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Open Architecture Systems for the Position-Force Real Time Robots Control with Compliance Function

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Abstract. This paper shows a new technical solution called OPEN ARCHITECTURE for the hybrid positioning and force robot control on six degrees-of-freedom (DOF) in a PLC multi-microprocessor system interfaced with PC in order to obtain high performances. Through the development of this method the system becomes open to new command and control functions: compliance and comprehensive actions. Mainly this architecture allows for real-time control having two information sources: dynamic force and static position measurements resulting from interaction between the work-piece and the environment. The implementation of the OAH open architecture Control System for robots with compliant wrist allows for the control of the hibrid 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. The obtained results prove a significant reduction of the execution time for the real time control of robot's position in Cartesian coordinates.

Key Words: real-time digital processing, position and force robot control, compliance robots, multi-microprocessor system, distributed and decentralized system, PLC, networks.

1 Introduction

In the following a new technical solution will be presented for hybrid position – force control of industrial robots on six degrees of freedom (DOF) in an open architecture with PC interfaced multi-processor PLC system in order to obtain new control functions.

Mainly, this architecture allows for real time control having two sources of data: measurements of dynamic forces and of static precision as interaction between the work-piece and the environment. 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_w 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. Both the angular error due to the force component $\partial\theta_F$, as well as the angular error due to the position component $\partial\theta_P$ are overlapped by a fuzzy controller.

Finally, the motion variation on the robot axis in relationship to the motion variation of the end-effector results from the relation:

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

2 Hybrid position – force control.

In the framework of the fabrication process, especially in automated assembling, compliance is necessary in order to avoid high impact forces, for correcting position error of robots or special mechanical processing devices and for allowing the relaxation of tolerances of the composing elements.

Compliance can be furnished either through passive compliance, like the Remote Centre of Compliance (RCC) [2], or through the active force control methods [5,6,7 and 12]. Whatever the case, there are fundamental problems to both techniques when implemented in industry. Passive compliance can diminish the robot's positioning capacity. Active compliance can experience problems with instability in a rigid environment.

Therefore, although more investigations concerning this research goal have been reported recently [2,5,7,8,9,11] a simple, economical and trustworthy method is still being sought.

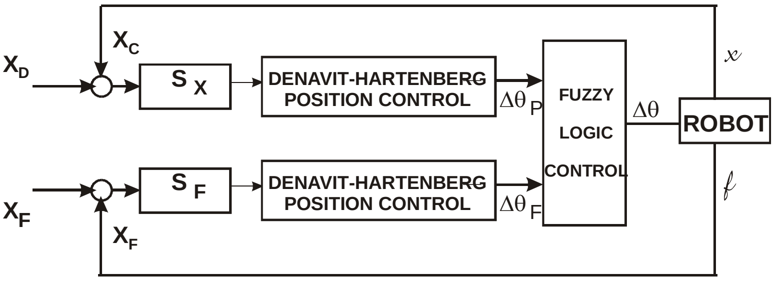

Fig.1. The general structure for hybrid control

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

$$Sx + Sf = Id \qquad (2)$$

More recent approaches lead to the following conclusion: with the aid of hybrid control, the robot's gripper acts as a rigid body, without mass, submitted to an external force $\boldsymbol{f_{des}}$ and connected through an ideal kinematical constraint to another body, whose velocity is $\boldsymbol{v_{des}}$.

3 The mathematical equations for hybrid position – force control

A hybrid position-force control system normally achieves simultaneous control of position and force. In order to determine the control relations in this situation, one divides the ΔX_P deviation measured by the command system into Cartesian coordinates into two sets: ΔX^F - corresponding to the force controlled component and ΔX^P - corresponding to position control with actuation on the axis, in accordance with the selection matrixes S_f and S_x [5,].

