Implementation of a DRC (Delayed Reference Control) for contact force control in robotic application.

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Abstract:- This paper presents a non-time based control scheme for a robotic mechanism interacting with the environment and/or a human operator. This new control is based on the modification of the desired input reference x_d. Contrary to a time-based control, where the function, $x_d(t)$, is commonly calculated off-line during a path-planning process, in the proposed controller, the desired input reference is a function of time and a variable which plays the role of a time delay: $x_d(t-T)$. For this reason this controller has been called *delayed reference control* (DRC). The time delay is properly calculated on-line according to the measured force signals in such a way to improve the interaction with the environment and/or the human operator. In fact, the DRC consists in a outer force feedback loop around an inner position feedback loop. Numerical simulations will prove the effectiveness of the controller by means of a simple 1 DOF mechanism.

Keywords:- delayed reference control, force control, non-time based control.

1 Introduction

In industrial applications, a number of robotic tasks require the robot to interact with the environment: components assembling, machining mechanical parts, scraping or polishing surfaces by applying a constant force, metal sheet bending [1]. Moreover in an ever increasing number of applications, robots interact with a human operator: haptic interfaces, surgical robots remotely operated by a doctor, robots used for orthopedic rehabilitation or neuro-rehabilitation [2]. In most of these applications, the robot is required to accomplish a task which consists in moving the end-effector along a given path and, at the same time, preventing the contact force, between the robot's end-effector and the environment, from exceeding a given value.

To fulfill the mentioned tasks, the robot end effector has to behave in different ways: in contact with a surface, it is required to assume a kind of compliant behavior to accommodate the interaction, while, during free motion mode, it has to follow a given path as accurately as possible. Therefore, unlike traditional PID, interaction based controllers are designed for working in two completely different modes: the contact and the free mode. In the first, force controlling is essential, in the second, path tracking is of main importance. In the last thirty years, several approaches have been proposed for reaching those goals. For example, in the case of time based controller are the *Stiffness control* [3], the *Impedance control* [4], the *Force control* [5], the *Hybrid position/force control* [6], the *Parallel force/position control* [7] and so on.

Although tracking controls are generally aimed at ensuring that the output of a system follows a desired path defined as a function of time (*trajectory following*), there are different applications where the desired path is defined through space only (*path tracking*) this difference allows to classify the controllers in two categories: time based, and non-time based controllers.

In a time-based control, the desired input reference is described as a function of time, the desired reference signal $x_d(t)$ which is commonly calculated off-line during the path-planning process, before the robotic task is executed. As a consequence, during the task execution, at each instant t^*, the control module is required to track an input reference $x_d(t^*)$, which can never be modified by any event or circumstance. Time-based controls, largely employed in industrial applications, are therefore preferable in trajectory following problems where time plays as action's reference. Non-time based approaches should be chosen for path tracking problems, where the desired state is not a function of time as in [8]. The basic idea behind these event-based methods is considering the reference input a function of a variable instead of a function of time: $x_d(l)$. Such a variable l is sensitive to the sensory measurement and the task. In the event-based approach the role of the path planner is changed. Instead of preplanning the input reference as a function of time, a new block is introduced in the controller to compute on-line the value variable l. This variable is computed on the base of the sensory measurement and is the base to generate the desired reference value. This paper presents a non-time based control scheme for a robotic mechanism interacting with the environment. In this new controller the desired input reference is a function of time and a variable which plays the role of a time delay: $x_d(t\text{-}T)$. The time delay is calculated on-line according to the measured force signals in order to improve the interaction with the environment. De facto, the DRC consists in a outer force feedback loop around an inner position feedback loop. The effectiveness of the controller has been proven numerically using a simple SDOF mechanism, while the experimental results will be presented in a accompaining paper.

The paper is set out as follows. The DRC theory as well as stability analysis are presented in Section 2 and 3. In Sections 4 the SDOF mechanism and the simulation results will be presented while in section 5 will be devoted to the conclusions and the final consideration.

