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Control for cooperative robot systems in tasks of manipulation in interaction with the environment

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ABSTRACT

A control scheme for a cooperative system consisting of ABB robotics arms is developed to perform manipulation tasks. The mathematical model of the object and the contact points is obtained by, analyzing internal and external forces/torques generated by the cooperative system according to geometry and stiffness of the object surface. A hybrid position/force-torque control system is implemented, which is formed by an internal PID position control loop and an external PI force-torque control loop, this scheme guarantees grip in the object handling. The cooperative system is reactive, this allows us to generate both, translation and rotation movements by a differential of force and torque respectively, a hybrid extended position/force-torque control is implemented to yield a differential.

1.INTRODUCTION

A manipulator robot is a mechanism formed generally by elements in series, articulated with each other, intended for the subjection or displacement of objects. Despite the wide range of activities that a manipulator robot can perform on its own, there are tasks for which the manipulation ability or versatility are limited, such as the manipulation of large objects whose weight can exceed the robot working capacity, to perform these tasks a system of cooperative manipulative robots is necessary. The cooperative robotic systems demand in the industry is increasing due to the complexity of tasks that are currently being developed.

When performing manipulation or grabbing, the cooperative system is in constant interaction with the object and the environment, according to the object/environment physical properties there are tasks where the implementation of a position control is not enough. Therefore, the force/torque control is important to know the force/torque generated by the cooperative system which could cause deformations to the object/environment, the hybrid position/force-torque control scheme encompasses

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position and force/torque control. The force/torque control is based on a capacitive impedance model, in which forces and torques of reaction are generated by the penetration that exists on the object surface (Caccavale 2008).

An important point to perform the manipulation and grasping tasks is the study of internal and external forces/torques, that are generated by the cooperative system interacting with the object (Carbone 2013). In manipulation tasks, two phases are proposed, first the grasping phase, in which the final effectors have contact with the object surface, the position/force-torque hybrid control is implemented to perform a grasping applying a desired force, in the second phase, which is the planning of rotational and translational movement maintaining the grasp, a hybrid extended position/force-torque control is implemented.

The control scheme experimental implementation is carried out on a cooperative system consisting of two ABB robots equipped with force sensors of 6 degrees of freedom at the final effector.

2. MODELING

The cooperative system consists of two robotic arms of six DOF, the dynamic model of each robotic arm is presented with free dynamics when the end effector does not interact with a reaction force that opposes its movement, and a constrained dynamics when there is interaction with the object/environment, generating reaction forces at the end effector. When performing manipulation or grasping tasks there is an interaction between the two robots that make up the cooperative system and the object to be manipulated, so the robotic arms present a constrained dynamics (Siciliano 2009), which for each robot arm *(i=1,2)* is given by Eq. (1),

$$D_i(q_i)\ddot{q}_i + C_i(q_i,\dot{q}_i)\dot{q}_i + Q_i\dot{q}_i + g_i(q_i) = \tau_i + J_i^T h_i \qquad (1)$$

where $D_i(q_i)$ is the positive definite symmetric inertia matrix, $C_i(q_i,\ddot{q}_i)$ is the centrifugal and Coriolis forces matrix, Q_i is the viscous friction coefficients matrix, $g_i(q_i)$ is the gravitational forces vector, q_i is the vector of generalized joint coordinates, τ_i is the input torque vector, J_i is the Jacobian matrix, h_i is the forces and moments acting at the end effector vector.

The cooperative system dynamic model is compactly written as shown in Eq. (2),

$$D(q)\ddot{q} + C(q,\dot{q}) + Q\dot{q} + g(q) = \tau + J^T h \qquad (2)$$

where $D(q) = blockdiag(D_1, D_2)$, $C(q,\dot{q}) = blockdiag(C_1, C_2)$, $g(q) = [g_1^T, g_2^T]^T$
$Q = blockdiag(Q_1, Q_2)$, $J = blockdiag(J_1, J_2)$, $\tau = [\,\tau_1^T\,,\ \tau_2^T]^T$, $h = [h_1^T, h_2^T]^T$,
$q = [q_1^T, q_2^T]^T$.

When the robotic arms interact with the object, their movement is dynamically coupled, for this reason it is important to know the object dynamics. Consider the

known object surface $S(x, y, z) = 0$, and the center of mass of the object as the reference frame Σ_e, as show in Fig. 1.

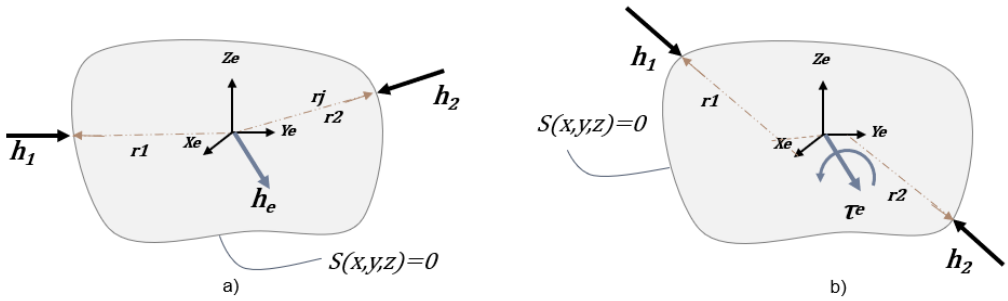

Fig. 1 Grip of an object, a) Resultant force, b) Resultant torque

The generalized forces applied at the contact points (h_1, h_2) are directed to the center of mass, producing two resultant forces, the external force h_e generates translational movement at the object, and the internal force h_i, which generates mechanical stresses in the object. If the generalized forces are not directed to the center of mass, Fig. 1b, they yield two resultant torques, an external torque that generates a rotational movement of the object, where the rotation pivot is the center of mass of the object, and an internal torque generating mechanical stresses.

