Adaptive Behavior Of An Electromechanical Arm Robot In a Case Of Physical Interaction With a Human Being

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A. A. Melnyk, P. Henaff, S. Razakarivony, V. Ph. Borisenko, P. Gaussier

***Abstract* — The aim of this paper is to consider the adaptation behavior of an electromechanical arm manipulator to the physical interaction of humans. Preliminary experiments to explore the possibility of adaptive interactions between an arm robot and a human without knowledge of the forces are investigated. A simple and efficient control adaptation of the system is implemented at the level of the electrical drive.**

I. INTRODUCTION

NOWADAYS, robotic arms have a high level of resolution for technical tasks, laid by the industry constraints, resulting in major breakthroughs in the field of control theory and computer systems. In humanoid robotics, further progress depends on the success in solving more fundamental problems like the reproduction of the faculty of learning and of the cognitive mechanisms in human beings when robots are interacting with humans physically or socially. In particular, the control of the physical interactions between humans and robots is a fundamental problem for humanoid robots [1].

In industry, there are a variety of tasks for which the robot manipulator interacts with an external force. The torque generated by the external force can be considered as a disturbance. The robot's controller can usually compensate the action of this disturbance by using different control methods. The specifics of physical human-robot interaction (pHRI) come from the great variations in interaction parameters: amplitudes, speeds and endurance of forces application on the part of the human being. These parameters are unknown and cannot always be measured.

In the area of the adaptive control of arm robot in interaction, a lot of previous works have been developed. The control of robot arms is often based on position, velocity, and torque measurements. Other approaches like polynomial family of PD-type controllers [2], adaptive iterative learning control [3] and nonlinear mixed H_2/H_∞ control [4], hybrid force/velocity control of industrial robot arms [5] have also been proposed for control of robot arms. The impedance control [6, 7] and compliance control [8, 9] have been suggested to realize the flexible motion of robot arms, and applied it to industrial robots [10, 11]. These control methods presuppose to modeling the dynamic characteristics between the end-effector and its environment.

The sensorless flexible control was suggested for create flexible motion of industrial articulated robot arms [12]. This method allows switching from a classical control law to a suitably defined hybrid force/motion controller that enables to keep the contact when collision is detected, while sliding on the obstacle, and regulates the interaction force. Other authors have proposed the force-free control approach [13]. This method can create the guided motion under ideal conditions. The robot arm could be moved by an external force under unnatural conditions as if there were no forces of gravity and no forces of friction.

All these approaches were especially developed for industrial applications for which the environment is partially known, for which the human who is interacting with the robot is a professional worker with “calibrated” behavior. In the case of human interactions with humanoid robots, the person can be anyone and her behavior could change every time. Then the controller must adapt itself to the large varieties of the human physical interaction.

In this paper, preliminary experiments to explore the possibility of adaptive interactions between an arm robot and a human without knowledge of the interaction forces are investigated. The control adaptation of the system is implemented at the level of the electrical drive.

After this introduction, the second section of this paper describes the physical interaction problem between human and robot arm used in the experiments. The problem is studied in two ways: simulation and modeling. Third section presents experiments in the adaptation algorithm accompanying an unknown external force for one of degree of freedom of the robot. Finally, in section four, a short summary and conclusion is given.

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II. Physical Interaction Problem Between Human And Robot Arm

A. Brief description and properties of manipulator

The research was carried on the manipulator Katana type 6M180 (company "Neuronics) Fig.1. Each axis of this Katana robot manipulator is separately controlled. This approach of control of multi-joint manipulators can be collectively called independent-joint control (i.e., decentralized control). This means that the control input of each joint only depends on the measurement of the corresponding joint displacement and velocity.

Fig. 1. Manipulator Katana 6M180.

The cascade control system includes the proportional-integral (PI) speed controller and the proportional (P) position controller. They are implemented in a particular firmware. An inner loop leads back the actual speed, compares it with the desired speed and closes the loop with a PI controller. An outer loop consists of the position feedback and a P controller. Each axis is driven with a DC motoreductor. As shown in Fig 2., the PI controller of the inner loop is adjusted with k_i and k_d parameter, while the parameter of the Proportional controller of the outer loop is k_p.

