# On the Control Problem of a Legged Robot

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**Abstract:** A walking machine is a system that presents many important control problems, since the dynamics of the machine changes with its configuration, especially when it has to obey a specific gait. However, minor attention has been paid to this difficulty. To ensure a good performance, this paper presents a simple, practical methodology for tuning the individual joint controller when it is subject to a specific gait. This methodology consists in a look-up table that updates filter parameters. This paper will consider the discontinuous gait and identify the main dynamic phases. It will also extend the same methodology to the wave crab gait. Some experiments performed on the RIMHO machine are reported, ending with comments and conclusion.

## 1. Introduction

At present, many aspects about legged robots are under scientific investigation. Gait generation is still an important field of research, as are walker mechanics and the study of force distribution to improve stability and avoid slippage. All these subjects must be explored to achieve successful construction of a walking machine. They have been studied in theory, and many important conclusions have been reported, but the incorporation of these results in a real machine is not easy to perform. Fundamental aspects of legged locomotion, pertaining to the problem of control ,are mainly related to the different locomotion phases within a particular gait, such as the passage from n-legs to m-legs support phases, the single leg transfer and the propulsion of the body using all legs. That means that the walking robot's dynamics is changing significantly, resulting in a complex control problem. This paper presents a qualitative methodology for identifying the main dynamic phases when the machine is subject to specific gait. In order to ensure good overall performance during this gait, a simple and practical strategy consisting in a look-up table for updating the controller parameters is used. The table has been prepared using an off-line identification of each joint in each of the dynamic phases mentioned below and deducing the filter parameters. The paper considers the discontinuous gait, which is characterized by a sequential leg-and-body motion. The same methodology will be extended to the wave crab gait.

The remainder of this paper is organised as follows : The overall view of the RIMHO walking robot and its control system are presented in Section 2. The joint control system is presented in Section 3. In Section 4 the main dynamic phases corresponding to a discontinuous gait are pointed out. The design problem is considered in Section 5. Experiments are reported in Section 6.

## 2. Description of the Machine[1, 2]

### a.- The RIMHO Mechanism

The RIMHO is a four-legged robot built to aid in basic research on legged locomotion and also to provide expertise in inspection tasks over unstructured environments. This walker may be classified as an insect type (Figure 1). Its four legs are based on a three dimensional cartesian pantograph mechanism, which consists of four links providing three degrees of freedom. This kinematic arrangement involves decoupling horizontal motion from vertical motion. The body of the RIMHO is 736 millimetres long, 710 millimetres wide, and 344 millimetres high, and the machine weighs about 60 kilograms. The longest leg link is 500 millimetres long. The machine's joints are driven by DC motors.