If only the position control is considered on the directions established by the selection matrix S_x, both the desired differential motions of the end-effector corresponding to control in position can be determined from the relation:

$$\Delta X_P = K_P \, \Delta X^P \qquad (3)$$

where K_P is the gain matrix, as well as the desired joint angles on the axis controlled in position:

$$\Delta\theta_P = J^{-1}(\theta) * \Delta X_P \qquad (4)$$

In continuing, also taking into consideration the force control on the other directions left, the relation between the desired angular motion of the end-effector and the force error ΔX_F is given by the relation:

$$\Delta\theta_F = J^{-1}(\theta) * \Delta X_F \qquad (5)$$

where the positioning error due to force ΔX_F is the motion 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 position deviation due to the desired residual force. Noting $\mathbf{F_D}$ as the desired residual force and $\mathbf{K_W}$ the physical stiffness the following relation is obtained:

$$\Delta X_D = K_W^{-1} * F_D \qquad (6)$$

Thus, $\mathbf{\Delta X_F}$ can be calculated from the relation:

$$\Delta X_F = K_F \left(\Delta X^F - \Delta X_D\right) \qquad (7)$$

where K_F is the dimensional relation of the stiffness matrix. Finally, there results the motion variation on the robot axis in relation to the end-effector motion variation from the relation:

$$\Delta\theta = J^{-1}(\theta)\, \Delta X_F + J^{-1}(\theta)\, \Delta X_P \qquad (8)$$

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 fig.2.

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.

In the following, these two control modes are executed concurrently. These relations have also been the basis of control experimentations with compliant joints on the PUMA560 robot, with direct rotation control on each robot axis through a server, whose soft allows that the trajectory data be stored "online" in a file for "offline" analysis [11].

For correct system identification, the numerous system parameters have been simulated with loading the data for the motion trajectory and the angular revolution into files.

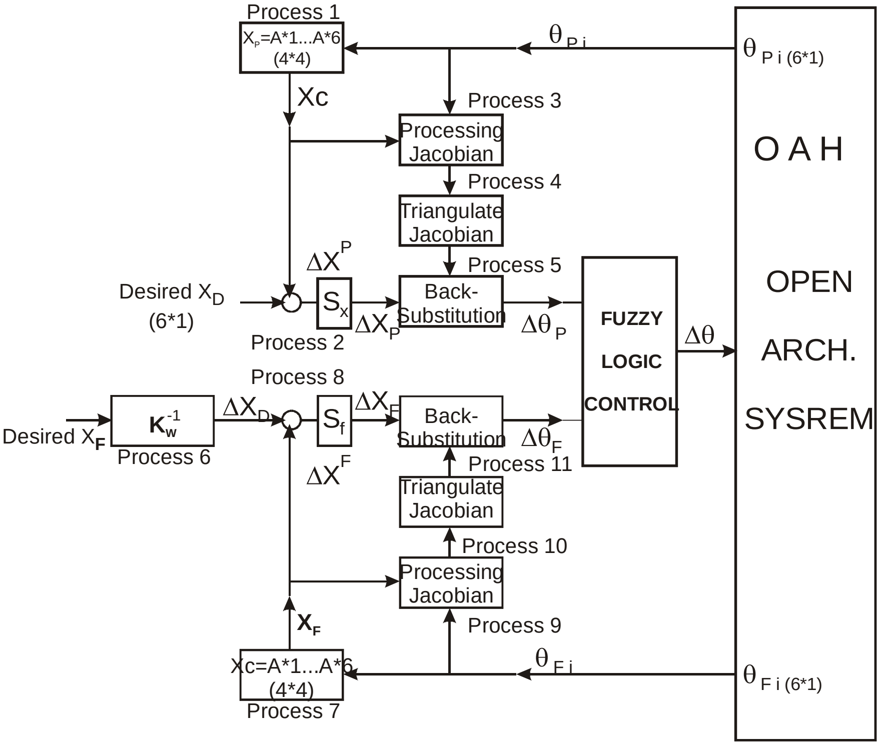

Fig.2. Hybrid position – force control based on the Denevit – Hartenberg model.

4 Compliant Robots Control with Tracking Function

Industrial robots used in automated assembling systems require supplementary compliance functions to correct positioning errors, to relax the tolerance between components and for absorbing the forces of impact with elements of the robot environment. The control system with open architecture (OAH) described in this paper allows for the realization of automated assembling systems, with the possibility of ensuring compliant adaptability.

