Robust Force Control Strategy based on Virtual Environment

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Abstract

The main goal of this paper is to present a force control strategy based on the Virtual Environment concept. This concept is a way to increase the robustness of force control schemes with respect to a variation of the environment characteristics. We first propose this approach, then we analyze it, and finally we adapt it to a classical external force control scheme. Experimental results with a DELTA fast parallel robot are presented to prove the efficiency of this method.

Keywords: Force Control, Robust Control, Experimentation

1 INTRODUCTION

When servoing robots with force control schemes, we usually face partly unknown systems: in fact, the manipulator is in contact with an environment whose characteristics are not well defined and may change. Since the environment exerts a direct influence over the controlled system, every modification of this environment modifies the whole system behavior.

Many researchers have been working on this problem and many practical tests have been performed that prove the efficiency of simple control laws based on an integral controller : they lead to a zero steady-state error in force. However, such an approach, as well as many others studied in [1], [2], [3], [4], present a very bad robustness with respect to a variation of the environment characteristics. It is obviously always feasible to tune a gain for a particular experimental setup; unfortunately a robot is dedicated to work in various situations: a robust force control law is then definitely necessary. Many robust solutions have been proposed by research workers such [5], [6], [7], [8], which need either the knowledge of the dynamic model of the system (robot and environment) or an identification of this one. The original solution that we propose and present in this paper considers only the knowledge of the upper boundaries of the environment stiffness and the static gain of the dynamic model of the robot.

First of all, we analyze the behavior of a linear monodimensional robot in contact with an environment, controlled by a force integral controller. In this simple case we emphasize the reasons that lead to the bad robustness. We then introduce the Virtual Environment concept, and analyze it on a basic control scheme. This scheme is then adapted to be used for robots by using an external force control scheme [9]. Experimentations with a DELTA robot are finally presented and the results are compared to those of the classical external position/force control law, proving the efficiency of this method.

2 VIRTUAL ENVIRONMENT CONTROL LOOP

The dynamic response of the force control loop for a manipulator depends on the controller, the actuator dynamics and the environment stiffness. However, an intensive industrial use could not change the controller gains at each step of the task which is performed if one of these parameters were modified. The parameter which can likely change during an experimentation period is the stiffness of the environment. Thus, we focus this study on reducing the influence of the stiffness by using a new method called *Virtual Environment*.

2.1 Principle

Let us consider the basic compliant contact case along the X axis by using a monodimensional linear robot (cf. figure (1)). M is the equivalent (robot + environment) mass of the compliant contact, D the equivalent damping parameter, K_e the equivalent stiffness parameter, X_0 the initial environment position, X the current robot position, F_c the force exerted by the robot and F the force reacting from the environment.

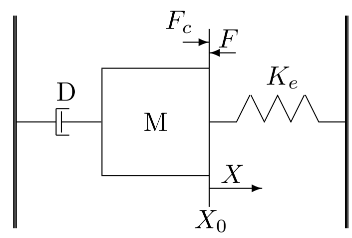


Figure 1: Monodimensional study case

In this linear case, we can express the differential equation of the system as:

$$M\ddot{X} + D\dot{X} = F_c - F \tag{1}$$

where F can be written:

$$F = K_e \Delta X \tag{2}$$

with $\Delta X = (X - X_0)$. Let us assume that $X_0 = 0$. Then, the transfer function of equation (1) can be pictured as follows (s is the Laplace parameter):

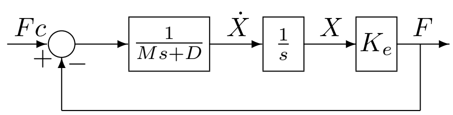


Figure 2: Monodimensional transfer function case

Equation (1) and figure (2) obviously show that any variation of the environment stiffness K_e will change the system behavior, the other parameters being constant. Therefore, we propose a solution to reduce the influence of the stiffness in order to obtain an invariant time response whatever the environment parameters, by adding a virtual stiffness K_v (cf. figure (3)). We choose to insert in the environment a virtual spring with a stiffness K_v higher than the real environment stiffness K_e.

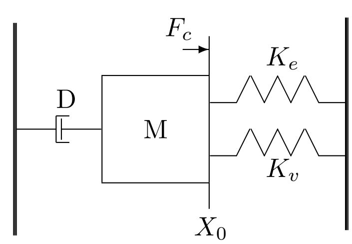


Figure 3: Basic monodimensional virtual environment

This solution can be expressed as:

$$M\ddot{X} + D\dot{X} = F_c - F^* \tag{3}$$

The resultant force F^* is due to the acting of the stiffnesses defined by the following equation:

$$F^* = F + F_v = F + K_v \Delta X \tag{4}$$

The virtual force F_v stems from the robot manipulator displacement and from the environment position ($\Delta X = X - X_0$) multiplied by the stiffness coefficient K_v. If K_v is much larger than K_e, we obtain the expected goal. Indeed, the effect of the variation of the environment stiffness K_e is reduced with respect to the total stiffness $K^* = K_v + K_e$. However, to verify equation (3), the virtual force vector F_v has to be substracted from the force control vector F_c. This operation must be carried out between the physical world (cf. figure (4) part 1) and the virtual world (cf. figure (4) part 2) built by the computer. Section (2.2) will explain how to do that.

