Hybrid Force-Position Control For Manipulators under Transitions Free to Constrained Motion

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***Abstract*—This paper presents a scheme hybrid force/position control for robots manipulators nonlinear of n-DOF based on the principle of orthogonal decomposition spaces by holonomic constraints, which ensures stability of the closed-loop system because adaptive control exchange force and position between the manipulators to be applicable in free motion and in constrained motion. The reaction force in the manipulator that occurs through contact of the robot end effector to the unyielding surface is obtained via Lagrange multiplier. This controller provides tracking path simultaneous and independent of force and position of robot arm whose end effector is in point contact with a rigid surface. The stability of schema is proved using Lyapunov methods. The proposed scheme is tested on a simulation and experimentation platform where the study is shown to apply the proposed control law consisting of a manipulator five degrees of freedom with open architecture and a force sensor, performing a task tracking position while profiling force is induced. The control provides true convergence errors force and position the system making. The scheme shows similarity between theoretical, simulation and experimental results, demonstrating the effectiveness of the proposed scheme.**

***Index Terms*—hybrid force position control, holonomic constraints, principle orthogonal, lagrange multipliers, adaptive control**

I. Introduction

There are currently two types of tasks that robot manipulators execute robot manipulators: (1) the simple, developed under free movement or work without contact with the environment in which only is needed the modeling the control of position tracking, and (2) the more complex, that developed in constrained environments where it is required that the manipulator is in contact with the environments, i.e., is mechanically coupling with the surroundings and which therefore requires a model that involves simultaneously monitoring the position and applied force.

Currently in the literature two types of force position control are studied: the impedance/admittance seen in [1] are used where static forces; and the hybrid force position [2] that uses dynamic forces.

In models of manipulators with free movement, the dynamics is described by differential equations; the same thing happens in controlling impedance/admittance so while the control involves a compromise between the tracking position and force.

In contrast to the dynamic control force position in restricted movement because there are restrictions on geometric paths when the contact and interaction with the environment occurs, the generalized variables directly affect; because of this methodology based on the geometric constraints infinitely rigid profile is used, better known as holonomic constraints, resulting in a system of Differential Algebraic Equations (DAE) and be known as orthogonal technique control [3]. This technique has proven very efficient in the convergence of position and force error, and since it requires additional knowledge about the structure of the remote environment the stability of the system is guaranteed. The control orthogonal makes decomposition into two vector spaces, one on force and other in speed, which allows simultaneous and independent control of both the force and position.

Research of this type of control are given in [4] where adaptive control of force and position based model (dashed), which is in a changing state depending on the conditions in the actual process the contact is proposed; in [5] the PD Adaptive Control force position under geometric constraints is proposed; [6] a non-redundant system of a gripper with multiple fingers on the principle of cooperatives with a compensation scheme all uncertain inertia dynamic force to ensure asymptotic stability in the contact forces and the movement of intends joints through the principle of orthogonality and impedance errors; in [7] is propose a control force position for cooperative robots ensuring the exponential convergence to zero of the force and position errors without making a compromise between either . All these investigations need to know the interface to implement these control laws also perform control only restricted movement.

Because of this, in this paper the modeling, simulation and experimentation of simultaneous and independent control motion of force position is shown for robot manipulators making the transition of movement of free to constrained environment to contact highly rigid surfaces. This means that the new system have the possibility that the end effector can move along a path of movement desired on a rigid surface while the desired force profile is imposed guaranteeing a fast convergence errors of position and force.

The paper is organized as follows. The robot model, as well as some properties is given in Section II. The

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force/position controller law for the manipulators is proposed in Section III. The modeling, simulation and experimentation are proposed in Section IV. The paper concludes in Section V.

II. Dinamic Model a Manipulator

A. *Dynamic Model.*

Assuming that (1) working with robots manipulators with n degrees of freedom, non-redundant, open kinematic chain with rigid links and joints; (2) The methodology for calculating of Euler-Lagrange dynamics is nonlinear and coupled; (3) The working environment is completely known, highly rigid and non-deformable, that is, exactly known function describing the interface $\varphi(q_i)$; (4) The control law is designed and implemented in the continuous time domain.

