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REAL TIME CONTROL SYSTEMS OF THE COMPLIANT ROBOTS WITH INSERTION FUNCTIONS

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Abstract

A new control method of the compliant robots control systems with function insertion is presented. It consists of a fuzzy multi-stage (*MS*) control on two different decision stages in order to determine the gripper's movement velocity that implies the realization of two fuzzy control loops one in position and the other in force. The architecture of the compliant robots control systems with function insertion allows for practically eliminating jamming and vibrations, having a fast response of the control loop.

INTRODUCTION

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) [1], or through the active force control methods [2, 5]. 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 a simple, economical and trustworthy method is still being sought.

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 the 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(θ) 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 added in overlap to 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:

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

In applying the robot hybrid position – force control method are necessary the determining of the input and output fuzzy variables, establishing the fuzification method and determining the inference table and defuzification method.

HYBRID POSITION – FORCE 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 figure1. 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 matrixes

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:

$$\mathbf{S_x + S_f = I_d} \qquad (2)$$

In more recent approaches [1,2] S_x and S_f are methodically deduced from the kinematical constraints imposed by the working environment. Let A and B be two full column rank matrices spanning the twist and wrench spaces of constraint.

They satisfy the relation:

$$A * B = 0 \qquad (3)$$

Then S_x and S_f can be determined through the relations:

$$Sx=(A^t\Psi A)^{-1}\ A^t\ \Psi \qquad (4)$$

$$Sf=(B^t\Psi^{-1}B)^{-1}B^t\Psi^{-1} \qquad (5)$$

where Ψ is usually a symmetrical matrix, positive defined.

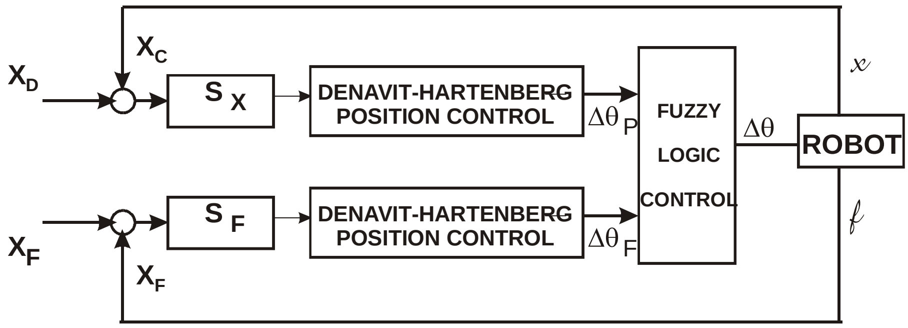

Fig. 1 The general structure for hybrid control

It is easily verifiable that [1,2,5], using any of the above approaches, S_x and S_f always fulfil:

$$\text{rang}\ (S_x) + \text{rang}\ (S_f) = 6 \quad \text{and} \quad S^t_x S_f = 0. \qquad (6)$$

The control rules are design to bring to zero the position errors $e_x=\Delta\theta_P$ and force errors $e_f==\Delta\theta_F$. For an ideal control system, the robot's behaviour is defined by:

$$S_x\ (\boldsymbol{v_{des}} - \boldsymbol{v}) = 0, \qquad (7)$$

$$S_f\ \ (\boldsymbol{f_{des}} - \boldsymbol{f}) = 0. \qquad (8)$$

where $\boldsymbol{v}$ is the velocity, $\boldsymbol{f}$ is the force and the index "*des*" specifies the reference parameter (the desired value). Velocity constraint is the only one taken into consideration here. Position constraint is satisfied as a consequence.

The relations 7-8 lead to the following conclusion [2,4]: 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 $\boldsymbol{v_{des}}$.

