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A new real-time control method for free locomotion in a walking robot

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Abstract: This paper presents a new real-time control method for free locomotion in a walking robot. The walking robot, named RIMHO, has been developed as an exercise in expert control of legged locomotion. A brief description of the robot and its model are given. A description of the relationship between the machine level and the control station level is presented. The paper also presents a new free locomotion method for forward and turning gaits. The locomotion method shows an interesting phrasing to solve the stability problem at the beginning of locomotion from any initial configuration of the robot. The new real-time control method is used by a human to operate the robot using a virtual reality representation in the control station machine. In this way, a three-dimensional graphical representation in real time is used to test the effectiveness of the locomotion.

Key words: legged locomotion, real-time control, robotics, walking machines.

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1 INTRODUCTION

Simulation technology is becoming a great tool at the same time as computer power increases. In the case of walking robots, it is very useful for the design, construction, and control of each part of the robot. New computers make it possible to research new strategies for walking, by simulating a sensor system and an imaginary robot's states to plan a locomotion solution in real time. Walking machines offer some advantage over wheeled vehicles in rough terrain, e.g. greater mobility, better isolation from terrain irregularities, less environmental damage, and better energy efficiency. These advantages made free locomotion appropriate for some emerging new potential applications such as planetary exploration, underwater tasks and forestry or industrial agriculture. Up to the present, many researches on gaits for legged robots have built simulators to understand how locomotion is performed in machines and its relationship to animal locomotion. This paper presents new findings about free locomotion gaits by using a three-dimensional graphical simulator as an interface with a human operator in the control station.

2 DESCRIPTION OF THE WALKING ROBOT

The RIMHO (Figure 1) is a quadruped walking robot that can be classified as an insect type. This robot has not been developed for any specific application, although we are interested in hostile environments. At present it is used as a test bed for various ideas concerned with walking vehicles [1]. Its four legs are based on a three-dimensional cartesian pantograph mechanism [2], which consists of four links that provide three degrees of freedom. The body of the RIMHO is 735 mm long, 710 mm wide and 344 mm high. The machine's weight is 65 kg, and the robot can carry 25 kg. The chassis and links are mainly made of aluminium. The leg positions are controlled with a personal computer. There are incremental optical encoders of 500 pulses per revolution attached to the motor shaft (12 in all). The RIMHO has a step height of 240 mm, and has been designed to do omnidirectional movements under the supervision of a Control Station.

3 KINEMATICS MODEL

The objective of keeping the robot's body in a required position and orientation, has led us to determine the kinematic model of the walking robot. The kinematics equations are quite simple if it is assumed that each part of every leg is a rigid body, and each leg is supported in a contact point on the ground. For the solution of the kinematics inverse problem we have placed a reference system fixed on the geometrical centre of the body, and four auxiliary reference systems distributed in the body (one for each leg). Figure 2 shows the coordinate systems and the vectoral relationships used in the model.

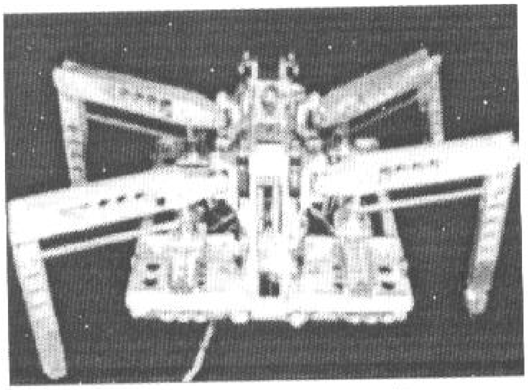

Figure 1 *The RIMHO walking machine.*

The geometry of one leg (Figure 3) permits us to define the A point placed on the joint as it produces displacement in the horizontal plane (XY), and the B point on the joint as up and down movements are made [3].

