The Architecture of Modular Walking Robot MERO
Support of the Heavy Load Transportation

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Abstract: - A modular walking robot can traverses most natural terrain. Walking robots better protect the environment, as their contact to the ground is discrete, which considerably diminishes the area underwent to crushing; the robot’s weight can be optimally distributed all over the supporting surface, by controlling the forces. Altering the distance to the ground, the robot can pass over young trees or other vegetation, growing in the passage area. The advantages of legged system for off-road have been gradually recognised. One of the most important advantages is mobility. The Modular walking robots represent a special category of robots, characterized by having the power source embarked on the platform. The weight of this source is an important part of the total charge that the walking robot must transport. 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 act it, should be minimal.

Key-Words: - Modular Walking Robot, Static Balancing, Shifting System, Gait, Stability margin

1 Introduction

In order to reach areas hardly to get to, and where man’s life were jeopardized, the scientific research has been tackling, during time, topics of different purposes and to achieve mechanisms, able by their skills, to cover several fields. Due to the special circumstances, regarding the vegetation and the terrain’s state, and viewing the environment protection, the wheeled or the caterpillar machines, aimed at such applications, have a restrained mobility and thus, they considerably destroy the environment, the vegetation, bushes and the young trees, when passing through.

Walking robots better protect the environment, as their contact to the ground is discrete, which considerably diminishes the area underwent to crushing; the robot’s weight can be optimally distributed all over the supporting surface, by controlling the forces. Altering the distance to the ground, the robot can pass over young trees or other vegetation, growing in the passage area.

Avoiding hurdles such as logs or tree trunks is a considerable advantage. Likewise, the movement on an unarranged terrain, represents another advantage of the walking robot, as against the other types of vehicles. The walking robot may change the running direction within a very narrow space.

1.1 Applications of MERO modular walking robot in farming and forestry

Compared to the wheeled or caterpillarred robot, the modular walking robot is a mechatronic system, its practical use requiring both the computer-assisted surveillance and the thorough checking by the movement systems.

The locomotion using feet as a movement system was reckoned as an inefficient movement means. Nevertheless, if we take into account the infrastructure’s costs to artificially create the roads for wheeled robots or own roads for the caterpillar robots, arguments for these two robot types, diminish, in some of the cases.

Here they are, the main features justifying the superiority of the modular walking robot as compared to the wheeled or caterpillarred ones:
- capability to move on unarranged grounds;
- by changing its height (ground clearance) the walking robot can step over certain hurdles; modular
- the possibility to change the configuration of the modular walking robot’s shift system;
- feet’s contact to the ground is discontinuous (it is accomplished only in the leaning phase), when a foot has the opportunity to select its contact point, while descending on the ground, contingent of the latter’s surface;
- the possibility to move on a soft ground, which is sometimes more difficult for the wheeled or the caterpillar robot;
- the modular walking robot’s active suspension, accomplished by setting proximity and force sensors in the outermost part of feet, enables the movement on uneven ground, under stable circumstances;
- the specific energy consumption is smaller with the movement on natural unarranged grounds as against other types of mobile robots;
- better preservation of the ground, that the robot moves on, especially in case it is made use of in specific farming or forestry activities;

terrain’s capability to keep water, it reduces the aeration, and it often considerably decreases the endurance to penetration and makes the terrain hard to plow.

As a result of the terrain’s degrading, its productivity strongly drops, and the crops sometimes diminish by 50 percent as compared to that on the non-compacted terrains.

Among the drawbacks of the walking robot, here they are some worth to remind you:
- movement checking is rather sophisticated thank to the - large number of freedom degrees;
- they develop rather small speed;
- they claim bigger manufacture, maintenance and exploitation costs.

In order to achieve complex missions, the modular walking robot, designed to be autonomous, needs a hierarchically intelligent control due to its specific natural working conditions, where inaccurate descriptive information and data concerning its own movements as well as the environment are received. The mechanical system is modular.

The experimental model of the six legged modular walking robot, built and tested in the Mobil Robots Laboratory of the POLITEHNICA University of Bucharest is shown in Fig. 1. A module of the robot (Fig. 2) is made of a body to which two legs are joined and has got within its structure the necessary elements of the actuator system.

![Fig. 1 Experimental model of the six legged MERO2 modular walking robot](image1)

![Fig. 2: Eight-legged modular walking robot; it is suggested support of technological equipments to work in farming and forestry](image2)
so that the mechanical work necessary for
displacement, or the highest power necessary for
act 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 to sustained 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 magnitude of reaction forces in kinematic
pairs and the actuators forces depend on the load
distribution on the legs. For slow speed, joint
gravitational loads are significantly larger than
inertial loads: by eliminating gravitational loads,
the dynamic performances are improved.