In the Katana robot the current consumed by the motor cannot be measured on the axis. But one can read the current pulse with modulation value (PWM) which is related to the amount of time, when the motor is under voltage.

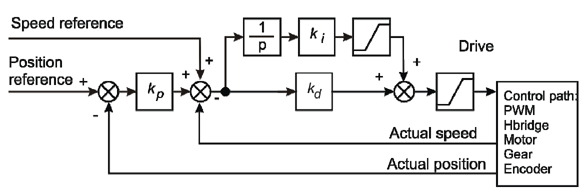

Fig. 2. Block scheme of cascade control structure of a joint-driven system (extracted from katana documentation [14]).

B. Mathematical model

The Lagrange dynamics provides a convenient description of the dynamical model of rigid robot manipulators [15, 16]. Let the robot manipulator have n links and let the $(n \times 1)$ – vector q of joint variables be $q = [q_1, \ldots q_n]^T$. Then the dynamic model of the robot manipulator will be described by Lagrange's equation (1):

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + \tau_g(q) = \tau \quad (1)$$

where $H(q)$ is the $(n \times n)$ inertia matrix, $C(q,\dot{q})\dot{q}$ is the $(n \times 1)$ vector of Coriolis and centrifugal forces, $\tau_g(q)$ is the $(n \times 1)$ vector of gravity force, and τ is the $(n \times 1)$ vector of joint control inputs to be designed.

Internal friction and disturbance inputs can be take into account in this model. Indeed, the non-conservative forces doing work at the manipulator joints. They are given by the actuation torques τ minus the viscous friction torques $F_v\dot{q}$ F_v denotes the $(n \times n)$ diagonal matrix of viscous friction coefficients), and the static friction torques $f_s(q,\dot{q})$. As a simplified model of static friction torques, one may consider the Coulomb friction torque $F_s sgn(\dot{q})$, where F_s is an $(n \times n)$ diagonal matrix and $sgn(\dot{q})$ denotes $(n \times 1)$ vector whose components are given by the sign function of the single joint velocities.

If the end-effector of the manipulator is in contact with an environment, a portion of actuation torques is used to balance the torques induced at the joints by the forces of contact. The torques are given by $J^T(q)h$ where h denotes the vector of force and moment exerted by the end-effector on the environment [17].

In that way, the equation of motion (1) can be written in the compact matrix form which represents the joint space dynamic model:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + F_v\dot{q} + F_s sgn(\dot{q}) + \tau_g(q) = \tau - J^T(q)h \quad (2)$$

A simple design method for manipulator control is to use a linear control scheme based on the linearization of the system at an operating point. An example of this method is a PD control without a gravity compensation scheme [15].

$$K_p(q_d - q) - K_v\dot{q} = \tau \quad (3)$$

Where K_p and $K_v \in R(n \times n)$ are positive-definite gain matrices. This controller is very useful for set-point regulation, i. e. $q_d = const$ [15]. When this controller is applied to (1) the closed-loop equation becomes:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + K_v\dot{q} + K_p e_q = 0 \quad (4)$$

where $e_q = q_d - q$, and the equilibrium point is

$$y = \left[e_q^T \quad \dot{q}^T\right]^T = 0$$

C. Simulation of the interaction

In this simulation, as a first approximation, the force exerted on the finger link manipulator is written as a pulse model:

$$F_H(t) = exp\ (-k_H.t) \quad (5)$$

where k_H is the force coefficient adjusted experimentally.

This force is exerted at the end of the arm like in the experiments presented in next subsection.

Based on the equations (2), (3) and (5) we have built a simulated model of a single joint manipulator in interaction in the Matlab package (Fig. 3 and Fig. 4).

