Fuzzy Dynamic Modeling for Walking
Modular Robot Control

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Abstract. The paper presents new concepts and approaches of multi-stage fuzzy method of walking robots using resolved acceleration control. Several compliant control methods were analyzed in order to obtain high performances in robot trajectory control, which generates position and force parameters for multi-stage fuzzy control, some of which include a dynamic model in loop control and some of which doesn’t include dynamic model. For real-time control of robot stability the mathematical modeling of the center of gravity position was realized, in order to allow control of the walking robot when moving on terrains with complicated configuration, and relations which are necessary for robot position coordinates of the center of gravity were established. The studies presented have demonstrated the possibility of implementing force control by resolved acceleration, where dynamics and kinematics stability are simultaneously achieved in rigid environments. The obtained results lead to a smooth transition, in walking robots movement, without discontinuities, from controlling in position to controlling in force and position.

Key-Words: fuzzy robot control, walking robot modeling, hybrid position-force control, robot dynamic control.

1. Introduction

The movement activity of walking robots and, mainly the walking, is included in the category of systems with a high degree of automation. The mechanical system must be equipped with a large number of degrees of mobility, in order to form complex synergies, and also to achieve coordinated movements of the legs. By using walking robots as a means of transport, some of the parameters characterizing the dynamic attributes may be subject to a wide range of changes. For example, the releasing of an additional load, changes weight, position of center of gravity and moments of inertia of the robot platform. A number of environmental factors can act on the walking robots, such as wind or other forces, whose influence can hardly be anticipated. The action of such disturbances may be a cause of significant deviations from the actual movements of the robot in relation to those prescribed [3, 11-13].

Developing and using methods for operative determination of the causes of deviations from the delivered movement, to highlighting the causes of deviation, and also avoiding these cases, is an appropriate mean of increasing command efficiency for walking robots and reduction of energy resources. Development of adequate mathematical model for studying walking robots movement is of interest, both in terms of composing the high-quality system for robot control and in terms of testing principles and simplifying assumptions, underlying the algorithms used to produce programs command. By applying such a model of walking robots, a considerable part of the studied algorithm assumptions can be revealed and eliminated in the design phase and using it for computer simulation requires less work and time [10, 15-17]. The walking robot is
considered as a set of articulated rigid solids, such as platform and leg elements. With the increasing number of legs of walking robot the actuation and control system becomes more complicated. Moreover, due to the increased number of support points, static and quasi-static movement becomes more stable. As noted above, quadruped robot motion is stable only under certain conditions, quite restrictive. Static stability problem is solved by calculating the extremity of each leg position in relation with the system of axes attached to the platform, with origin at the center of gravity of it. Walking robots with the most stable configurations in static terms, are those equipped with more than four feet (six or eight), in which movement can be done using different types of stepping.

Robust and reliable operation of walking robots in contact with objects in their environment is the basic requirement for stable control of the robot-object interaction that led to the development of many control methods [1-3]. A simple method in which contact force is used to modify the reference trajectory position of the robot end-effectors was proposed by Whitney (1977) and is known as "adjustment of the position". The well-known hybrid force-position control method proposed by Raibert, Craig (1981) and Manson (1980) provides separate processing and also processing by different laws for position and force control by decomposition of the robot environment in "position sub-space" and "force sub-space". By applying this approach, some Cartesian coordinates of the end-effectors are in position control while others are under explicit force control. A force control method based on position, known as "control of the resistance movement at bending" was presented by Lawrence and Stoughton in 1987 and Kazerooni, Waibel, and Kim in 1990. Expanding the same method, Salisbury (1980) presented an active control method of the end-effectors apparent stiffness of the robot, in the Cartesian space, in which the reference position is used as the contact force control, and not used as reference points for forces. In a similar paper, Hogan (1985, Karen 1986) introduced "impedance control", which aims to establish a desired dynamic relationship between the end-effectors robot position and contact force.