Therefore, the power consumption for to
sustained the walking machine body in
gravitational field can be reduced by using the
balancing elastic systems and by optimum design
of the leg mechanisms. The potential energy of
walking machine is constant or has a little
variation, if the static balance is achieved. The
balancing elastic system is formed by rigid and
linear elastic elements. The purpose of this paper is
to presents an elastic system which can be attached
to the mechanism leg to reduce the actuator forces
and moments magnitudes. This system used the
linear helical springs.

2. The synthesis of static balancing
elastic systems

The more usually constructions of leg mechanisms
has three degree of freedom (Fig. 3). The proper
leg mechanism is a plane one and has two degree of
freedom. This mechanism is articulated to the body
and it may be rotated around a vertical axis. For to
reduce the power consumption by robot driving
system it is necessary to use two balancing elastic
systems. One must be setting between links 2 and
3, and the other - between links 3 and 4. Because
the link 3 is not fixed, can’t be setting the second
balancing elastic system. Therefore, the leg
mechanism schematised in fig. 3 can be balanced
partially only.

It is well known and demonstrated that the weight
force of an element which rotate around a
horizontal fixed axis can be exactly balanced by the
elastic force of a linear helical spring [7].

![Fig.3 Elastic system for the discrete partial static balancing of the leg mechanism](image-url)

The spring is jointed between a point belonging to
element and a fixed one. The major disadvantage of
these simple solution is that the spring has a zero
undeformed length. In practice, the zero free length
is very difficult to achieve. The opposite assertions
are theoretically conjectures only. A zero free
length elastic device comprised a compression
helical spring. In the construction of this device,
some difficulties arise, because the compression
spring, corresponding to the calculated feature,
must be prevented from buckling. A very easy
constructive solution, which the above mentioned
disadvantage is removed, consist in assembly two
parallel helical springs, as show in Fig. 3.

3. Optimization of walking robot’s
shifting systems

There are two possibilities in order to decrease the
energy consumption of a walking robot. One of
then is to optimize the shifting system of the robot.
That could be perform by the kinetostatics
synthesis of the leg mechanism with minimization
of energy consumption during a stepping cycle.

While the leg is in a support phase, the energy
is consumed by the motors of active kinematics
pairs from the leg mechanism. In the transfer phase,
the energy is consumed only for overcoming the
frictional forces from the kinematics pairs, and can
be neglected. This approximation is much more
effectiveness while the structure of the leg
mechanism is simpler. Because the energy
consumption from the support phase is bigger than
the transfer phase of the leg, from the power point
of view, the stepping cycle is reduced to the
support phase. A second possibility to decrease the
energy consumption is the static balancing of leg
mechanism [7].
The simplest constructional solution for the leg mechanisms of the walking robot uses the revolute pairs only. The hydraulic linear motor has only a prismatic pair (fig. 4). This mechanism consists of two plane kinematics chains.

![Fig.4 Mechanism of the leg](image)

One of these kinematics chains is formed by the elements (1), (2) and (3), and operated in the horizontal plane. The other kinematics chain operated in the vertical plane and is formed by the elements (4), (5), (6), (7), (8) and (9). The lengths of elements (6) and (7), i.e. the distances GH and HP respectively, are calculated in terms of the field in which the P point of the low end of the leg is displaced. The magnitudes of the driving forces $F_{d1}$ between the piston (4) and the cylinder (5) and $F_{d2}$ between the piston (8) and the cylinder (9) are calculated with following relations:

$$F_{d1} = \left[ (mg - R_{ih}) (Y_G - Y_E) - R_{ax} (X_G - X_E) \right] \frac{1}{EG};$$

$$F_{d2} = \left[ (mg - R_{ow}) (Y_L - Y_J) - R_{ox} (X_L - X_J) \right] \frac{1}{JL};$$

where:

$$R_{ax} = \frac{R_{ox} (Y_G - Y_J) - R_{ax} (X_G - X_J) - D + C (X_G - X_J)}{(X_G - X_J) Y_G - Y_E - Y_G + Y_I};$$

$$R_{ow} = \frac{R_{ox} (Y_J - Y_I) - R_{ow} (X_J - X_I) - D + C (X_J - X_I)}{(X_J - X_I) Y_J - Y_E - Y_J + Y_H};$$