COMPLIANT CONTROL OF INDUSTRIAL ROBOTS WITH INSERTION FUNCTIONS

The insertion operation is another way of using the compliant joint system with assembling robots. Using passive compliance ensures an adaptable output, which allows the control system to auto-correct in establishing an accord to dimensional uncertainties in an insertion operation. An example of insertion is introducing a shaft into a hole, represented graphically in figure 2, where the chamfered edges and tolerance must be 0.025mmm. In this case, the force sensors allow for control of the contact force, thus avoiding a mechanical jamming. The hole and/or the shaft to be inserted must have chamfered edges in order to ensure the positioning tolerance in the approach phase. The shaft held by the robot gripper must be able to be brought over the hole with a positioning error smaller than the chamfered edges of the hole or the shaft. A control method consists in evaluating the measured force on each control axis and assigning a constant step value in order to reduce the contact force. As resulting from the research of T.Goto and T. Kyooo, there is obtained a high number of steps for a complete insertion, which hinders the work speed, leading to the possibility of jamming if the system parameters are incorrectly chosen or the friction is too great.

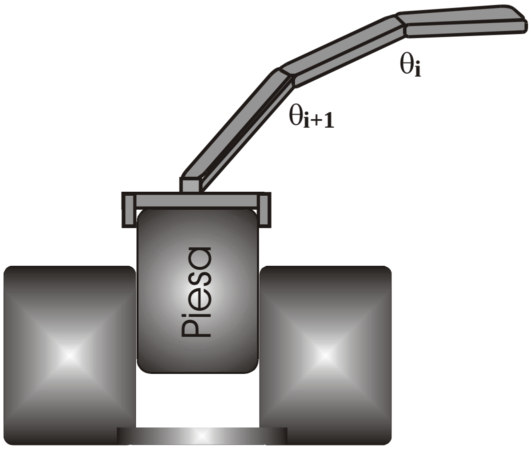

Fig. 2. Graphic presentation of the insertion process

A new control method, which practically eliminates jamming and has a fast response of the control loop, is presented in figure 3. It consists of a "multi-stage" fuzzy control (***MS***), which entails the realization of two fuzzy control loops, one in position and the other in force on two different decision stages in order to determine the speed of the gripper**.**

MS fuzzy control has multiple rule bases, where the result of an inference of the rule base is transmitted to the next stage [2, 5]. In this way the most important dimensions of the inference can be grouped into smaller sets and combined with base rules. In the MS structure, the results of the rule base of the control of position P are transmitted to the rule base of the PF position – force control.

This structure is similar to a hierarchical structure of the regulators, based on characteristics. In terms of control, based on the characteristics of the positioning functions, P is of high level and ensures system control should disturbance dynamics appear or if are generated commands and the main function is force and generally controls the system to avoid jamming. The control returns the functions base P when the system dynamic is settled.

The basic idea of the controller is to assign the speed on each axis for the given deflection in the corresponding direction in a heuristic way, in which a human operator might accomplish the insertion. The task of the controller is to assign the measured deflection of the fuzzy variables, i.e. "positive great" (PM), and to evaluate the decision rules through inference. So that, it can finally establish the value of the output variable, i.e. the velocity as fuzzy variable, which best follows the controlled parameter.

The configuration of the decision rules and of the fuzzy variables used in making the decision depends on the problem of specific control. There are taken into consideration the deviation in position of the compliant joints ***e*,** the rate of position deflection Δ***e*** and the contact force Δ***f*** as entry data.

The values of deflection detected through sensors are quantified in a points number corresponding to the discourse universe elements, and then the values are assigned as grades of membership in a few fuzzy subsets.