2 The DRC theory

A simple environment-robot interaction task is considered. Although the dynamic model is very simple (SDOF system), it is sufficient to give the physical insights into the DRC method applied to force control and to perform the stability analysis. The extension of the DRC to a MDOF system doesn't represent a major difficulty. The model would represent the following case: a robot end-effector, simulated by a mass m and a internal damping c, driven by a command u, collides with an obstacle of stiffness k_e generating a contact force F_e. The dynamic equation of the system is:

$$m\ddot{x} + c\dot{x} = u - F_e \qquad (1)$$

Equation (1) represents the equation of motion of a mass moving along the x-axis, but it could represent also the equation of a rotating system and the DRC approach would not change

It has been decided to model the interaction with a spring like behavior since is rather common to simulate both passive and reactive contacts as in [9] and [10].

When there is no contact, the displacement x could be regulated by means of a traditional time-based controlled. Assuming to adopt a PD controller and the presence of a sensor measuring the mass displacement, the control law computes the force u as:

$$u = k_P e + k_D \dot{e} = k_P (x_d - x) + k_D (\dot{x}_d - \dot{x}) \qquad (2)$$

where k_p, k_d, e and x_d are the proportional, the derivative gain, the error and the desired displacement. It is assumed that such a regulation system is stable when the contact does not occur. Yet, in case of contact, high contact force could be generated. To avoid this problem, the PD control will be modified adding a DRC controller.

Usually the desired trajectory of a joint is planned off-line. The desired displacement is given as a function of a scalar l, $x_d=g(l)$. The task will be completely executed when the variable l reaches a final value l_f. If time-scaling is not applied, the desired displacement is given directly as a function of time $x_d=g(t)$. It is also assumed that $g(0)=0$, $dg/dl_{l=0}>0$, meaning that the contact is planned to occur at time $t=0$ and that the contact time will be longer than zero.

The DRC introduces a delay T on the time that defines the desired displacement. Therefore, instead of $l=t$, the new relationship between time and scalar l is $l=t\text{-}T$, and the desired displacement becomes $x_d=g(t\text{-}T)$. The delay T, could be computed on the base of sensor measuring the contact force F_e as:

$$T = \int_0^t c\left(F_e\right) d\bar{t} \qquad (3)$$

where the function $c(F_e)$ has the following properties: is zero when the contact force is zero and increases with the contact force.

The first property assures that, if the contact does not occur, the delay introduced by the DRC controller is null: thus the performances of the systems are not modified with respect to control law (2). The second property assures that, in case of contact, the robot end-effector will slow down or stop before too high level of force F_e builds up. A simple linear function satisfies the two requested properties:

$$c\left(F_e\right) = a\, F_e \qquad (4)$$

where α is a constant. In this case the desired displacement becomes:

$$x_d(t-T) = g(t - a\int_0^t F_e\, d\bar{t}) \qquad (5)$$

The whole control scheme of the system is shown in fig.1. By replacing Equations (2), (3) and (5) into Equation (1), the closed-loop non linear dynamic equation of the system is obtained:

$$m\,\ddot{x} + c\,\dot{x} = k_P\left(g(t - a\, k_e\int_0^t x\, d\bar{t}) - x\right) + \\ + k_D\left(\frac{d}{dt}\left(g(t - a\, k_e\int_0^t x\, d\bar{t})\right) - \dot{x}\right) - k_e\, x \qquad (6)$$

It can be proved that the value $x_{eq}=1/ak_e$ represents the equilibrium point for the system, and in this case the contact force becomes:

$$F_{eq} = k_e\, x_{eq} = 1/a \qquad (7)$$

where the higher the parameter α is, the lower the contact force at the equilibrium is. Note that a is the only parameter that affects the contact force at the equilibrium, that the DRC controller does not affect the dynamic performances of the system during the non contact phase, that it limits the contact force during contact phase only and that its effectiveness is not affected by the position regulator.