$$R_{ox} = \frac{Q(x (Y_P - Y_H) - Q (X_P - X_H) - B + A (X_L - X_H))}{X_L - X_H} = X_L - X_H = \frac{X_J - X_I}{Y_J - Y_I};$$

$$A = \frac{m_B (X_G - X_j) + m_S (X_G - X_G)}{X_L - X_J};$$

$$C = \frac{m_B (X_G - X_j) + m_S (X_G - X_G)}{X_G - X_J};$$

$$B = g (m_B (X_H - X_G)) - (m_S + m_B) (X_L - X_H));$$

$$D = g (m_B (X_I - X_G)) - (m_S + m_B) (X_I - X_G));$$

$$R_{ax} = -Qx - R_{ax};$$

$$R_{ax} = (m_B + m_S) g - Qy - R_{by};$$

The $X_G$ and $Y_G$ represent the coordinates of gravity center of element $i$.

The mechanical work of the driving forces $F_{d1}$ and $F_{d2}$, performed in the $T$ time when the robot body advances with a step by one single leg, has the form:

$$W = \int_0^T (F_{d1} \frac{dEG}{dt} + F_{d2} \frac{dJL}{dt})dt,$$

where:

$$\frac{dEG}{dt} = \frac{1}{EG} \left[ (X_G - X_E) \frac{dX_G}{dt} + (Y_G - Y_E) \frac{dY_G}{dt} \right];$$

$$\frac{dJL}{dt} = \frac{1}{JL} \left[ (X_L - X_J) \frac{dX_L}{dt} + (Y_L - Y_J) \frac{dY_L}{dt} \right];$$

$$EG = \sqrt{(X_G - X_E)^2 + (Y_G - Y_E)^2};$$

$$JL = \sqrt{(X_L - X_J)^2 + (Y_L - Y_J)^2};$$

$$X_G = X_I + GI \cos(\phi_{HI} - \beta);$$

$$Y_G = Y_I + GI \sin(\phi_{HI} - \beta);$$

$$X_L = X_P + PL \cos(\phi_{PH} - \alpha);$$

$$Y_L = Y_P + PL \sin(\phi_{PH} - \alpha);$$

$$\alpha = \arccos \frac{HP^2 + LP^2 - HL^2}{2HP \cdot LP};$$

$$\beta = \arccos \frac{HI^2 + GI^2 - GH^2}{2HI \cdot GI};$$

$$\phi_{hi} = \arccos \left[ \frac{V_1 U_1^2 + V_2^2 - W_2^2}{U_1^2 + V_1^2} \right];$$

$$U_1 = 2HI (X_P - X_H), V_1 = 2HP (Y_P - Y_H),$$

$$W_1 = HP^2 + (X_P - X_I)^2 + (Y_P - Y_I)^2 - HI^2;$$

$$\phi_{hi} = \arccos \left[ \frac{V_2 U_2^2 + V_2^2 - W_2^2}{U_2^2 + V_2^2} \right];$$

$$U_2 = 2HI (X_I - X_H), V_2 = 2HI (Y_I - Y_H),$$

$$W_2 = HI^2 + (X_P - X_I)^2 + (Y_P - Y_I)^2 - HP^2;$$

$$\frac{\Delta \phi_{hi}}{dr} = \frac{HI}{E} \frac{\Delta Y_P}{dr} \cos \phi_{hi};$$

$$\frac{\Delta \phi_{hi}}{dr} = \frac{PL}{E} \frac{\Delta Y_P}{dr} \cos \phi_{hi};$$

$$E = HP \cdot HI \sin(\phi_{HI} - \phi_{PH}) \neq 0.$$

The minimization of the mechanical work of the driving forces is done with constrains which are limiting the magnitudes of the transmission angles of the forces in the leg mechanism, namely:

$$R_1 = \Psi - \delta_{min} \geq 0; R_2 = \delta_{max} - \Psi \geq 0; R_3 = \Theta - \delta_{min} \geq 0; R_4 = \delta_{max} - \Theta \geq 0;$$

and the magnitude of the $\Theta$ angle between the vectors $HP$ and $HI$. This angle depends on the maximum height of the obstacle over which the walking robot may passes over, and on the
maximum depth of the hallows which it may be
steppes over:

\[ R_5 = \Phi - \lambda_{\min} \geq 0; \quad R_6 = \lambda_{\max} - \Phi \geq 0, \]