According to the scheme of Fig.4 there is no compensator gravity, the modelized human force, following the equation

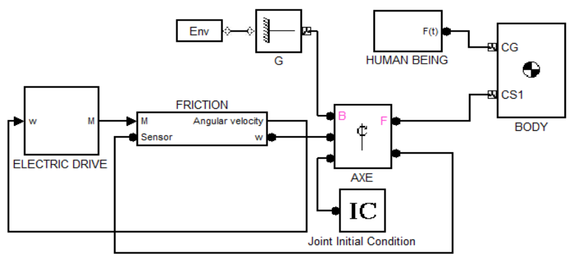

Fig. 3. One axis robot dynamic model implementation in MATLAB/SimMecanics.

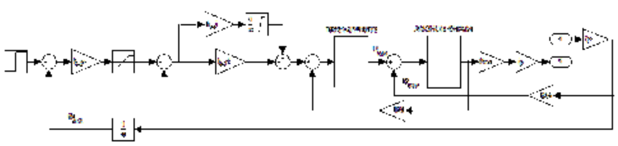

Fig.4. Electric drive model with independent joint control implementation in MATLAB/Simulink.

(5), is applied to the link of the simulated manipulator. Fig 5 and Fig. 6 show the effects on angle joint variation KΘ(t) and motor current I(t) by applying this external force. The independent joint control system compensates this force like as a disturbance. We can see that this compensation depends on the gains of outer loop k_p and inner loop k_i and k_d.

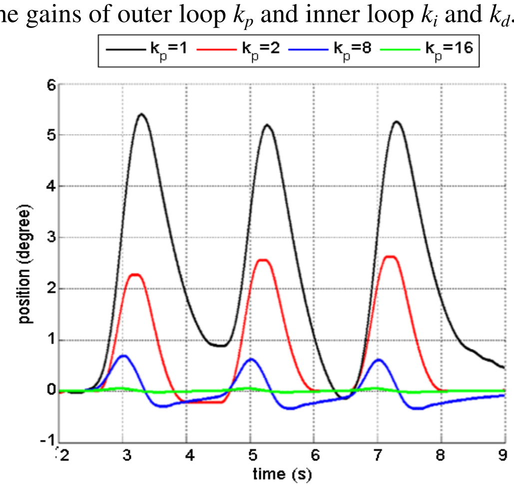

Fig. 5. Simulation of the influence of coefficient k_d of the speed -PI-controller on the characteristics of the joint movement (articular position).

D. *Experiment: interaction between passive robot arm and human arm*

The goal of these experiments is to estimate the response of the manipulator to a series of unknown external forces perturbations exerted by a human (in the vertical plane). Two types of series of forces are applied to the elbow axe, at the same point (see Fig. 7). Scenario A: the intensity of the force is gradually increasing. Scenario B: intensity of the force is suddenly increasing.

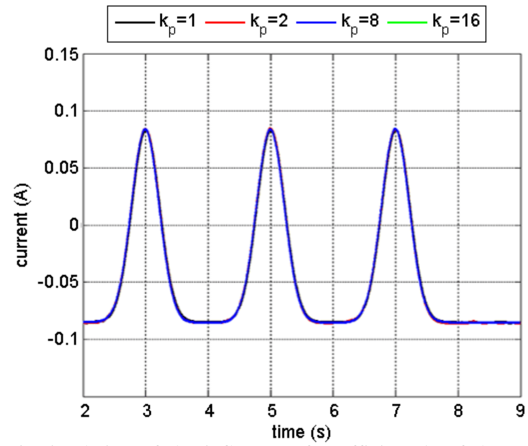

Fig. 6. Simulation of the influence of coefficient k_d of the speed -PI-controller on the characteristics of the joint movement (motor current).

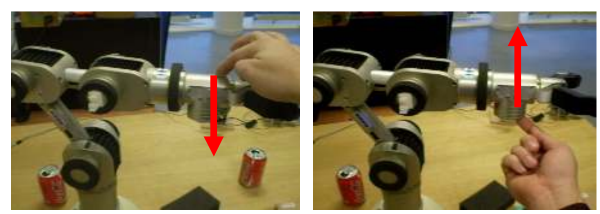

Fig. 7. Experiment of Robot Katana under influence of an external unknown force.