When performing manipulation or grasping tasks, each end effector exerts a force F_i and a torque M_i at the contact points of the object which are call generalized forces h_i. The grasping matrix $W = (w_1, w_2)$, maps these forces to the object reference system Σ_e. Eq. (3)

$$h_e = [w_1, w_2][h_1^T, h_2^T]^T = Wh \tag{3}$$

where,

$$w_i = \begin{bmatrix} I_3 & O_3 \\ -S(r_i) & I_3 \end{bmatrix} \tag{4}$$

$S(.)$ is an antisymmetric matrix operator, r_i is called virtual tensor.

The dynamic equation of the object can be expressed as, Eq. (5)

$$M_e \dot{v_e^e} + C_e(v_e^e)v_e^e + g_e^e = h_e^e \tag{5}$$

where,

$$M_e = \begin{bmatrix} m_e I & O \\ O & J_e^e \end{bmatrix}, \qquad C_e(v_e^e) = \begin{bmatrix} m_e S(\omega_e^e) & O \\ O & S(\omega_e^e) J_e^e \end{bmatrix},$$

$$g_e^e = \begin{bmatrix} -m_e g_0^e \\ 0 \end{bmatrix}, \qquad v_e^e = \begin{bmatrix} \dot{p}_e^e \\ \omega_e^e \end{bmatrix},$$

$$h_e^e = \begin{bmatrix} F_e^e \\ M_e^e \end{bmatrix}$$

v_e^e is the vector of linear and angular velocities of Σ_e, m_e is the object mass, J_e^e is the object's inertia tensor referred to Σ_e, g_o^e is the vector of gravitational forces, h_e^e is the wrench exerted by the manipulators on the object, h_e is the vector of resulting generalized forces.

The Matrix W is full-row rank, for a given h_e, the inverse solution is given by:

$$h = W^* h_e + V h_i = h_E + h_I \tag{6}$$

W^* denotes pseudoinverse of W, V is a full-column rank matrix spanning the null space of W, $h_i$represents the vector of internal forces and h_E represents the vector of external forces, it is show as, Eq. (7)

$$h_E = W^* W h \tag{7}$$

h_I represents the vector of forces mapped at the contact points, resulting from the internal forces of the object, and is given by,

$$h_I = V V^* h \tag{8}$$

3. CONTROL SCHEME

A hybrid position/force-torque control scheme is implemented on the cooperative system to perform manipulation tasks, the control scheme is formed by an internal position control loop and an external force-torque control loop.

The internal position control loop brings the end effector to a desired position X_d, which is the contact point on the object surface. Direct kinematics determines the cartesian positions of the end effector as the joint variables function $X = f(q)$, if the position control is based on the error of the joint variables e_q, the position error signal is obtained as,

$$e_q = q_d - q \tag{9}$$

where q_d are desired joint variables and q are the current joint variables of the robot. The inverse kinematic provides the joint variables according to the cartesian positions $q = f(X)$, $X \in \mathbb{R}^{6x1}$ is the position and orientation vector of the end effector.

The force control comes into operation when the end effector has reached the

desired position and is in contact with the object, the force control is based on a capacitive impedance control, in which the forces and reaction torques are generated by the penetration that exist on the object surface and the stiffness of it. (Hogan 1985), in the hybrid position/force-torque control scheme to the internal position control loop, an external force/torque control loop is added, as shown in Fig. 2.

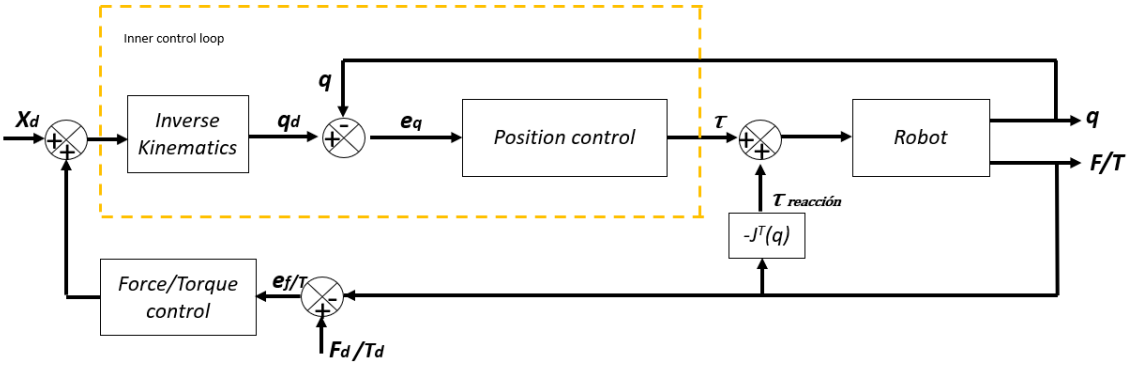

Fig. 2 hybrid position/force-torque control.

In this work a position PID control is considered, as well as a PI control based on the force/torque error e_h,

$$e_h = h_d - h_m \tag{10}$$

h_d is the desired force/torque, h_m is the measured force/torque at the end effector.

The force/torque control loop adds a reference position X_r to the desired position X_d, generating a commanded position X_c,

$$X_c = X_d + X_r \tag{11}$$

where,

$$X_r = K_{hp} e_h + K_{hi} \int e_h dt \tag{12}$$

$k_{hp}, k_{hi} \in \mathbb{R}^{6x6}$ positive diagonal matrices corresponding to proportional and integral gains of PI force control.