Considering a robot manipulator composed with n–joint degrees of freedom. The robot satisfied a task on space of three-dimensions maintaining contact with a rigid environment, represented by m-restrictions. The dynamics of the system is given as follows.

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + F\dot{q} + g(q) = \tau - J^T_{\varphi+}(q)\lambda \quad (1)$$

$$\varphi(q) = 0 \quad (2)$$

where $q \in \mathbb{R}^n$ is the vector of generalized joint coordinates, $H(q) \in \mathbb{R}^{nxn}$ is the symmetric positive definite inertia matrix, $C(q,\dot{q})\dot{q} \in \mathbb{R}^n$ is the vector of Coriolis and centrifugal, $F \in \mathbb{R}^{nxn}$ is a diagonal positive definite matrix accounting for viscous friction, $g(q) \in \mathbb{R}^n$ is the vector of gravitational torques and $\tau \in \mathbb{R}^n$ is the vector of torques acting on the joints, $\lambda \in \mathbb{R}^m$ is the vector of Lagrange multipliers (physically represents the applied forces at the m-contact points to the environment), $\varphi(q) = 0$ is the geometric function the holonomic constraint which describes rigid surface of the environment where the robot makes contact, $J_\varphi(q) = \frac{\partial\varphi(q)}{\partial q} \in \mathbb{R}^{mxn}$ is the Jacobian of the holonomic constraint. $J_{\varphi+}(q) = J_\varphi(q)\left[J_\varphi(q)J^T_\varphi(q)\right]^{-1} \in \mathbb{R}^{mxn}$ stands for the Penrose's pseudoinverse.

B. *Principle of Orthogonal Decomposition*

The principle of orthogonal decomposition is based on the physical property that when force on a rigid surface (restriction) is printed, and simultaneously moves over it, the velocity vector is contained in the plane tangent to the point of contact, whereas the application of the force is perpendicular to the plane. To preserve this property, the restriction is manipulated to derive two orthogonal subspaces. These subspaces give rise to two transformations which are used to obtain a suitable representation that will eliminate cross terms in the stability analysis, so that they can be made simple controller with simple stability tests, but convergence properties of position and force.

These transformations are used to make the orthogonal projection of the vector $\dot{q}$ on articular space *(n-m)* dimensional (tangent space) orthogonal to the vector Jacobian $J^T_\varphi(q)$ and the orthogonal projection of the integral error of contact force on the vector Jacobian $J^T_\varphi(q)$ (see Fig. 1); the tangent plane can be represented in matrix form by $Q(q) = I - P(q) \in \mathbb{R}^{nxn}$ (were $P(q) = J^T_{\varphi+}(q)J_\varphi(q) \in \mathbb{R}^{nxn}$) are two matrices orthogonal, that is, $Q(q)P(q) = 0$ (in fact $Q(q)J^T_\varphi(q) = 0$ and $J_\varphi(q)Q(q) = 0$). Given that $\varphi(q) = 0$, the vector $\dot{q}$ can be written as $\dot{q} = Q(q)\dot{q}$.

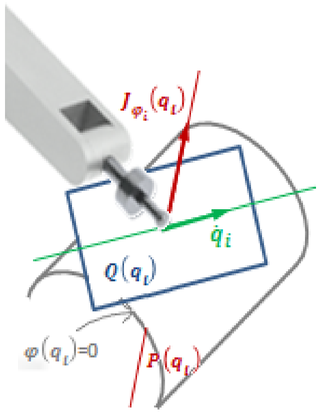

Figure 1. Orthogonal projection.

C. *Modeling of Force*

Restrictions of position, velocity and acceleration are given by

$$\varphi(q) = 0 \;\rightarrow\; Q(q)\dot{q} = \dot{q} \quad (3)$$

$$\dot{\varphi}(q) = J_{\varphi+}(q)\dot{q} \equiv 0 \quad (4)$$

$$\ddot{\varphi}(q) = J_{\varphi+}(q)\ddot{q} + \dot{J}_{\varphi+}(q)\dot{q} \equiv 0 \quad (5)$$

These restrictions must be met when the robot is in a constrained motion. Whereas (a) the end effector of the robot arm is stiff, (b) the restricted surface is not deformable, (c) the kinematics of the manipulator is known, (d) the manipulator satisfies the constraint contact all the time and (e) the robot is not redundant.