The reduced equation for the twelve joints (three for each leg) to solve the kinematics inverse problem may be expressed as,

$$\begin{pmatrix} X_A \\ Y_A \\ Z_B \end{pmatrix}_i = \begin{bmatrix} \frac{L2}{L5} & 0 & 0 \\ 0 & \frac{L3}{L5} & 0 \\ 0 & 0 & -\frac{L2}{L1} \end{bmatrix} \times \left\{ \begin{bmatrix} \cos\gamma\cos\psi & \begin{matrix} -\sin\gamma\cos\theta\cos\psi \\ -\sin\psi\sin\theta \end{matrix} & \begin{matrix} \sin\gamma\sin\theta\cos\psi \\ -\sin\psi\cos\theta \end{matrix} \\ \sin\gamma & \cos\gamma\cos\theta & -\cos\gamma\sin\theta \\ \sin\psi\cos\gamma & -\sin\psi\sin\gamma\cos\theta & \begin{matrix} \sin\theta\sin\gamma\sin\psi \\ -\cos\theta\cos\psi \end{matrix} \end{bmatrix} \times \begin{pmatrix} P_X - CR_X \\ P_Y - CR_Y \\ P_Z - CR_Z \end{pmatrix}_i - \begin{pmatrix} V_X \\ V_Y \\ V_Z \end{pmatrix}_i \right\} \tag{1}$$

where $L5 = L1 + L2 = L3 + L4$; $L1 = 14 = 400$ mm; $L2 = 13 = 100$ mm; P_i is a vector from the fixed inertial system to the endpoint of the leg i; $i = \{1, 2, 3, 4\}$; CR is a vector from the fixed inertial system to the geometrical

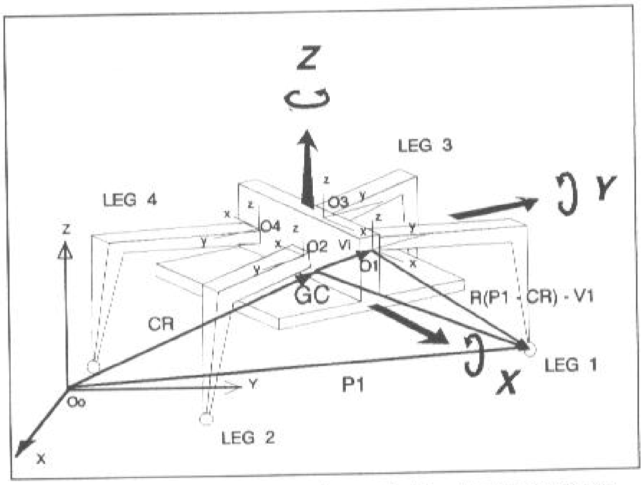

Figure 2 *The coordinate systems and vectoral relationships for the RIMHO.*

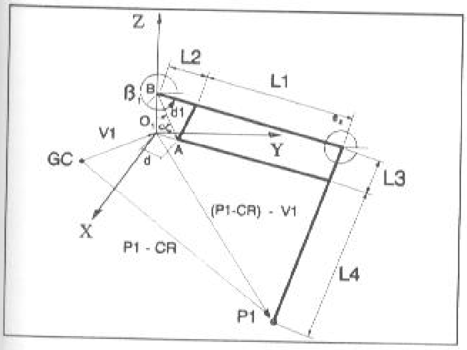

Figure 3 *Geometric parameters for the mechanism of leg 1.*

center of the body; V_i is a vector from the geometrical centre of the body to the origin O_i of each leg; θ, ψ, γ define the orientation of the body in the X, Y and Z directions, respectively. The locomotion movements are designed for a low velocity, 25 mm/s up and down, and 100 mm/s as the highest forward speed. Equation 1 shows three different actions for walking in an instant of time: linear movement in a leg, linear movements in the body, and turning the body.

