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The Hybrid Position and Force Control of Robots with Compliance Function

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Abstract. This paper shows a new method for the hybrid position-force control of robots with compliance function on six axis of freedom degrees in system multi-microprocessor in order to obtain high performances. For this purpose kinematics and kinetostatics analysis are performed, and the mathematic model of the inverted kinematics is determined for controlling the main trajectory of the robot. Related to this there is presented an Open Architecture system for the robot position control in Cartesian coordinates through real time processing of the Jacobean matrix obtained out of the forward kinematics using the Denevit-Hartenberg method and calculating the Jacobean inverted matrix for feedback. The obtained results prove a significant reduction of the execution time for the real time control of robot's position in Cartesian coordinates and increased flexibility.

*Key Words***:** real-time digital processing, hybrid position-force control, compliance function, multi-microprocessor system.

1. Introduction

Data acquisition systems for robot positions control in real time need flexibility, accuracy, high-speed processing and feedback control. The robots' flexibility can be improved if the target generated in the environment coordinates is calculated while moving from the previous point. This can be control for various positions and velocities in the environment coordinates but more processing is needed. A robot can be considered as a mathematical relation of actuated joints which ensures coordinate transformation from one axis to the other connected as a serial link manipulator where the links sequence exists. Considering the case of revolute-geometry robot all joints are rotational around the freedom axis. In general having a six degrees of freedom manipulator the mathematical analysis becomes very complicated. There are two dominant coordinate systems: Cartesian coordinates and joints coordinates. Joint coordinates represent angles between links and link extensions. They form the coordinates where the robot links are moving with direct control by the actuators. The position and orientation of each segment of the linkage structure can be described using Denavit-Hartenberg [D-H] transformation [11]. Considering that a point in j, respectively j+1 then ${}^{j}P$ can be determined in relation to ${}^{j+1}P$ through the equation :

$$ {}^{j}P = {}^{j}A_{j+1} \cdot {}^{j+1}P, \qquad (1) $$

where the transformation matrix ${}^{j}A_{j+1}$ is defined by the robot's mechanical structure. The control using forward kinematics consists of transforming the actual joint coordinates, resulting from transducers, to Cartesian coordinates and comparing them with the desired Cartesian coordinates. The resulted error is a required position change, which must be obtained on every axis. Using the Jacobian matrix inverting it will manage to transform the change in joint coordinates that will generate angle errors for the motor axis control. The robot joint angles, θ_c, are transformed in X_c - Cartesian coordinates with D-H transformation, where a matrix results from (1) with θ_j -joint angle, d_j -offset distance, a_j - link length, α_j - twist.

Position and orientation of the end-effectors with respect to the base coordinate frame is given by X_C :

$$X_C = A_1 \cdot A_2 \cdot A_3 \cdot .... \cdot A_6 \quad . \qquad (2)$$

Position error ΔX is obtained as a difference between desired and current position. There is difficulty in controlling robot trajectory, if the desired conditions are specified using position difference ΔX with continuously measurement of current position $\theta_{1,2,.....6}$.

The relation, between the end-effector's position and orientation at a given time considered in Cartesian coordinates and the robot joint angles $\theta_{1,2,.....6}$, is :

$$x_i = f_i(\theta) \, , \qquad (3)$$

where θ is vector representing the degrees of freedom of robot. By differentiating we will have:

$$\delta\, {}^6X_6 = J(\theta) \bullet \delta\theta_{1,2,.....6} \, , \qquad (4)$$

where $\delta\, {}^6X_6$ represents differential linear and angular changes in the end-effectors at the currently values of X_6 and $\delta\theta_{1,2,.....6}$ represents the differential change of the set of joint angles [5, 8,12]. J (θ) is the Jacobian matrix in which the elements a_{ij} satisfy the relation:

$$a_{ij} = \delta f_{i\text{-}1} / \delta \theta_{j\text{-}1} \, , \qquad (5)$$

where i, j are corresponding to the dimensions of x respectively θ .

