DESIGN AND MOTION SYNTHESIS OF MODULAR WALKING ROBOT MERO

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Abstract:

The walking robots are built to displace the loads on the not-aligned terrain. The mechatronic walking system protects much better the environment when its contact with the soil is discrete, a fact that limits the area that is crushed appreciatively. At the Polytechnic University of Bucharest a walking modular robot to handle farming tools has been developed. This walking robot has three two-legged modules. Every leg has three freedom degrees and a tactile sensor to measure the contact, which consists of the lower and upper levels. The body of the MERO (MEchanism RObot) walking robot carries a gyroscopic bearing sensor to measure the pitch and roll angles of the platform. The legs are powered by hydraulic drives and are equipped with potentiometric sensors. They are used to control the walking robot in the adaptability to a natural ground. A vehicle like that is Romanian Walking Robot MERO (Fig.1).

Keywords: *walking robot, modular walking robot, robot control, and shift mechanism.*

1. Introduction

Modular Mobil Walking Robot represents a special category of robots, characterised by having the power source embarked on the platform.

This weight of this source is an important part of the total charge that the walking machine can be transported.

That is the reason why the walking system must be designed so that the mechanical work necessary for displacement, or the highest power necessary for acting it, should be minimal.

The major power consumption of a walking machine is divided into three different categories:

- the energy consumed for generating forces required sustaining the body in gravitational field; in other word, this is the energy consumed to compensate the potential energy variation
- the energy consumed by leg mechanism actuators for the walking robot displacement in acceleration and deceleration phases
- the energy lost by friction forces and moments in kinematic pairs.

The modular walking robot weight can be distributed optimally on the support areas by controlling the forces and the variation of the distance from the soil level, allowing robots to walk over young trees or other plants, growing along the passage area [4],[3]. The easiness in obstacle avoidance - tree stumps, logs, felled trees is another advantage of walking robot use.

2. Building of experimental MERO modular walking robot

The creation of a autonomous walking robot, equipped with capabilities such as objects handling, shift, perception, navigation, learning, reasoning, data storing and intelligent checking, enabling them to carry out missions such as changing the parts multitude of a dynamic world, is a target focusing the activities by many scientific research teams of several countries worldwide.

The MERO modular walking robot, made by the authors, is a multi-functional mechatronic system designed to carry out planned movements aimed at accomplishing several-scheduled target. The walking robot operates and completes tasks by permanently interacting with the environment where known or unknown physical objects and obstacles are. Its environmental interactions may be technological (by mechanical effort or contact) or contextual ones (route identification, obstacle avoidance, etc).

The successful fulfilment of the mission depends both on the knowledge, the robot, through its control system has on the initial configuration of the working place, and by those obtained during its movement as well as.

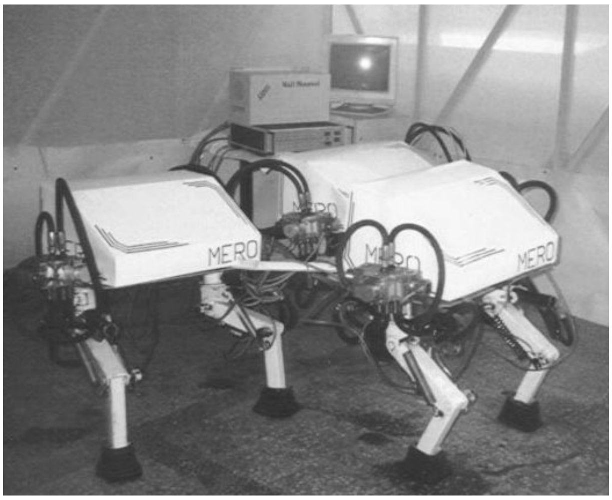

Fig.1. General view MERO modular walking robot.

The MERO modular walking robot is made up of the following parts:

a) the mechanical system made up of one, two or three modules articulated and shaped according to the requirements of the movement on an uneven ground, the robot's shift system is thus built that it may accomplish many toes' trajectories, which can alter by each step.

b) the actuating system of feet has a hydraulic drive;
c) the distribution system is controlled by 12 or 18 servo-valves, according to the robot's configuration;
d) the energy feeding system;
e) the system of data acquiring on the shift the system's configuration and the environment;
f) the control panel processing signals received from the driving and the acquiring systems.

