FORCE SENSING AND CONTROL DURING MOVEMENT OF THE MODULAR WALKING ROBOT MERO

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Abstract - In the history of scientific research there are many examples of designing robotic devices like mechanical toys and anthropoid robots. Since long ago, many research teams worldwide have been focused on goals such as creating an autonomous walking robot equipped with functions like handling objects, locomotion, perceiving, navigation, learning, judgment, information storage and intelligent control, and that can carry out tasks like altering the multitude of the parts belonging to a dynamic universe. The last ten years a large number of vehicles have been developed for their mobility characteristics over irregular surfaces. The modular mechatronic mobile system MERO* (MEchanism RObot* Pelecudi Ch et.al.) by reconfiguring their architecture are built to displace the heavy loads on the irregular surfaces. The main characteristic of the modular modular mechatronic walking system is that they are able to move away on not arranged, horizontal and rough terrain. The modular mechatronic system protect much better the environment when its contact with the soil is discrete, a fact that limits appreciately the area that is crushed (fig.1). The modular mechatronic mobile system MERO 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. Architect of the reference structure of walking robot has three two-legged modules. Every leg has three freedom degrees (RRR), a slip sensor and tactile sensor to measure the contact which consists of lower and upper levels. They are used to control the walking robot in the adaptability to a natural ground.
The paper presents some aspects of sensing and motion control walking robots (the complex sliding phenomenon, moving them in terms under conditions) and stability displacement of the modular mechatronic system MERO.

Keywords: Mechatronic mobile system, modular walking robot, mechanism, gait, stability, level control.

1. Introduction

The access of man to dangerous areas where his safety is jeopardized made the scientific research approach topics of various purposes and conceive devices that through their performances aim at covering different fields. The architecture of these systems is quite different and depends on their purpose and destination.

Scientists of all times have been permanently mesmerized and have studied the simplest but the most important movement, namely the mechanical movement of humans and animals and that are not anthropomorphic.

Mankind is so much anthropomorphism addicted that it is almost impossible for it to conceive or imagine automatic systems, even having artificial intelligence.

How do animals walk, how do birds fly, have always been and it will probably remain the inspiration sources and tasks of the scientific research.

The animals using their feet to walk can move freely, with substantive easiness in comparison with what the man - made robot can do.

The walk is defined by the manner the waking robot moves between two points, under specific circumstances. To achieve and guide a walking robot requires thorough knowledge about all walking possibilities because choosing the number of legs and their structure depends very much on the selected walk. The selection of the walk type depends on several elements such as: shape and consistency of the ground the robot walks on walk stability driving and controlling the movements of the elements of the walking systems, speed and mobility movement requires.

To use the moving robot as a means of transport, several parameters that characterize its dynamic features can be changed within a wide enough range. Thus, for instance, the occurrence of the supplementary load aboard would change the weight, the center of gravity position, the body inertia moments. The wind and other different forces may act upon the robot and their influence can hardly be anticipated. The action of any kind of similar disturbances might be a cause that produces considerable deviations from the established
moving track of the robot.

It is very difficult to select the type of walk, mainly during real walking.

Therefore, it is necessary that the ground surface to be defined before selecting the walk.

The walking robot’s steps are a sequel of movements of the legs, coordinated with a succession of movements of the body for the purpose of moving the robot from one place to another.

Walking main feature is the very fact that the movement is not affected by the terrain’s configuration.

Figure 1: General view - Experimental model of the six legged MERO modular walking robot [4]

More and more applications requiring movement on a natural, unarranged terrain, made the feet-movement solution become more and more attractive.

Floods, earthquakes and other natural disasters make impossible the movement of vehicles in the affected areas which is why reconfiguration MERO walking robots can be a solution for moving technological equipment in these areas.

The main feature of legged locomotion is the fact that movement is not affected by land configuration.

