THEORY AND APPLICATION OF EXTENSION HYBRID FORCE-POSITION CONTROL IN ROBOTICS

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The paper presents advanced method for solving contradictory problems of hybrid position-force control of the movement of walking robots by applying an "Extension Set". Starting from the extension distance defined by Prof. Cai Wen, the founder of Extenics, there are determined the 2D space dependent function on position and force in relation to standard positive field on position respective on force. The generalization of the extension distance and dependent function using Extenics Multidimensional Theory eliminates the crisp logic matrix of Cantor logic which describes the position-force sequences. Thus was developed an optimization method for hybrid position-force control which ensures positioning precision and robot motion stability on rough terrain.

Keywords: extenics multidimensional theory, extenics logic, hybrid force-position robot control, robot motion stability

1. Introduction.

The control strategy of walking robots must take into account a series of factors in order to develop new technological capabilities of the control system, such as: form and consistency of the walking terrain; walking stability; the command and control of the movement system elements; reaching the speed and mobility necessary for movement. The robust and secure working of walking robots in contact with objects in their environment is the basic requirement for accomplishing tasks for the given application. Stable control of the robot-object interaction implies a difficult problem from a dynamic standpoint.

The walking robots motion control 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 (DOF), in order to form complex synergies and to achieve coordinated movement of the legs. The action of such disturbances like an additional load, changes in weight, position of center of gravity and the robot platform inertial moments and may be a cause of significant deviations from the robot prescribed motion. A number of compliant control techniques are known

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for obtaining high performance in robot trajectory control, some of which include a dynamic model in the control loop: solved acceleration loop (Luh, Walker and Paul), operational space method (Khatib), impedance control (Hogan, Kazerooni, Sheridan) and others which do not include dynamic models: hybrid control (Railbert si Craig) and rigidity control (Salisbury).

An important role in controlling walking robots is the force-position control. Craig and Raibert first proposed combining position and force information into the control system in nondeterministic environments. An and Hollerbach have shown that some of the force control methods, including hybrid control, are unstable. Zhang showed that the hybrid control system might become unstable under certain configurations of the robot. Analyzing proposed solutions by Fisher and Mujtaba, 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.

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 [4,5]. 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. In order to increase mobility and stability in real conditions and to obtain superior results relating to the possibility of moving walking robots on terrains with close configuration to real situations such as slope walking, overtaking or avoiding obstacles and starting from similar research applied to humanoid robots [14-16], was developed research regarding the integration of compliant control and fuzzy control into the hybrid position force control system architecture for hexapod walking robots.

Extenics has been used since 1983 by Cai Wen and it has been successfully used in various applications. Extension Set Theory [1-3, 6-9] is a mathematical formalism for representing uncertainty that can be considered an extension of the classical set theory. It has been used in many different research areas [10-13, 17-22]. Extenics is a theory to solve the contradiction problem, it will be a new way to look for and find knowledge through analysis the contradiction in robotics, mechatronics and real time control systems. An advanced method for solving contradictory problems of hybrid position-force control of the movement of walking robots by applying an “Extension Set” is presented in papers.

The final conclusions lead to development of a methodology that allows obtaining high level results for hybrid position-force control using extended transformations and an optimization function generated by the extended dependence function in 2 D space.

2. The extension hybrid force-position control

Hybrid position – force control of industrial robots equipped with compliant joints must take into consideration the passive compliance within the system. The generalized surface on which the robot labours must be defined into a constraint space with six degrees of freedom (DOF), with position constraints along the normal to this surface and force constraints along the tangents. On the basis of these two constraints, the general scheme of hybrid position – force control is described in figure 1. Out of simplification considerations the coordinate transformations are not noted. The variables X_C and F_C represent the Cartesian position, respectively the Cartesian force exerted upon the environment.

The selection matrices. Considering X_C and F_C as expressed in environment – specific coordinates, the selection matrices S_x and S_f can be determined, which are diagonal matrices with 0 and 1 as diagonal elements, and fulfill the relation:

$$\mathbf{Sx + Sf = I} \qquad \mathbf{(1)}$$

In new approaches [4, 15] Sx and S_f are methodically deduced from the kinematical constraints imposed by the working environment.