3. On the shift system mechanisms of the MERO modular walking robot

For the walking robot to get high shift performances on an as different terrain configurations as possible, and for increasing the robot's mobility and stability, under such circumstances, it is required a very careful survey on the trajectory's control, which involves both to determine the coordinates of the feet's leaning points, as related to the robot's body, and the calculation of the platform's location during the walking, as against a set system of coordinates in the field.

These performances are closely connected with the shift system's structure and the dimensions of the compound elements. For simplifying its moulding, it is accepted the existence of a point-shaped contact between the foot and the leaning area.

Studying the real situations of the shift by walking, analysing different types of walking as well as the issues related to the quasi-static and dynamic stability of the walking, made us to design and manufacture a modular walking robot. The constructive solutions we adopted for the platforms and the shift system mechanisms, allow the robot to enjoy a maximal adaptability to the most different moving ways. It is obvious that, from this point of view, the shift system mechanism is the most important element of the mechanical system.

The shift system mechanism of any walking robot is built so that we could achieve a multitude of the toes' trajectories.

These courses may change according to the ground, at every step. Choosing a certain trajectory depends on the topography of the surface, which the robot is moving on. As one could already notice, during the time, the shift mechanism is the most important part of the walking robot and it has one or several degrees of freedom, contingent of the kinematic chain that its structure relies on.

Considering the fact that the energy source is fixed on the robot's platform, the dimensions of the legs mechanism's elements are calculated using a multicritical optimisation proceeding, which includes several restrictions.

The objective function may express:
- the mechanical work needed for shifting the platform by one step,
- the maximum driving force needed for the leg mechanism,
- the maximum power required for shifting.

These objective functions can be considered separately or simultaneously. The minimalisation of the mechanical work consumed for defeating of the friction forces can be considered in the legs mechanisms' synthesis also by a multicritical optimisation.

The kinematic dimensions of the shift system mechanism elements are obtained as a result of several considerations and calculation taking into account the degree of freedom, the energy consumption, the efficiency, the potential distribution, the kinematic performances, the operation field and the movement regulating algorithm.

The walking robot's leg (Fig.2) is made up of a 3*R* spatial mechanism, operated by three linear hydraulic motors. The working area's dimensions were induced from the condition that the robot is able to step over the obstacles whose dimensions were initially established. The leg mechanism together with the driving system, the location sensors, the contact and force sensors, all make up one module of the shift system called the *leg of the robot*.

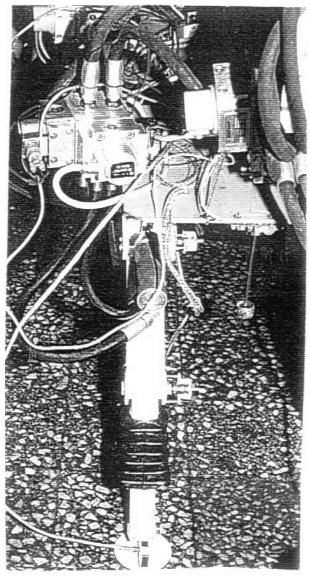

Fig. 2. The leg mechanism of the MERO walking robot.

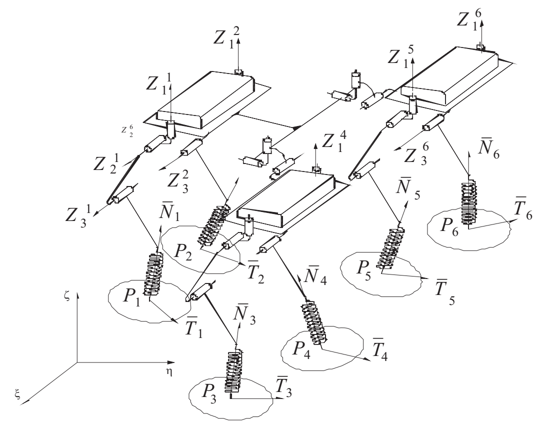

Fig. 3. The kinematic scheme of the MERO modular walking robot's mechanical system.