The inverse Jacobian transforms the Cartesian position δ^6X_6 respectively ΔX in joint angle error ($\Delta\theta$):

$$\delta\theta_{1,2,...6} = J^{-1}(\theta) \cdot \delta\, {}^6X_6 \, , \qquad (6)$$

The Jacobian computation consists in consecutive multiplication of manipulator A matrix. Gaussian elimination provides an efficient implementation of matrix inversion. The method consists of reducing the J matrix to the upper triangulate form and finding errors in $\Delta\theta$ joint coordinates using back-substitution. The joint angle errors $\Delta\theta$ can be used directly as control signals for robot motors.

2. Hybrid position and force control of robots

As part of the manufacturing process, especially with regards to the automation assemblers, the compliance is necessary to avoid power impact forces, to correct position error of robots or of special mechanical processes devices, and to allow tolerant relaxation of component elements. The compliance can be fulfilled either through passive compliance, as in Remote Center of Compliance (RCC) [3] or in many other of its versions [1, 2, 7, 8, 9], or through force control active methods [4, 6]. In any case, there are fundamental problems in both tehniques, when these are implemented in industry. Passive compliance can lower robot position capacity. The active compliance can have problems with sensibility in a rigid enviroment. That is why, although recently a lot of investigations regarding this research purpose have been reported [5, 10], a simple, economical and reliable method is still being sought.

Hybrid position and force control of industrial robots equipped with compliant joints must take into consideration the passive compliance of the system. The generalized area where a robot works can be defined in a constraint space with six degrees of freedom (DOF), with position constrains along the normal force of this area and force constrains along the tangents. On the basis of these two constrains there is described the general scheme of hybrid position and force control in figure 1. For simplification the coordonate transformations are not noted. Variables X_C and F_C represent the Cartesian position and the Cartesian force exerted onto the enviroment.

The selection matrices. Considering X_C and F_C expressed in specific frame of coordinates, its can be determinate selection matrices S_x and S_f, which are diagonal matrices with 0 and 1 diagonal elements, and which satisfy relation:

$$S_x + S_f = I_d \, . \qquad (7)$$

In approaches [5, 6, 10] S_x and S_f are methodically deduced from kinematics constrains imposed by the working environment. Let A and B be two matrixes with full column rank that satisfy the equation $A^tB = 0$ and correspond to the twist and wrench spaces of constraint, then there can be determined S_x and S_f through the relations:

$$S_x = (A^t \Psi A)^{-1} A^t \Psi \quad , \qquad (8)$$

$$S_f = (B^t \Psi^{-1} B)^{-1} B^t \Psi^{-1} \quad , \qquad (9)$$

where usually Ψ is symmetrical matrix, positively defined.

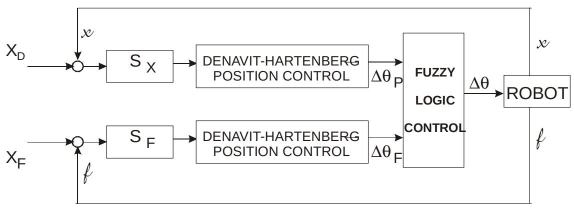

Fig. 1. General structure of hybrid control.

Mathematical equations for the hybrid position-force control. A system of hybrid position–force control normally achieves the simultaneous position–force control. In order to determine the control relations in this situation, ΔX_P – the measured deviation of Cartesian coordinate command system is split in two sets: ΔX^F corresponds to force controlled component and ΔX^P corresponds to position control with axis actuating in accordance with the selected matrixes S_f and S_x. If there is considered only positional control on the directions established by the selection matrix S_x there can be determined the desired end-effectors differential motions that correspond to position control in the relation:

$$\Delta X_P = K_P \, \Delta X^P \ , \qquad (10)$$

where K_P is the gain matrix, respectively desired motion joint on position controlled axis:

$$\Delta\theta_P = J^{-1}(\theta) \cdot \Delta X_P \ , \qquad (11)$$

Now taking into consideration the force control on the other directions left, the relation between the desired joint motion of end-effectors and the force error ΔX_F is given by the relation:

$$\Delta\theta_F = J^{-1}(\theta) \cdot \Delta X_F \ , \qquad (12)$$

where the position error due to force ΔX_F is the motion difference between ΔX^F – current position deviation measured by the control system that generates position deviation for force controlled axis and ΔX_D – position deviation because of desired residual force. Noting the given desired residual force as F_D and the physical rigidity K_W there is obtained the relation:

$$\Delta X_D = K_W^{-1} \cdot F_D \ , \qquad (13)$$

Thus, ΔX_F can be calculated from the relation:

$$\Delta X_F = K_F \, (\Delta X^F - \Delta X_D) \ , \qquad (14)$$

where K_F is the dimensionless ratio of the stiffness matrix.

Finally, the motion variation on the robot axis matched to the motion variation of the end-effectors is obtained through the relation:

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

3 Open architecture Control System (OAH) for the Robot Control

The implementation of the OAH Open Architecture Control System for robots with compliant wrist allows for the control of the hybrid position and force in Cartezian coordonates through real time processing of the Jacobine matrix obtained out of the forward kinematics using the Denevit-Hartenberg method and calculating the Jacobine inverted matrix for control in closed loop. Using the joint rate control reprezentation, having J(θ) as the position Jacobian matrix and ΔX as the generalized position error vector, this process is analyzed in a simultaneous two-way fashion: the first to determine the ΔX_F matrix corresponding to the force controled component and the second to determine the ΔX_P matrix corresponding to the position controled component. The $\Delta\theta_F$ joint error of the force component and the $\Delta\theta_P$ position component error are insered to a fuzzy controller. The system architecture is presented in figure 2.

The programmable automate in decentralised and distributed structure (PLC0) ensures the control of the freedom axis and of the robot execution elements. The real position on each motion axis is read through a specialised module for counting impulses from a incremental transducer (IGR) or through the high counting speed specialised modules SA93 with self contained central unit and display on

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an SAE MT65 intelligent terminal with multifunctional keyboard. Six LENZE incremental transducers of 2,048 increments per rotation generate measurement impulses. Thus the counting of 2,048,000 impulses on each axis is ensured, sufficient compared to the maximum of 480,000 impulses, with a 0.001 mm resolution that can be processed on the free axis.

The PLC ensures a maximum number of 62 digital inputs, 16 digital outputs and 80 other configurable inputs/outputs. The communication between the PC and the PLC is made through an RS-232 serial interface using from PLC the DRUK and EMAS function block.

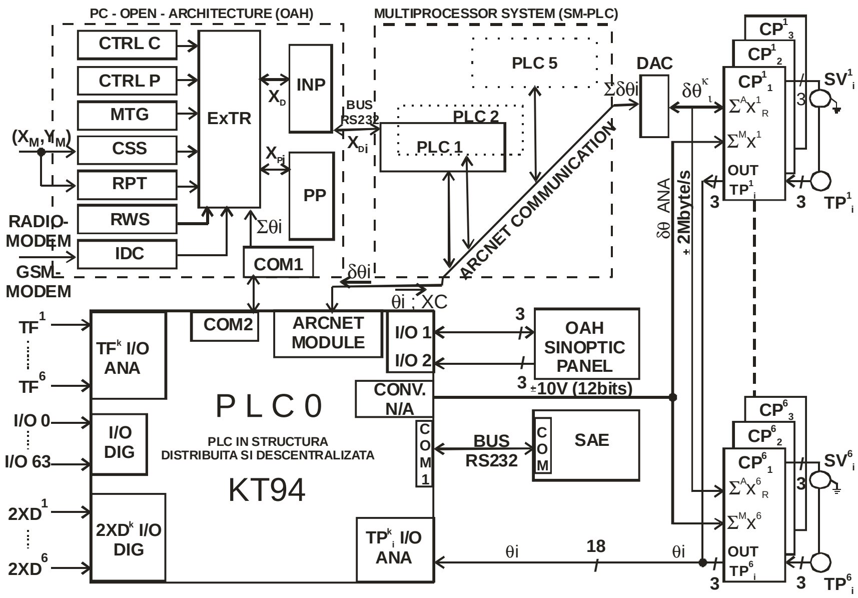

Fig. 2. Open architecture systems for the compliance robot control.

