Modeling and Hybrid Position-Force Control of Walking Modular Robots

LUIGE VLADAREANU¹, GABRIELA TONT², ION ION³, VICTOR VLADAREANU³
DANIEL MITROI³

¹ Institute of Solid Mechanics of Romanian Academy, C-tin Mille 15, Bucharest 1, ROMANIA,
² University of Oradea, UniversităŃii 1, zip code 410087, Oradea, ROMANIA
³ Politehnica University of Bucharest, Splaiul Independentei 125, Bucharest 5, ROMANIA
luigiv@arexim.ro; www.acad.ro

Abstract. The paper presents new concepts and approaches of applied mathematics in modeling and hybrid position-force control for walking modular robots, developing an open architecture real time control multiprocessor system, in view of obtaining new capabilities for walking robots. A strategy is developed for the dynamic control of the movement of walking robots using the Zero Moment Point method by processing inertial information of force, torque and tilting and by implementing intelligent high level algorithms. For the modeling of some of the movements of the walking robot, the equation of a simple inverted pendulum was adopted, with a joint in the single support phase, which opposes the dampening forces of the leg joints. For other movements new control strategies were conceived through sequential analyses and local modeling of the movement parameters. The complexity of the movement mechanism of a walking robot was taken into account, being a repetitive tilting process with numerous instable movements and which can lead to its turnover on rough terrain. The control system architecture for the dynamic robot walking is presented in correlation with the control strategy.

Key-Words: walking robot modeling, hybrid position-force control, multi-microprocessor system, robot dynamic control.

1. Introduction

Walking robots, unlike other types of robots such as those with wheels or tracks, use similar devices for moving on the field like human or animal feet. The leg is not a continuous transportation system as the wheel. Therefore, it should be lifted from the surface of support, moved forward in the direction of walking and then sat down, then a new cycle begins with another leg. Because a walking robot has two or more feet, its movements must be coordinated in order to ensure movement in terms of stability of the system. An important role in controlling walking robots is the force-position control. Craig and Raibert [1] first proposed combining position and force information into the control system in nondeterministic environments. Starting from the method proposed by Craig and Raibert, which is the reference in hybrid position-force control, Zhang and Paul [2,3] have modified hybrid control scheme from the Cartesian formulation to the formulation of a joint space using the same separation method constraints and position of the Cartesian force. In both cases, the advantage of hybrid control is that information about the position and strength are analyzed independently to emphasize the well-known control techniques for each one, and are combined only to the final stage, when both were transformed into moments of the joints. An and Hollerbach [4] have shown that some of the force control methods, including hybrid control, are unstable. Zhang [3] showed that the hybrid control system might become unstable under certain configurations of the robot. Analyzing proposed solutions by Fisher and Mujtaba [5], we can see they have brought improvements in walking robots control system based on the definition of conditions of stability and developed a stable hybrid control architecture [6,7,8].

A special problem is a dynamic gait control of walking robots. So, there is a known control strategy of the dynamic walking humanoid robots, based on the walking pattern generation on the time path of stable zero point (ZMP) and stability by monitoring online [9].

When analyzed from different viewpoints, in movements such as walking on
rough terrain, running or fast walking, the dynamic of the centre of gravity can be defined by the simple mechanical action of springloading the leg during positioning (Blickhan 1989, Cheng 1990) known as SLIPs – Springloaded Inverted Pendulums (Schwind and Koditschek 1997). Using compliance for representing these movement systems not only has the advantage of allowing energy to be reused, but also ensures the effective reduction of the centre of gravity during ground impacts. Another advantage of compliant representation of a leg is to shape and potentially simplify the control of highly dynamic movements (Cavagna 1977, Dickinson 2000). Until now dynamic control of a stable movement on rough terrain for walking modular robots remains an unresolved problem. Starting from similar research applied to humanoid robots [9, 10, 11], in order to increase mobility and stability of modular walking robots movement, this paper approaches the new concepts of applied mathematics in modeling and hybrid position-force control for walking modular robots, developing an open architecture real-time control multiprocessor system. The main strategy to the dynamic control of the movement of walking robots lies in the Zero Movement Point (ZMP) method by processing inertial information of force, torque and tilting and by implementing intelligent high level algorithms.