The paper develops a multi-stage fuzzy method for robots walking loop control by including a dynamic model that should provide improvement on stability robot motion in the control loop. To this end, several compliant control methods were considered, in which some of them include a dynamic model in control loop control with the settled acceleration (Luh, Walker and Paul 1980), operational space method (Khatib 1980;1987), impedance control (Kazerooni, Houpt and Sheridan 1986), and some of which not include dynamic model: hybrid control (Railbert and Craig) and rigidity control (Salisbury 1980). The control system architecture by dynamic models through fuzzy multi-stage method is presented where control method through resolved acceleration had been chosen as compliant control method. The results of the rules base analysis are presented, in which, the loop reaction for force is dependant on the values of inference from fuzzy control of component P together with a set of membership functions for inputs and outputs.

2. The position modeling of the center of gravity.

In order to control walking robots when traveling on ground surface a mathematical modeling for position of the center of gravity was necessary in the first round. The geometric center "O" is defined as the point of intersection for the diagonals of the polygon formed by the junction points of the platform legs and center of gravity (Fig. 1). Taking into account the Xp, Yp, Zp positions of walking robot legs a mathematical model to express the kinematic center of gravity of the walking robot has been developed. To determine the support polygon position in relation to the platform, using Denovit – Hartenberg method, where Z_i (i = 1-6 or i= 1-4 and j = 1-3) and m_j (i = 1-6, j = 1-3) is the foot mechanism elements mass, a transformation of P_i support point coordinate from O_{X_iY_iZ_i} system to the O_{X_0Y_0Z_0} system has been performed.

The stability condition is that the vertical projection of center of gravity G on the surface of the support to be within the support polygon system. Since the positions of centers of gravity of each leg mechanism element are in relation with their own systems are known, relationship for the robot center of gravity position coordinates needed for real-time control of robot stability were determined:
\[ X^k_G = \sum_{i=1}^{6} \sum_{j=1}^{3} m^j \cdot X^k \cdot G^j \]

where, \( X^k = \{X, Y, Z\} \) for hexapod walking robot and \( i=1-4 \) for quadruped walking robot. Knowing the position of the center of gravity, we determined \( X^k \) by derivation the speed and \( \ddot{X}^k \) by double derivation the acceleration.

![Mathematical modeling of center of gravity for modular walking robots](image)

Fig. 1 Mathematical modeling of center of gravity for modular walking robots

Maintaining the vertical center of gravity in the area of support is even more difficult if the robot moves on a slope. In this case, the burden of maintaining stability depends on the transported weight \( (f_i) \) and the \( X_C \) distance from the surface points of support to center of gravity [4, 5, 14]. Stability is obtained by reducing the \( X_C \) component along with increasing the task \( f \), depending on the slope where the robot moves. A method of testing involves an evaluation task and assigning the robot a constant value of step size in order to obtain robot stability. As a result, it might get a high number of steps for a complete stability, which depends on the speed of the robot and the obstacles encountered on the path of movement. This can lead to the overthrow of the robot if not chosen correctly.

A new control method applied to eliminate robot instabilities and which has a fast response control loop consists of a “multi-stage” (MS) fuzzy control. This method requires completion of two fuzzy control loops, one in position and another in force, on two levels (“stage”) of different decision, to determine distance \( X_P \) from the surface support points to the center of gravity.

### 3. Fuzzy Dynamic Modeling

Several compliant control diagrams were analyzed in order to obtain high performances in robot trajectory control, which generates position and force parameters for multi-stage fuzzy control, some of which include a dynamic model in loop control [6, 8, 9]: control with the settled acceleration (Luh, Walker si Paul 1980; Shin si Lee 1985), operational space method (Khatib 1980;1987), impedance control (Hogan 1985a-c, Kazerooni, Sheridan si Houpt 1986; Kazerooni, Houpt si Sheridan 1986), and some of which not include dynamic model: hybrid control (Railbert si Craig) and rigidity control (Salisbury 1980). Stability analysis and experimental implementation are presented, which demonstrate not only that by using dynamic models is achieved a more accurate control, but also that using an inadequate dynamic model can lead to an unstable control of the force in some cases.