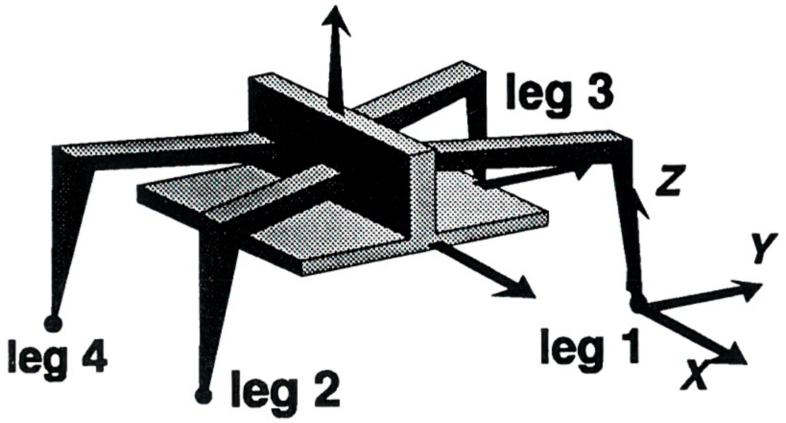

Figure 1a. RIMHO Reference Frames

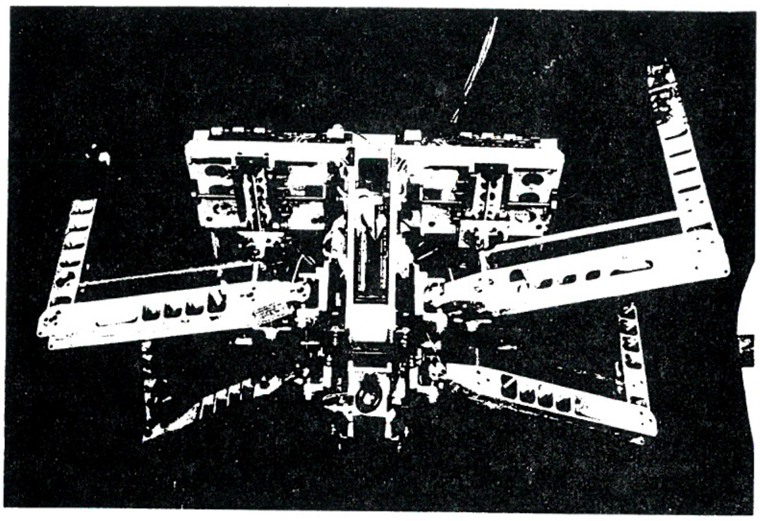

Figure 1b. RIMHO Walking Machine

The machine is equipped with three kinds of sensors:

1.- Incremental optical encoders for feeding back the shaft positions.
2.- Contact sensors on the sole of each foot to report whether the foot is on the ground or not.
3.- Two perpendicular coupled inclinometers for levelling control.

### b. The RIMHO Control System

The RIMHO Control System, outlined in Figure 2, follows a hierarchical structure. This system is physically divided into two levels: the control station level and the machine level. These two levels work through separate computers connected via RS232.

The machine level runs on a VME system on board the vehicle. This system works as a stand-alone system, and it consists of two Motorola processors that perform general-purpose processing for the walking robot. One of them takes care of the joint controllers, and the other processor works as a host processor supervising the entire system and handling the communications with the control station, based on a PC computer, which is located outside, away from the machine. Interprocessor communication on the machine level takes place through shared memory, and communications with the control station level are achieved serially using a suitable protocol.

All twelve joints in the machine are driven by DC servomotors. Each motor is controlled by a dedicated HCTL-1100 microcontroller that interfaces motor drivers with processors. This device is presented in the next section.

Apart from the proprioceptive sensors employed in the actuation control system, the RIMHO has a contact sensor on the sole of each foot that reports whether the foot is on the ground or not. These sensors permit the system to modify a flat terrain gait and to adapt it to a relatively smooth terrain. Other on board sensors include a two-axis inclinometer that gives the machine's roll and pitch tilt. The next step in the Sensor System will incorporate four three-axis force sensors on each foot.

The control station level runs on a PC computer, and it is divided into three sub-levels : the upper sub-level is the man/machine interface, the middle sub-level is the pilot, and the lower sub-level includes communications with the machine, the command interpreter, and the command sequencer.

## 3. The Joint Control [3, 4]

To address the multi-axis problem in RIMHO robot control, suitable boards (compatible with the PC Bus) are used. One board can control up to 4 robot joints. They are based on the HCTL-1100, which is a general purpose motion control IC. These control boards perform all the real-time intensive digital control calculations, freeing the host processor for other high level tasks, such as navigation, piloting, etc. Another advantage is the programmability of all control parameters, which are accepted asynchronously with respect to the control axis functions. A maximum flexibility with quick control system design using a minimum number of components, is provided. The microcontrollers receive input commands from the host processor, and the position is fed back from the optical encoders.