4 THE CONTROL SYSTEM STRUCTURE

The control system structure consists of two levels: Control Station Level and Machine Level. These two levels work in separate computers connected via an RS-232. All twelve joints in the machine are driven by DC servomotors. Each motor is controlled by a dedicated microcontroller that provides the interface between motor drivers and processors. Apart from the proprioceptive sensors employed on the actuation control system there are four contact sensors (one for each leg). These sensors determine whether the foot is on the ground or not, and permit us to modify the decision for walking according to the internal and external locomotion parameters.

The automatic free locomotion decisions are based in the structure control shown in Figure 4. An interesting possibility is to plan a locomotion mission over different terrain using simulation. The locomotion plan is supervised for the gait and attitude controllers. In this way, new conditions are analysed to get new experiences in the walking process and improvement to the controllers. These experiences are useful for locomotion control in real time. The environment control implements the combination of the real and artificial environments with the intention of providing information to

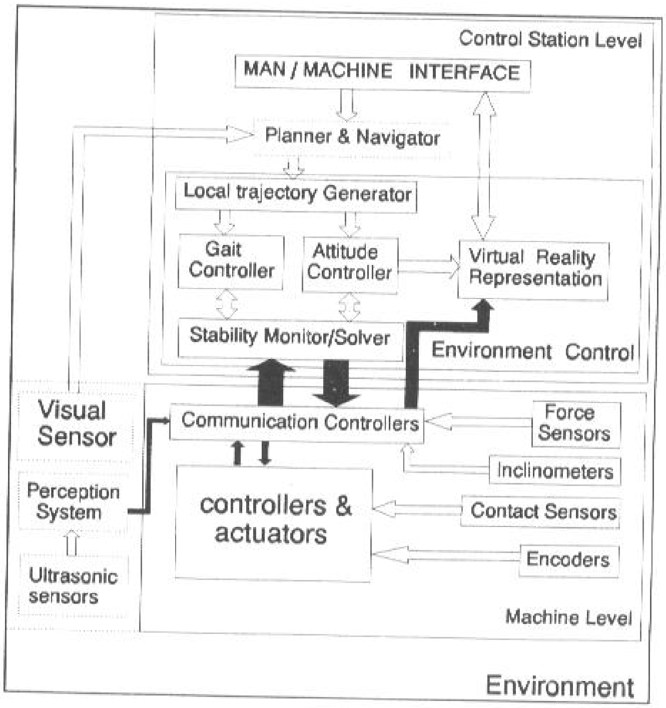

Figure 4 *The RIMHO control system.*

the human operator. The man/machine interface enables the operator to drive or select free locomotion in order to get the walking machine into a required position and orientation. We define two classes of sensor:

1 *Internal.* These sensors are used to measure the internal characteristics of the robot (position, internal forces, orientation, and state of the legs).
2 *External.* These sensors essentially provide information about the place in which the robot is walking (TV camera) and the irregularities of the terrain (ultrasonic sensors).

The technical design also establishes the relationship between the sensors and actuators in order to control the global configuration of the walking robot. The free locomotion actions are based on new locomotion knowledge. This locomotion knowledge presents good stability and mobility in the machine for practical locomotion in real time.

5 NEW LOCOMOTION KNOWLEDGE

In this research the process for walking is considered to be movement under static stability. So, when the robot walks there are at least three legs supporting the body, and the projection of the centre of gravity of the body (GC) in a horizontal plane is on the supporting polygon (see Figure 5). To evaluate stability we use the stability margin, which is defined as the minimum distance between the vertical projection of the centre of gravity of the body, on a horizontal plane, and the border of the support polygon. The problem to select all possible movements and get the sequential moves for the locomotion process without loss of stability or significant decrease in the robot's mobility has led us to research the free locomotion problem [4].

We divide the supporting polygon into four triangles: A, B, C and D (see Figure 6).