The analysis of hybrid control stability were made for the case where the robot foot is in free space and not interacting with the environment. The Cartesian positions and speeds are calculated from the positions and speeds of each torque and also by direct kinematics (Raibert si Craig), through the diagram from figure 2. Thus, we obtain the law of motion:

\[
\tau = K_{pp} J^{-1} (X_d - X) + K_{p} J^{-1} S (X_d' - X') + K_{f} J^T (I - S)(F_d - F)
\]

where \( \tau \) is the torque vector, \( X \) is the vector of position, and \( X_d \) is the initial vector of position, \( J_d \) is the Jacobian matrix and \( K_{pp} \) is the advance matrix of position in torque coordinates. From the analysis, it is established that the robot foot is initially in a stable position in accordance to the roots location diagram. Then, the robot is displaced across X direction with a small force towards a more stable configuration. The system became unstable at approximate \( \theta_2 = 75^\circ \), and also at \( \theta_2 < 79.5^\circ \) in accordance to roots location diagram. Thus, it is found that the robot foot, under hybrid control, can become a set of steps and articulation positions and lead to a stable movement.
Hybrid control analysis by Routh criteria in instability conditions. It was analyzed the way that appropriate selection of the steps can manage the stable hybrid control-for example, by increasing the amortization steps. The analysis shows that selection of the steps can not be made randomly. Actually, when \( k_{p2} < 0 \) and \( k_{p1} > 0 \), the force control is stable, but position control is unstable, because the positive feedback is created for the second articulation. If both of the parameters are positive and constant, then it has to be selected the following parameters: \( k_{p1} > 95k_{p2} \), \( k_{v1} > 95k_{v2} \), in order to guarantee stability in the un-singular space, where \( K_{v1} \) is the advance matrix of speed in couple coordinates.

Hybrid control analysis for the robot foot in contact with a stiffness environment. By analyzing the polynomial characteristic of the matrix system it is established that there is at least the dependence for \( k_{v1}/k_{v2} \) rapport, as in the previous situation. Thus, the instability propriety of the hybrid controller is contact independent. A robot in contact with environment does not solve this instability problem, because the instability is generated by the interaction of the inertia matrix and reverse Jacobian.

Analysis of control through resolved acceleration stability for the case when robot foot is in free space and is not interacting with the environment. The modified control through the resolved acceleration (Shin and Lee) is given by the relation:

\[
\epsilon_f = MJ^{-1}[S(X_d^* + K_v(X_d^* - X^*) + K_p(X_d - X)) - J\dot{q} + \beta + J^T(I - S)F^*]
\]

where \( M \) is the inertia matrix, \( \beta \) represents Coriolis and centriped couple and \( g \) is the gravity couple vector, \( F^* \) is the control vector for active control of the force, which is the only changing from the initial statement (fig. 3).
From the analysis made, results that unlike hybrid control, inverse Jacobian matrix do not interact in a damaging way with the inertia matrix because latter it is nullified. The answer is also stable for the same triangular course, the control by resolved acceleration follows the desired route much more accurate than the control hybrid. This stability property is robust to modeling errors. Even with 50% error in the inertial parameters, their own values remain negative.

**Analysis of control with resolved acceleration for robot leg in contact with a rigid ground.** Analyzing the polynomial characteristic coefficients of the matrix and applying the Routh criterion to show sufficiency, it is noted that there are two roots with negative real parts and two imaginary roots. The two negative real roots are from the position-controlled part and the two imaginary roots are from the force-controlled part. In conclusion, the robot is always stable regardless its configuration, as in the case with no contact.

It was made a comparison study for the performance of compliant control methods presented. From the study, results that **dynamic instability** occurs when the robot comes in contact with a rigid medium and bounces uncontrollably on that surface. **Kinematic instability** is presented in the hybrid control but not in control of rigidity or control with resolved acceleration.