To model the force, of (1) the acceleration of the robot dynamics is obtained and substituted into (5)

$$\ddot{\varphi}(q) = J_{\varphi+}(q)H(q)^{-1}\{\tau + J^T_{\varphi+}(q)\lambda - C(q,\dot{q})\dot{q} - F\dot{q} - G(q)\} + \dot{J}_{\varphi+}(q)\dot{q} \quad (6)$$

Solving for λ

$$\lambda = \frac{1}{J_{\varphi+}(q)H(q)^{-1}J^T_{\varphi+}(q)}\left[\{\ddot{\varphi}(q) - \dot{J}_{\varphi+}\dot{q}\} - J_{\varphi+}(q)H(q)^{-1}\{\tau - C(q,\dot{q})\dot{q} - F\dot{q} - g(q)\}\right] \quad (7)$$

In equation (7) λ is the force that occurs when in contact the end effector of the robot with the not deformable surface, the equation can be simulated as a differential equation of second order.

III. Desing Law Control

A. *Nominal Reference*

The position and force error is.

$$e = q - q_d \quad (8)$$

$$e_\lambda = \lambda - \lambda_d \quad (9)$$

where $q_d \in \mathbb{R}^n$, is the variable generalized of the position desired and $\lambda_d \in \mathbb{R}^m$ is the desired force value.

Employing the projection matrices must reference signal for the manipulator is

$$\dot{q}_r = Q(\dot{q})[\dot{q}_d + \alpha(e)] + \beta J_{\varphi+}^T(q)\left[e_\lambda + \gamma \int_0^t (e_\lambda) dt\right] \quad (10)$$

where $\alpha \in \mathbb{R}^{nxn}$, $\beta, \gamma \in \mathbb{R}^{mxm}$ are positive constants matrices.

In order to enter the nominal reference signal in the control law, defined the variety of residual error $s \in \mathbb{R}^n$, given by

$$s = \dot{q} - \dot{q}_r = s_p + s_f \quad (11)$$

with $s_p = Q(\dot{q})[(\dot{e}) + \alpha(e)]$ and $s_f = J_{\varphi+}^T(q)\left[\beta e_\lambda + \gamma \int_0^t (e_\lambda) dt\right]$.

B. Law Control: PD + Adaptive + g(q)

The dynamic model of (1) has the property of linearity in the parameters and with an appropriate parametric model definition

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + F\dot{q} = Y(q,\dot{q},\ddot{q})\hat{\theta} - g(q) - J_{\varphi+}^T(q)\lambda \quad (12)$$

where $Y(q,\dot{q},\ddot{q}) \in \mathbb{R}^{nxp}$ is the regressor y $\hat{\theta} \in \mathbb{R}^p$ is the constant parameter vector.

The tracking error dynamics is given by

$$H(q)\dot{s} + C(q,\dot{q})s + Fs = \tau - Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta} - g(q) - J_{\varphi+}^T(q)\lambda \quad (13)$$

where $Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta} = H(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + F\dot{q}_r$.

Once the parametric model of the robot manipulator, the control law used is as follows:

$$\tau = Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta} - g(q) - K_s Q(q)[\dot{e} + \alpha e] + \beta J_{\varphi+}^T(q)\lambda - \gamma \quad (14)$$

and system parameter vector is updated by the following law of adoption.

$$\dot{\hat{\theta}} = -\Gamma Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)^T s \quad (15)$$

where $K_s \in \mathbb{R}^{nxn}$ and $\Gamma \in \mathbb{R}^{pxp}$, are positive definite matrices.