The cross of verteces (CV) is a new locomotion parameter defined in this paper. It is used for a number of purposes: to place the projection of the GC in a final position for the start of a new step, to finish the global step of the robot, and to decide the trajectories for the legs and the robot's body. The security radius permits us to avoid the calculation cost of the real position of the robot's centre of gravity. We consider that the centre of gravity is within the circumference of the security radius. The centre of this circumference is in the centre of gravity of the body (GC), and the error in the real position may be considered in any locomotion direction. We have confirmed by experiment that the robot shows good stability for a security radius of 60 mm.

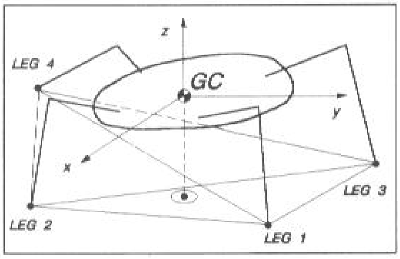

Figure 5 *Supporting polygon.*

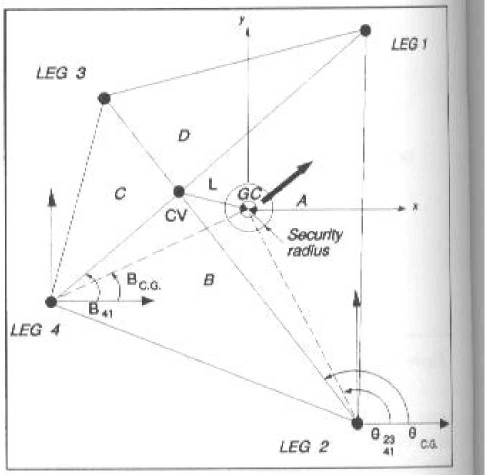

Figure 6 *Parameters defined in the supporting polygon.*

The work space of the robot has been evaluated to permit only movement in real conditions, and avoid possible interference and impacts with the legs or the terrain when the robot is walking (see Figure 7).

The displacement margin of the body (Sc), is defined as the minimum distance between the borders of the work space and the actual position of each leg in the direction of locomotion. The value of Sc denotes the mobility of the robot and its influence on the stability produces new evaluations to consider.

The displacement margin of the legs (Sp), is defined as the distance from the actual position of a leg to a cross point between the border of the work space and the vector of the locomotion direction.

The method of obtaining the free locomotion gaits is based on Figure 8. The first step of this method consists in calculating the position of the GC in the supporting polygon, and then evaluating the locomotion parameters according in which section of the supporting polygon is the GC. After calculating the locomotion parameters, a selection is made in order to move the element that shows the best stability and mobility conditions. In this way, a free locomotion solution begins to take form.