The hybrid position/force-torque control implemented in each robot of the cooperative system guarantees a correct grip on the object to be manipulated. To generate a movement of rotation or translation an hybrid extended position/force-torque control is implemented, to which is added a position control loop that provides the force-torque differential h_M that generates the desired movement $\tilde{x}_d(t)$, for this loop a PID control based on position error $e_x \in \mathbb{R}^{6x1}$ which is shown in Eq. (13),

$$h_M = K_{xp} e_x + K_{xi} \int e_x dt + k_{xd} \dot{e_x} \tag{13}$$

where $k_{xp}, K_{xi}, K_{xd} \in \mathbb{R}^{6x6}$ are positive diagonal matrices corresponding to the proportional, integral and derivative gains of the position PID control. A new reference torque-force h_T is generated which is the sum of the desired torque-force h_d and the force h_M. The hybrid extended position/force-torque control scheme is shown in Fig. 3.

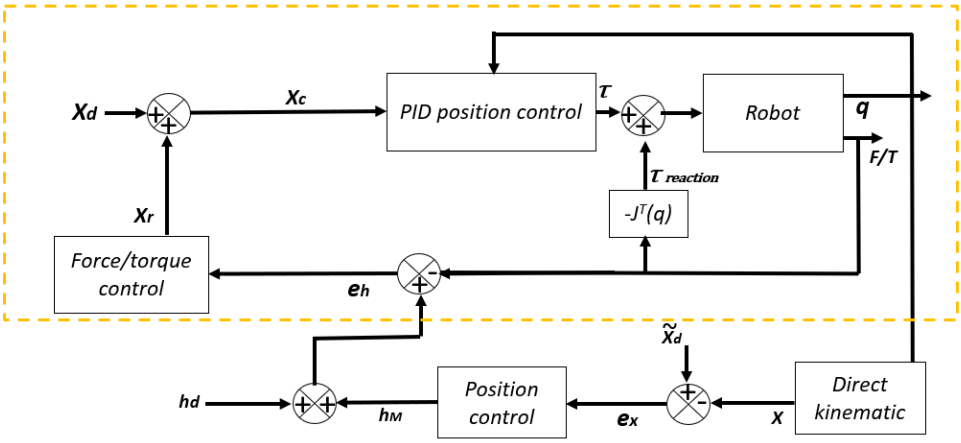

Fig. 3 Hybrid extended position/force-torque control.

The hybrid extended position/force-torque control implementation in the cooperative system's robots varies according to the object movement that it is desired to produce, either rotational or translational.

3.1 Closed loop analysis

The closed loop analysis of the hybrid position/force-torque control is performed, its implementation is considered in the closed-architecture ABB industrial robot, considering contact with a surface.

The dynamic motion restricted model of a manipulator robot is shown in Eq. (1), the restriction is generated when the robot is in contact with a surface, any configuration that satisfies the surface equation $S(X) = 0$, belongs to the set $\mathcal{X}$, i.e., if $X \in \mathcal{X}$ the equation of the surface is fulfilled.

The dynamic model of the Eq. (1) does not consider the dynamics of the actuators, which for this case are motors of the BLDC (Brushless DC) type. The relationship between the voltages V applied to the motors and the torques generated in the articulations, considering actuators with linear dynamics (Kelly 2005), is given by,

$$D_j \ddot{q} + D_f \dot{q} + D_r \tau = D_k V \tag{14}$$

where for a robot manipulator of 6 degrees of freedom, $V = [v_1, \dots v_6]^T$ and

D_r, D_f, D_r, D_K are diagonal matrices that are given as,

$$D_j = diag\{J_{m1}, \dots, J_{m6}\}, \tag{15}$$

$$D_f = diag\{f_{m1} + \frac{K_{a1}K_{b1}}{R_{a1}}, \dots, f_{m6} + \frac{K_{a6}K_{b6}}{R_{a6}}\}, \tag{16}$$

$$D_r = diag\{\frac{1}{r_1^2}, \dots \frac{1}{r_6^2}\} \tag{17}$$

$$D_K = diag\{\frac{K_{a1}}{R_{a1}r_1}, \dots, \frac{K_{a6}}{R_{a6}r_6}\}, \tag{18}$$

for each motor $(i = 1, \dots..6)$:

J_{mi} : rotor inercia [kg·m2],
K_{ai} : motor-torque constant [N·m/A],
R_{ai} : armature resistance [Ω],
K_{bi} : back emf constant [V·s/rad]
f_{mi} : rotor friction coefficient [N·m]
r_i : gear reduction ratio usually chosen so that $\mathrm{r\_i} >> 1$ In this work this case is assumed

clearing τ from Eq. (14),

$$\tau = D_r^{-1}D_K V - D_r^{-1}D_j\ddot{q} - D_r^{-1}D_f\dot{q} \tag{19}$$

replace Eq. (14) in the Eq. (1), and grouping terms results,

$$\left(D_r D(q) + D_j\right)\ddot{q} + D_r C(q,\dot{q})\dot{q} + \left(D_r Q + D_f\right)\dot{q} + D_r g(q) = D_K V + D_r J^T(q)h \tag{20}$$

the Eq. (20) corresponds to the dynamic model of the manipulator that includes the mechanical system of the manipulator and the dynamics of the actuators, where now the input control is the voltage applied to the motors.