Another important consideration is that, at the equilibrium point, the derivative of the desired displacement (eq.5) is zero. It means that once the contact occurs and the equilibrium is reached, the desired displacement x_d remains constant. This condition will remain until contact occurs. Assume that the surface is removed at time t_{ev} from that instant on, the delay T will remain constant assuming the value:

$$T_{ev} = a k_e \int_0^{t_{ev}} x\, d\bar{t} \qquad (8)$$

The desired displacement will be $x_d=g(t-T_{ev})$ and if no other contact occurs, the task will be completed at the instant $t=l_f+T_{ev}$. As result the DRC controller makes the system take more time to execute the task which is in fact suspended for a time T_{ev} starting from the contact instant and finishing when the contact force is removed.

This behavior is required in all those applications where time is not a critical variable compared to the necessity of having a bounded and constant interacting contact force.

3 Stability analysis of the DRC

To complete the analysis of the DRC, a dynamic stability verification will follow. Let us consider the system at the equilibrium point x_{eq} assuming:

$$\ddot{x} = 0, \qquad \dot{x} = 0, \\ x = x_{eq} = 1/\left(a\, k_e\right), \qquad F_e = 1/a \qquad (9)$$

In this case the desired displacement at the equilibrium point, $x_{d\text{-}eq}$ assumes the value:

$$x_{d\_eq} = \frac{1}{a}\left(\frac{k_p + k_e}{k_p\, k_e}\right) \qquad (10)$$

The value of the scalar l that defines the desired displacement at the equilibrium is

$$l_{eq} = g^{-1}\left(x_{d\_eq}\right) \qquad (11)$$

For simplicity, the desired displacement can be approximated around the point $l=l_{eq}$ trough a Taylor expansion as:

$$g(l) \cong g(l_{eq}) + \left(dg/dl|_{l=l_{eq}}\right)(l - l_{eq}) =$$
$$x_{d\_eq} + b\ (l - l_{eq})$$
(12)

Replacing Equation (12) into (6), and deriving it, a linear third-order ordinary differential equation is obtained:

$$m\dddot{x} + (c + k_D)\ddot{x} + (k_P + k_D b\ a\ k_e + k_e)\dot{x} +$$
$$k_P b\ a\ k_e x = k_P b$$
(13)

By analyzing the coefficient of the eq.13 according to the Routh-Hurwitz method the stability of the system can be studied. All the coefficients of the equation are positive and as shown in Appendix A, if $k_d\ (c+k_d)-k_p m<0$, the system is stable if and only if

$$a < a_{MAX} = \frac{(c + k_D)(k_e + k_P)}{k_e b\,[k_P m - (c + k_D)]}$$
(13)

This represents a drawback because it defines a lower bound for the contact force. In the specific case $F_{eq}>1/a_{max}$. If one tries to lower the force by increasing the value of α, above a_{max} the system would become unstable.

4 Numerical results

Let us consider the system as depicted in fig.2 with m=19Kg, c=20Ns/m k_e=10 N/m and α=1. Assuming k_p=4000N/m and k_d=370Ns/m, the value of α_{max} that assures system stability is equal to 40.57. Suppose that the end-effector moves along a straight line and that between time $t=3s$ and $t=6s$ there is the contact as in fig.3. Note that the task is delayed for the contact time and the parameter T remains constant once the contact ends at $t=6s$ as in fig.4. Fig.5 shows the trend of the contact force, (as from eq.7 around the value Fe=1/α=1), while fig.6 shows the requested control force.

Fig.7 to 10 show the same quantities when the parameter α is equal to 100 and than the system becomes unstable (higher than α_{max}). It is worth noticing that, as expected, the contact force has a lower amplitude (fig.9), while the control forces reaches much higher levels (fig.10).

5 Conclusion

This paper presented a non-time based control scheme (called delayed reference control (DRC)) for a robotic mechanism interacting with the environment and/or a human operator. The control can represent an alternative to control tasks involving force control problems. In fact, the DRC consists in a outer force feedback loop around an inner position feedback loop. The DRC controller affects the dynamic of the system only during the contact phase.

The controller can be employed in all that robotic tasks which require the interaction between the robotic system and the environment, such as machining, polishing, human-robot interacting.