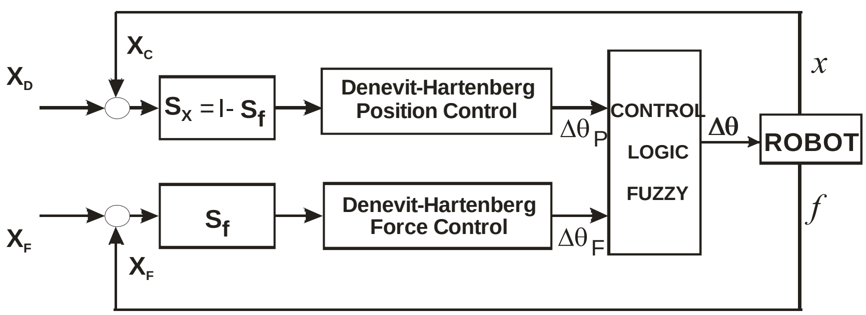

Fig. 1. The section matrices for hybrid force-position control

We intend to replace the S_x and S_f matrices which contain crisp logic values with K_x and K_f which contain values of the dependent function of the position error K_x and the force error K_f with respect to the Standard Positive Field (SPF).

Thus, considering the universe of discourse in figure 2 an the relation between the intervals in figure 3 [2], we will replace the crisp logic values 1 in matrices S_x and S_f with the K_x and K_f coefficients which result from the error positioning corresponding to the standard positive field.

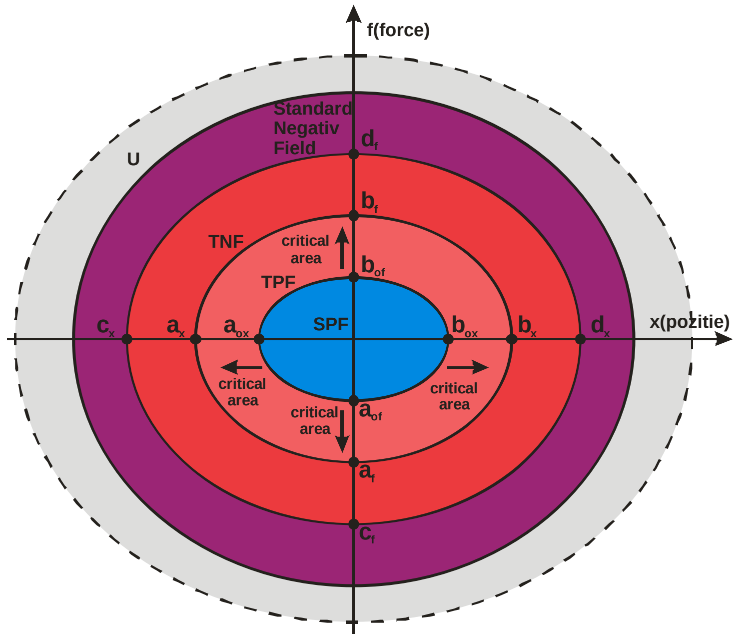

Fig. 2. Classification of Universe of Discourse (U)

The relation for the extension set defined by Prof. Cai Wen is [1,2]:

$$\tilde{E}(T)=\left\{\left(\varepsilon,y,y'\right)|\varepsilon\in U,y=k\left(\varepsilon\right)\in I;T_{\varepsilon}\varepsilon\in T_{U}U,y'=T_{k}k\left(T_{\varepsilon}\varepsilon\right)\in\Re\right\} \quad (2)$$

for an universe of discourse U, in which ε is an element of U, k is a mapping of U to the real numbers' set, $T=(T_U, T_k, T_\varepsilon)$ is a transformation, y=k(ε) is the dependence function of $E(T)$, $y'= T_k k(T_\varepsilon \varepsilon)$ is the extension function of $\tilde{E}(T)$, and T_U, T_k, T_ε are transformations of the universe of discourse U through dependent function k and element ε.

In this paper we will consider the case in which the extension set of the transformation depends on ε, and the transformation T_k is implemented only on element ε, which leads to T_U=e (the unity matrix Id), T_k=e, T_UU=U si T_kk=k, respectively:

$$\tilde{E}(T)=\tilde{E}(T_{\varepsilon})=\left\{\left(\varepsilon,y,y'\right)|\varepsilon\in U,y=k\left(\varepsilon\right)\in I;T_{\varepsilon}\varepsilon\in U,y'=k\left(T_{\varepsilon}\varepsilon\right)\in\Re\right\} \quad (3)$$

The case of the extension set with transformations depending on the dependence function k(ε) and the general case for transformation T_u being implemented on the universe of discourse U, depending on the change of k, noted T_k, will be studied in future papers.