2. The static and dynamic stability modeling of the walking robots gait

The main difference between walking on uneven land and walking on a flat horizontal is that the projection center of gravity of the robot on the supporting surface changes position in relation to the sides polygon of support; if his tilt on the uneven ground exceeds a certain limit, this projection is no longer located within the polygon of support. If regular walking on a bumpy field is symmetric with respect to longitudinal and lateral axes of the body, earlier longitudinal stability limit is equal to limit of posterior longitudinal stability. The movement on a slope, both climbing and downhill, previous and posterior longitudinal stability limits are reduced accordingly, by switching the projection center of the center of gravity. To evidence the movement of walking robots a sensor is used that measures the tilt of the platform in two planes. To improve the stability of the robot to travel on a slope, there are two strategies, namely: a) lowering the body height and adjusting its position and b) reducing stride length.

Quasi-dynamic analysis of stability modeling robot displacement in the direction required with a given speed. Starting from walking robots mechanical structure presented in figure 1 and 2, there were defined equations of motion of the robot platform and legs Pi. Each leg has three degrees of freedom, with generalized coordinates, the angles θ1i, θ2i and θ3i, i = 1, 6. Cartesian coordinates of point Pi (fig. 1) at the ends of leg i, with the system attached to the platform, can be expressed in terms of angles θ1i, θ2i and θ3i, and leg length elements by the equations:

\[
\begin{align*}
x' &= \left[l_1 \sin \theta_1^i + l_2 \sin(\theta_2^i - \theta_1^i)\right] \sin \theta_3^i; \\
y' &= \left[l_1 \sin \theta_1^i + l_2 \sin(\theta_2^i - \theta_1^i)\right] \sin \theta_3^i; \\
z' &= l_1 \cos \theta_1^i - l_2 \cos(\theta_2^i - \theta_1^i), \quad i = 1, 6.
\end{align*}
\]

Fig.1. The walking robot mechanical structure

For that point P, to move in the direction of speed vector, defined by v module and cosinuses directories m1, m2, m3 it is necessary to achieve the following conditions:
The platform and legs of walking robot

Thus, with the purpose of fixing the position of the platform, resulting in a system of 18 equations, linking the coordinates of points in support of the six legs, coordinated values for any of these items and all parameters values, determines the platform position. The equations (4) which mainly depend on the walking type and topography of the terrain, can be used to construct control algorithms. After processing, the coordinates for feet extremities are given in the form:

\[ x_{pi} = x_0 + k_i(l_1 \sin \theta_i^j + l_2 \sin(\theta_i^j - \theta_i^1)) \sin \theta_3^j; \]
\[ y_{pi} = y_0 + k_i(l_1 \sin \theta_i^j + l_2 \sin(\theta_i^j - \theta_i^1)) \cos \theta_i^j; \]
\[ z_{pi} = z_0 + l_1 \sin \theta_i^j + l_2 \sin(\theta_i^j - \theta_i^1), \quad i = 1, 6. \]

This system consists of 18 equations containing 22 unknowns, namely: the origin of coordinates \(x_0, y_0, z_0\), angles \(\theta_1^j, \theta_2^j, \theta_3^j, i = 1, 6\), and time \(t\). In this case, the system is equivalent to an indefinite coefficients system with 1540 coefficients, which shows the diversity of possible movements of the robot with six legs. If the trajectory of point \(O(x_0, y_0, z_0)\) is given, the number of unknowns of this system is reduced to 19, and in the equivalent system is only one arbitrary coefficient, which can be determined from the differential equation for a value of time \(t\). For this case, very simple, we have: \(\theta_1^i = x_{fi}, \theta_2^i = x_{fi} - 1, \theta_3^i = x_{fi}, t = x_{ti}, i = 1, 6\). After
differentiation, it the following system of equations results:

\[ k_1 \left[ l_1 \cos x_{3i-2} - l_2 \cos(x_{3i-1} - x_{3i-2}) \right] \sin x_{3i} dx_{3i-2} + \\
+ k_2 l_2 \cos(x_{3i-1} - x_{3i-2}) \sin x_{3i} dx_{3i-1} + \\
+ k_1 \left[ l_2 \sin x_{3i-2} + l_2 \sin(x_{3i-1} - x_{3i-2}) \right] \cos x_{3i} dx_{3i} + \\
+ \left( \dot{x}_0 - \dot{z}_c \right) dx_0 = 0. \] (6)

\[ k_1 \left[ l_1 \cos x_{3i-2} - l_1 \cos(x_{3i-1} - x_{3i-2}) \right] \cos x_{3i} dx_{3i-2} + \\
+ k_2 l_2 \cos x_{3i} \cos(x_{3i-1} - x_{3i-2}) dx_{3i-1} - \\
- k_1 \left[ l_2 \sin x_{3i-2} + l_2 \sin(x_{3i-1} - x_{3i-2}) \right] \sin x_{3i} dx_{3i} + \\
+ \left( \dot{y}_0 - \dot{y}_c \right) dx_0 = 0. \]

\[ l_1 \sin x_{3i-2} - l_2 \sin(x_{3i-1} - x_{3i-2}) dx_{3i-2} - \\
- l_2 \sin(x_{3i-1} - x_{3i-2}) dx_{3i-1} - \left( \dot{z}_0 - \dot{z}_c \right) dx_0 = 0. \]

To determine the sizes of balancing forces, which must be developed by the actuators driving the leading couplings of the robot legs mechanisms - to move the platform with a given speed - it is necessary after differentiation to determine the distribution of accelerations, taking into account the masses and reaction forces. With such analysis, it is possible to establish whether it can achieve the desired speeds and types of walking, which is determined by the third level.


The walking robot is considered as a set of articulated rigid solids, which are standing as a platform and leg elements. With the increasing number of walking robot legs, the driving and control system is becoming more complicated. Moreover, due to the increased number of points of support, the static and quasi-static displacement becomes more stable. As noted above, the walking robot movement is stable only under certain and quite restrictive conditions. The static stability problem is solved by calculating the extremity of each leg position according to the system of axes attached to the platform, with origin at the center of gravity of it.

In order to carry out new capabilities for walking robots, such as walking down the slope, going by overcoming or avoiding obstacles, it is necessary to develop high-level intelligent algorithms, because the mechanism of walking robots stepping on a road with bumps is a complicated process to understand, being a repetitive process of tilting or unstable movements that can lead to the overthrow of the robot. The chosen method that adapts well to walking modular robots is the zero moment point ZMP (Zero Moment Point) method [9,10,11]. During research there was developed a new strategy for the dynamic control for walking robot stepping using ZMP and inertial information. The control diagram, presented in figure 4, includes pattern generation of compliant walking, real-time ZMP compensation in one phase - support phase, the leg joint damping control, stable stepping control and stepping position control based on angular velocity of the platform. In this way, the walking robot is able to adapt on uneven ground, through a real time control, without losing its stability during walking.

Walking robot control strategy is based on three approaches: real-time balance control, walking pattern control and predictable motion control. Real time balance control of the robot using sensorial feedback, has 3. online types of control loops: damping control, ZMP compensating control, stepping timing control. Damping control strategy aims to eliminate the oscillations that occur in the single support phase. The oscillations amplitude is measured in real time by a torque transducer mounted on the robot joints, having compliant control functions of robot movement. A simple inverted pendulum equation with a joint in the single support phase, which opposes the damping forces of the leg joints was adopted for robot motion modeling.

ZMP compensation control strategy. The damping loop is not sufficient to maintain a stable walking motion because of the ZMP movement. So, there was developed a ZMP compensator in a phase, respectively in single support phase (FSU), where the platform will move back and forth according to ZMP dynamics. Control strategy consists in mathematical modeling of ZMP compensator through the springloaded inverted pendulums.
Gait timing control strategy. Timing control at landing avoids instabilities on the robot motion at landing. This module generates a signal to block the walking diagram if the foot doesn’t touch the ground at the end of phase 2 and 4. This way the command to move the leg is stopped, until the leg touches the ground, as a result of the inertia movement.

The walking pattern control, may be changed periodically according to the information received from an inertia transducer during each walking cycle. The control pattern of the walking model contains two control loops in real time: the amplitude control for platform balance and advance/rotate control of the platform.