Examples of robot response to the perturbation of scenario "A" and "B" are depicted on Fig. 8 and Fig. 9. The action of the perturbation can be decomposed of two phases. During the first phases (phases a and c on Fig. 8) the human pushes the arm that moves away from its initial position. In the second phase (phases b and d), the human stops to push and the arm returns to its initial position. The average of speed and current are presented in Tables I and II.

By comparing the response to disturbance of the joint, we can see that the displacement is almost the same for both types of human disturbance. So we can see that in the non aggressive scenario A, the influence of the external force causes an articular displacement of around 3 degrees and the maximal current consumed by the PWM module is about 284 mA, the influence of this force causes the speed up to

0.0055 rag s-1. Scenario B is more aggressive: the influence of this force causes the speed up to 0.0107 rad·s^{-1} and the current consumed up to 236 mA, the joint displacement 2.5 degrees.

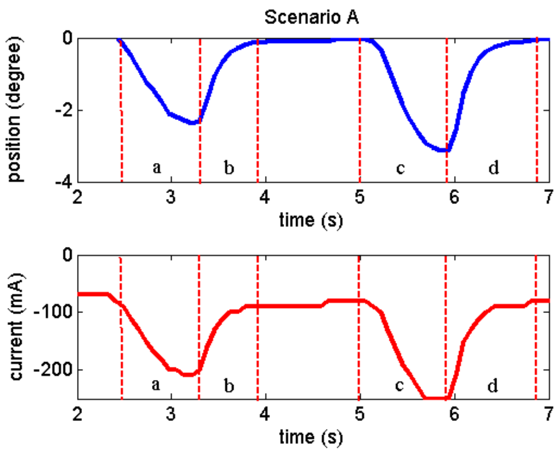

Fig. 8. Dependences of angle joint variation ΔΘ(t) and motor current I(t) in case of the non aggressive perturbation (scenario "A").

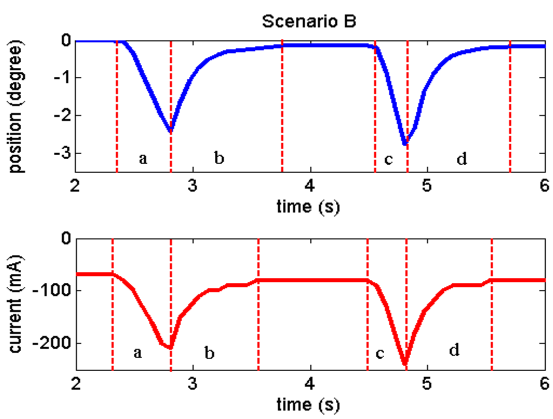

Fig. 9. Dependences of angle joint variation ΔΘ(t) and motor current I(t) in case of aggressive perturbation (scenario "B").

TABLE I. PERTURBATION OF THE TYPE "A"

Phase	Angular velocity mean value, rad · s^{-1}	Current mean value, mA
a	0.0047	161.3
b	0.0039	100.1
c	0.0062	199.8
d	0.0055	107.6

TABLE II. PERTURBATION OF THE TYPE "B"

Phase	Angular velocity mean value, rad · s-1	Current mean value, mA
a	0.0085	140.1
b	0.0037	100.3
c	0.0130	114
d	0.0065	118.7

The response of system to a perturbation by scenario "A" for different values of the proportional gain k_d of the speed loop is depicted on Fig. 10. The results are very similar to the simulations of section II C except for the current when k_p= 16 because the control loop is very strong.

We see that, for low values of the gain, the system undergoes external force with a large angular variation because the control strength is "soft". By increasing the gain, the system becomes more "rigid". However, for all cases, changes in current are almost identical to the order of 0.1 A. Compared to the simulation, the differences in the current profile are caused by approximate allowance for the friction forces and the perturbation force, an approximate calculation of the mass of the investigated joint.