The microcontroller compares the desired position (or velocity) to compute the control signal using a programmable digital filter, D(z), with the following transfer function:

$$D(z) = \frac{K(z - a / 256)}{4(z + b / 256)}$$

where K, a and b are programmable parameters. The filter output is transformed by means of a PWM port into the motor's command (a pulse width modulated signal with the correct polarity (sign) that is needed by the power board, that uses H-bridge amplifiers). Loop control is outlined in Figure 3.

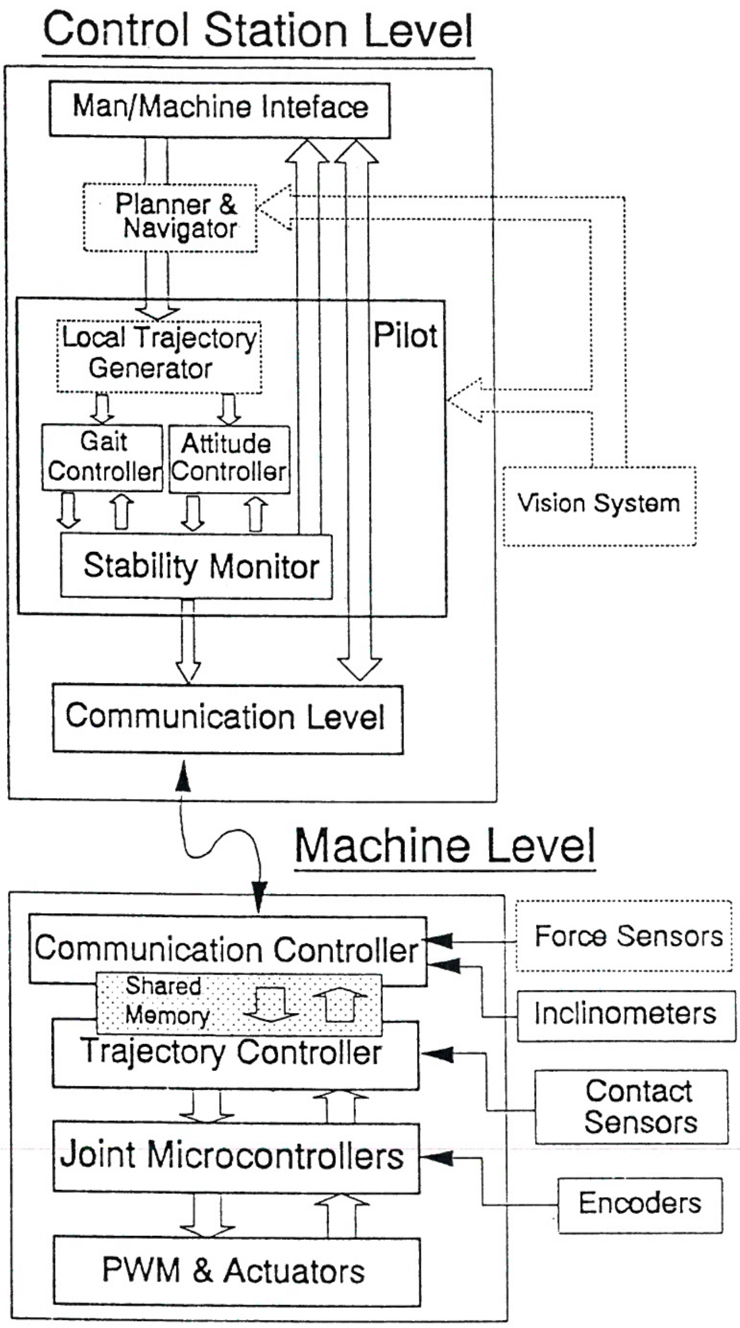

**Figure 2 - RIMHO Control System**

A trapezoidal profile is used to control the drives. It performs point-to-point position moves and profiles the speed trajectory to trapezoid or triangle. The operator specifies the desired position, maximum velocity, and acceleration, and then the internal profile generator produces a position profile. The PWM signal has a frequency of (External Clock)/100, and the duty cycle is resolved in the 100 clocks. In the present case, 2 Mhz clock gives a 20 Khz PWM frequency.