**Kinematic instability in hybrid control through Railbert and Craig method** depends on the kinematic structure, the reports of the steps of various joints and the robot configuration foot. In addition, by adding more depreciation or speed steps, system instability persists. Modified control by resolved acceleration or operational space method is stable because the inertia matrix is also included, canceling the destabilizing effects of the inverse Jacobian. If dynamic modeling is accurate, the robot motion is completely decoupled from the top in Cartesian coordinates. Even if the dynamic modeling has a 50% error, simulations have shown that resolved acceleration is still stable.

**Fuzzy multi-stage method using control by resolved acceleration of walking robots.** In figure 4 is presented the control system architecture by dynamic models through fuzzy multi-stage method where it had been chosen as compliant control method, the control method through resolved acceleration.

Controller tasks were defined, as a decision rule and the fuzzy variables used in decision-making. The deviation values detected by the sensor values were quantified in a number of points corresponding to elements of the discourse universe, and then values were assigned as membership levels in some fuzzy subsets. Relations between inputs, for example deviations measured, or outputs, as the example of speeds, and the membership level were defined in accordance with the experiments and the demands of the task. Fuzzy values were chosen as follows: NM - negative big, Nm - negative medium, Nm - negative small, ZO - zero, Pm - positive small, PM - positive medium, PM - positive big.

![Fig. 4 Control system architecture through resolved acceleration using multi-stage fuzzy](image-url)
Figures 5-7 presents membership functions set for inputs and outputs. Control value with the highest membership level was selected. The rules are evaluated at regular intervals, the same as a conventional control system. Defuzzification method was chosen as the center of gravity of the area method.

Choosing a universe of discreet discourse allows the using of PLC system from control system architecture of the HFPC walking robots, in order to generate fuzzy output variables in a reduced processing time. By applying fuzzy logic control, we obtain a smooth transition, in walking robots movement, without discontinuities, from controlling in position to controlling in force and position.

4. Results and conclusions

To verify the theoretical results, has been developed an application for simulation of walking robots movement through virtual projection. The application purpose consists in generating, displaying and sending the references to the walking robot made out 3 modules of 2 feet each, positioned at the corners of a triangle. Since the adopted walking is tripod, it shall be deemed to exist three legs moving simultaneously on the same path, one from each module).
The patterns are introduced by the developer, in the operation manual, automatic or received by serial transmission as a file. Each file is associated with a single module consisting of 2 feet, moving the other 4 feet is similar to these two. At this walking style two situations occur:

- the platform is moving in a discreet way on movement intervals with stationary points
- the platform is moving with a constant speed all the time in which the feet follow their trajectories.

The application contains two sections with 2 feet from the side seen displayed in 2D for a better observation of the movement. The sections include the possibility to set the status of each leg, respectively, top end defined as fixed or the part that is connected to the platform defined as fixed, both reported to the system of axes of the foot. The approach is related to the leg axes system because in the second case, if the platform is in motion, we consider the point between the leg and platform as a virtual fixed point, the tip moving in relation to the platform.

In figure 8 is observed graphically the path followed by the robot leg simultaneously with the path followed by the robot platform. The position in Cartesian coordinates of the robot environment and angular values of joints, depending on the robot control law applied, are displayed on-line.

Stability analysis and experimental implementation have demonstrated that the use of dynamic models may lead to obtaining a robust and safe functioning of walking robots with environmental impact. Moreover, using an inadequate dynamic model can lead to the unstable control of the force in some cases. Modified by resolved acceleration control or operational space method is stable because the inertia matrix is also included canceling the destabilizing effects of the inverse Jacobian.

A compliant control system architecture has been developed in which dynamic models were integrated into a multi-stage fuzzy control structure using the control method with resolved acceleration. The results of the rules based on the analysis, allowed obtaining a loop reaction force dependent on the values of inference from fuzzy control of component P together with a membership functions set for inputs and outputs.

The studies presented have demonstrated the possibility of implementing force control by resolved acceleration where dynamics and kinematics stability are simultaneously achieved in stiffness environments. The obtained results lead to a smooth transition, in walking robots movement, without discontinuities, from controlling in position to controlling in force and position. Furthermore, we achieve a fast response of control loop maintaining robot stability in the process of stepping on uneven ground.

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