C. Stability Analysis

A passivity analysis for manipulator slave indicates that the following candidate function V qualifies as a Lyapunov function.

$$V_s = \frac{1}{2}s^T H(q)s + \frac{1}{2}\gamma\left[\int (e_\lambda)dt\right]^2 \quad (16)$$

The total derivative of Lyapunov immediately leads to

$$\dot{V}_s = \frac{1}{2}s^T \dot{H}(q,\dot{q})s + s^T H(q)\dot{s} + \gamma(e_\lambda)\int (e_\lambda)dt \quad (17)$$

How $H(q)\dot{s} + C(q,\dot{q})s + J_{\varphi+}^T(q)e_\lambda + K_s s = 0$. It must be $\dot{s}_s = -H(q)^{-1}[+(q,\dot{q})s + J_{\varphi+}^T(q)e_\lambda + K_s s]$ then

$$\begin{aligned}\dot{V}_s &= \tfrac{1}{2}s^T \dot{H}(q,\dot{q})s - s^T \mathrm{C}(q,\dot{q})s \\ &\quad - s^T[J_{\varphi+}^T(q)e_\lambda + K_s s] + \gamma(e_\lambda)\int (e_\lambda)dt \\ &= \frac{1}{2}s^T[\dot{H}(q,\dot{q}) - 2C(q,\dot{q})]s - s^T K_s s \\ &\quad - s^T J_{\varphi+}^T(q)e_\lambda + \gamma(e_\lambda)\int (e_\lambda)dt \\ &= -s^T J_{\varphi+}^T(q)e_\lambda + \gamma(e_\lambda)\int (e_\lambda)dt\end{aligned} \quad (18)$$

Substituting equation (11) in the expression $s^T J_{\varphi+}^T(q)e_\lambda$, we have:

$$\begin{aligned} s^T J_{\varphi+}^T(q)e_\lambda &= \{Q(\dot{q})[(\dot{e}) + \alpha(e)]\}^T J_{\varphi+}^T(q)e_\lambda \\ &\quad + \left\{J_{\varphi+}^T(q)\left[\beta e_\lambda + \gamma \textstyle\int_0^t (e_\lambda)dt\right]\right\}^T J_{\varphi+}^T(q)e_\lambda \\ &= \{[(\dot{e}) + \alpha(e)]\}^T Q(\dot{q})J_{\varphi+}^T(q)e_\lambda \\ &\quad + \left\{\left[\beta e_\lambda + \gamma \textstyle\int_0^t (e_\lambda)dt\right]\right\}^T J_{\varphi+}(q)J_{\varphi+}^T(q)e_\lambda \\ &= \beta(e_\lambda)^2 + \gamma(e_\lambda)\textstyle\int_0^t (e_\lambda)dt \end{aligned} \quad (19)$$

Finally

$$\dot{V}_s = -s^T K_s s - \beta(e_\lambda)^2 \leq 0 \quad (20)$$

If follows that all motions tends toward the set satisfying he equality $s = 0$.

IV. Simulation and Experimentation

In this section, the results of modeling, simulation and experimentation showing the effectiveness of the proposed control scheme. The tested used to perform the simulation consists of robot manipulators Catalyst of five degrees of freedom.

A. Simulation Transition Free to Constrained Movement

The proposed control is programmed on a MatLab Simulink® solver ode23tb. The schema system used to perform the simulation is depicted in Fig. 2.

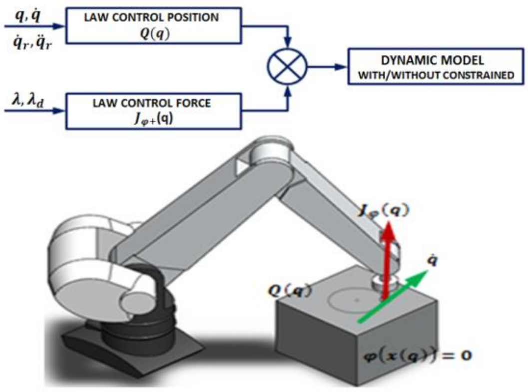

Figure 2. System schema.

The dynamic simulations study of free to constrained motion. The simulation starts moving the manipulator in free environment and through the programmed path is carried on a constrained motion in an estimated time; into the constrained environment where it is continuous with the desired path induced force profile. The data path and force profile is shown in Table I and Table II.