Based on the characteristics of assembled parts, the assembling operations can be represented through a small number of primitives, like sliding, insertion and screwing [3,11]. Sliding can take place on one or more planes, for which the edges' tracking function is essential. Edges' tracking is also a basic element for many fabrication operations, like two-flat-surface grinding.

The tracking process on one of the robot axis with force control on the other two axis is represented graphically in fig.3. The edge which is to be tracked consists of two surfaces. One of them is assumed to be a flat surface, and these two surfaces form an arbitrary angle α. Monitoring is achieved by moving along the edge, while maintaining contact in the other two directions. As presented in fig.3, the contact forces on the directions Z and X are controlled, and motion on Y is controlled through position.

The edges' monitoring process can be divided into three phases: approach, search and monitoring.

The approach phase: The robot approaches an edge with a specified velocity $\boldsymbol{v_a}$, with position control on all axis according to a control process in position. The positioning error must be smaller than half the opening of the tracking device, which is easily attainable. When the end-effectors come into contact with a part of an edge, a contact force is detected. Through the detected force, with the help of the force transducer, the motion in this direction is halted and the control system will ensure: *a)* force control in this direction and *b)* position control in all other directions.

The search phase: At the end of the approach phase, one side of the gripper has contact with the tracked surface and the other side of the gripper is situated on the other side of the edge. In this case, corresponding to the search phase, the command system will generate for the approach a motion trajectory perpendicular to a specified search velocity $\boldsymbol{v_s}$. When this part of the gripper also has contact with the edge, the search phase is at an end and the force control is assigned to the direction of the search.

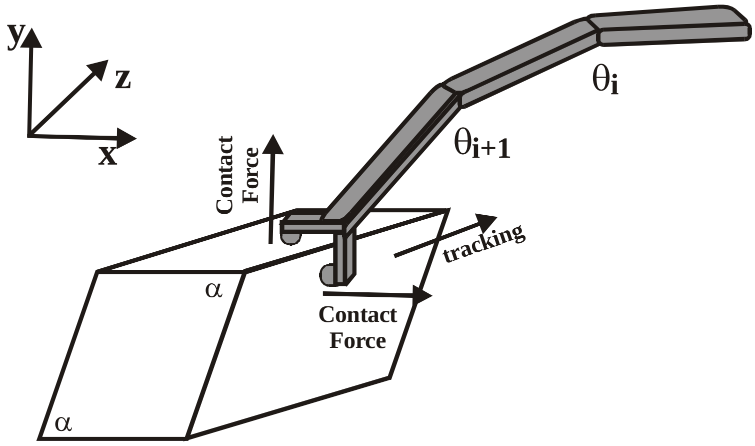

Fig.3. Graphical representation of the edge tracking process

The monitoring phase: when the other two phases are over, both surfaces of the edge are in contact with the tool. From this point on the monitoring phase begins with a desired monitoring velocity $\boldsymbol{v_t}$, along the third perpendicular axis on the direction of the approach and the search. In this phase, force is controlled in the normal directions of two surfaces, and position is controlled in the other directions.

The implementation of this method in the control system with open architecture previously studied can be done easily in real time, due to the advantages this control system offers.

Thus, the edges' monitoring phases can be generated through the compliant control module by developing the hybrid position-force control method presented in fig.4. Executing this task can be done in real time by a PC with great processing power and speed, the role of this task being to generate the positions and forces according to the tracking algorithm previously presented.

In realizing the application, it must be taken into account that the contact force must be selected in conformity with the task requirement, and the physical stiffness of the compliant device is different on each contact direction, which leads to different deviations, from and around each axis.

Moreover, if as reference is applied a high contact force for a contact surface which is not smooth, it is reasonably probable that monitoring be blocked due to friction. In this case, it is recommended that the control system should allow for a relatively high monitoring velocity, a relatively small search velocity and the existence of an approach velocity.