Modular walking robots have a number of principle advantages over wheeled and caterpillar machines:

- displacement on rough terrain (can move over terrains with obstacles up to the size of a leg);
- possibility of changing the height (ground clearance) allows such robots displace over rough terrain and overcome certain obstacles;
- robot configuration may change depending on the objective;
- feet contact to the ground is discontinuous (in phase support), the leg being able to select the focal point depending on the surface soil;
- can work in a complexly-structured environment (sloped, confined work and operation, etc.) and move on consolidating ground and unknown terrain with varying load capacity;
- can displace on soft ground, sometimes more difficult for robots with wheels or tracks;
- active suspension, legs are fitted with force and proximity sensors, allowing movement in terms of a better stability on rough terrain configuration;
- specific energy consumption less than the movement on natural terrain of other types of mobile robots;
- better preserve soil while moving, especially, when used in specific activities in agriculture or forestry (fig.1);

2. Movement simulation modular walking robot MERO by Denavit – Hartenberg formalism

Let us a modular walking robot consists of three modules. [3],[9],[5],[7]. Each module has two 3-DOF legs, symmetrically arranged on the platform axis (fig.1, fig.2.)

The legs on the right – onto the movement direction are superscript marked with $2i$ $i=1,6$, whereas the legs on the left with $2i-1$. Each platform of the rear modules is connected to the platform of first module by a 3-DOF kinematic chain with two links and three rotational pairs. The axes if these pairs are concurrent and perpendicular two by two.

In order to carried out the movement simulation of a leg, a coordinate axes system is attached to each link, with the Denavit – Hartenberg rule [1]. This formalism may not only simplify the problem formulation, but can also yield considerable advantage in the solution of simulation problem. The pairs of each leg are numbered consecutively from A which is pair number 1 to C which is pair number 3.

The Denavit - Hartenberg systems attached to each link are subscript numbered as the pairs respectively. The platform is designed as link number (0) and the remaining links are numbered consecutively. All pairs of the leg mechanism are rotational and actuated ones.

Figure 2: The Denavit – Hartenberg axis system attached of modular walking robot for a leg mechanism RRR[1].[1]
The parameter $\theta_i$ is the angle between positive $O_iX_i$ and the positive $O_{i+1}X_{i+1}$ axes, as seen from positive $O_{i}Z_{i}$.

The parameter $s_i$ is defined as the distance from $O_iX_i$ to $O_{i+1}X_{i+1}$ axes, measured along the $O_{i}Z_{i}$ axis.

Under this definition, the Denavit – Hartenberg transformation matrix $A_i^j$ has the well-known form:

$$
A_i^j = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos \theta_i & \sin \theta_i & s_i \\
0 & -\sin \theta_i & \cos \theta_i & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
$$

(1)

To mould the walking robot’s moves is assumed that:

The kinematical length of the binary link (1) is null and it is connected to the platform (0), by pair A and to the link (2) by pair B; the axis of pairs A and B are perpendicular.

the binary link (2) is connected to the link (1) by the pair B and to link (3) by the pair C; the axis of pairs B and C are parallel.

The $A_3^j$ matrix performed the coordinate transformation of a point belonging to link (3) from $O_3^jX_3^jY_3^jZ_3^j$ system to $O_1^jX_1^jY_1^jZ_1^j$ system attached to link (2). In a similar manner, the coordinates of lower end point $P$ belonging to link (3) from $O_3^jX_3^jY_3^jZ_3^j$ system to $O_1^jX_1^jY_1^jZ_1^j$ system attached to the platform (0) is performed by the equation

$$
\begin{pmatrix}
X_{1P}^j \\
Y_{1P}^j \\
Z_{1P}^j
\end{pmatrix} = \prod_{i=1}^{3} A_i^j \begin{pmatrix}
1 \\
X_{1P}^j \\
Y_{1P}^j \\
Z_{1P}^j
\end{pmatrix}
$$

(2)

This matrix equation described the geometrical model of the leg 1 and 2 of the walking robot. The goal of the direct kinematic analysis is to calculate the position, velocity and acceleration of the end point P, in terms of the pair variables $\theta_i^j, i = \overline{1,3}$. In inverse kinematic analysis, matrix equation (2) is solved with respect to the pair variables $\theta_i^j, i = \overline{1,3}$.

The positions of the point P and the positions of the platform with respect to the reference coordinate axes system $O_{XYZ}$ fastened to the ground are considered as known. Therefore, the position of the point P with respect to the platform coordinate axes system are known.

Keeping stable is a special problem that occurs while the robot walks, when one or more legs are in the transfer phase. When all the legs are in the support phase, it is obvious that the protection of the center of gravity is within the support polygon.