The effectiveness of the controller has been proved by means of a simple 1 DoF mechanism which has been employed to mimic the interaction between a robotic system and a human operator.

Appendix A

According to Routh-Hurwitz theory, the Equation (12) is stable if and only if the following inequalities are satisfied

$$B_1 = m > 0, B_2 = c + k_D > 0,$$
$$B_3 = k_P + k_D b a k_e + k_e > 0,$$
$$B_4 = k_P b a k_e > 0$$
$$U_1 = (B_2 B_3 - B_1 B_4)/B_2 =$$
$$\frac{(c + k_D)(k_P + k_D b a k_e + k_e) - m k_P b a\, k_e}{(c + k_D)} > 0$$
$$U_2 = (U_1 B_4 - B_2 U_3)/U_1 = k_P b a k_e > 0$$

Note that B_1, B_2, B_3, B_4 and U_2 are greater than zero.

In case the proportional gain of the PD controller k_P and/or the mass of the joint m are too high, which is a common situation in a controlled system, it could occur

$$k_D(c + k_D) - k_P m < 0$$

As a consequence, in order to satisfy the inequality $U_1 > 0$, the parameter a has to be less than the value

$$a_{MAX} = \frac{(c + k_D)(k_e + k_P)}{k_e b\,[k_P m - k_D(c + k_D)]}$$

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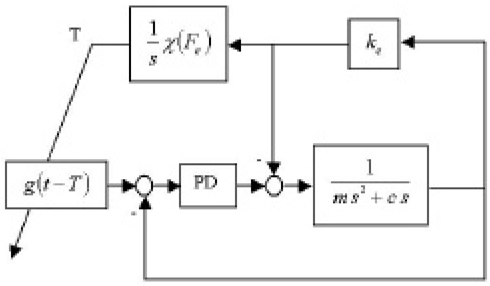