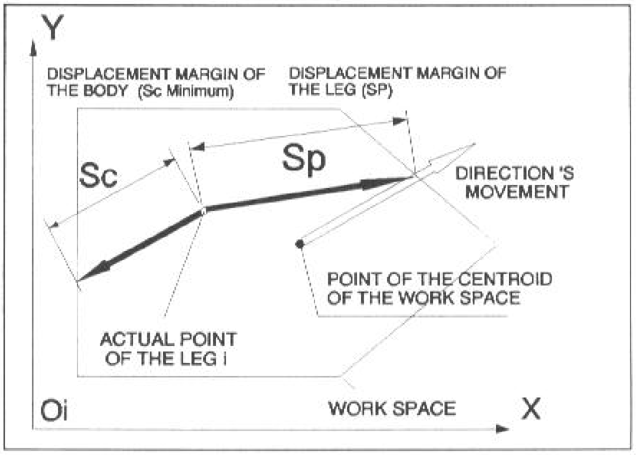

Figure 7 *Locomotion parameters in the work space of a leg.*

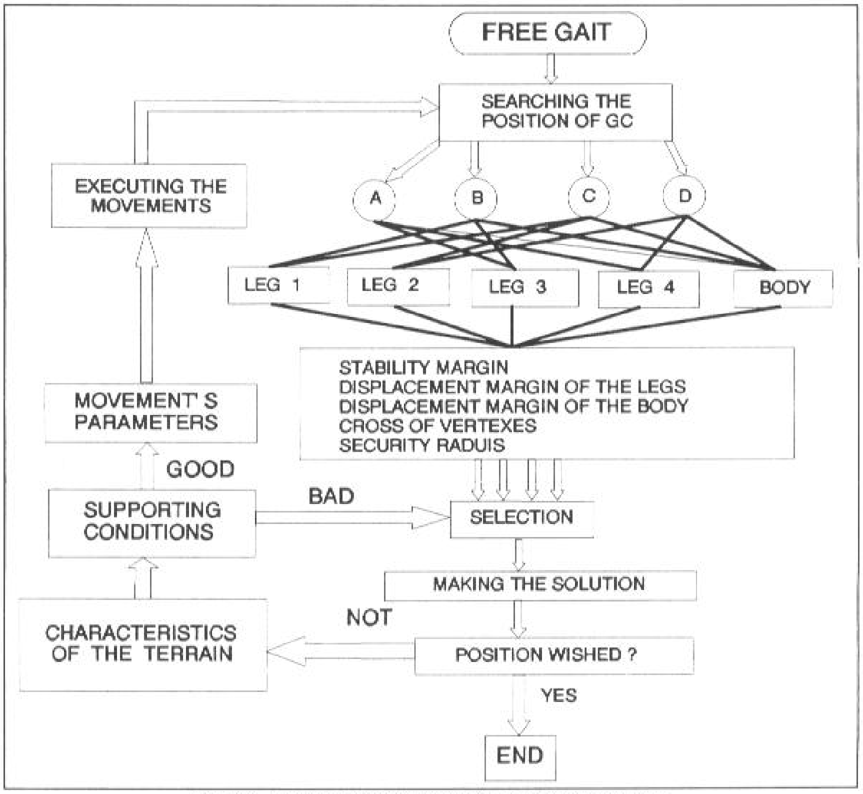

Figure 8 *Diagram of decisions to obtain free locomotion gaits.*

Figure 8 shows that the terrain characteristics will be evaluated if the total displacement of the robot is not complete. After this, the supporting conditions are evaluated to determine if a new selection is necessary (bad conditions) or whether the computation of the parameters of movements is complete (good conditions). From the execution of the movements we get a new configuration of the robot. There is then a new supporting polygon to evaluate and the method is begun again. The execution of the free gait can be stopped by the human operator.

6 EXPERIMENTS

The free locomotion experiments have been analysed for the two types of gaits: forward and turning.

1. *Forward*: This kind of locomotion enables the robot to walk in a straight line. The walking directions obtained in our experiments take values from 0 to 360 degrees, wave-crab angle. The initial geometry at the beginning of a walk is not fixed, and the sequence obtained in some cases are repetitive and some times not, depending of the evaluation of the internal and external parameters.
2. *Turning*: This kind of locomotion permits to walk the robot on a circumference trajectory. The gravity center of the body is moved at the same time as the orientation is changing. The locomotion begins from any initial configuration.

6.1 Forward gait

In the case of forward locomotion, we have tested the stability for different wave-crab angles. Figure 9 shows the trajectories obtained when the robot made five steps on an irregular terrain with a incremental direction of 30°.

The trajectories show that the free locomotion gaits get good results for the robot displacement. The following empirical equation for the trajectories of the legs has been obtained by simulation, and later verified with experiments.

$$\mathrm{d}X_{\mathrm{LEG}} = \left(1 - \frac{1}{3 * N.STEP}\right)\Delta X_{\mathrm{LEG}} \cos\sigma - \left(1 - \frac{1}{3 * N.STEP}\right)\overset{\Delta Y}{\Delta X}_{\mathrm{LEG}} \sin\sigma \qquad (2)$$

$$\mathrm{d}Y_{\mathrm{LEG}} = \left(1 - \frac{1}{3 * N.STEP}\right)\Delta X_{\mathrm{LEG}} \sin\sigma + \left(1 - \frac{1}{3 * N.STEP}\right)\overset{\Delta Y}{\Delta X}_{\mathrm{LEG}} \cos\sigma \qquad (3)$$