For the industrial robot used in this work it is assumed that $r_i \gg 1 \forall_i (i = 1, ..6)$, so in Eq. (17) it turns out that $D_r \approx 0$, and considering this, Eq. (20) can be approximated as shown in Eq. (21)

$$D_j\ddot{q} + D_f\dot{q} = D_K V \tag{21}$$

For ABB industrial robots a closed architecture is maintained so that the position control algorithm is not accessible, and it is assumed that it has a position PID control. In the movement programming only the desired positions X_d, are provided, which contains the desired position and orientation information of the robot end effector. The position error in the joint space is defined as,

$$e_q = q_d - q \tag{22}$$

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$$\delta X = X_d - X \tag{23}$$

the position PID control that is assumed is defined as,

$$V_{PID} = K_P e_q + K_I \int e_q dt + K_D \dot{e_q} \tag{24}$$

where $K_P, K_I, K_D \in \mathbb{R}^{6x6}$ are positive diagonal matrices for the manipulator robot of six degrees of freedom.

Assumption the controller gains K_P, K_I, K_D have been properly tuned by the robot manufacturer to achieve, $e_q \approx 0$ and $\dot{e_q} \approx 0$ for time varying trajectories $q_d(t), and \;\; e_q = \dot{e_q} = 0$ for a constant q_d. therefore, the PID control achieves $\delta X \approx 0$ and $\delta \dot{X} \approx 0$ for time varying $X_d(t)$, and $\delta X = \delta \dot{X} = 0$ for a constant X_d.

By substituting Eq. (24) in Eq. (21) one gets,

$$D_j \ddot{q} + D_f \dot{q} = D_K (K_P e_q + K_I \int e_q dt + K_D \dot{e_q}) \tag{25}$$

where $D_k K_P, D_k K_I, D_k K_D \in \mathbb{R}^{6x6}$ are diagonal positive matrices.

Remark Eq. (25) shows that for large gear reduction ratios the high nonlinear dynamics of the robot manipulator becomes not only approximately linear but also decoupled. However, care must be taken since in reality the position vector q in Eq. (25) is nor free but constrained by the force h even though it does appear explicitly. The usefulness of Eq. (25) relies in the fact that it allows to implement a force control action indirectly just by properly choosing the desired position trajectories.

4. EXPERIMENTAL PLATFORM

The experimental platform consists of two industrial ABB brand robots Fig. 4, each robot has a control unit, and are equipped with a force/torque sensor of six degrees of freedom, one of the JR3 brand and another ATI brand, there is a computer for the communication interface between the force sensors and the control units.

The ABB hardware and software modules are not available for cooperative task, for this, the digital inputs and outputs of the robot control unit are used, these digital signals are activated and deactivated by means of a programming code.

The robotic arms have closed architecture, so the desired routines and algorithms are programmed in RAPID ABB's own high-level programming language.

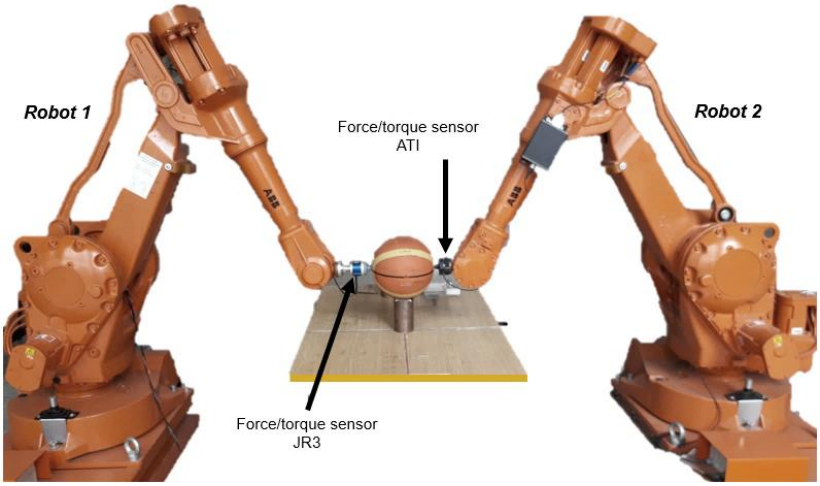

Fig. 4 Cooperative robotic system.

5. EXPERIMENTAL RESULTS

This section describes the experiments carried out, as well as the results obtained graphically. The object to be manipulated is a basketball ($m_e = 620g$), defining a global reference frame located at the midpoint between the robots. The sampling time of each iteration is formed by the reading of the force/torque sensors, the synchronization event and the execution of movement, which for robot 1 is [0.04s] for robot 2 [0.06s]. Two experiments are presented which are described below.

In the first experiment the final effectors are perpendicular to the object surface, collinear with each other, directed to the center of mass of the object, the objective of this experiment is the object manipulation generating rotational and translational motion by means of force control and torque, the gains of the force, torque and position control loops for each robot are shown at the table 1.

Table 1. PI force-torque, PID position z-y, gains.

	Robot 1 (R1)	Robot 2 (R2)
PI Force control gains:		
k_{hp}	0.015	0.015
k_{hi}	0.5	1
PI Torque control gains:		
k_{hp}	0.12	0.12
k_{hi}	4.75	5.5
PID Position-z control gains:		
k_{zp}	0.08	0.08
k_{zi}	1.126	1.126
k_{zd}	0.07	0.07
PID Position-y control gains:		

k_{yp}	-	0.866
k_{yi}	-	0.563
k_{yd}	-	0.08

The stages of this experiment are:

1) Contact - The two robots start synchronized, using the ABB position control they are positioned on the object surface, comprising time 0-10 [s], the desired positions are, R1 $X_d = [0, -120, 0][mm]$, R2 $X_d = [0, 120, 0][mm]$.
2) Grip - Both robots have to apply a desired force [35 N] to generate a correct grip of the object by means of the hybrid position/force-torque control, when this desired force is reached, the robots separate the object from the base maintaining this force of grip Time 20-42 [s].
3) Rotational movement - To generate rotational movement of the object there is a force control which maintains a correct grip and a torque control which by means of the hybrid extended position/force-torque control implemented in both robots generates a differential torque, thus obtaining rotational movement of the object where the pivot of rotation is the center of mass of the object. It is worth mentioning that the torque read by the two sensors varies due to the distance between the contact point end effector and the position of the gauges in the force/torque sensor. A desired torque path is programmed to change the initial conditions of the differential torque,

$$R1: T_d = 0.5 * (t)/14$$
$$R2: T_d = -1.2 * (t)/14$$

time 52-66 [s], the desired z-position trajectories are:

$$R1: \widetilde{z_d} = 9.83cos(0.139t_{aux}) - 9.83 + z$$
$$R2: \widetilde{z_d} = -9.83cos(0.139t_{aux}) + 9.83 + z$$

z is the position measured when starting the differential torque. Time 66-110 [s]

4) Translational motion - At this point the hybrid extended position/force-torque control is implemented for the robot 2, which tracks the position trajectory, the desired trajectory is,

$$R2: \tilde{y}_d(t_{aux}) = -50cos(0.0785t_{aux}) + 50 + y$$

t_{aux} is the auxiliary time in the routine, starts at zero when the displacement starts, y is the position measured when starting the differential force, the force control of the robot 1 is in reaction, maintaining the same force. Time 120-200 [s]

5.1 Results

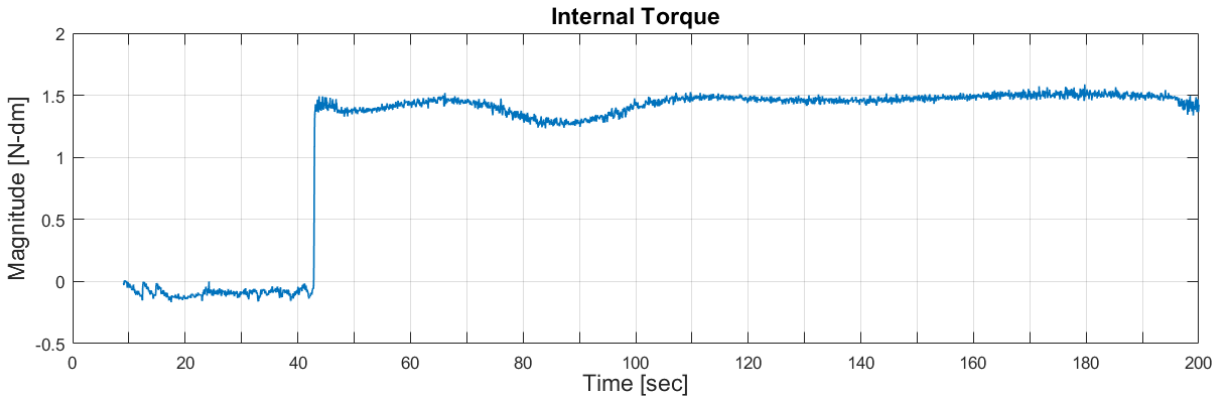

Fig. 5 Internal torque

The generalized forces/torques applied at the contact points generate internal/external forces/torques in the object, in Fig. 5 it can be seen that when the rotational movement is carried out (time 50-100s) the internal torque changes creating internal tensions in the object, when the translational movement is made (time 100-200s) the inclination generated by the rotation is maintained, that is why no variation is observed, when the cooperative system lifts the object, the internal torque is generated by the gravitational force $(g = 9.81m/s^2)$ and the weight of the ball, (time 44s). In Fig. 6 observe the external torque which generates movement of the object, when the differential torque is realized (time 55-110s) notice the direction of rotation depending on the object reference frame, and a constant torque is maintained when the translational movement is made.

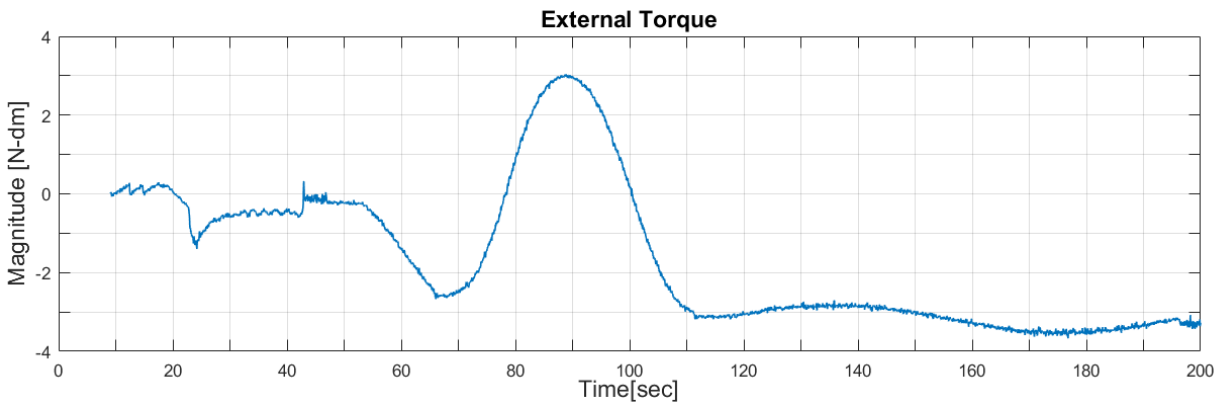

Fig. 6 External torque

The internal force is show in Fig 7, it has variation when performing the rotational and translational movement, maintaining a grip force of [35 N].