For modeling of platform balance amplitude was used inverse pendulum method according to lateral balance. In terms of control strategy, periodically adjust the lateral balance amplitude of the platform in order to move ZMP, corrected by measuring ZMP during each walking cycle. Changing the platform balance amplitude is achieved by offsetting the position of the legs which are in contact with the ground so that actual ZMP amplitude (measured) can converge to the average reference ZMP.

Rotation/advance platform control strategy, driven at the walking on a slope, allows the central position of the platform to move in the opposite direction to the inclined transverse plane so that the swinging movement can be well balanced. To measure the platform motion, the command system processes on-line the analog signal from an inertia transducer mounted on the robot platform. Position vector of the platform is obtained through an iterative relation of integration for angular error vector of the platform between the unique support phases (FSU) 1 and 3, amplified by a gain coefficient determined experimentally. In the walking pattern control, the gait phases related to the cycle time have been taken into consideration (fig.5), where: \( t_{0}-t_{1} \) is starting phase 1, \( t_{0}-t_{2} \) is stage 2 having \( t_{2}-t_{3} \) FSU and \( t_{3}-t_{4} \) FDS, \( t_{4}-t_{7} \) is stage 3 respectively \( t_{7}-t_{9} \) stage 4 with FSU and FDS.

The predictable motion control is based on generating probable robot movements achieved by processing earlier movements, in order to avoid overthrowing the walking robot. Anticipating robot movements is obtained through experimental statistic information, taking into account the margins of stability.
prevention of abnormal conditions and processing of additional movements. It has two online control loops.

**Control of landing position.** The proposed solution to HFPC walking robots for controlling the landing position is to compensate foot landing position on ground, in order to walk towards the direction of the fall, by a twisting movement of the platform, obtained through overlapping a law of motion determined experimentally on a normal movement around the z axis of the robot leg. Position vector of the foot in the landing phase is determined as an iterative relation in which along with the prescribed vector of landing position is added an error vector multiplied with an gain factor. The error vector is obtained through the difference between average angular speeds and stable angular speeds of the advance respective torsion velocity.

![Fig. 5. Walking phases and time cycle](image)

**Control of tilt over the side of safety of the robot.** The tilt control loop prevents the fall of the walking robot in lateral directions, in case of moving on a bumpy field or external forces. To avoid these instabilities that may lead to the overthrowing of the robot, the exceeding of the inside and outside inclination edges is determined in real time through iterative integration of the angle of rotation of the platform in torsion movement during the $\tau$ period from starting phase 1 (fig. 5). If exceeding the inclination edges, the angle of rotation of the leg joint is offset by a predefined algorithm depending on the value of the angle of rotation motion of the platform.

**Generating the walking pattern.** Types of walking robot patterns are generated by three programs-block, located in the PC-OAH system namely control block of walking pattern, which determines the sequence and legs motion mode, control block of static stability, which provides robot movement so that the projection of the center of gravity of the system remain within the convex polygon formed by the points of support leg; block control of the platform that maintains prescribed height and horizontal position of the platform. Starting from the graphical representation of a hexapod robot with tripod walking style, were defined walking phases that are required to efficiently control walking robot in different situations, with graphical representation in figure 5.

**Phase support** (double-phase support - FDS) corresponds to the initial position of the robot, considered the early work phase of the robot legs. Robot motion in support phase is limited to movement in the given direction of the three legs. For this purpose the position controllers $CP^k_{i}$, $i=1-3$, $k=1-6$, are getting the values from the cosinuses directories and movement speed, calculated on the multiprocessor system SMLPC. There were previously determined conditions for defining motion in each phase.

**In the single support phase (FSU),** the horizontal position and the prescribed height of the platform are restored, and - if necessary - moving the center of gravity is moved in stability. To maintain the platform in a horizontal position the information provided by transducers of position - horizontal (or verticality) is used that sense walking robots deviation platform, from the horizontal position. Restoring the horizontal position of the platform is achieved at the expense of vertical movement of different legs of support, as decided by the block maintaining the balance.