Thus are transmitted from the PLC to the PC the current angle motion values in absolute value $\sum\theta_{ci}$. From the PC to the PLC are transmitted continuously the reference positions on each axis X_{DI}, in conformity with the technological program X_{pi} values. On the *manual* function the values for the reference angle positions on each motion axis θ_{ri} are transmitted, generated directly by the INTERPOLATOR. On the *automat* function, the values for the reference angle positions on each motion axis $\partial\theta_{ri}$ are generated from the PLC multiprocessor in real time through the ARCNET communication network, based on the mathematical model, by applying the Denevit-Hartenberg method and determining the inverted Jacobian matrix. Input parameters are: from the PC, the technological position given by the X_{Pi} technological contouring program, processed and transformed by the INTERPOLATOR into reference position coordinates from the X_{DI} robot environment; and from the PLC0 the θ_{ci} current angular values.

The **PLC (SM-PLC) and PLC0 multiprocessor system** is meant to send, in real time, through the ARCNET fast communication network, the angular reference positions for the position regulator type PIDT soft implemented on the PLC.

There were identified 11 main processes for robot control:

- process 1 – current position determined by the matrix in X_C Cartesian coordinates
- process 2 - error position resulting in δX_C Cartesian coordinates
- process 3 - Jacobian matrix setting;
- process 4 - triangular Jacobian matrix obtaining
- process 5 - processing of joint errors $\delta\theta_{1,2,\ldots,6}$ by inverse substitute

Process 6 determines the position deviation on the force-controlled axis to a F_D desired residual force. Processes 7–11 are identical as functions and control mode with processes 1–5 but correspond to force controlled axis.

With the help of the relations from the mathematical model the execution program for the PLC0-PLC11 has been conceived and executed, in which each central unit has the role of MASTER communication by data flux through the ARCNET network.

The **PC-OAH system** allows the introduction of new control functions on the basis of supplementary programs, which makes for an open system. Due to high processing speed with operation systems, which allow for programming in evolved programs, the basic functions can be implemented, using an ExTR real time multitask executive: interpolation, the operator interface main program (PP), the technological operating system, as well as programs with functions of compliant control (CTRL C), pressure control (CTRL P) and/or image recognizing.

The **PLC (SM-PLC) and PLC0 multiprocessor system** is meant to send, in real time, through the ARCNET fast communication network, the angular reference positions for the position regulator type PIDT soft implemented on the PLC. The proportionality range, the gain factor, the integration and derivation time are established in the PLC0 central unit program depending upon the answer constant of the mechanical system.

PLC0 generates the current values θ_{ci} (i = 1–6), calculated through the ITI incremental transducer and transmitted through the ARCNET network to the PLC1–PLC5 multiprocessor system. In the active topology [7, 11] for process (1) each PLC generates an ascendant data flux from PLC0 to PLC5 by processing the transformation matrix ${}^{i}A_j$ from i axis to j axis, to obtain the coordinate matrix in j axis, resulting in the coordinates for the robot environment $X_C = {}^{1}A_6 = A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5 \cdot A_6$. In the active topology for process (2) the ${}^{i-1}A_j$ matrixes are stored for each PLC, the Cartesian coordinates X_i in i axis, by multiplying with ${}^{1}A_{j-1}$, are determined and the δX_C position variation is calculated.