TABLE I. PATH PROFILE

Geometric Profile	
$\varphi(\mathrm{x(q)}) = A(x_i - x_0) + B(y_i - y_0) + C(z_i - z_0) = n \cdot X = 0$	
$n = [A\ B\ C] = [0\ 0\ 1]$	
$X = [(x_i - x_0), (y_i - y_0), (z_i - z_0)]^T$	
$(x_i = 0.25), (y_i = 0), (z_i = 0)$	
Path $t < 10seg$	Path $t \geq 10seg$
$x_d = r * cos(w * t) + dx$	$x_d = r * \cos(w * t) + dx$
$y_d = r * sin(w * t) + dy$	$y_d = r * \sin(w * t) + dy$
$z_d = -0.1 * t + dz$	$z_d = dz$
$(r = 0.05, w = 2 * pi/10, dx = 0.2, dy = 0, dz = 0)$	

TABLE II. FORCE PROFILE

λ_d	0	$t < 20\ sec$
	$(t - 20) * 1$	$20 \leq t < 30\ sec$
	$10 + 5\sin(2 * \pi * t/10)$	$30 \leq t < 70\ sec$
	$10 - (t - 70) * 1$	$70 \leq t < 80\ sec$
	0	$t \geq 80\ sec$

In the following figures the control performance is observed when there is a transition of free to restricted movement and delay induced in the communication channel.

In Fig. 3 the tracking position cartesian space observed and changes state free to restricted movement, in Fig. 4 the tracking force profile and force error is shown. A deviation of the position error is observed 1 μm and the force is 0.50 N. These results when the system is in transition from free to constrained shows that the position and force errors converge asymptotically to zero smoothly as control signals. In Fig. 5 is observed on behavior controls.

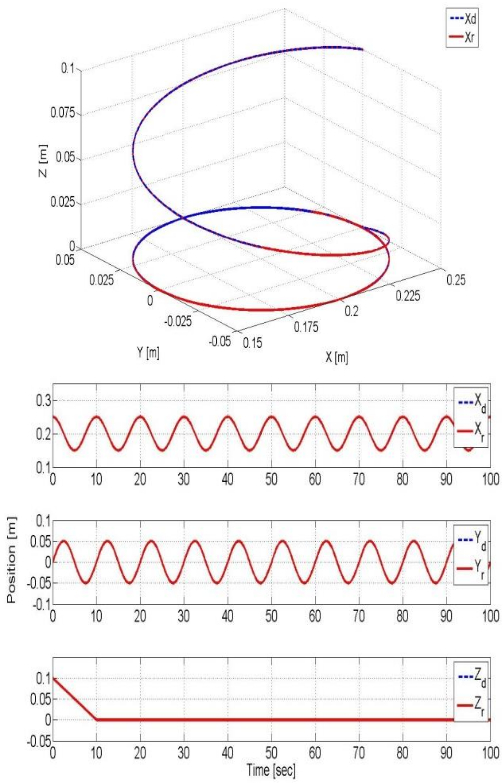

Figure 3. Position tracking in cartesian space with transition free to constrained motion.

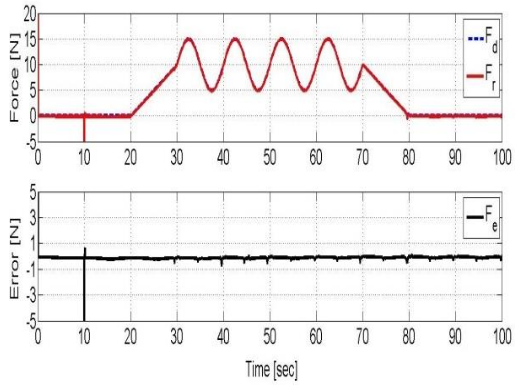

Figure 4. Tracking force profile and force error with transition free to constrained motion.

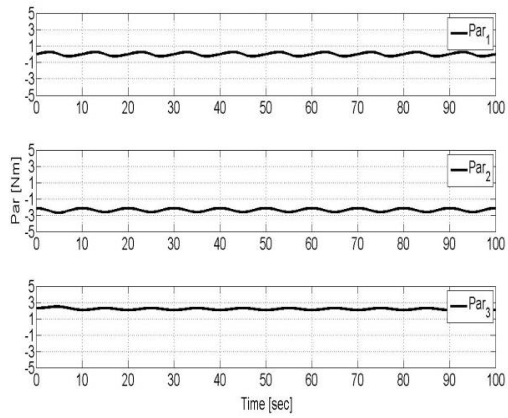

Figure 5. Torque control with transition free to constrained motion.