The movement system of the walking robot, as designed in the Figure 2, has three degree of freedom and a quite simple mechanical structure, being made up of three serially connected bars and three linear hydraulic motors. Two analog-digital and one digital-analogue interfaces (Fig. 5) and a processing computer derived from a *PC* acquire the measured data. The values found as a result of the measurements, enabled us to draw the diagrams emphasizing the variation of the kinematic and kinetostatic parameters of the MERO walking robot's movement system.

When drafting the MERO modular walking robot, it was succeeded a drop in the power consumption by both methods, namely by reducing the power consumption by an optimal designing of the legs' mechanisms, the cut in the power used by the robot by balancing the weight forces of the platform and the legs' elements, with the help of the system for static balancing). Figure 3 shows one of the robot's legs, equipped with the balance springs.

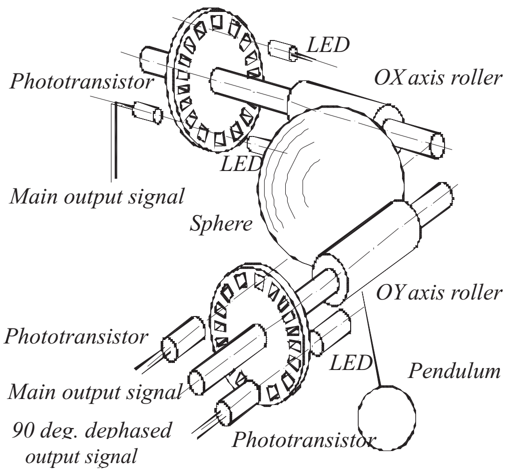

Fig. 4. Stance transducer.

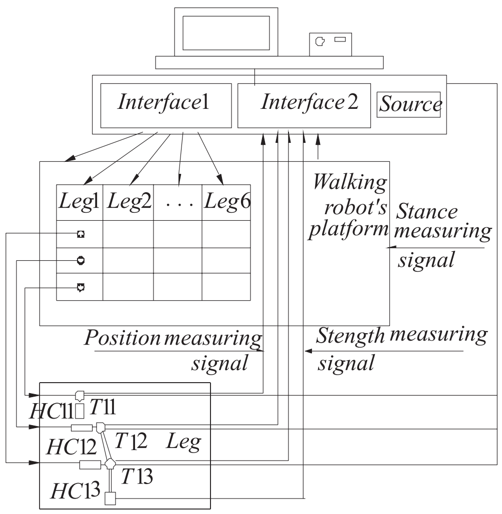

Fig. 5. Block scheme of acquiring data system.

In order to determine the walking robot's walking stance while moving (maintenance of horizontal position), we attached the platform a sensor made up of two incremental transducers aimed at perceiving the walking stance (Fig. 4). It determines the platform's leaning both at the sagittal and frontal level. The sensor is made up of a body hanged by a rigid rod to a sphere leaning on two rollers.

4. Mathematical modelling of gait for modular mobile walking robot

A cycle of the movement of the leg of a walking robot has two phases: *the support phase* and *the transfer phase*. In the first phase, the leg's support part has a direct contact with the walking surface area. In the transfer phase, the leg of the robot is above the walking surface and is moving so that it realizes the stability state on the whole of the walking robot. The walk of the robot is characterized by the order *raise* and *seat* of the legs and by the trajectory form of the theoretical support point in comparison with the platform. To establish the walking order it is needed to number the legs. The state of the leg (i) at a given time [1], [4] is described by a state's function $q^i(t)$, that has only two values, 0 and 1, as it follows:

$$q^i(t) = \begin{cases} 0 & \textit{support phase;} \\ 1 & \textit{transfer phase.} \end{cases}$$

On the interval $[0, t_1]$, the leg is in the support phase. On the interval $[t_1, t_2]$, the leg is not leaning upon the support surface and it is in the transfer phase. On the interval $[t_2, t_3]$, the leg is on the support surface again, etc.