If one or more legs are in the transfer phase, the geometry of the support polygon changes and it the risk that the protection of the center of gravity moves outside the support polygon.

Solutions to such situations depend on how the modular walking robot is configured.

In (Fig.3) where are shown a sequence of the computer simulation of the successive gait of the modular walking robot, in C++ and in (Fig.4) animation gait in Studio Max Animation.

The gait described in the following section was developed with the purpose of easing the simulation and providing a better understanding of different walk strategies of leg RRR) in different configurations.

Two main configurations were taken into consideration: RRR - 3 module assembly one module in the front and two modules in the back, in a triangle shape, in (Fig.3).
The software application was built using Visual Studio .NET integrated development environment, was written in C# language and was mainly built around DirectX display SDK (software development kit), package responsible for the on-screen representation of the modular robot configuration. There are two distinct windows that start when the application is launched: The control window and the visual window in (Fig 4). The control window supplies the user with every tool needed to simulate different aspects of the robot unlike the visual one that only shows the graphic representation of the before mentioned robot.

Reaction forces modeling in walking robots control

Distribution of reaction forces from the supports of the legs is one of the important problems that must be resolved to organize movements on land legs walking robots with relief complicated. Friction cones of the supports are circular and can be oriented arbitrarily and the points of support - whether they are more than three - are not covered by a plan. [3],[5],[9], [8],[7],[6],[2]

When the number of support points is greater than three, the problem of determining the distribution of forces is statically indeterminate. To calculate these forces is necessary to know the layout and terrain feature and the positions, dimensions and materials of components of the robot (kinematic and organological size, modules of elasticity).

Choosing an element of this set is based on the travel restrictions imposed on the system. In some cases, the set of admissible solutions can be null if data movement is impossible to achieve, or may be formed from a single element and then there is only a possibility of realization of movements, without being able to take into account additional restrictions.

For a given configuration of the system displacement, the forces of reaction of the supports are determined unequivocally. The leadership of walking robots with many legs, an optimal distribution of reaction forces of the supports can be taken into account in determining the stepping strategy.

The walking robots moving on a terrain, strewn with many obstacles, which can be convex or concave, there is a danger that the position for these robots are not stable.

One of conditions imposed on the motion of walking machines is the stability. The movement of the legged robots can be divided in two modes:
- under condition of the static stability;
- under condition of the dynamical stability.

The main difference between robots which walked under the static stability and under the dynamical stability conditions originates from the fact that during statically walking, the vertical projection of the gravity center of the robot must lies into the supporting polygon, where as during the dynamical walking, this condition can be not satisfied.

The problem of quasi-static stability analysis in condition of arbitrary step when the accelerations of points of component elements are much smaller than gravity acceleration is identical with the problem of stability analysis when the robot does not walk. The inertial forces are neglected and the walking can be controlled in a kinematics way.

The investigation of statically stability is based on the notion namely hardening configuration. Hardening configuration is a term used to indicate the rigidly structure of the robot, obtained through the shutting off the driving motors.

The position of the walking robot is stable if the hardening configuration is in posture of stable equilibrium under the action of gravity forces.

The hardening configuration is statically stable if it accomplished the following conditions:

The vertical projection of the gravity center of the robot in its entirety (platforms, connecting elements and leg chains, control system and driving, pregnancy, etc.) must be inside the supporting polygon. The supporting polygon is the minimum convex area which is obtained by connecting all support points. A body at rest in a gravitational field, subject to ideal connections, has the differential of the gravity center elevation equal with zero.

Vertical projection of the care center of gravity G of the robot is inside the support polygon if all the distances di, measured from this point to a PiPi+1, sides are positive, assuming that the supports on the perimeter of the polygon are numbered clockwise (Fig.5).

Magnitudes of these distances are calculated with the following:

\[
P_i \ldots G \ldots P_{i+1}
\]

**Figure 5: Polygon support of a walking robots**

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For establishing the stable positions of a walking robot it is necessary to determine the forces distribution in the shifting mechanisms.

Determination of the real forces distribution in the shifting mechanisms of a walking locomotion system which moves in rugged land at low speed is necessary for the analysis of stability. The position of a walking system depends on the following factors:
- the shape of terrain surface;
- the configuration of walking mechanisms;
- the masses of component elements and their position of gravity centers;
- the stiffness of terrain;
- the values of friction coefficients between terrain and feet.