where σ is the orientation of the body in the plane XY; ΔX_{LEG} is the partial increment in the X direction of the leg; ΔY_{LEG} is the partial increment in the Y direction of the leg; $\mathrm{d}X_{\mathrm{LEG}}$ is the total displacement of the leg in the X direction; $\mathrm{d}Y_{\mathrm{LEG}}$ is the total displacement of the leg in the Y direction; $N.STEP$ is the step number. The behaviour of the stability shows a moderate security according with the minimum values of Sm (see Figure 10).

6.2 Turning gait

The disposition of the legs in the body and the work space limits are the most important parameters to determine the minimum radius for the free turning gait.

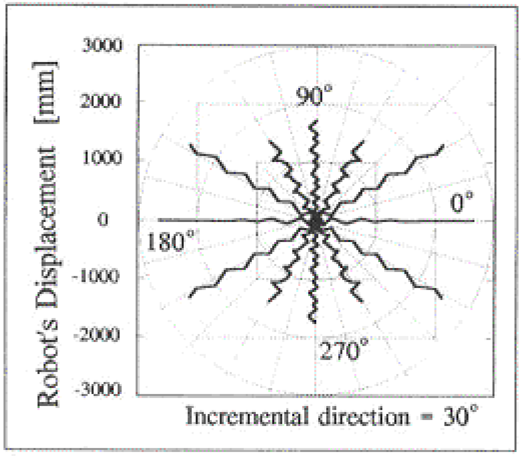

Figure 9 *Trajectories of the robot for different directions.*

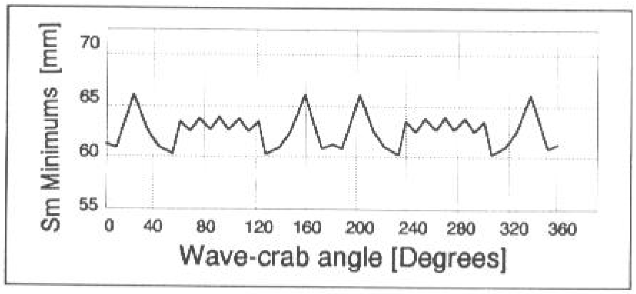

Figure 10 *Minimum values of the Sm for the free forward gait.*

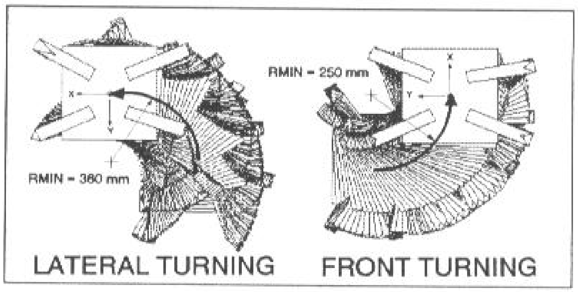

Figure 11 *Lateral and front turning free gait trajectories.*

At the movement, we have defined two types of turning mode: lateral and frontal (see Figure 11).

The sequences observed in the robot for the turning modes are non-periodic. In accordance with the locomotion parameters, the stability of the robot was maintained in each instant time. The minimum radius for the lateral and front turning free gaits are 360 mm and 250 mm, respectively.

7 CONCLUSIONS

The real-time control method proposed in this paper for free locomotion gait can easily be drived by a human operator. The strategy to form a free locomotion process in real-time is one of the reasons the control system works efficiently for practical locomotion. A contribution to the free locomotion theory for walking machines is the definition of a new parameter the cross of verteces. This parameter can be extended to walking robots with more than four legs. An advance in solving the stability problem is the innovative treatment of the supporting polygon. We consider that the free locomotion gaits can be characterised with five parameters: stability margin, security radius, displacement margin of the body, displacement margin of the legs, and the cross of verteces.

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