Development and Control of a Sensor Based Quadruped Walking Robot

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Abstract

This paper describes the development and control of a quadruped walking robot, named as KAISER-II.

The control system with multiprocessor based hierachical structure is developed. In order to navigate autonomously on a rough terrain, an identification algorithm for robot's position is proposed using 3-D vision and guide-mark pattern Also, a simple attitude control algorithm is included using force sensors.

Through experimental results, it is shown that the robot can not only walk statically on even terrain but also cross over or go through the artificially made obstacles such as stairs, horizontal bar and tunnel-typed one.

1. Introduction

The legged machine has off-road mobility, and due to this particular capability, the walking robot may replace human workers in nonplanar environments such as pipelined floor or under-sea, and this applies for nuclear power plants, undersea exploration or millitary purpose.

In the past 3 decades, the walking robots have been studied in various manners : ASV (Song and Waldron, 1988)[1], OSU Hexapod (McGhee and Iswandhi, 1979)[5], TITAN III(Hirose, 1984)[4], CMU Hopping machine (Raibert, 1984)[3] and WL-10RD (Takanishi et al., 1985)[2] are notable examples.

Their organization and characteristics mainly depend on the number of legs and on whether the control system is contained in the robot or not.

To develop a walking robot system, it is necessary to incorperate various technologies in the fields of mechanical design, control and computer science. Also, for autonomous navigation and terrain adaptation capability, there are many problems to be solved such as : gait generation, control system design problems and sensor integrated control using 3-D vision and force sensors, etc.

During the past 3 years, we developed two quadruped walking robots, KAISER-I, and II, and we shall describe the 2nd version.

The robot is equipped with 3 major sensors: two cameras for 3-D visual information processing, four force sensing resistor and a rate gyroscope for attitude control. Its control system has a multiprocessor based hierachical structure which is composed of supervisory controller, gait controller and servo controller.

The control system structure and the robot mechanism is described in section 2. In section 3, the robot's 3-D position identification algorithm and the attitude control algorithm are explained. Finally, for the validity of the proposed control system and algorithms, experimental results of crab walking and obstacle-crossing is shown.

2. Mechanism and Control System

2.1 Mechanism

As the walking robot can carry all its driving units together with its body, energy efficiency must be considered in mecanical design of a walking robot. Also, considering walking capability, we design the walking robot which can walk on even terrain at its maximum speed of 0.15 m/s and can climb stairs of 50% grade with kepping its body level.

Based on these design principles, KAISER-II was fabricated as shown in Fig. 1. It has four legs made by the material of carbon fiber epoxy for lightening weight as well as high degree of strength. Each leg has 3-d.o.f. and takes the shape of a pantograph mechanism in x-,z-direction, a 4-bar straight line generator in y-direction. This mechanism allows independent movement in each direction. Therefore, energy consumption can be reduced[4].in addition, kinematic relations are simplified. And the detailed specifications of KAISER-II are as followings :

-. Total weight : 75 kg
-. Body size : 820 x 430 x 416 [mm]

-. Walking volume of a leg : 1000 x 300 x 650 [mm]
-. Magnifying ratio of pantograph : 5:1 in x-axis, 4:1 in z-axis
-. Actuators : DC servo motor of 100W, 60W, 100W in x-,y-,z-axis, respectively
-. Reduction gear ratio : 1:1, 480:1, 8:1 in x-,y-,z-axis, respectively

In the center of body, two cameras are mounted, which can move in vertical and horizontal direction by step motors.

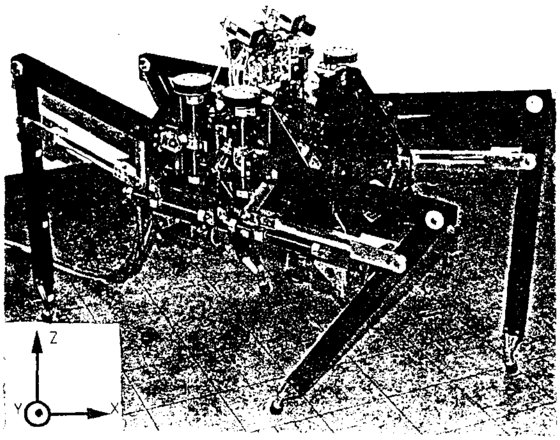

Fig. 1. Overview of KAISER-II

2.2 Control System

The overall control system of KAISER-II has the hierachical structure

While each system has its own functions, it must be coordinated so that the total system may perform any tasks assigned by human operator. This coordination capability is provided by supervisory controller. Thus, the supervisor schedules the executing sequence of a series of jobs for a given task. After that, considering synchronization between jobs, the supervisor distributes them to each system.