The active surface of the foot is relatively small and it is considered that the reaction force is applied in the gravity center of this surface. The reaction force represents the resultant of the elementary forces, uniformly distributed on the foot sole surface. The gravity center of foot active surface is called theoretical contact point. The modelling the reaction forces Ri corresponding to the support points in the walking robot's movement mechanisms generally represents the solution of the following static equilibrium equation system:

$$
\overline{N}_i + \overline{T}_i + \overline{R} = 0, \ i = 1, 3,
$$

$$
\sum_{i=1}^{3} \overline{r}_i \times (\overline{N}_i + \overline{T}_i) + \overline{M} = 0,
$$

where:
- $\overline{N}_i$ and $\overline{T}_i$ are the normal and tangent components of the reaction force in support point i;
- $\overline{r}_i$ is the position vector of the application point of the reaction force $\overline{R}_i = \overline{N}_i + \overline{T}_i$, in relation to the coordinate axis system annexed to the platform;
- $\overline{R}$ - represents the resulting force of the forces applied to the elements of the walking robot;
- $\overline{M}$ - is the resulting momentum of the forces applied to the elements of the walking robot, calculated in the origin of the coordinate axis system annexed to the platform.

In the case of a uniform straight-line movement of the walking robot on a plane horizontal surface, the reaction forces $\overline{R}_i$ in the support points only have the normal component $\overline{N}_i$ and represent the solutions of the following static equilibrium equation system:

$$
\sum_i \overline{N}_i + \overline{R} = 0; \ \sum_i \overline{r}_i \times \overline{N}_i + \overline{M} = 0;
$$

The last three items are considered known, as the forces applied to the robot elements – within the mentioned working conditions – are solely the elements’ own weights and the weight of the load.

As the robot’s movement is straight and uniform and there is no slipping, the friction forces between its legs and the ground is zero. These forces have values different from zero only if the robot movement is not straight and uniform or if the support surface is not plane and horizontal.

The inertial forces and momentums of the leg elements can be neglected. It is of note that this situation – representing an extremely ideal reality – is very rarely met in practice and, as such, the results obtained by solving the system (5) have only theoretical importance.

Determining the real distribution of forces in the leg mechanisms of a walking locomotion system, with the classical notations in figure 6, which is moving over rough terrain, is necessary in order to calculate the robot position and to analyze its stability.

As a given time, the position of a walking system depends on the following factors: the surface form of the terrain it moves on, the values of the friction coefficients between the terrain and the legs, the configuration of the legs, the rigidity of the terrain the robot is walking on.

![Figure 6: Mathematical modeling of the contact of the modular walking robots walking with the ground](image)

As the active support surface area of the last leg element, on the terrain where the movement takes place, is relatively small, it is accepted that the reaction force is applied in the weigh centre of this surface. This is the resulting force of the elementary forces, evenly distributed on the entire active surface, with which the last leg element is supported on the terrain. The weight centres of the active surface, for the support of leg i, is called the theoretic point of support and has the notation Pi. In order to determine the robot position, it is necessary to determine, in each support point, the values of the components of the reaction force between leg and
ground, namely: the normal component $\vec{N}$, perpendicular on the terrain surface in the contact point and the tangent component $\vec{T}$, or the Coulomb friction force – contained in the plane tangent to the terrain surface in the contact point. The value of this vector cannot be greater than the product between the module of the normal component and the respective friction coefficient, between leg and ground. If the value of the tangent component of the reaction force goes beyond this limit, the leg will slip on the support surface until it reaches a stable position, in which the value of this component is equal or below the mentioned limit.

For real time control, albeit these concepts were taken into account, much simpler solutions problem of determining the stable position of a walking robot on an arbitrary terrain does not have a unique solution. For each leg there is an interval, which includes all support point in which the equation $\mu N \geq T$ is verified. ‘Equal’ corresponds to the domain limit.

The studies and theoretical research, seen as a global approach, lead to a large volume of calculations in modelling and controlling the walking robots motion, which has allowed us to determine solutions, described below, were preferred, which avoid the inclusion of laborious calculations in modelling the control process of walking robots.