Using a 2 Mhz clock, the programmable sample time varies from 0.064 ms to 2.048 ms. It is important that the sample rate be a multiple of the PWM frequency in order to avoid residual harmonics which results in a frequency conflict. The sample time must be a multiple of the shortest sample time which is 0.05 ms.

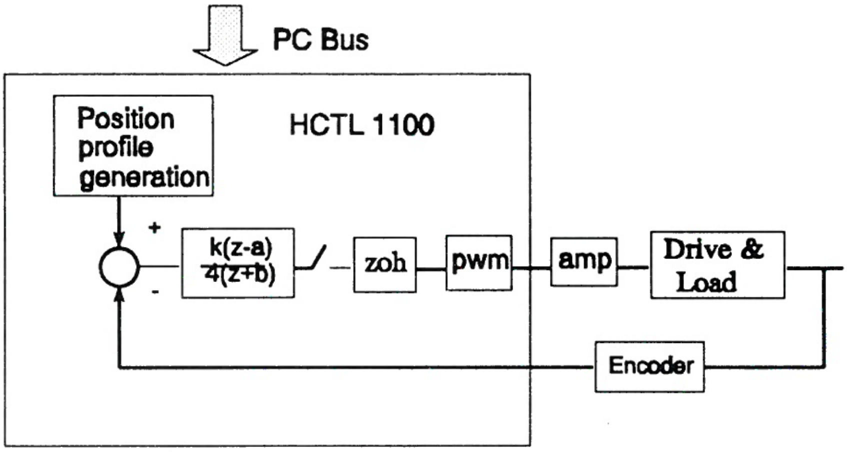

**Figure 3. Servomechanism Loop Control**

## 4. The Important Dynamic Phases[5]

As it is widely known, there are many possibilities of selecting gaits for a walking robot. This section investigates the controller tuning when the robot must obey a specific gait. To simplify the question, only motion over a flat surface, using the discontinuous and wave gaits, will be considered. In order to recognize the important phases, one cycle of the discontinuous gait is briefly presented. The cycles of the wave crab gait will be deduced directly.

One cycle of the discontinuous gait consists of 6 stages.

1. The first leg is shifted from its initial position to a new one, following some kind of trajectory and ending in reaching the ground.
2. The second leg does the same as the first
3. The body is moved in a certain distance in some direction.
4. The third leg is shifted.
5. The fourth leg is shifted the same manner as the third.
6. The body is moved the same distance as in the third stage, and the sequence of the gait ends.

We can distinguish among three different dynamic phases:

1. The shifting of a leg
2. Supporting the body weight on three legs
3. Propulsion of the body with four legs.

In the wave crab gait, the body is moved at a constant velocity with a crab angle (which may be null), and there is one tree-leg propelling phase which corresponds with the tree-leg supporting phase in the discontinuous gait.

So the machine still has three different phases, which are the following:

1. The shifting of a leg
2. Propulsion over three legs.
3. Propulsion over four legs.

In order to maintain performance throughout the motion, it is important to approach each one of the phases mentioned above as a problem, and tune the controller accordingly.

## 5. The Design Problem [4]

All the joints are independently controlled. The methodology adopted here is to draw up a table of parameters of the filters for the appropriate phase. The table is obtained by identifying each axis in the phases mentioned below and by deducing the appropriate tuning using the pseudo dead-beat control .

**Tuning the controllers :**

Each axis is identified as a second order system with the following discrete transfer function:

$$H(q^{-1}) = q^{-1}\frac{b_0 + b_1 q^{-1}}{1 + a_1 q^{-1} + a_2 q^{-2}}$$

$$b_0 > 0, \ b_1 > 0$$

$$a_2 > 0, \ a_1 = -1 - a_2$$

where q is the forward shift operator.