At a moment of time, the state of the walking robot with N legs is defined by a N-dimensional vector q, named *the vector of the legs states*. The vector's components $q^i, i = \overline{1,N}$, are formed by the functions of the legs' states, ordered by their

$$q = \left[q^1, q^2, \ldots, q^N\right]^T, \tag{1}$$

so that the first component of the vector defines the state of the leg 1, the second one is the state of the leg 2, etc.

It is assumed that in any finite interval of time there is a finished number of moments that define the values of the functions $q^i(t)$. The q states, which appear at every change of the value of the function $q^i(t)$, are numbered chronologically as they are carried on. As a result, the walk of a walking robot is described by a succession of states $(q_j), j = 1, 2, \ldots$.

Therefore, it has to be lifted away from the support phase, moved towards the advance direction of the mechatronic mobile system and then lay down, following another cycle with another leg.

As the Modular Mobil Walking Robot has two or more legs, these moves have to be coordinated, so that the move is ensured in conditions of the stability of the system. In order to allow a theoretical approach of the gait of the mechatronic mobile system it is necessary to define a lot of terms. Let us consider a scheme of a hexapod mechatronic mobile system, numbering each leg. In order to achieve and manage a hexapod.

Modular Mobil Walking Robot - it is necessary to know all the walking possibilities, because the selection of the legs number and its structure depends on the selected type of the gait. The selection of the type of gait is a very complicated matter, especially in the real conditions of walking on the rough terrain.

The longitudinal stability margin, S_l is the shorter of the distances from the vertical projection of the centre of gravity to the front and rear boundaries of the support pattern, as measured along the direction of motion (see Figure 6).

If certain obstacles occur on the walking surface, a special crossing gait must be used, after learning the dimensions of such obstacles.

Depending on the type of the obstacle, its surpassing can be made by the precise arrangement of the legs in the permitted areas around the obstacle. In such a case, the periodic gait, named *"follow the leader"* is highly recommended In case of walking on an unarranged terrain, due to the great diversity of the obstacle dimensions and forms, precise walk is not recommended.

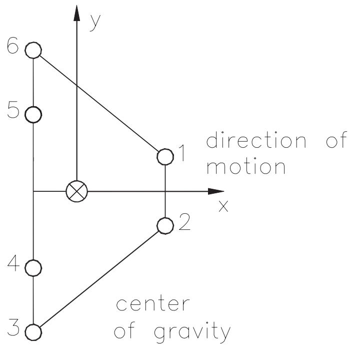

Fig. 6. The longitudinal stability margin.

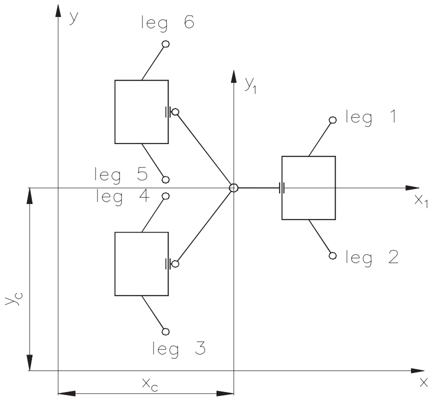

Fig. 7. The model a modular walking robot.

Figure 7 shows the model of a modular hexapod walking robot. The body coordinate system x-y is attached to the body centre and the x-axis is aligned with the body longitudinal axis. The centre of gravity is coincident with the body centre. Each leg is assigned a number as is shown in the Fig. 7. Each leg is represented by a line segment which connects the foot point and hip point is considered unlimited (i.e. the workspace of each leg is unlimited).

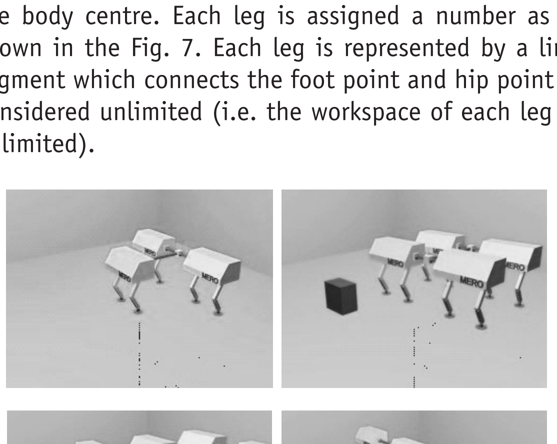

Fig. 8. Computer graphics simulation the gaits of the modular walking robot.