Walking robot motion control using walking blindly moving can be decomposed into two complementary processes, namely active control and outfit control.

Active control uses body bias to maintain a desired orientation so that the vertical projection of the centre of gravity of the robot to find inside the support polygon, to achieve static conditions.

Active control is provided via contact sensors and transducers that measure forces at the contact areas of feet with, the ground.

Active control extends platform joints, to create the conditions for a robot motion control by force steps through uneven terrain displacement.

Contact sensors ensure and protect the load. [2], [8], [7], [10]

To control the walking robot shift in structured or less structured environments we need the following specific 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 over the objects handling.

Data acquisition system of "MERO" modular walking robot figure 1: [2], [5], [4].
- the position sensor measuring the pair’s variables, namely the relative positions of the kinematic elements adjacent to the driving pairs;
- the feet’s tactile transducers signaling the feet’s contact with the support area;
- the force cell measuring the reaction forces between ground and feet;
- the verticality sensors measuring the platform’s deviations from the horizontal positioning unless any further conditions;
- the measuring systems of the platform’s height as compared to the ground’s surface;
- the measuring devices in the transfer phase of the feet’s height as against the ground’s level.

These sensors convert the mechanical variation of a quantity (force, torque, linear displacement, angular) the variability of electrical parameters (resistance, voltage, current) through electrorezistive transducers (TER).

Force transducers (Fig.8) located at the ends of the modular walking robot foot and incremental hold sensor allows the robot to control the orientation of the tilt adjustment in both the sagittal and frontal plane.

In order to verify the results obtained by solving analytical elastic element of the transducer was analyzed by finite element method.[8],[5],[3]

The sensing and motion control allow identification and measurement of contact forces with the ground through a transducer element whose elastic deformation is caused by a ball that sends robot step foot contact with the ground under the weight of the burden robot foot and additional load for transported technological installations. Contact forces are determined using strain gauges of the measurement module whose deformation generates an analog signal processed with the power regulator.
The device sensing (3), (Fig.8) and motion control by force is a hardware and software system (how to upgrade) that has two different types of sensors (sliding on two axes and strength). The intelligence given by a micro-integrated controller provides a force control loop to keep it from slipping. It controls allowable values and is attached to the feet of robot (1) with protect (2) has the composition and distribution mains pressurized fluid (6), proportional pressure regulator (5), electronic module setting reference point (4), power regulator (8), PC controller (7).

![Figure 8: Force sensing system and sliding for leg](image)

3. Simulation

In order to better understand and test the types of force sensing and control devices, for the leg of the MERO robot a few computer simulation were carried out.

The virtual simulation environment was created using DirectX and OpenGL technologies in a Windows based software developed by the authors. This environment includes the different types of terrains that a robot could encounter in real world conditions like straight and smooth sections, rough sections with hurdles, gaps and obstacles, steps, angled planes and many others, basically any kind of real world terrain type that the authors considered and entered into the software’s terrain library.

For the simulation of the force sensing device attached to the leg of the robot, the RRP-model of the robot was also constructed virtually and introduced in the virtual environment.

![Figure 9: Computer simulation for applications with MERO robot leg](image)

The ground contact, slip possibility and applied force provided by the force sensing device were generated by a software function and fed into the movement algorithm of the MERO robot. Different terrain types and different slipping scenarios were generated in order to observe the influence of the leg’s slip possibility and to get a starting point in introducing the parameters that the force sensing and control device provide, into the movement algorithm.

Tests and simulations were also done on the gripper module. In this case, an incremental PID pressure regulating algorithm is used to provide enough force to the gripper in order to restrict slipping of the handled object in lifting or moving operations.

A PID regulator model for the gripper was included in the software that in conjunction with a slipping and force sensing generator function that provides test data to the virtual model helps in gathering test data for the real model’s optimization.

The application described here was developed with the purpose of easing the simulation and providing a better understanding of different strategies for a “contact” signal was received from one of the feet’s touch sensors.

4. Results and conclusion

The MERO type transducers used in walking robots offers both force control and robot protection.

Solutions found by the authors has enabled sensing and control device, which senses touch motion, force measurement and slip to transfer objects through grasping and fixation devices attached to robots and robots stepped force and slip that in a control slip by force increase positioning accuracy and safety requirements of the application,
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5. References