To tune the filters, the pseudo dead-beat control is used. The controller structure obeys the following expression:

$$D(q^{-1}) = \frac{1}{b_0 + b_1}\left[\frac{1 - a_2 q^{-1}}{1 + \left(\frac{b_1}{b_0 + b_1}\right) q^{-1}}\right]$$

which has the same structure as the filter implemented on our microcontroller. There the parameters are set up automatically by the model's parameters.

With this tuning, the closed loop transfer function is approximated to a first order function with the following discrete transfer function :

$$G(q) = \frac{1 - \alpha}{q - \alpha}; \quad \alpha = 1 - \frac{1}{b_1}$$

**Hints on the pseudo dead-beat algorithm**

The pseudo dead-beat requires that both the error and the signal control be zero in a minimum time, hence it is easy to find out the structure of the filter. This method requires that the system which is going to be controlled presents some integrations, hence the model of the axis is considered in position and not in velocity. The pure dead-beat has never scored in practice, but the pseudo dead-beat algorithm offers good performance and may be the simplest one to use in exerting reasonable control in the near optimal time sense. In practice, the pseudo dead-beat depends on the sampling rate and on the accuracy of the plant model, so if the sampling rate is faster with respect to overall system dynamics, then saturation will appear in the transient behaviour due to the limitation in control signal, and the optimal time sense will be lost. The optimal feature will also be lost if the model is not accurate.

In conclusion, the pseudo dead-beat provides an algorithm that generates automatic tuning as a function of the model's parameters, that may be easily extrapolated should there be any errors in identification .

## 6. Experiments

Each axis is identified in all the three different phases. and data on controller parameters are collected. Clearly, an extensive table is not as advantageous as a smaller one, consisting of rounded -off data for all the joints driven in the same direction.

Experimentally, it has been noted that the x-axis and y-axis have quite similar tuning, due to machine symmetry, and all the data obtained displayed little variance. This tuning is valid for the discontinuous gait and the wave crab gait. It only depends on the state of the machine. It has also been noted that tuning largely differs between the z-axis and the x,y-axes.

Table 1 Axes Parameter

| | | X | Y | Z |
|---|---|---|---|---|
| **Transfer Leg** | **K** | 32 | 32 | 25 |
| | **a** | 240 | 240 | 240 |
| | **b** | 126 | 126 | 160 |
| **Propelling body over four legs** | **K** | 28 | 28 | 30 |
| | **a** | 235 | 235 | 233 |
| | **b** | 126 | 126 | 126 |
| **Propelling body over three legs** | **K** | 28 | 28 | * |
| | **a** | 235 | 235 | * |
| | **b** | 126 | 126 | * |

X, Y, and Z are the motors that drive each leg through the x, y, and z axes, respectively.

All the data are programmable parameters according to the discrete transfer function of the filter.

To indicate the response behaviour of the three axes transferring a leg, the experiment shown in Figure 4. has been included.