5 Open architecture (OAH) systems for hybrid position – force control of industrial robots

The architecture of the hybrid position – force control system in Cartesian coordinates, on the basis of numerical processing, in real time, of the Jacobean matrix obtained from direct kinematics through the Denevit – Hartenberg matrix and determining the inverse Jacobean matrix for control in closed loop is presented in fig.4.

The composing elements of the real time control system correspond to a standard open architecture OAH [9,12]. The same basic architecture is also used in controlling and reducing structural dynamic vibrations, with its characteristics from both the hardware point of view for measuring the forces from the joints and determining the position error in the robot environment introduced by the force, as well as from the program (task) point of view of realizing a compliant control (CTRL C) or prehension functions (CTRL P).

The programmable automate in decentralized and distributed structure **(PLC0)** ensures the control, command and actioning of executing elements. This allows, in addition to standard architecture, for determining the position error in the robot environment due to forces in the robot joints through measurement, analogue – numerical conversion and processing of forces from the robot joints and transmitting this data to the SM – PLC multiprocessor system, consisting of processors PLC6 – PLC10.

The PLC (SM – PLC) multiprocessor system and **the PLC0** have the task of transmitting in real time, through the ARCNET fast communication bus, the angular reference positions for the PIDT type position regulator, implemented through software on the PLC0. The proportionality band, the amplification factor, the integration and derivation time are established, depending on response constants of the mechanical system, in the central unit program of the PLC0 for control in position, respectively in the 9300EP frequency converter for the speed loop, the current control and the magnetic flux of the axis motors.

The PLC0 generates the current values θ_{ci} (with i=1-6) through the incremental transducers EN_i interface using specialized ICSD07D1 modules or the 3 axis central control unit SA93. This is transmitted to the multiprocessor system consisting of PLC1 – PLC5 through ARCNET bus.

Eleven processes (tasks) have been identified for realizing the real time control function of the robot's position [9,12] as shown in fig.3 and fig.4.