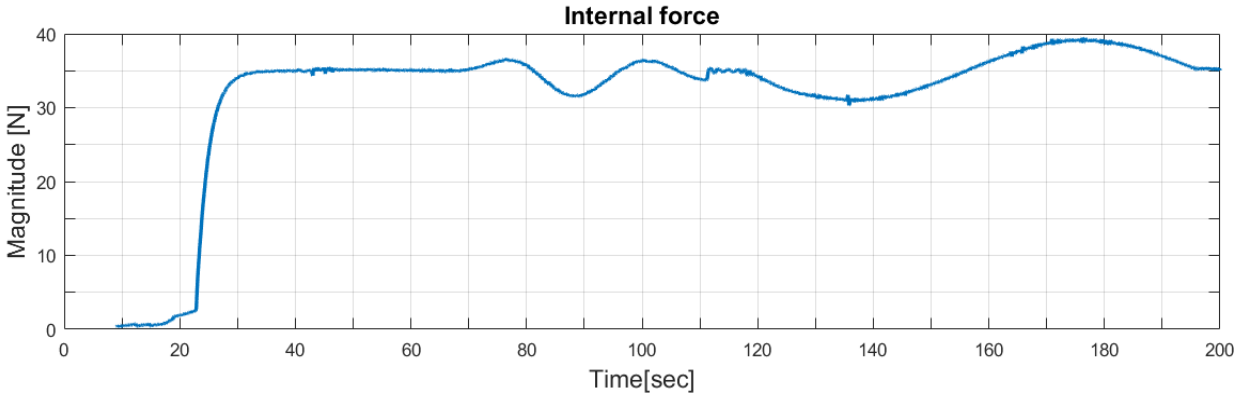

Fig. 7 Internal force

Fig. 8 shows the desired torque trajectory, which is used to generate initial conditions for the differential torque, (time 52-68s)

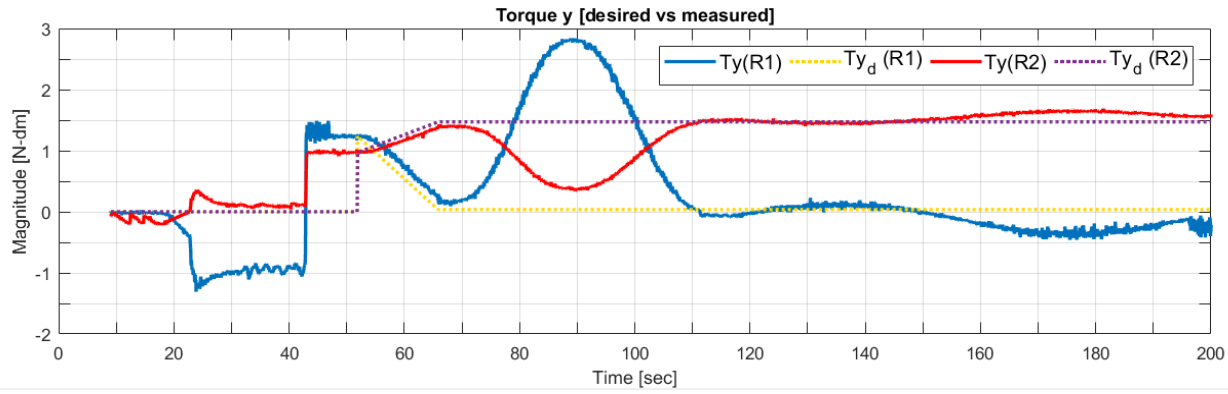

Fig. 8 Torque *y*

In Fig. 9 the desired position of the control loop added to the hybrid position/force-torque control scheme is observed to produce the differential torque. In Fig. 10 notice the position of the end effectors on the *y* axis.

