mathbf{T}\,^{B}\boldsymbol{X}_i \tag{6.1}$$

Using the above given relation we obtain the $^{A}x_i{}^{A}y_i$ coordinates which are then used for generation of the leg-end positions at the beginning of the support phase during the turning motion

$$\begin{aligned} ^{A}x_i &= ^{B}x_i \cos\alpha - ^{B}y_i \cos\alpha + s\cos\alpha \\ ^{A}y_i &= ^{B}x_i \sin\alpha + ^{B}y_i \cos\alpha + s\sin\alpha \end{aligned} \tag{6.2}$$

7. Sensors

7.1. Force sensing

The simplest way to walk on a soft soil is to use fix locomotion cycles. However, non-homogeneity of the soil mechanical properties and unevenness of the terrain may result in noticeable disturbances of machine motion. To obtain a smooth motion, there is a need to individually correct the motion of each leg in accordance with its sinkage. In a simpler case where the soil properties are known, the correction of the leg-end position can be computed on the basis of the commanded force, without badly affecting the quality of motion. The sinkage should be considered, and the problem of proper leg-load distribution should be solved if the soil properties are not known or the terrain is uneven (see Debao et al., 1999; Hartikainen, 1996). The force-controlled walking machine would give additional advantages by increasing energy efficiency by a reduction in internal forces between the legs and providing the desired support forces regardless of the behavior of the terrain that is walked on.

For the position-force control of the leg-end the following relation has been implemented

$$\Delta z_{i+1} = (z_{ref} - z_i)k_p - (f_{ref} - f_i)k_f \tag{7.1}$$

where $z_{i+1} = z_i + \Delta z_{i+1}$ and z_i, z_{i+1} are the vertical leg-end coordinates (in the frame connected to the hip, this frame is non-moving in relation to the body), z_i is the reference value for the previous micro-step, z_{i+1} – for the actual micro-step, z_{ref} is the desired value during the support phase (constant), f_{ref} is the reference force (in our experiments this value was constant for whole support phase), f_i is the vertical force measured in the previous control step, k_p, k_f are the proportional gains. It is easy to notice that the factor k_p determines the legs return motion (to z_{ref}) after a change of position caused by a force impulse, k_f determines the leg-end force sensitivity. k_f to k_p ratio decides if the leg is more sensitive to force error or – to position error.

In practical implementation, relationship (7.1) was supplemented by logic rules which filtered the force measurement noises and limited the leg-end displacement during one control step. The k_f equal to 0.08 and k_p equal to 0.25 were used. The force control for the compliance control formula (7.1) was tested. The obtained results shown that the leg-end position was corrected accordingly to the changes of the ground reaction force (see Debao et al., 1999; Zielińska et al., 1999).

8. Sensors for environment exploration

The theoretical study includes development of the environment exploration strategy using sensory information. Crucial problems involve recognition of obstacle and motion planning using information from external sensors (onboard sensors monitoring the walking machine and environment interaction). In the current design, contact (touch) sensors on the leg-ends and ultrasonic range finder are considered. The ultrasonic-range finders mounted on the leg-ends and oriented horizontally will be used to detect distance to obstacles. They will play a crucial role in the adaptive planning of the leg motion, coordinated by a sophisticated free gait algorithm that attempts to overcome small obstacles.

The behavioral method of the free gait planning utilizing the biological hypothesis of the two-stage motion planning (as in the human brain) will be adapted for that purpose, see Zielińska (1997).

The experimental tests for the ultrasonic sensors were done, Fig.7 shows the angular range in horizontal plane of POLAROID sonar in relation to the distance of obstacle (every point is an average value of 30 measurements). The decrease of the angular range in relation of the distance is typical for sonar. The

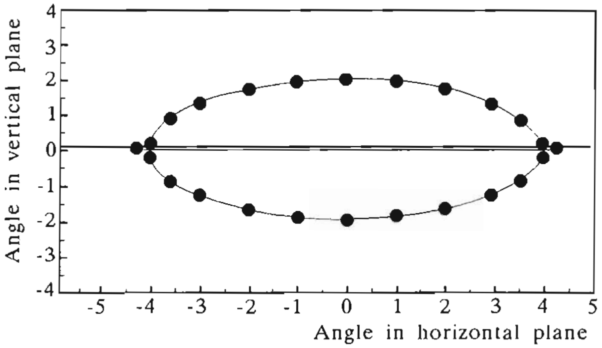

Fig. 7. Angular range of ultrasonic sensor

recorded data (Fig.7) is put into consideration with regard to design of number of the sensors and their localization across the walking machine body. From the data given, the assumption of the sonar sensitivity to obstacles located not further that 0.25 m decreases the required number of sensors and simplifies the control software responsible for sensory information. For a longer range (about 2 m) the number of sensors must be increased by at least two times. The final choice of the expected range of the sonar (and the quantity) will be related to the obtained speed and reaction time (ability to avoid obstacles) of the walking machine. For the proper design of sensory equipment the analysis of the sensor range in the vertical plane is also important.

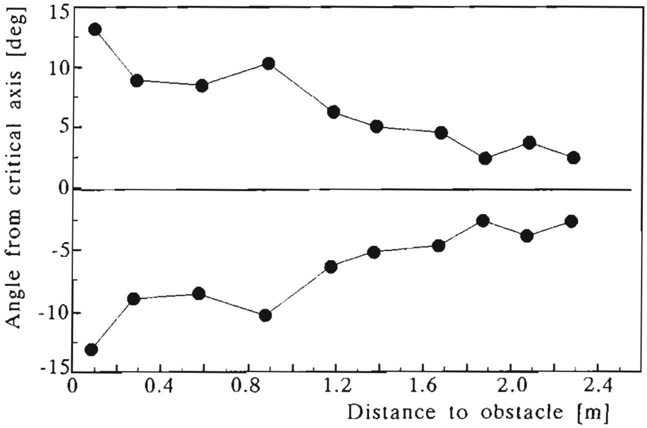

Fig. 8. Range of ultrasonic sensor in vertical plane

Fig.8 shows a vertical cut of ultrasonic sensor beam within the range of

1.5 m from the sensor. The sensor range across verticals is about two times smaller than the range in horizontal planes. These features must be considered as the sensors are dedicated not only to detection of the distance to obstacles but also to recognition of their sizes, see Zielińska and Szabelak (1998).

9. Conclusion

The development and usability of walking machines can be constantly improved by the aid of proper design. The final goal of this work is to develop an autonomous walking machine, which will be optimal from the point of view of energy consumption and will be able to operate autonomously in natural conditions. The main assumptions used for the design of the control system considering the problem of environment recognition using sensors are shown in this paper. The current research focuses on the synthesis of the control software and experimental tests of walking behavior.

Acknowledgments

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Projekt systemu mechanicznego i systemu sterowania maszyny kroczącej

Streszczenie

Autorzy opisują problemy projektowe aktualnie budowanej sześcionożnej maszyny kroczącej. Najpierw opisana jest struktura mechaniczna, następnie struktura sprzętowa. Dalej przedyskutowano zagadnienia związane z syntezą systemu sterowania, planowaniem chodu oraz detekcją siły i odległości. Podane są wybrane wyniki eksperymentów.

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