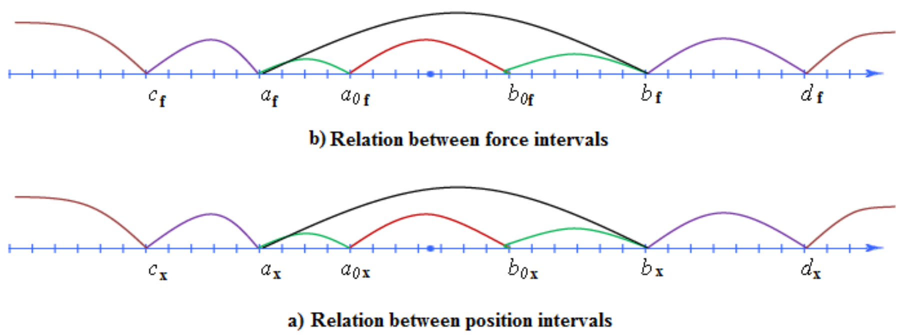

Fig. 3. The relation between the intervals

Dependent function k(x), k(f) to enable the calculation of correlation do not have to rely on subjective judgments or statistics, it can quantitatively and objectively describe the elements having the nature or character at a certain extent and the process of quantitative change and qualitative change. This allows correlation function out of bias caused by subjective judgments.

In order to determine the dependence function in 2D space, generated by the position and force, we start from the extension distance defined in 1983 by Prof. Cai Wen. The dependence function, according to Yang and Cai (1999) [7], through a point which belongs to the set of real numbers $\Re$, is given by the relation:

$$k(z)=\begin{cases}\dfrac{\rho(x,X)}{D(x,X_0,X)}, & D(x,X_0,X)\neq 0, x\in X\\ -\rho(X,X_0)+1, & D(x,X_0,X)=0, x\in X_0\\ 0, & D(x,X_0,X)=0, x\notin X_0, x\in X\\ \dfrac{\rho(x,X)}{D(x,X,\hat{X})}, & D(x,X,\hat{X})\neq 0, x\in\Re-X\\ -\rho(x,\hat{X})-1, & D(x,X,\hat{X})=0, x\in\Re-X\end{cases} \tag{4}$$

in which x is replaced by the object of study, the position error ε_x , the force error ε_f respectively and $\hat{X}$ is transitive positive field (TPF).

In order to move into 2D space we will use the generalization theory for the distance and dependent function to nD. In Extenics, the relation that can exist between a point $x\in\mathbb{R}^n$ and a set $A\subseteq\mathbb{R}^n$ is to be extended, with the intention of expressing more than the simple idea that $x\in A$ or $x\notin A$. In order to obtain this result we propose replacing the indicator δ defined by

$$\delta(x,A) = \inf_{y\in A} d(x,y) \quad (5)$$

where d is distance on $\mathbb{R}^n$, with the indicator $\mathfrak{s}$ defined as follows [O.I. Sandru, 21]:

$$\mathfrak{s}(x,A) = \begin{cases} \delta(x,A), & x \in \complement A \\ -\delta(x,\complement A), & x \in A \end{cases} \quad (6)$$

where by $\complement A$ we denoted the absolute complement of A, i.e. $\complement A = \mathbb{R}^n \setminus A$.

This new indicator keeps into 2D space all the properties of the indicator:

$$\rho(x,[a,b]) = \left| x - \frac{a+b}{2} \right| - \left| \frac{b-a}{2} \right|, \quad (7)$$

introduced by Cai Wen in [1] for the particular case where $x \in \mathbb{R}$ and the set A is an interval of the real numbers' set of the form $[a,b]$, with $a < b$.

Using the s indicator we can build a new Extenics Theory indicator [21]:

$$\mathfrak{S}(x,A,B) = \frac{\mathfrak{s}(x,A)}{\mathfrak{s}(x,B) - \mathfrak{s}(x,A)} \quad (8)$$

defined for any $x \in \mathbb{R}^n$ and for any sets A and B in $\mathbb{R}^n$ for which $\overline{A} \subset \overset{o}{B}$.

By generalizing the distance and dependent function in Extenics to nD and applying a transformation T_k=e, T_UU=U and T_kk=k, the transformed position and force error can be determined and introduced into the robot's hybrid position-force control loop in the relation (15) for each dimension or the relation (17) into 2D space, which will maintain the two contradictory position-force components in the standard positive field.

3. Architecture of the Extension Position-Force Control System

The architecture of the Extension Position-Force Control System, presented in Figure 4, consists of a series of modules whose aim is to solve the contradictory problem of hybrid position – force control for the movement of robotic and mechatronic systems. This is obtained conceptually by replacing the 0 and 1 logic values from the selection matrices S_x and S_f, depending on the position-force sequences in Cantor logic, with values of the dependent function using extension distance.