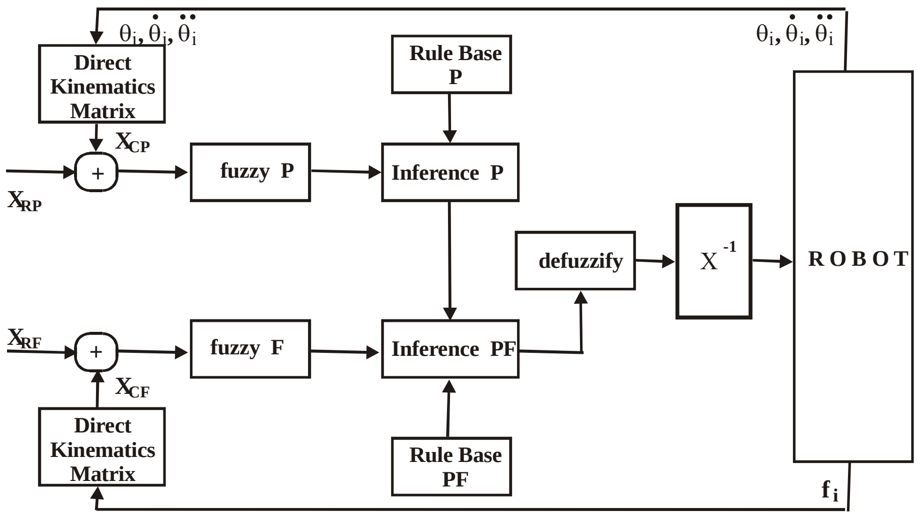

Fig. 3 Fuzzy "multi-stage" control (FMS) for inseration processes

The relationship between the inputs, i.e. the measured deflections, and outputs, i.e. velocity, and the grades of membership can be defined in conformity to the operator's experiences and the demands of the robot charge. There are defined empirically the membership functions for all input and output elements. The fuzzy variables have been chosen as follows: NM – negative great, Nm – negative small, ZO – zero, Pm – positive small, PM – positive great.

Δ *e*

		NM	Nm	ZO	Pm	PM
	NM	NM	NM	NM	Nm	Nm
	Nm	NM	Nm	Nm	Nm	Pm
e	ZO	NM	Nm	ZO	Pm	PM
	Pm	Nm	Pm	Pm	Pm	PM
	PM	Pm	Pm	PM	PM	PM

Fig. 4. ***P*** *Rule Base*

By analyzing the rule base it can be observed that the force feedback is function of the inference results of the fuzzy control P component. The two rule bases are presented in figure 4 and figure 5. The rule base P is easily modified from a typical linear rule base, allowing for the replacement of all Zero (ZO) values, except the centre of the rule base.

Fuzzy value P

		NM	Nm	ZO	Pm	PM
	NM	NM	Nm	NM	Pm	PM
	Nm	NM	Nm	Nm	Pm	PM
Δ*f*	ZO	NM	Nm	ZO	Pm	PM
	Pm	NM	Nm	Pm	Pm	PM
	PM	NM	Nm	PM	Pm	PM

Fig. 5. ***PF*** *Rules Base*

In this fashion, the P rule base will pass onto value ZO only when both the error, as well as changes in the error terms are ZO, which is to indicate that the system has been settled.

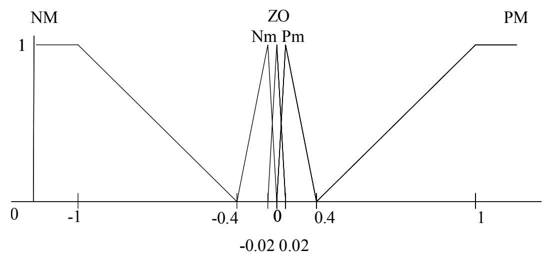

Fig. 6. Error input fuzzy sets

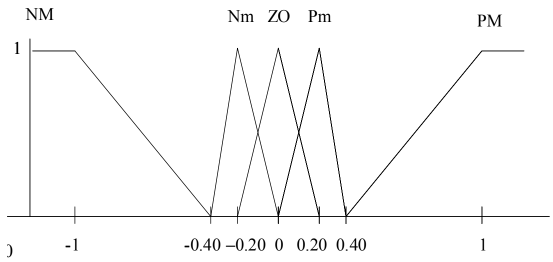

Fig. 7. Rate error input fuzzy sets

For a certain set of inputs, i.e. the measured deflection, the evaluation of fuzzy rules produces a fuzzy membership set for system control. In order to take a concrete action, one of these values must be chosen. In this application, the control value with the highest degree of membership has been selected. The rules are evaluated at equal intervals, in the same way as a conventional control system. Figures 6–9 present the membership function sets for inputs and outputs.