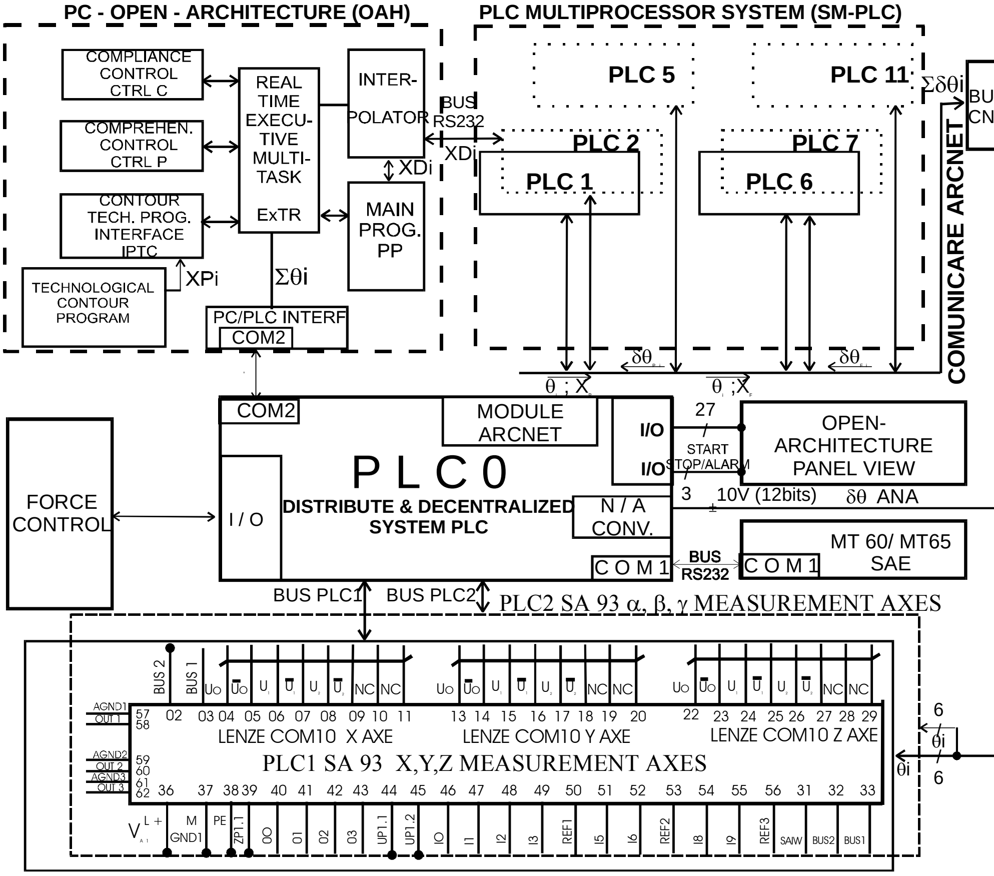

Fig.4. Open architecture systems for the hybrid position – force control of robots

In active topology for process (1) each PLC generates a data flux, ascending from PLC0 to PLC5 by calculating the transformation matrixes $^{i}\mathbf{A}_{j}$ from axis **i** to axis **j**, in order to obtain the coordinate matrix in axis **j**, finally yielding the coordinates in robot environment:

$$X_C = {}^{1}A_6 = A_1*A_2*A_3*A_4*A_5*A_6 \qquad (9)$$

In active topology for process (2) for each PLC level the matrixes $^{i-1}A_i$ are stored, the Cartesian coordinates X_i in axis **i** are determined by multiplying with $^{1}A_{j-1}$ and the position variation δX_C is calculated. Generation of the Jacobean matrix is obtained in process (3) through an ascending data flux in correlation with process (1). As the processing of matrixes $^{1}\mathbf{A}_{j}$ is being done, the PLC0 is assigned to the Jacobean matrix of (3x1), noted as $J(\theta_1)$, respectively the PLC5 to the Jacobean matrix of (3x6), noted as $J(\theta_5)$.

The active topology of process (4) brings the Jacobean matrix to the triangular form by determining the pivot element and the elements of the new matrix A_{ij} from the relation:

$$A_{ij} = A_{ij} - u_{ik} \cdot A_{kj}, \qquad (10)$$

where: i = k+1, ... , n and j = k+1, ... , n. Also:

$$u_{ik} = \frac{A_{ik}}{A_{kk}} \quad \text{with } i = k+1, \ldots, n. \qquad (11)$$

In a sequential process with process (4) takes place the active process (5) which determines, by employing inverse substitution, the angular deviation value $\delta\theta_i$, conformant to the relation:

$$\delta\theta_{1,2,..6} = J^{-1} \cdot (\theta) \cdot \delta^6 X_6 \qquad (12)$$

To each PLC a column of the Jacobean matrix has been allotted, the data flux being from the PLC0 to the PLC5 for triangulation and from the PLC5 to the PLC0 for inverse substitution.

Starting from this representation the architecture of the hybrid position–force control system was developed with the corresponding transformations applicable to systems in open architecture and distributed and decentralized structure. In comparison to the basic OAH systems' structure [9,10], the processors 6–11 are additionally introduced. Process 6 determines for a desired residual force F_D the position deviation on the axis controlled in force.

Processes 7 – 11 are identical as of functions and control mode with processes 1 – 5, but correspond to the axis controlled in force. Thus, the hybrid position – force control system studied allows for realizing industrial robots of automatized assembling, obtaining remarkable performances.

On the basis of the characteristics of the assembled components, the assembling operations can be processed and controlled in architecture with an OAH system by introducing a reduced number of hardware modules and specialized programs, which lead to new and complex functions for the control of industrial robots such as sliding, insertion and screwing.

The obtained results prove a significant reduction of the execution time for the control program of robot's position in Cartesian coordinates if compared with processing time of 5,37 ms respectively 5,46ms resulted from other experiments [3], [4].

Furthermore, this reduced execution time ensures that the feedback loop is closed in a short time allowing other processes to be executed in real time, e.g. the control of comprehensive force, pattern recognition, compliant control and allows the CISC host computer to provide a flexible and friendly interface with the human operator

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