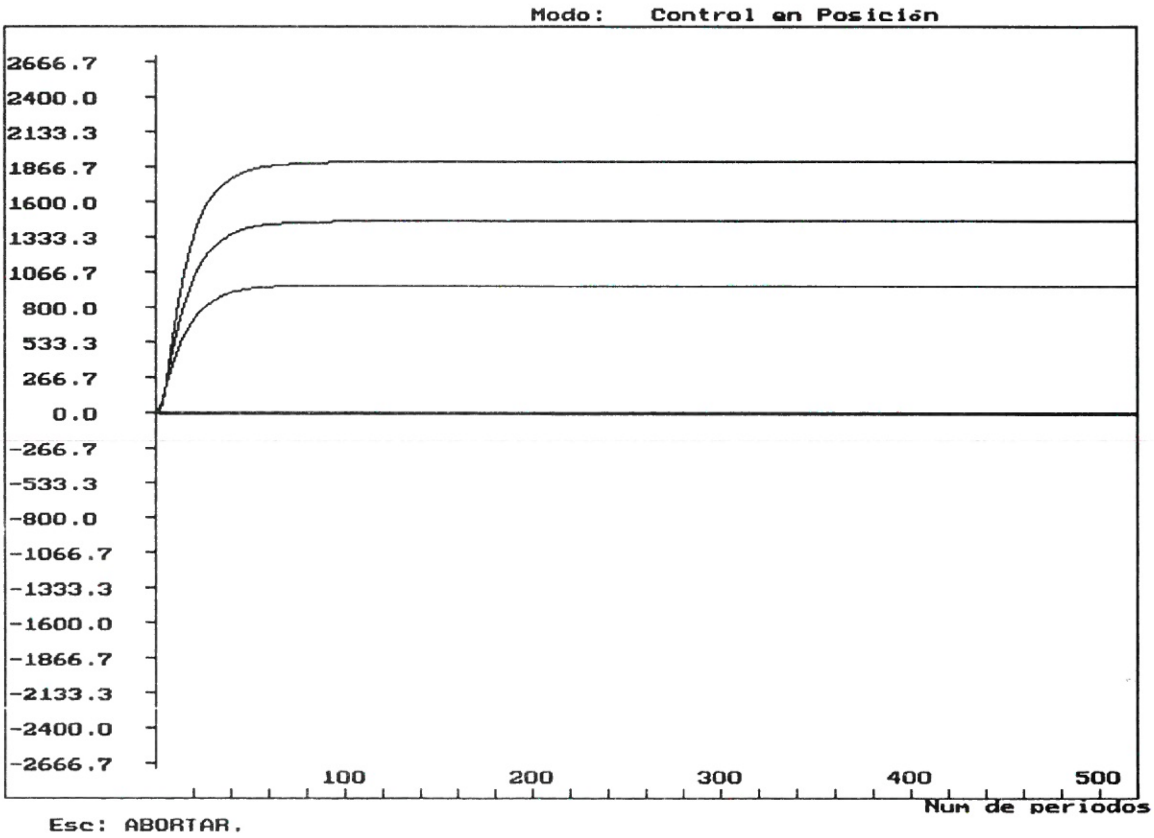

Figure 4. Transfer leg x=1000; y=1500; z=2000

## 7. Conclusion

In this paper a brief description of a four -legged locomotion robot has been made, and its control problem, when it has to obey a specific gait, has been approached by dividing the gait into different dynamic phases. Experimental results and practical considerations about the different controller's parameters values were also reported.

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## REFERENCES

1. JIMENEZ, M. A. , GONZALES DE SANTOS, P., and ARMADA, M. A. , **A Four-Legged Walking Test Bed**, 1st IFAC International Workshop on Intelligent Autonomous Vehicles. Hampshire, UK ,1993.
2. ARMADA, M. A. **Telepresence and Intelligent Control for a Legged Locomotion Robot**, Expert Systems and Robotics, NATO ASI Series Vol .F71, SPRINGER-VERLAG, 1991.
3. ALIANE, N., ARMADA, M. A. and VARGAS, C. M., **Self-Tuning Compensator for Walking Robots**. 23rd ISIR, Barcelona, Spain, 1992.
4. ALIANE, N. , **Identificación y Ajuste Automático del Filtro para el Control Digital de Motores CC** , IAI- Internal report , April 1992 .
5. ARMADA, M. A. , ALIANE, N. , GONZALES DE SANTOS, P. and JIMENEZ, M. A., **Controller Tuning for a Four-Legged Locomotion Robot**, IEEE International Conference on System, Man, and Cybernetics, Le Touquet, France, 1993
6. ÅSTRÖM, K. J. and WITTENMARK, B. , **Computer Controlled Systems**, PRENTICE -HALL, 1984
7. BENJAMIN,C. K,, **DC Motors and Control Systems**, SRL PUBLISHING COMPANY, Illinois, USA,1978.
8. STUART, B., **Real-Time Computer Control : An Introduction**, PRENTICE HALL, New York, USA, 1988.