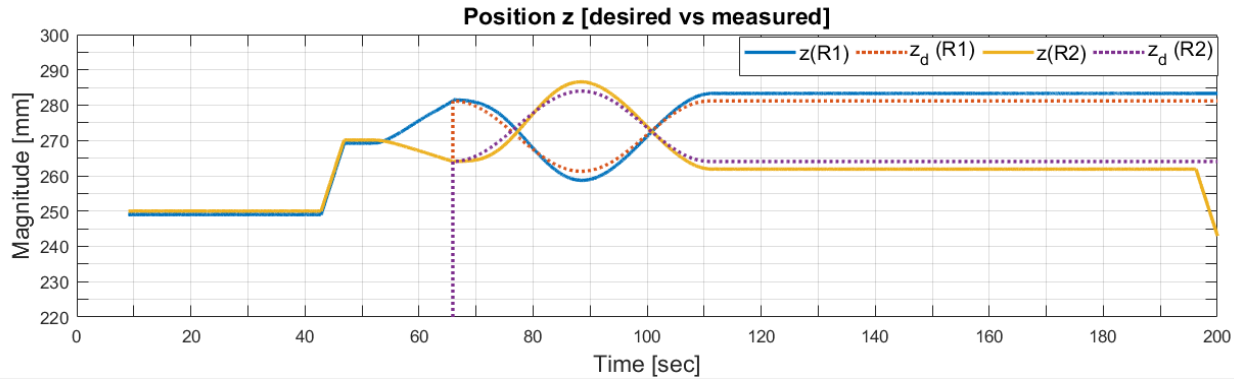

Fig. 9 Position *z*

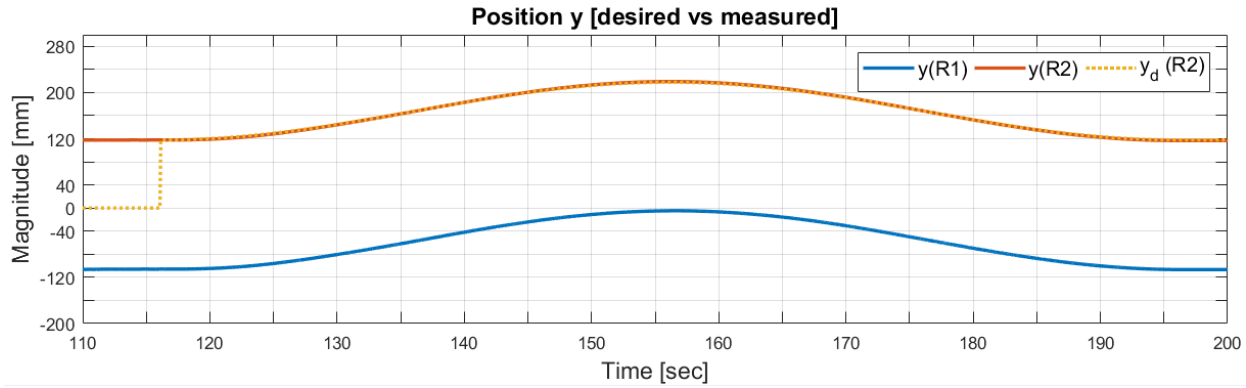

Fig. 10 Position *y*

Fig. 11 the force measured by the force/torque sensor in its x-axis reference frame is observed.

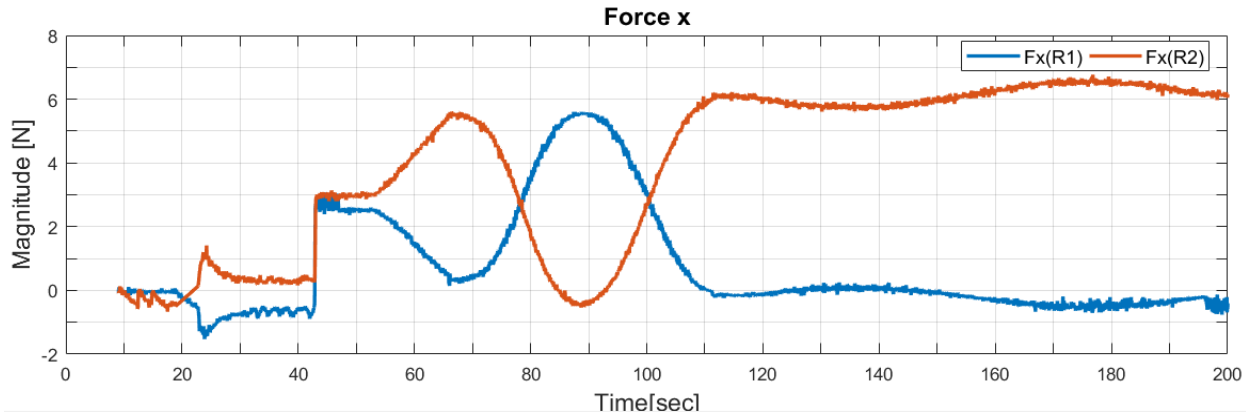

Fig. (11) Force *x*

In the second experiment, the robot end effector makes an orientation change in position of fifteen degrees in the y-z plane, the end effectors are not collinear with each other, the objective of this experiment is the manipulation of the object generating rotational and translational movement taking into account the decomposition of forces generated by the change of inclination and variation of torque reading by the position of the end effector. The gains of the force, torque and position control loops for each robot are shown in the table 2.

Table 2 PI force-torque, PID position yz, gains.

	Robot 1 (R1)	Robot 2 (R2)
PI Force control gains:		
$k_{hp}y$	0.015	0.0072
$k_{hi}y$	1	0.25

$k_{hp}z$	-	0.0075
$k_{hi}z$	-	0.025
PI Torque control gains:		
k_{hp}	-	0.24
k_{hi}	-	15.5
PID Position-yz control gains:		
k_{yp}	-	0.866
k_{yi}	-	0.563
k_{yd}	-	0.866
k_{zp}	-	1
k_{zi}	-	0.66
k_{zd}	-	1

The stages of this experiment are:

1) Contact - The two robots start synchronized, using the ABB position control they are positioned on the object surface. Time 0-10 [s], the desired positions are, R1 $X_d = [0, -120,0][mm]$, R2 $X_d = [0,120,0][mm]$.
2) Grip - Both robots have to apply a desired force [35 N] to generate a correct grip of the object by means of the hybrid position/force-torque control, when this desired force is reached, the robots separate the object from the base maintaining this grip force. Time 10-45 [s].
3) Orientation change - Robot 2 changes orientation fifteen degrees at the y-z plane while maintaining the end effector at the contact point. Time 54-74 [s]
4) Rotational movement - There is a force control for a correct grip of the object, and the torque control tracks the desired torque trajectory which is,

$$R2: T_d = 0.4cos(0.157t_{aux}) - 0.4 + Ty$$

Ty is the torque measured when starting the torque control.
Robot 1 maintained only in reaction to force control. Time 74-134 [s].
5) Translational motion - At this point the hybrid extended position/force-torque control is implemented at the robot 2, which tracks the position trajectory. The desired trajectory is,

$$R2: \tilde{y}_d(t_{aux}) = -50cos(0.0785t_{aux}) + 50 + y$$

y is the position measured when starting the position control. Time 134-224 [s].

Results

In this experiment the robot 2 end effector, changes orientation fifteen degrees in the y-z plane, this end effector applies force/torque at the contact point, now there is a decomposition of forces by the inclination, that is because to maintain an internal force of 35 [N] in the z component, the applied force increases 2 [N] show in Fig. 12, the variation created in time (135-205s) is due to the differential force applied to generate

movement. In Fig. 13 notice the position on the y-axis of the final effectors when applying the differential force.