The terrain used in the study is two-dimensional, unarranged terrain. The terrain is divided into many cells and each cell is about the size of a footprint. The cells are classified into two types: a permitted cell and a forbidden cell. A forbidden cell is not suitable for a foot to tramp on it due to weakness of the soil structure, a ditch, or other reasons. A collection of many forbidden cells is a forbidden area.

5. Hybrid control of MERO modular walking robot stability

Walking robots may have a lower or higher autonomy degree. This autonomy has in view the power source's supply capability but also orientation and perception capabilities as regards the terrain configuration, the robot is running upon and its decision making and the motion manner towards a target.

To plan the movements is necessary only for the walking robots at a low autonomy degree and which move according to a previously scheduled program. Walking robots having a high autonomy as concerned the decision making, should benefit from appropriate driving programs and obviously from high-speed computers.

To control the walking robot shift in structured or less structured environments we need the following specifical functions:

- the environmental perception and shaping using a multisensorial system for acquiring data,
- data collecting and defining the field configuration,
- movement planning,
- analysis of the scenes.

Control of the robot stability entails that the vertical projection of the G system gravity centre on the supporting surface must be inside the supporting polygon. The geometric centre position O is defined as the diagonals intersection point of the polygon formed by the points, where the legs are connected to the platform, and $G_{(GxGyG,zG)}$ as the gravity centre position of robot.

Maintaining the vertical of the centre of gravity in the support surface is increasingly difficult if the robot is moving on a slope. In this case maintaining the stability depends on the transported load (f_i) and on the distance X_C from the surface of the support points to the centre of gravity. Stability is obtained by reducing the X_C component when the f_i load increases taking into account the moving slope of the robot.

A control method consists in evaluating the robot load and assigning a constant step value in order to obtain robot stability. As a result, there is obtained a high number of steps for a complete stability, depending on the robot's speed and the obstacles met by the robot, which can lead to the robot being overturned.

A new control method, which practically eliminates instabilities and has a fast response of the control loop, is presented in Figure 9. It consists of a "multi-stage" fuzzy control $(\boldsymbol{MS})$, which entails the realization of two fuzzy control loops, one in position and the other in force on two different decision stages in order to determine the distance X_C from the surface of the support points to the centre of gravity.

MS fuzzy control has multiple rule bases, where the result of an inference of the rule base is transmitted to the next stage [2]. In this way the most important dimensions of the inference can be grouped into smaller sets and combined with base rules. In the MS structure, the results of the rule base of the control of position P are transmitted to the rule base of the PF position - force control.

By analysing the rule base, it can be observed that the force feedback is a function of the inference results of the fuzzy control P component. The rule base P is easily modified from a typical linear rule base, allowing for the replacement of all Zero (ZO) values, except the centre of the rule base.

For a certain set of inputs, i.e. the measured X_C, the evaluation of fuzzy rules produces a fuzzy membership