This is followed by a domain extension transformation for position S_{Kx}, respectively for force S_{Kf}, which generates a new selection matrix with correlation coefficients for position and force respectively.

Thus, a module which calculates the position extension distance CDEP, receives the current position signal X processed by a Carthesian coordinate calculation module CCC through direct cinematic, of the robotic and mechatronic system SRM and in reference to the standard positive interval of the position reference X_o, defined experimentally, calculates the position extension distance $\rho(X,X_o)$, which it sends to the module calculating the position dependence function CFDP. The extension position distance $\rho(X,X_o)$, according to extension theory, is calculated as the distance from a point, in this case the current position signal X, to an interval, in this case the standard positive interval for reference position X_o. Similarly, the data for calculating the force extension distance is calculated by the CDEF module, which works quasi-simultaneously with the CDEP module which calculates the extension position distance.

There are defined experimentally X_o for position and $\mathbf{X_{Fo}}$ for force as belonging to the standard positive domain (DSP) for position and force respectively of the accepted errors, where a_{ox} and b_{ox} are the maximum allowable negative and positive position errors and a_{of} and b_{of} are the maximum allowable negative and positive force errors. There are also defined experimentally $\mathbf{X_{CR}}$ for position and for $\mathbf{X_{FCR}}$ force as belonging to the transitive positive domain (DTP) for position respectively force of the critical error in which it is still possible to control the movement of the robotic and mechatronic system (SRM) in order to bring the position and force errors into the standard positive domain (DSP).

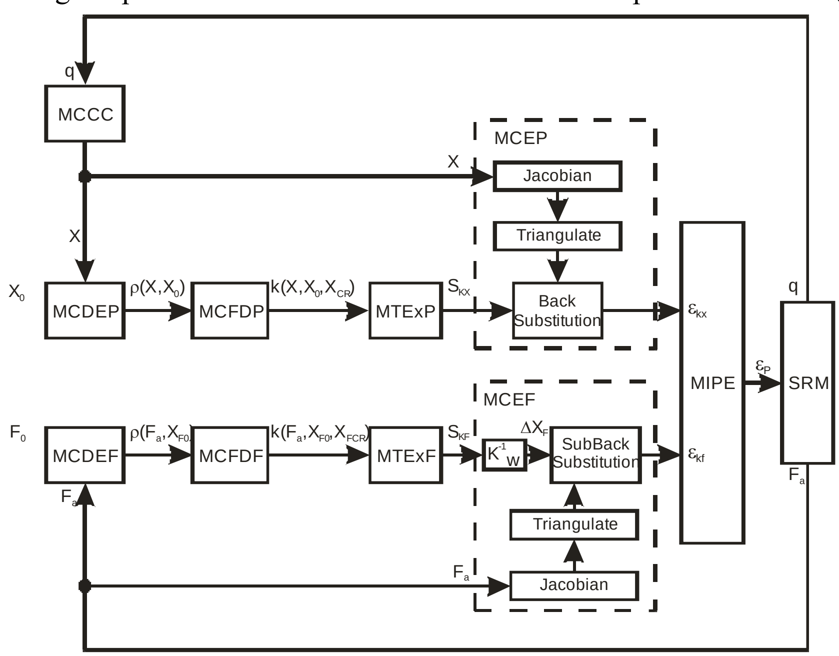

Fig.4. Architecture of the Extension Hybrid Position-Force Control System for explicit control

The position dependent function $K(X, X_o, X_{CR})$ of the current position signal X in relation to the standard positive interval of the reference position X_o and the transitive positive interval for position $\mathbf{X_{CR}}$ is determined according to extension theory in the CFDP module. This has the maximum value of $K(X_o)=M_P$ equal to the proportional amplification component of the position controller on the standard positive interval for the reference position X_o. Moreover, in order to not saturate the position loop, the dependent function for position $K(X, X_o, X_{CR})$ has a lower limit of 0 if the current position signal X is within the intervals X_o and $\mathbf{X_{CR}}$.

A new selection matrix S_{Kx} with the correlation coefficients for position is generated by the extension transformation module for position TExP which receives the dependent function signal for position $K(X, X_o, X_{CR})$ from the CFDP module and replaces the elements with value 1 in the position selection matrix with correlation coefficients for position , determined through an extension transformation in domain. For force similar processing takes place by using the CDEF, CFDF, TExF AND CEF modules, while quasi-simultaneously applying the position processing.

By applying the explicit sequential force-position control method on the two components, position in the CEP module and force in the CEF module, the position error and force error signals ε_{Kx} and ε_{Kf} respectively are determined with the aim of closing the system control loop in position and in force.