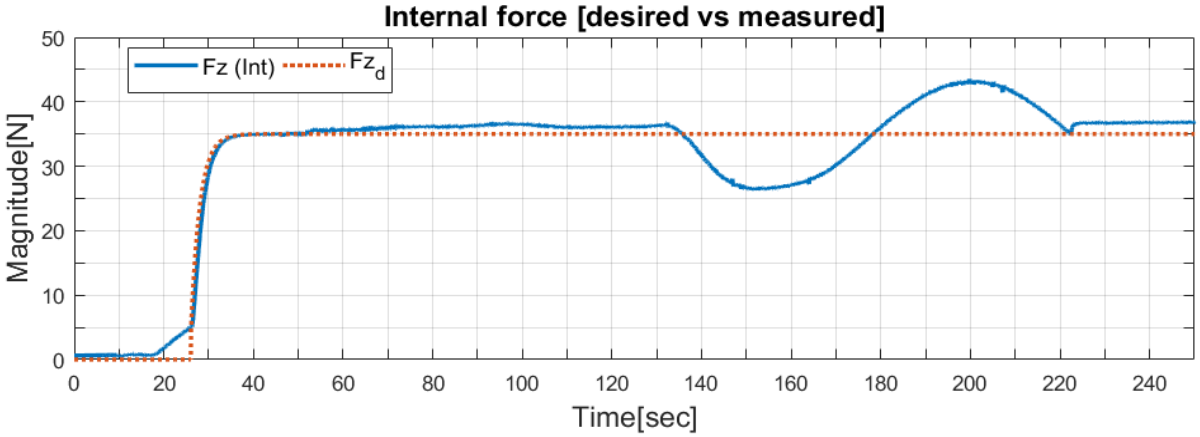

Fig. 12 Internal force

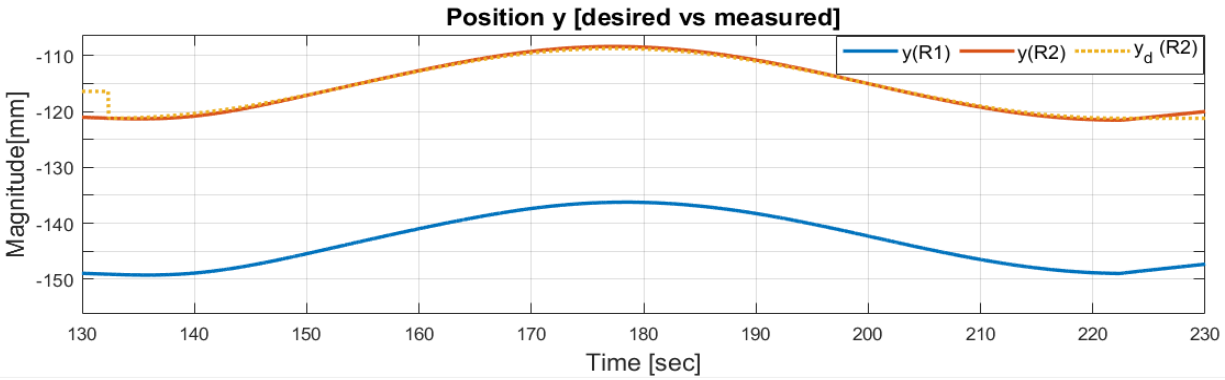

Fig. 13 Position *y*

In Fig. 14 the desired torque path is shown which generates rotational movement of the object, the robot 1 is only in reaction, the pivot turn is now the contact point of the end effector of the robot 1.

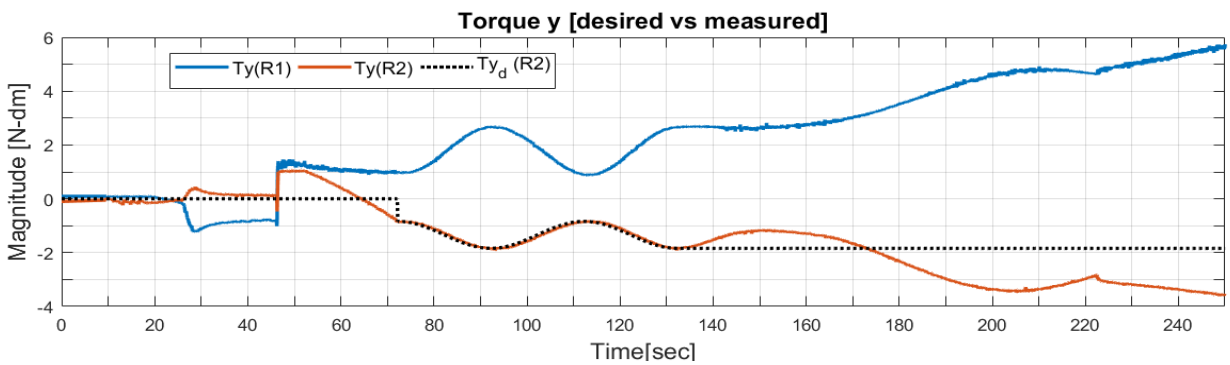

Fig. (14) Torque y

6.CONCLUSIONS

By means of experimental results it was demonstrated that correct manipulation and grip tasks can be performed implementing the control schemes described in this work, despite the closed architecture of the ABB industrial robots the implementation of control schemes was developed successfully.

The end effectors were designed to generate punctual forces at the object, by implementing different geometries at the final effectors, the force/torque measurements made by the sensors have a variation and it is recommended to recalibrate them.

According to the closed-loop analysis of the hybrid position / force control described above, by making a correct tuning in the force control loops PI and position PID errors will tend to zero, corroborating the obtained results.

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