Fig.1: DRControl schema

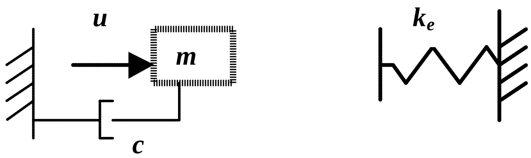

Fig.2: Test system

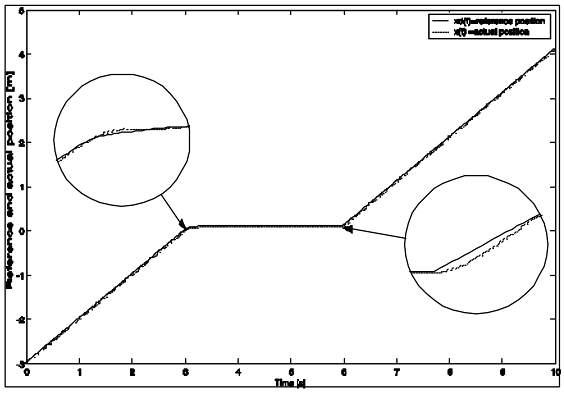

Fig.3: Desired and actual position of end-effector - stable system

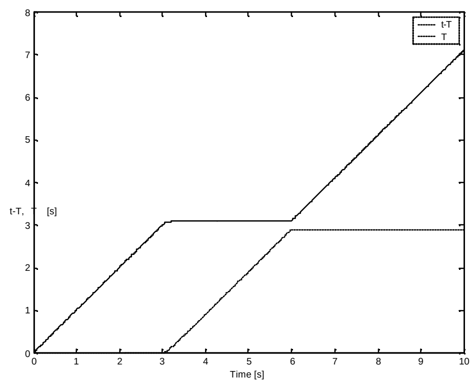

Fig.4: Plots of *t*-*T* and *T*- stable system

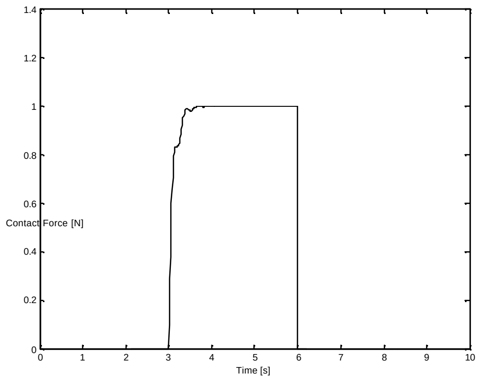

Fig.5: Contact Force - stable system

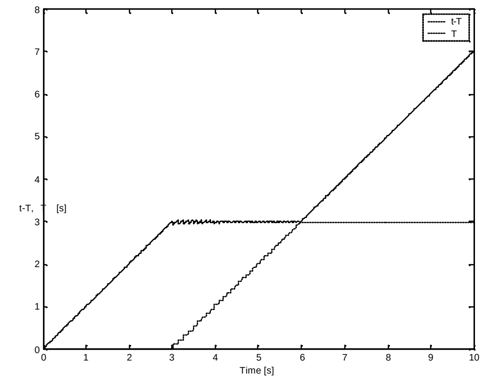

Fig.8: Plots of *t*-*T* and *T* - unstable system

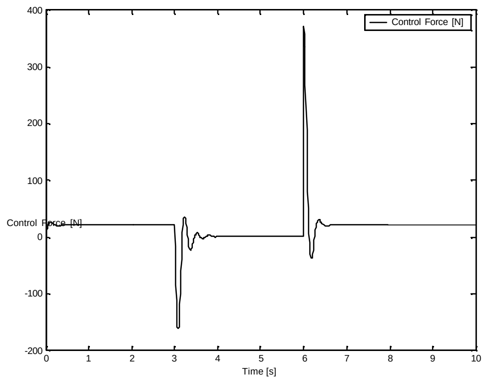

Fig.6: Control force – stable system

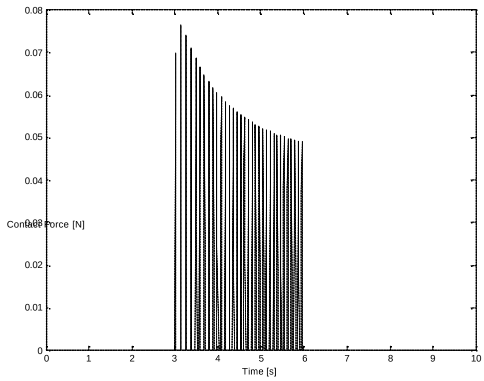

Fig.9: Contact Force - unstable system

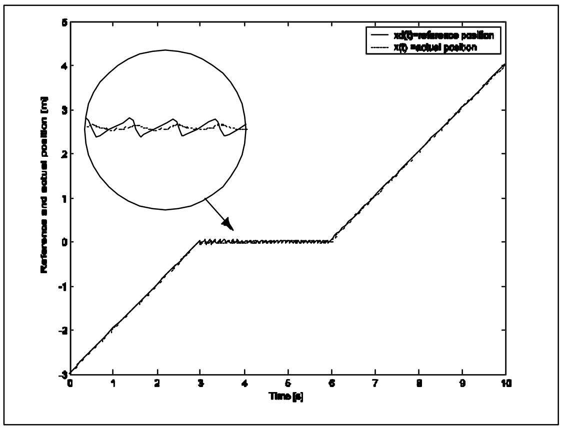

Fig.7: Desired and actual position of end-effector - unstable system

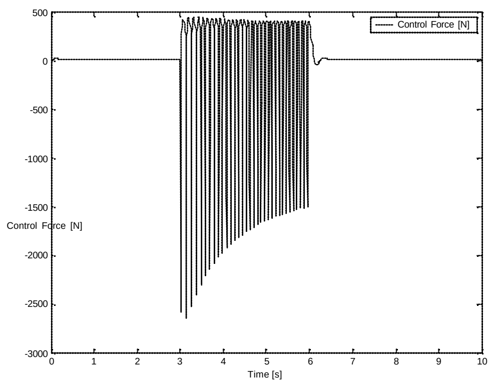

Fig.10: Control force – unstable system