The hybrid position – force control in Cartesian coordinates, conceived as a control system in open architecture (OAH), is realized by processing in real time the Jacobean matrix obtained from direct kinematics through the Denevit – Hartenberg method with the calculus of the inverse Jacobean matrix for control in back loop. Noting with $J(\theta)$ the Jacobean matrix of position and with ΔX_P the generalized vector of position error, the real time control process is realized simultaneously in two ways: a way for determining the ΔX^F matrix, which corresponds to the force controlled component, and a second way for determining the ΔX^P matrix, which corresponds to the component controlled in position. A hybrid position-force control system normally achieves simultaneous control of position and force.

Results the motion variation on the robot axis in relation to the end-effector motion variation from the relation:

$$\Delta q = J^{-1}(q)\ \Delta X_F + J^{-1}(q)\ \Delta X_P \tag{9}$$

where ΔX_F can be calculated from the relation:

$$\Delta X_F = K_F\,(\Delta X^F - \Delta X_D) \tag{10}$$

and K_F is the dimensional relation of the stiffness matrix. Noting F_D as the desired residual force and K_W the physical stiffness the following relation is obtained:

$$\Delta X_D = K_W^{-1} F_D \tag{11}$$

In same mode, both the desired differential motions of the end effector corresponding to control in position can be determined from the relation:

$$\Delta X_P = K_P \, \Delta X^P \qquad (12)$$

where K_P is the gain matrix.
Moreover the desired movement angles on the controlled axis in position are given by the relation:

$$\Delta q_P = J^{-1}(q) \;\; \Delta X_P \qquad (13)$$

Taking into account force control on the remaining directions, the relation between the desired angular movement of the end-effector and the force error ΔX_F is:

$$\Delta q_F = J^{-1}(q) \;\; \Delta X_F \qquad (14)$$

where the position error ΔX_F due to force is the movement difference between ΔX^F the current position deviation measured by the command system which generates the position deviation for the axis controlled in force and ΔX_D – the deviation in position due to the desired residual force.

Thus results the motion variation on the robot axis in relation to the end-effector motion variation from the relation:

$$\varepsilon_p = \Delta q = J^{-1}(q) \, \Delta X_F + J^{-1}(q) \, \Delta X_P \qquad (15)$$

Finally, an intelligent module processes the MIPE error, receiving the position error signals from the module calculation the position error CEP and the force error signals from the module calculating the force error CEF and generates the position error on each axis of freedom (DOF) of the robotic and mechatronic system SRM through PID or intelligent control such as fuzzy control or neutrosophic control and sends the signal to the robotic and mechatronic system SRM.

The architecture of the hybrid position – force control system of robots with six degrees of freedom based on the Denevit – Hartenberg transformations is presented in figure 4. The device sensors are used in two ways. In position control, the information obtained from the sensors is used to compensate the deviation of the robots' joints, due to the load created by external forces, so that the apparent stiffness of the robot's joint system is emphasised.

In force control, the joint is used as a force sensor, so that the manipulator is led in the same direction as the force received from the sensors, allowing the desired contact force to be maintained.

The implementation methodology of this advance method for hybrid position-force control of the walking robot consists in determining experimentally the standard positive field and the transient positive field for each control component, applying the transformation on the force and position error taking into account their real position in relation to the standard positive field, defined by points a_{0x} and b_{0x} for position, respectively a_{0f} and b_{0f} for force, resulting in a transformed position and force error which represents the optimized function for hybrid position-force control. The universe of discourse is configured to admit a transient negative field (TNF), defined by points c_x and d_x for position, respectively c_f and d_f for force, so that passing these points the position and force errors will be limited so as not to lead to controller saturation and all the negative effects that derive from it.

4. Results and Conclusions

The obtained results lead to an advanced method of solving the contradictory problem of hybrid position-force control for robot movement by applying an "Extension Set", which allows the two contradictory elements, force and position, to be controlled simultaneously in real time, allowing for improvements in the movement precision and stability of the robot. Starting from the extended distance given by Prof. Cai Wen the dependent function in 2D space generated in position and force is determined.

By replacing crisp logic values in the S_x and S_f matrices depending on the force-position sequence with values of the Extension Distance and Dependent Function for 2D space given by O.I. Sandru, a method is developed for optimizing hybrid position-force control which ensures positioning precision and stability for the robot.

The final conclusion lead to the development of a methodology which will allow high level results for hybrid force-position control, by using an extended transformation using as an optimization function the dependence function based on extension distance, in comparison to the classical method using sequential matrices corresponding to Cantor logic.

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