B. *Resultados Experimentales*

Theory and simulation developed is tested in this section, for which the CRS-5 Catalyst robot open architecture where a force sensor integrates JR3 is employed. Restriction platform is composed of rigid steel plate covered with a melamine surface as shown in Fig. 6. The data path profile shown in table 1 and force profile applied once contact is 10 N in the period from 20 to 80 seconds.

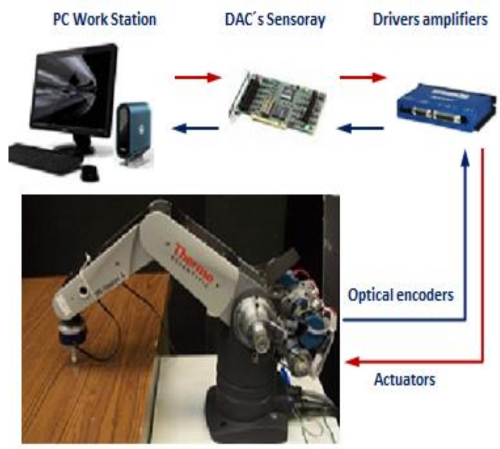

Figure 6. Platform experimentation

The sampling time for information processing is 0.001 milliseconds to ensure that the system operates in the continuous time domain.

The Fig. 7 shows tracking the joint variables. The Fig. 8 shows the observation joint error and Fig. 9 the cartesian error; which serves to appreciate more easily control the performance.

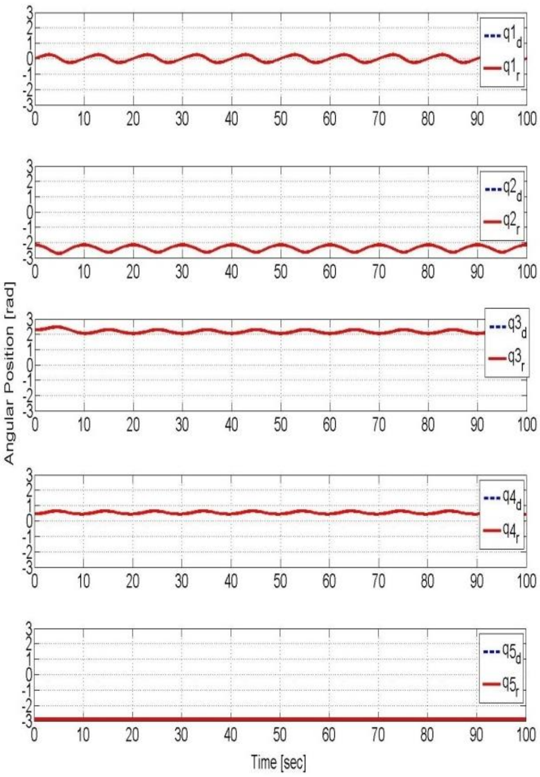

Figure 7. Tracking joint variables with transition free to constrained motion.

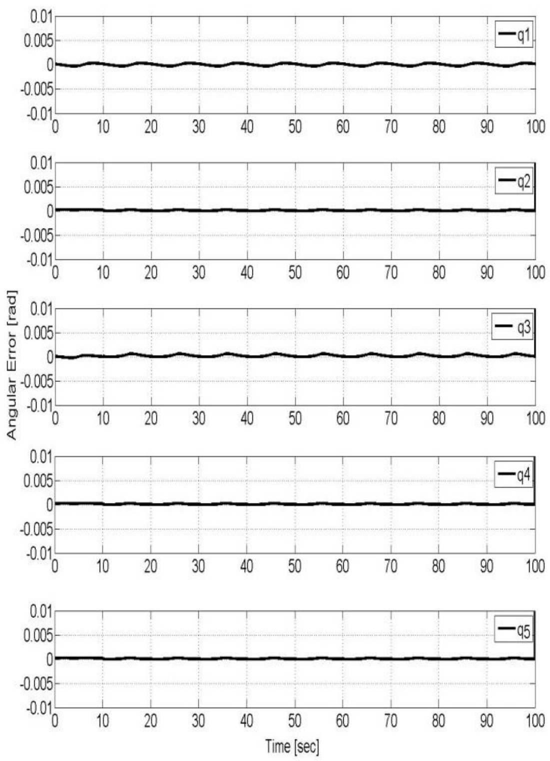

Figure 8. Joint error with transition free to constrained motion.