**The limits of safety have been defined,** according to the value imposed to the limit of stability for a system of walking and/or sizes depending on the reaction forces of the contact points of the feet with the supporting surface. MERO robot experimental results are presented in figure 6. Bringing the projection center of gravity of walking robots in the area of stability, meaning inside the polygon of support is achieved by horizontal movement of the platform, controlled by the block maintaining stability.
Another phase in research development was to establish programming strategies for control schemes reported in control loops and phases of walking robot, as follows: in balance control is achieved damping control, ZMP compensation, position control on landing phases 1, 2 FSU, 3 and 4 FSU; within walking pattern control it’s achieved the platform balance amplitude control and the controller for advance/rotation in phases 2 FDS and 4 FDS; within predictable motion control we have the tilt over robot controller, in phases 1 and 3, respectively the control of landing position in phases 2 FSU and FDS, 4 FSU and FDS.

Choosing the movement period of the robot to 3.7 s, we’ve obtained its natural frequency of 0.27 Hz. Double support phase portion in a walking cycle is approximately 10% to 20% for humanoid robot, while for the HFPC robot was experimentally determined as only 5% because HFPC MERO has no joint in the palm the robot. Lateral balance movement of the platform is essential to moving the ZMP on each foot while walking.

4. Results and conclusions

The research evidences that stable gaits can be achieved by employing simple control approaches which take advantage of the dynamics of compliant legs. This allows a decentralization of the control system, through which a central command establishes the general movement trajectory and local control laws presented in the paper solve the movement stability problems, such as: damping control, ZMP compensation control, gait timing control, walking pattern control, predictable motion control. Based on studies and analysis, the compliant control system architecture [6, 7, 10] was completed with tracking functions for HFPC walking robots, presented in figure 7 which, through the implementation of many control loops in different phase of the walking robot, led to the development of new technological capabilities, to adapt the robot walking on sloping land, with obstacles and bumps. In this sense, a new control algorithm has been studied and analyzed for dynamic walking of robots based on sensory tools such as force/torque and inertial sensors. Distributed control system architecture was integrated into the HFPC architecture so that it can be controlled with high efficiency and high performance.

The command for walking robots is achieved by a control system with three levels. The first level is to produce control signals for motor drive mounted on leg joints, ensuring the robot moving in the direction required with a given speed. The language for this level is that of differential equations. The second level controls the walking, respectively it coordinates the movements and provides the data necessary data to achieve progress. At this level, work is described in the language of algorithms types of walking. The third level of command defines the type of walking, speed and orientation. At this level, the command may be provided by an operator who can use the control panel, in pursuit of its link with the robot, to specify the type of running and passing special orders, for the definition of the vector speed of movement.

To maintain the platform in a horizontal position, information provided by the horizontality or verticality transducers is used, that sense walking robots deviation platform to the horizontal position. Restoring the horizontal position of the platform is achieved at the expense of vertical movement of different legs of support, as decided by the block to maintain balance. Returning to the fixed height of the platform is achieved by using information provided by the height transducer of the platform, by simultaneous control of vertical movement of all legs in support phase.
From analysis performed results effectiveness of proposed control strategy for a modular walking robot with application to MERO modular robot. The position of each actuator is controlled by a PD feedback loop, using encoder like transducers. In HFPC control system, the PC system sends the reference positions to all actuators controllers simultaneously at an interval of 10 ms (100 Hz). Reference positions for the control of 18 actuators and actual positions on each axis robot obtained through interpolation are processed at an interval of 1 ms (1 kHz).

The control system is distributive with multi-processor devices for joint control, data reception from transducers mounted on the robot, peripheral devices connected through a wireless LAN for off-line communications and CAN fast communication network for real time control. The HFPC system was designed in a distributed and decentralized structure to enable development of new applications easily and to add new modules for new hardware or software control functions. Figure 7 shows the general configuration of the HFPC system for ZMP control method.

The results obtained through simulation and experiments show an increase in mobility, stability in real conditions and obtaining of high performances related to the possibility of moving walking robots on terrains with a configuration as close as possible to real situations, respectively developing new technological capabilities of the walking modular robot control systems for slope movement and walking by overtaking or going around obstacles.

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