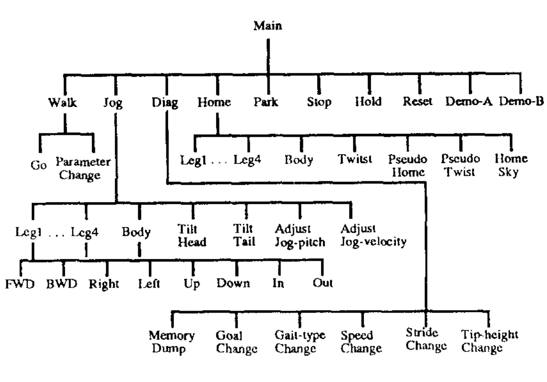

Fig. 2. Hierachical menus

Besides of coordination capability, the supervisor provides the hierachical menus (shown in Fig. 2) as an user-friendly man-machine interface. Using these menu, operator can monitor the status of the robot system in real time and can modify several parameters such as gait-pattern, walking stride, etc.

The vision system is capable of 3-D visual information processing, so it measures the distance to obstacles and robot's 3-D position in a world coordinate frame using a proposed guide-mark pattern (GMP). Especially, this 3-D vision system is indespensible for autonomous navigation capability.

The gait controller is inherent part of walking robot's control system in comparison of mobile and industrial robot's one. Under the consideration the robot's static stability, it plans the trajectories of each leg and body. This gait controller can generate a crab gait for omnidirectional walking and a obstacle-crossing gait.

According to the desired position and speed given by the gait controller, the servo controller controls each leg's (12 d.o.f. in all) positions and speeds by means of 12 position controllers and servo amplifiers. Moreover, the servo controller has the hardware units for interfacing the 12 force sensors and a rate gyroscope.

In the view of hardware configuration of the total control system, MVME147 system is used as a host computer and a 32-bit cpu board (MVME133A) is assigned to each controller. As the result, the total control system has a multiprocessor structure of a time shared/common bus-type as shown in Fig.3. The communication between controllers is accomplished by a proposed handshaking-protocol, via a dedicated space in common memory. Whereas, each controller can execute its own algorithms under the small-sized multi-t king O/S, called VMEexec.

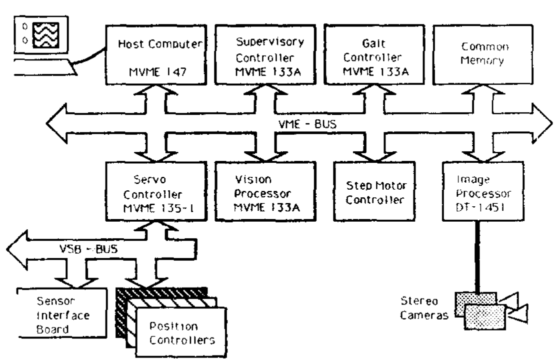

Fig. 3. Overall control system of multiprocessor structure

3. Capabilities of handling uncertainties

3.1 Identification of robot's 3-D position

Consider the case which the robot walk along a path described in world coordinate frame. With the roughness of terrain and uncertainties of robot itself, the robot's position have to be identified so that the robot can execute a task more accurately.

So far, several identification algorithms for mobile robot in 2-D space have been investigated[12]-[13]. These method, however, cannot be applicable to the walking robot's case. Because, in walking robot's case, it is essential to identify the robot's orientation as its posture together with its 3-D position. Also, some algorithms for 3-D case has been reported[14], but these are complex or iterative methods.

Thus, using streo vision and a proposed GMP, a new identification algorithm for a walking robot is proposed ,which offers a closed-form solution.