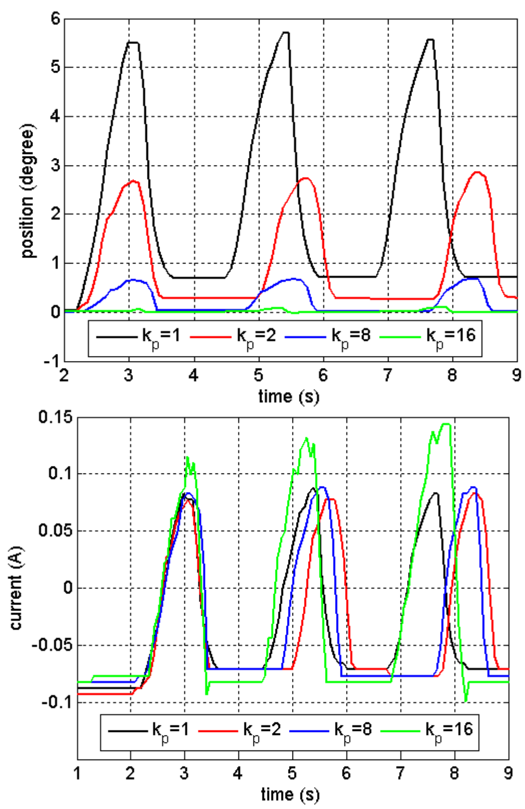

Fig. 10. Experimental dependences of the influence coefficient k_d of the PI-controller of speed on the character of the movement system.

III. EXPERIMENT OF ADAPTATION ALGORITHM ACCOMPANYING THE EXTERNAL FORCE

In the interaction between robot and human, one way is the “following robot”, i.e; the robot follows the force applied by human. The robotic arm accompanies the human arm in its movement depending on the intensity of the force and direction (two directions in our experiment: up or down). We propose to modify the feedback loop, i.e. to change the position set point when the interaction is detected and adapt this set point to the direction and intensity of force applied by human. (Fig. 11).

Fig. 11. Adaptation algorithm experimented on the robot manipulator Katana when interacting with a human.

A. Adjustment of the reference of position loop step-by-step

In this control algorithm, small step by step movements of the electromechanical system are processed using the value of the minimum displacement Θ_{min}. By using the measured current of the PWM module, we create a new desired input for the position loop. Thus the control law is:

$$\begin{cases} \Theta_{i+1} = \Theta_i + \Theta_{min} & if \quad I > I_{min} \\ \Theta_{i+1} = \Theta_i - \Theta_{min} & if \quad I < -I_{min} \\ \Theta_{i+1} = \Theta_i & if \quad I = 0 \end{cases} \qquad (6)$$

Where I_{min} the non-sensitive zone to reject the noise of measured current (adjusted experimentally). The results of physical interaction are depicted on Fig. 12.

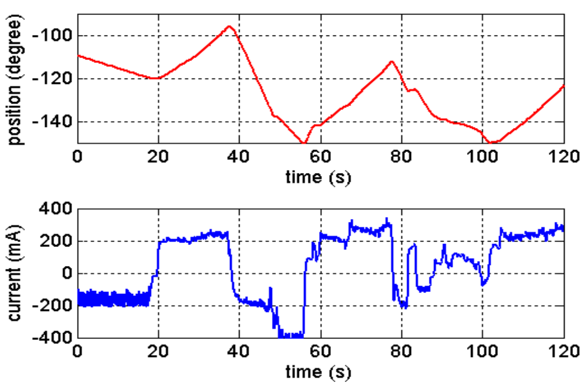

Fig. 12. Dependences of angle joint variation ΔΘ(t) and motor current I(t) when according step-by-step the set point position following the variation of the PWM current.

The manipulator link is led by the human. It is necessary to make the link repeating trajectory and peculiarities of motion of the man's hand that pushing the arm. (fig.11). The table III presents the values of the angle of displacement of joint under the action the force of human being: average of the absolute value of velocity, eq. (7) (i.e. displacement) and active value of current, eq. (8).