(6)

where: \( \Psi = \Phi_{HI} - \beta - \arctan \frac{Y_G - Y_E}{X_G - X_E}; \)

\[ \Theta = \varphi_{HP} + \arccos \frac{H^2L^2 + H^2P^2 - L^2P^2}{2HL \cdot HP} - \arctan \frac{Y_J - Y_L}{X_J - X_L}; \]

\( \Phi = \Omega_{HP} - \Phi_{HI}. \)

The \( \Psi \) angle is measured between the vectors \( GE \) and \( GI. \) The dimensions \( HI, HP, LP, \)
\( HI, \alpha \) and \( \beta \) of the elements and the coordinates \( X_E, \)
\( Y_E, X_I, Y_I, X_L, Y_L \) of the fixed points \( E, I \) and \( J \)
are considered as the unknowns of the synthesis problem. The consumed power for acting the leg mechanism is calculated by the relation

\[ P = F_{d1} \frac{dE_{G}}{dt} + F_{d2} \frac{dJL}{dt}. \]

(7)

The maximum power value is minimized by constrains (4), (5) and (6).

4. The control system of the MERO modular walking robot

The robot is controlled by a computer that has been configurred for this application, and which operates four or six legs with hydraulically actuators. Each leg has three articulated joints, equipped at their lower end of the lower arm with the force measuring sensor.

There are 18 analog outputs and 12 analog inputs of 18 bits each to adjust the \( 3 \times 6 = 18 \) axes as well as to record the information supplied by the six force measuring sensors.

The control system was developed around the CP303 – 34x86 processor board from compact PCI – PEP modular computers, with QNX real time operating system. The control system contains four sub-parts: path planner, path-traking controller, legs servo-controllers and position estimation including issues regarding the robot platform stability. The control structure is actually a classical one. For testing of the modular walking robot, an integrated virtual environment aiming to study the stepping process, detection/recognition of the obstacles and avoiding collision will be developed.

The simulation will use for testing both navigator and pilot level for the mobile robot.

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 movements planning is necessary only for the walking robots with a low autonomy degree and which move according to a previously scheduled program. The walking robots having a high autonomy should benefit from appropriate driving programs and obviously from high-speed computers. In order to control the walking robot shift in more or less structured environments, the following specific functions are needed:

- the environmental perception and shaping using a multi-sensorial system for data acquiring;
- data collecting and defining the field configuration;
- movement planning;
- analysis of the scenes;
- control over the handling of the objects, if any.

The control system of the walking robot is modularly, the blocks named leg controllers and the aggregate conceived, as shown in figs. 5. The basic elements are conversion modules. The other elements can be considered as auxiliary, and they are passive elements, but essential to the system’s good functioning.

One can find the program guiding the movement, the keyboard operability and the walking sequels in the computer’s memory and stored on its hard disk as executable files and they fulfill the following functions:

- edit and memorize the movement and adjustment parameters in the form of real time files;
- operate the robot’s movement, launch or stop some movement sequences by the keyboard;
- main parameters can be visualized in real time, as they are required to elucidate, test and adjust the system as a whole;
- calculate and check the movement control, regulate the position, its force sensors detect the steps, automatically generates the movement laws (space, speed, acceleration), real time interpolation, automatic estimation of the offset servo-valves, convert direct and indirect coordinates systems, attached to the walking robot’s elements [5].

The mechanical, hydraulic, electrical and conducting systems are functionally interconnected and they cooperate in fulfilling the duties the operator claims. Nevertheless, a precise and stable functioning requires that the axis position be automatically maintained according to the internal position reference in the computer’s memory, so that the robot’s axes could precisely and repeatedly carry out the movement laws generated by the robot’s guidance program. As it is shown, in the computer’s memory records two
automatically run functions, namely those of the offset adjustment, estimation and compensation.

The multi-sensor system consists of:
- sensors to survey the system components (parameters of the actuating, supplying and distributing system);
- sensors to survey and control forces, positions, speeds, accelerations and targets;
- sensors to scan route, proximity, to video control in order to acquire images, as well as the computerized system needed for image analysis, parameter extraction, coordination of the navigation systems etc.

The system of the information transfer and processing will consist of the module for data transmission and the controller of the data and images transmission and reception. A proper work and functioning of the autonomous motion systems implies the existence of a careful coordination between motion planning, environment perception and control performance, in order to get a suitable behavior within loosely structured environments.

6. Conclusions

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 tasks. The walking robot operates and completes tasks by permanently inter-acting with the environment where there are known or unknown physical objects and obstacles. Its environmental interactions may be technological (by mechanical effort or contact) or contextual ones (route identification, obstacle avoidance, etc).

The successful fulfillment 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.

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