3.1.1 Position Identification

In the coordinate frames established as shown in Fig. 4, the robot's position and orientation can be identified by specfying the homogeneous transformation matrix ${}^{W}_{R}T$. Since the relation between the coordinate frame of the robot and that of the camera's is given as the transformation matrix ${}^{C}_{R}T$, it is necessary only to find the matrix ${}^{W}_{C}T$ according to the equation,

$$ {}^{W}_{R}T = {}^{W}_{C}T \cdot {}^{C}_{R}T $$

Fig.5 shows that the feature points on GMP form a coordination frame (GMP coordinate frame) and the transformation matrix ${}^{W}_{G}T$ is given. Then, the equation can be obtained as following :

$$ {}^{W}X_C = {}^{W}_{G}T \cdot {}^{G}X_C \qquad (3.1) $$

where,

$$ {}^{W}X_C = \begin{bmatrix} {}^{W}P_C & 1 \end{bmatrix}^T = \begin{bmatrix} x_C^W & y_C^W & z_C^W & 1 \end{bmatrix}^T $$

$$ {}^{G}X_C = \begin{bmatrix} {}^{G}P_C & 1 \end{bmatrix}^T = \begin{bmatrix} x_C^G & y_C^G & z_C^G & 1 \end{bmatrix}^T $$

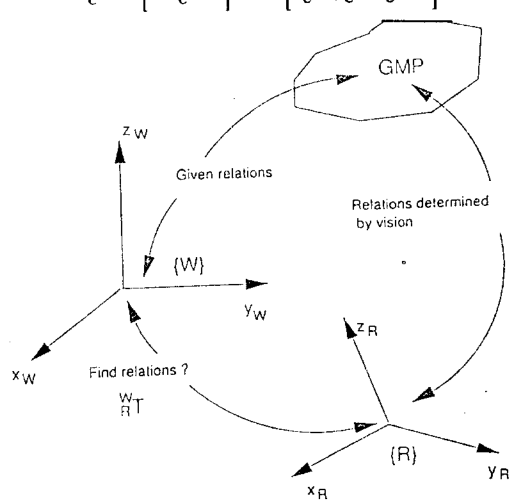

Fig. 4. Relationship between coordinate frames

And the vector ${}^{G}X_C$ can be calculated geometrically by the 3-D visual information processing. Consequently, the position vector ${}^{W}X_C$ which is the 3-D position of the camera in world coordinate frame can be calculated independently with the robot's orientation.

3.1.2 Orientation Identification

For a feature point F_i on GMP, the following equation can be derived.

$$ {}^{W}X_{F_i} = {}^{W}_{C}T \cdot {}^{C}X_{F_i} \qquad \text{for } i=1,2,\ldots,n $$

This equation can be rewritten as

$$ \begin{bmatrix} {}^{W}P_{F_i} \\ \\ 1 \end{bmatrix} = \begin{bmatrix} {}^{W}_{C}R & {}^{W}P_C \\ \\ 0 & 1 \end{bmatrix} \begin{bmatrix} {}^{C}P_{F_i} \\ \\ 1 \end{bmatrix} \qquad \text{for } i=1,2,\ldots,n $$

$$ {}^{W}P_{F_i} = {}^{W}_{C}R \cdot {}^{C}P_{F_i} + {}^{W}P_C $$

$$ {}^{W}P_{F_i} - {}^{W}P_C = {}^{W}_{C}R \cdot {}^{C}P_{F_i} $$

And let ${}^{W}P_{F_i} - {}^{W}P_C$ be P_i , then,

$$ P_i = {}^{W}_{C}R \cdot {}^{C}P_{F_i} \qquad (3.2) $$

With three feature points, the equation (3.2) can be represented as

$$ \begin{bmatrix} P_1 & P_2 & P_3 \end{bmatrix} = {}^{W}_{C}R \cdot \begin{bmatrix} {}^{C}P_{F_1} & {}^{C}P_{F_2} & {}^{C}P_{F_3} \end{bmatrix} \qquad (3.3) $$

$$ {}^{W}_{C}R = \begin{bmatrix} P_1 & P_2 & P_3 \end{bmatrix} \cdot \begin{bmatrix} {}^{C}P_{F_1} & {}^{C}P_{F_2} & {}^{C}P_{F_3} \end{bmatrix}^{-1} \qquad (3.4) $$

As the result, we see from (3.4) that the rotation matrix ${}^{W}_{C}R$ related to the robot's posture is obtained.