$$\Omega_{av} = \frac{1}{T}\int_0^T |\omega(t)|dt \quad (7)$$

$$I_{act} = \sqrt{\frac{1}{T}\int_0^T [i(t)]^2 dt} \qquad (8)$$

TABLE III. VALUES OBSERVED DURING THE EXPERIMENT IN FIG.12

Period of time, s	0.30-19.5	19.5-37.6	37.6-55.9
Rotation, deg	10	25	55
Average of the absolute value of velocity , rad·s-1	0.0021	0.0029	0.0069
Active value of current, mA	175	212	278
Period of time, s	55.9-77.6	77.6-102	102-120
Rotation, deg	38	38	25
Average of the absolute value of velocity , rad·s-1	0.0042	0.0044	0.0033
Active value of current, mA	230	106	233

Table IV shows data when the man applied physical force to the link in various directions. The time intervals were from 18 to 20 seconds on average. The smallest move, achieved with the manipulator link, was 10 degrees with the average angular speed 0.0021 rad.s^{-1}. The average value of the registered current was 175 mA during the given interval. The largest move achieved was 55 degrees with the average angular speed 0.0069 rad.s^{-1}, with an average current of 278 mA. To the question if he had been feeling comfort when interacting with the robot, the man said that it had not been exactly the case. First, the arm bounced; second, he had some difficulties to take up the needed positions.

B. Adjustment of the reference proportionally to the movement.

This approach provides to change of reference for position loop. The reference is computed proportionally to the human interacting forces. The coefficients of regulators do not change during the experiment. The previous algorithm can be modified to make the adjustment of the task for position loop proportional to the difference of current displacement $\Delta_\Theta = \Theta_i - \Theta_{i-1}$ caused by the external force. This control law (eq. (9)) is simpler than the first one (eq. (6)):

$$\Theta_{i+1} = \Theta_i + \Delta_\Theta \cdot K \qquad (9)$$

The results of physical interaction are depicted on Fig. 13. The comparaison of the performances of the two proposed algorithms shows that the the first algorithm allows an average of 31 degrees in the motion displacement for an average current of 205 mA (1 degree consumes approximately 4.46 mA).

The second algorithm allows a similar motion displacement (average of 33 degrees) but for a current average of 68 mA (1 degree consumes 2 mA approximately).

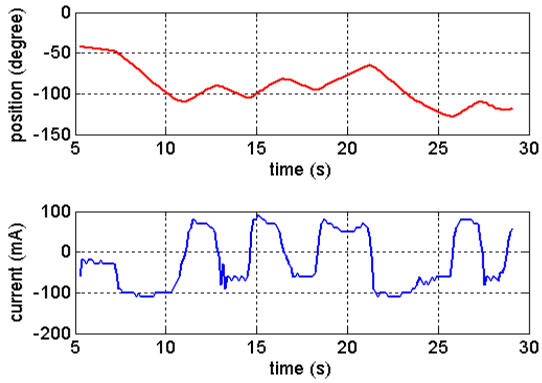

Fig. 13. Dependences of angle joint variation ΔΘ(t) and motor current I(t) during operation according to the algorithm for adjustment of the reference proportionally to the movement.

TABLE IV. VALUES OBSERVED DURING THE EXPERIMENT OF FIG.13

Period of time, s	7.15-10.9	10.9-12.8	12.8-14.6
Rotation, deg	61.6	19.5	15
Average of the absolute value of velocity , rad·s-1	0.0348	0.0232	0.0190
Active value of current, mA	95.1	60.3	61
Period of time, s	16.5-18.2	18.2-21.3	21.3-25.8
Rotation, deg	13	31	63
Average of the absolute value of velocity , rad·s-1	0.0163	0.0219	0.0305
Active value of current, mA	50.8	59.1	86

IV. CONCLUSION

The objective of this preliminary work was to study the possibility of on-line adapting the position reference of a robot arm that undergoes human interactions. In this paper, we experimented two control algorithms on one joint of a manipulator Katana.

We have shown that it is possible to control a degree of freedom based on the simple adaptive algorithms. Two control algorithms were compared. The control approach based on the interaction forces measured through the joint articular displacements is better in terms of power consumption. This work may be extended to the complete control of the manipulator. Future work will involve adapting a dynamic movement of the arm to a dynamic interaction of man. We will implement a control law in order that the robot adapts its movement to a rhythmic movement imposed by human. This adaptation algorithm will be based on rhythmic controllers models inspired by biology.

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