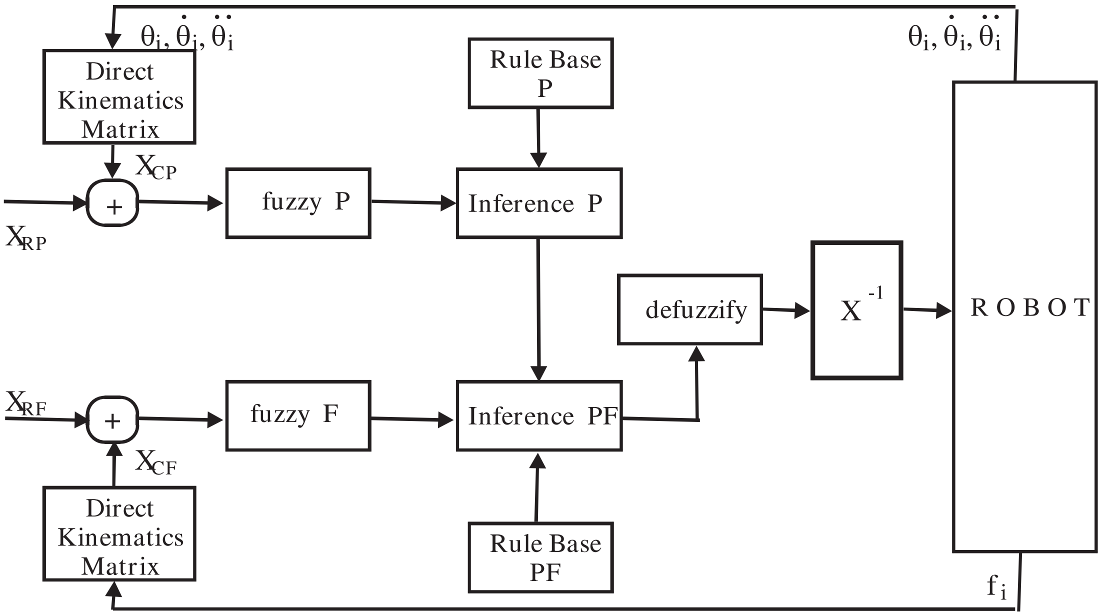

Fig. 9. Fuzzy "multi-stage" control (FMS) for MERO modular walking.

In terms of control, based on the characteristics of the positioning functions, P is of high level, generally controls the system to avoid any instability of the robot and ensures system control should dynamic disturbances appear or if commands are generated and the main function is force. The control returns the functions base P when the system dynamic is settled.

The task of the controller is to assign the measured X_{CP} of the fuzzy variables, i.e. "positive great" (PM), and to evaluate the decision rules through inference. So that, it can finally establish the value of the output variable, i.e. the velocity as fuzzy variable, which best follows the controlled parameter.

The configuration of the decision rules and of the fuzzy variables used in making the decision depends on the problem of specific control. The values of deflection detected through sensors are quantified in a number of points corresponding to the discourse universe elements, and then the values are assigned as grades of membership in a few fuzzy subsets.

The relationship between the inputs, i.e. the measured deflections, and outputs, i.e. velocity, and the grades of membership can be defined in conformity to the operator's experiences and the demands of the robot charge. There are defined empirically the membership functions for all input and output elements. The fuzzy variables have been chosen as follows: NM - negative great, N_M - negative medium, Nm - negative small, ZO zero, Pm - positive small, P_M - positive medium, PM - positive great.

set for system control. In order to take a concrete action, one of these values must be chosen. In this application, the control value with the highest degree of membership has been selected. The rules are evaluated at equal intervals, in the same way as a conventional control system.

The result of logical inference also represents fuzzy values which are applied to the defuzzify mode. The defuzzify represents a transformation of the fuzzy variables defined on the output discourse universe in a numerical value. This processing is necessary because the control in the case of fuzzy regulators is done exclusively with crypted values. Choosing defuzzify method the weight centre of the area the defuzzify output is determined. Choosing a discreet discourse universe allows for using the multiprocessor systems for generation the fuzzy output variables with a reduced processing time.

By applying the fuzzy logic control, there is obtained a linear passing, without discontinuities, in controlling the distance X_C from the surface of the support points to the centre of gravity. Moreover, a fast response of the control loop is obtained while maintaining the stability of the robot.

6. Conclusions

The MERO modular walking robot was developed at University "Politehnica"of Bucharest in the MERO-TEHNICA laboratory. Such module robot has two/four/six legs with three degrees of freedom each. The body of modular walking robot carries a gyroscopic attitude sensor to measure the pitch and roll angles of the body.

The legs are powered by hydraulic drives and are equipped with joint angle potentiometer transducers. Each leg has three degree of freedom and a tactile sensor to measure the contact, which consists of lower and upper levels. The MERO type transducers used in walking robots offer both force control and robot protection. Each of the feet is equipped with stain gauged force sensing device optimised by finite element analysis. Each of the rotational pairs is closed-loop controlled by software servo-controlled by an external computer.

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