From the requisites of GMP as mentioned above, it may be summarized that GMP must form a coordinate frame having feature points more than 3 points. To meet this requirement, a simple triangle-typed GMP is devised.

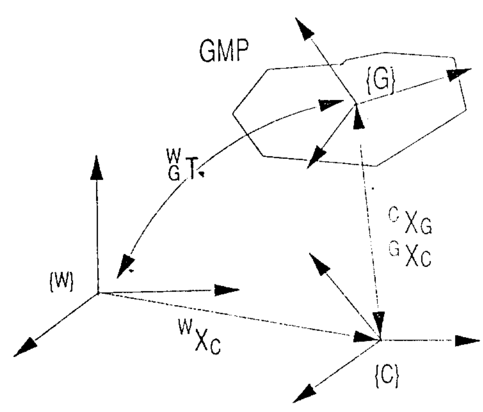

Fig. 5. GMP coordinate frame

3.2 Attitude Control

In the case of walking on even terrain, it is not so difficult to control the robot's attitude. Since each leg may be located on the same position as the calculated one in advance.

Whereas, without any information about the roughness of terrain and with a pre-planned gait, the robot can not walk ahead stablely because of its body inclination.

To solve this problem, some kind of sensors are needed. Although the robot is equipped with stereo vision sensor, it is not adequate to measure the roughness of terrain in real time.

Thus, the force sensors, FSR(Force Sensing Resistor), are attached on the each sole of foot. If no uncertainty of robot itself are envolved, it is sufficient to use FSR as a touch sensor on hard ground.

However, as the robot has the mechanical uncertainty due to the looseness of joints and deformation of body, so the robot body droops in the side of a swing leg. Therefore, to control the attitude of body, the leg's length to be moved downward must be adjusted.

For this reason, a heuristic algorithm of attitude control is proposed as shown in Fig.6. The value α is the leg's length of difference between desired one and measured one for keeping the body flat. From the many experiments of walking on even terrain, the average value of α is obtained. Using this value α related to the amount of deformation, it is shown in Fig. 7 that the robot can walk with small fluctuation of body.

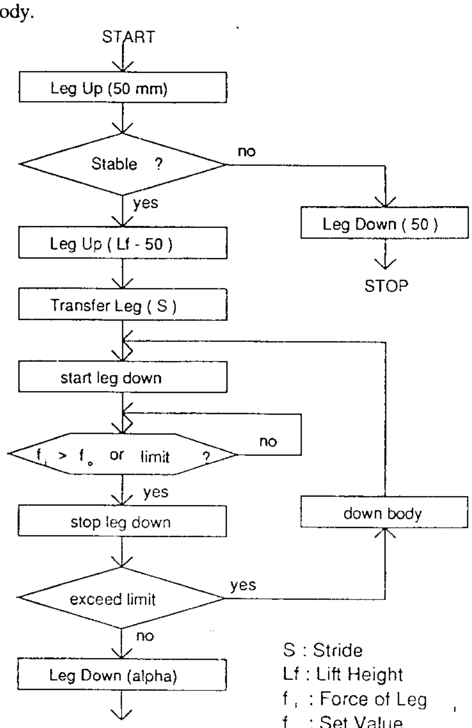

Fig. 6. Flowchart of a proposed algorithm for attitude control

In this experiment, we use several wooden blocks which are 12mm, 31mm, 51mm high, respectively.

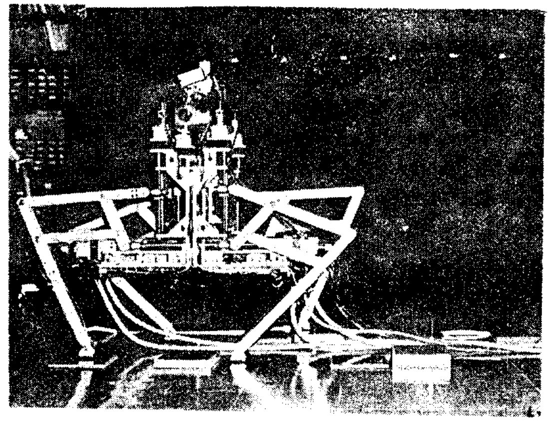

Fig. 7. Walking on unknown rough terrain with the attitude control

4. Experimental Results

We have performed various experiments to examine the capability of KAISER-II and the overall control system.