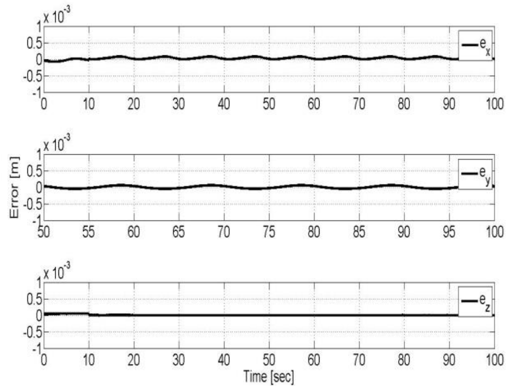

Figure 9. Cartesian error with transition free to constrained motion.

Finally, the Fig. 10 shows the path of force profile, together with the force error obtained by the controller.

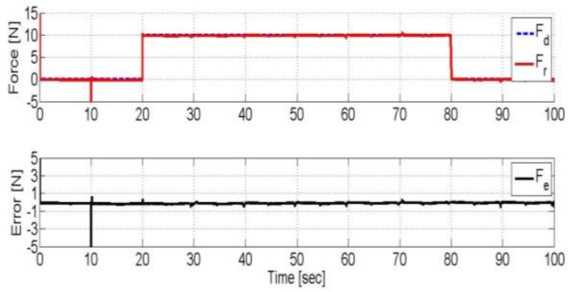

Figure 10. Tracking force profile and force error with transition free to constrained motion.

V. Conclusions

A modeling, simulation and experimentation of hybrid force position control has been proposed based on the principle of orthogonal decomposing into position and force subspaces, considers geometric holonomic constraints.

Results are presented through the simulation and experimentation of system. The control PD+Adaptive+g proposal has high efficiency and stability both in free and constrained environment such that error of the position and force convergence asymptotically to zero simultaneously and independently.

As future work will develop, comparing this type of control with existing literature sliding mode of first and second order to develop a new control.

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References

[1] N. Hogan, "Impedance control: An approach to manipulation: Part—III Applications," *Journal of Dynamic Systems, Measurement and Control*, vol. 107, no. 1, pp. 17-24, 1985.

[2] J. J. Craig and M. H. Raibert, "A systematic method of hybrid position/force control of a manipulator," in *Proc. IEEE Computer Software and Applications Conference*, 1979, pp. 446-451.

[3] S. Arimoto, Y. H. Liu, and T. Naniwa, "The orthogonalization principle for robot manipulators," *IFAC Congress on Automatic Control*, vol. 1, pp. 507-512, 1993.
[4] P. Akella, V. Parra-Vega, S. Arimoto, and K. Tanie, "Discontinuous model-bases adaptive control for robots executing free and constrained tasks," *IEEE Transactions on Robotics and Automation*, vol. 4, pp. 3000-3007, 1994.
[5] L. L. Whitcomb, S. Arimoto, T. Naniwa, and F. Ozaki, "Adaptive model-based hybrid control of geometrically constrained robot arms," *IEEE Transactions on Robotics and Automation*, 1996.
[6] V. P. Vega, A. R. Angeles, S. Arimoto, and G. Hirzinger, "High precision constrained grasping with cooperative adaptive hand control," *Journal of Intelligent and Robotic Systems*, vol. 32, pp. 235–254, 2001.
[7] A. R. Angeles and V. P. Vega, "Control adaptable de posición y fuerza para multi-robots manipuladores trabajando en un esquema cooperativo," *Revista Cient fica IPN*.

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