The result of logical inference also represents fuzzy values which are applied to the defuzzify mode. The defuzzify represents a transformation of the fuzzy variables defined on the output discourse universe in a numerical value. This processing is necessary due to the fact that the control in the case of fuzzy regulators is done exclusively with cript values.

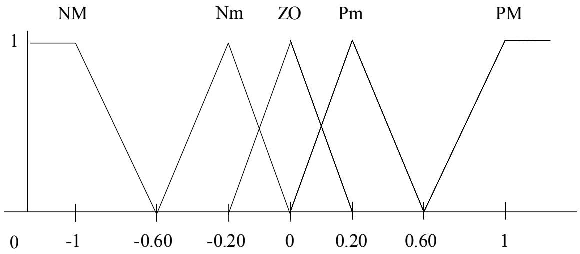

Fig. 8. Force error fuzzy sets

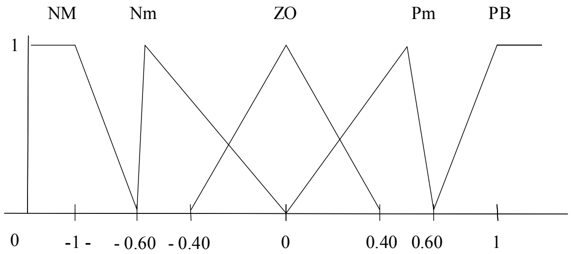

Fig. 9 Output fuzzy sets

Choosing as defuzzify method the weight centre of aria, the calculation of the defuzzify output is given by the relation:

$$O \to o_{crisp} = \frac{\int_U u \cdot \mu_0(u)du}{\int_U \mu_0(u)du} \qquad (9)$$

For a discreet output discourse universe U the computation relation of the weight is reduced to the relation:

$$O \to o_{crisp} = \frac{\sum_{a_i \in U} a_i \mu_0(o_i)}{\sum_{a_i \in U} \mu_0(o_i)} \qquad (10)$$

Choosing a discreet discourse universe allows for using the PLC0 system [6] for generation the fuzzy output variables with a reduced processing time.

By applying the fuzzy logic control, there is obtained a linear passing, without discontinuities, from the position control to position and force control. Moreover, a fast response of the control loop is obtained and jamming is virtually eliminated.

SUMMARY

The new control method of the compliant robots control systems with function insertion consists of a fuzzy multi-stage (MS) control on two different decision stages in order to determine the gripper's movement velocity that implies the realization of two fuzzy control loops one in position and the other in force. The controller´s basic concept is to ensure velocity on each axis, for the given deflection in the corresponding direction, like a human operator that would perform the insertion. The controller's role is to ensure the measured deflection of the fuzzy variables and to evaluate the decision rules through inference, so that, in the end, it is able to establish the value of the output variable, for instance the velocity as a fuzzy variable, which best follows the controlled parameter. The relation between the inputs, such as the measured deviations, or outputs, such as the velocities, and the degree of membership can be defined according to the operator's experiences and the robot task's requirements. The result of the logical inference also represents fuzzy values that apply to the defuzzify mode. The defuzzyfied outputs are generated by choosing as a defuzzyification method the weight centre of the aria method. Generating a discreet discourse universe makes it possible to use a PLC system for generating the fuzzy output variables within a short processing time. The architecture of the compliant robots control systems with function insertion allows for practically eliminating jamming and vibrations, having a fast response of the control loop. By applying the fuzzy logical control a smooth passing, without any discontinuities, is obtained from the control in position to the control in force and position. Moreover, a fast reply from the control loop is obtained and jamming respectively vibrations are practically eliminated.

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