On the walking on even terrain, KAISER-II can walk straightly at speed of 0.03m/sec with its maximum leg's stride of 850mm. According to the design specification, the maximum speed of static walking is 0.15m/sec. But, the closer to the maximum speed, the more dynamic effects are appeared.

In addition to the straight walking, Fig.8 shows that the robot execute the crab walking at the crab angle of 8 degrees. The maximum crab angle is about 17 degrees in the forward direction.

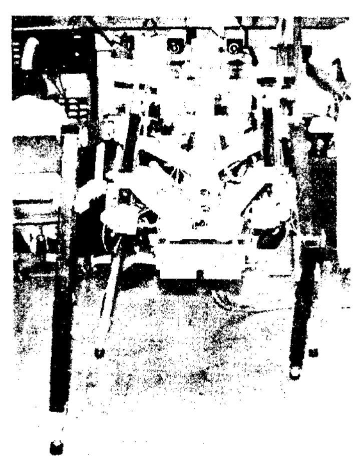

Fig. 8. Crab walking

For the adaptive walking over irregular terrain, three kinds of experiment are executed. These are :

1) walking across the horizontal bar of the height of 20cm, after the vision system measures the distance between the robot and the horizontal bar using a GMP. (Fig.9)
2) walking up and down the stairs of 40% grade. (Fig.10)
3) walking through the tunnel-typed obstacle which has lower height of 30cm than the robot's normal one with pitching motion of 5 degrees. (Fig.11)

5. Conclusion

This paper has presented the overall control system of KAISER II and a sensor integrated control algorithm for handling uncertainties. Through various experiment of walking on uneven terrain, the capability of the developed KAISER-II system was verified.

Especially, the details of the gait generation algorithm and the mechanical design have been reported in another papers[10]-[11]. However, many unsolved problems are still remained.

To enhance the capability of autonomous navigation, the path planning of walking robot and sensor fusion algorithms will be studied in further research.

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Fig. 9. Walking across the horizontal bar

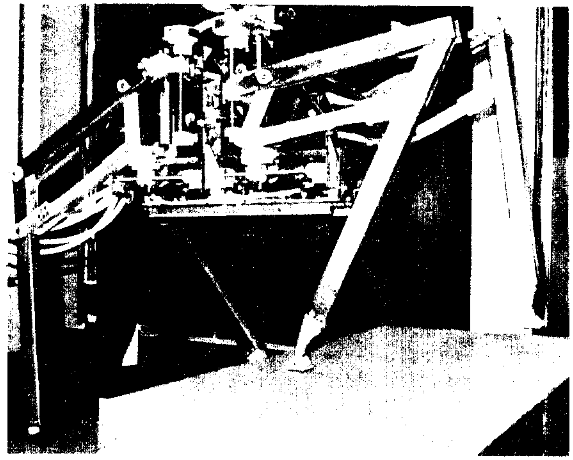

Fig. 10. Walking on stairs

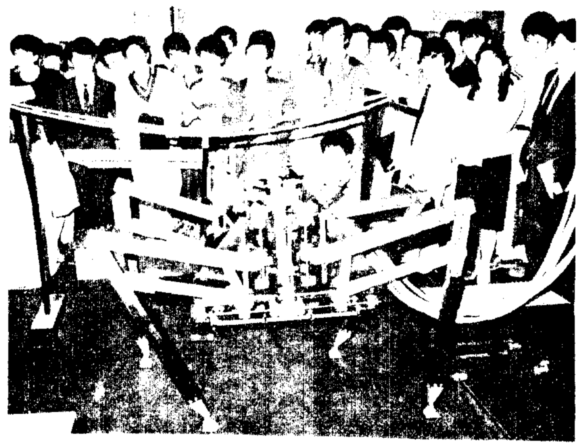

Fig. 11. Walking through the tunnel-typed obstacle

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