4. Experimental results

Experimental results have shown that the robot's control system in real time with Open Architecture (OAH) ensure flexibility, short time execution, the precision targets and repeatability of the moving programs, eliminating completely the closed systems with projects meant for specified applications. The OAH control system allows the insertion of new control functions based on supplementary programs, which makes it an open system. Supplementary developments in order to increase the performances or new functions adding are possible only by modifying the software relating to the control modules in PC-OAH for laborious computations, respectively in the PLC multiprocessor for complex real time control. This system can be integrated using field bus having the ADVANT OCS, ARCNET, PDnet, MODBUS, Profibus, RCOM network for increasing communication safety. This allows the increasing of the connected number modules, the system becoming more powerful, with only three conductors for communication. In developing the open architecture system for hybrid position and force control, fuzzy variables for input and output of the system and the membership function reflecting the deflection in Cartezian coodonates are studied. The results show that the approach by fuzzy control leads to a better control of robots with compliant functions with only a few steps to full insertion and jamming avoidance.

Moreover using intelligent PLC the system is ready for automations with I/O redundant and feasible module, distance text display, interface with robots and different local modules, supervised in hierarchic structures. The obtained results prove a significant reduction of over 50% of the execution time for the control program of robot's position in Cartesian coordinates if compared with processing time resulted from other experiments [3, 5]. Owing to the great computation speed of microprocessor systems and serial connection links for data transmission, the time necessary for establishing the inverted matrix is short enough to allow the robot control in real time, with no influence in performing the other programs.

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5. REFERENCES

1. N.Jalili, An Infinite Dimensional Distributed Base Controller for Regulation of Flexible Robot Arms, Journal of Dynamic Systems, Measurements and Control, 123(4), pg.712-719, 2001
2. L.Vladareanu, T. Peterson – New Concepts for the Real Time Control of Robots by Open Architecture Systems, Machine Building, vol.55, ISSN 0573-7419 no.11, 2003
3. Yangsheng Xu, R.P.Paul, A Robot Compliant Wrist for Automated Assembly – Proceedings of the IEEE International Conference of Robotics and Automation, p.1750-1755, 1990
4. T. Yoshikawa, T. Sugie, M. Tanaka, Dynamic Hybrid Position-Force Control of Robot Manipulators – Controller Desing and Experiment, IEEE Journal of Robotics and Automation, 1988, vol.4, no.6, p.699-705
5. L.D.Joly, C.Andriot, V.Hayward, Mechanical Analogic in Hybrid Position/Force Control, IEEE Albuquerque, New Mexico, pg. 835-840, April 1997
6. L.D.Joly, C.Andriot, Imposing Motion Constraints to a Force Reflecting Telerobot through Real-Time Simulation of a Virtual Mechanism, International Conference on Advanced Robotics, Sant Feliu de Guixols, Spain, 1995
7. Sidhu G.S. – Scheduling algorithm for multiprocessor robot arm control, Proc. 19th Southeastern Symp., March,1997
8. Vladareanu L, Vogelsang G. - Real Time Control by INTER-CPM Acquisition System of the Five Axes MINI Machanical Centers - MT'2003 International AMSE Conference of Management and Technology, April 23-25 of 2003, Havana, Cuba.
9. S.B. Cononovici, W. Racovita, I. Nitu, Fundamentals of a contact tracking control strategy for Industrial Robots, Machine Building, vol.55, ISSN 0573-7419 no.11, 2003.
10. Yoshikawa T., Zheng X.Z. - Coordinated Dynamic Hybrid Position/Force Control for Multiple Robot Manipulators Handling One Constrained Object, The International Journal of Robotics Research, Vol. 12, No. 3, June 1993, pp. 219-230.
11. Denavit J., Hartenberg RB - A kinematics notation for lower-pair mechanism based on matrices. ASMEJ. Appl. Mechanics, vol.23June 1955, pg.215-221.
12. Vladareanu Luige, Open Architecture Systems for the Compliance Robots Control, WSEAS Transactions on Systems, issue 9, Volume 5, September 2006, ISSN 1109-2777, pg. 2243-2249