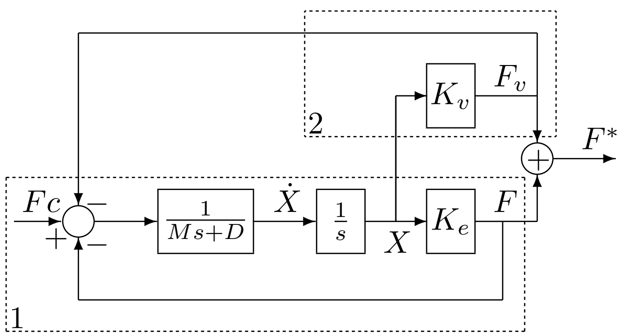


Figure 4: Monodimensional transfer function case with virtual environment

The force vector F^* becomes the new quantity to consider. However, the initial force vector F remains always the main variable to control. Also, we have to estimate the desired force value F_d^* in order to obtain the force value F equal to the initial desired value F_d. The simple solution we propose is to use the following relation:

$$\frac{F^*}{F_d^*} = \frac{F}{F_d} \tag{5}$$

In this case if the control loop on F uses an integral gain (which is the most common case), the limit of equation (5) can be written as:

$$\lim_{t \to \infty} \frac{F^*}{F_d^*} = 1 \tag{6}$$

Equation (5) can be rewritten as follows:

$$F_d^* = F_d \frac{F^*}{F} \tag{7}$$

which, using equation (4) and figure (4) leads to:

$$F_d^* = \left\{ \begin{array}{l} F_d \left(1 + \frac{K_v(X - X_0)}{F}\right), if\, F \neq 0,\, X > X_0(contact) \\ F_d, if\, F = 0,\, X \leq X_0(no\, contact) \end{array} \right\} \tag{8}$$

We can now verify the validity of our assumption described by equation (5). To do this, let us rewrite and sample equation (8) by using the relations (2) and (4). After some mathematical manipulations, we obtain the following equation:

$$\Delta X_{d_{n+1}} = A + \frac{B}{\Delta X_{d_n}} \tag{9}$$

with $\Delta X_{dn} = X_{dn} - X_0$ (at sampling time n), $X_{dn} = \frac{F_{dn}}{K_e}$, $A = \frac{K_v X_0}{K_v + K_e} + \frac{F_d}{K_e}$ and $B = -\frac{K_v}{K_e(K_e+K_v)} F_d$. From this equation, when n tends to infinity one gets two solutions:

$$\Delta X_1 = \frac{F_d}{K_e}, \qquad \Delta X_2 = \frac{K_v X_0}{K_e + K_v} \tag{10}$$

Solution ΔX_2 does not belong to the set defined by the first term of equation (8) whose boundary is defined by $X > X_0$. Therefore, it remains ΔX_1 which enables to reach the expected solution F_d: $F = K_e \Delta X_1 = F_d$.

2.2 Implementation architecture

The method introduced in section (2.1) and illustrated by figure (4) needs some adjustments to be implemented on a real system. The controller deals with the computation of the virtual force whereas this force has to be substracted from the physical world variable F_c. Therefore, we propose to evaluate the behavior of the scheme of figure (5) which should be equivalent to that of figure (3) in order to maintain the robustness properties expressed equation (4). Figure (5) shows that the external force/control loop architecture has been chosen [9]. The additional virtual force architecture has to be analyzed in order to verify equation (3). To implement the virtual loop on the monodimensional external control law, we insert a gain K_α within the feedback of the virtual force loop (cf. figure (5)).

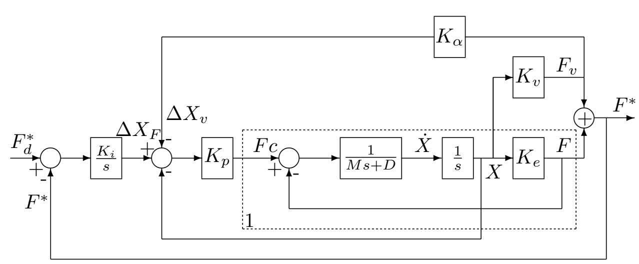


Figure 5: Monodimensional control loop

Figure (5) shows that it exists $K_\alpha = f(K_v, K_p)$ such that equation (3) is verified and the virtual environment approach is validated.

However, for a multi-dimensional real robot K_p and K_v are no longer the only gains between the Cartesian space and the contact force space. Additional non-linear gains stemming for instance from the Inverse Kinematics Model, the amplifiers, or the actuators should be taken into account but are generally unknown or cannot be modeled. Therefore we will analyze the behavior of the control scheme represented in figure 5 for K_α unknown. The conclusions of this analysis would be similar for a multi-dimensional real robot.

From figure (5), we can derive the following equation:

$$\frac{F^*(s)}{F_d^*(s)} = \frac{1}{As^3 + Bs^2 + Cs + 1} \tag{11}$$

with:

$$\left| \begin{array}{l} A = \frac{M}{(K_e+K_v)K_i} \\ B = \frac{D}{(K_e+K_v)K_i} \\ C = \frac{K_e+K_p(1+K_\alpha K_v)}{(K_e+K_v)K_i} \end{array} \right| \tag{12}$$

The main goal of the virtual force control loop is to reduce the influence of the variation of K_e on the time response. To evaluate this influence on the monodimensional external control loop, we now study the sensitivity of C, because it is the only term in equation (12) that contains K_α:

$$C = \frac{K_e + K_p(1 + K_\alpha K_v)}{(K_e + K_v)K_i} \tag{13}$$

The error can expressed as:

$$\Delta C = \frac{K_v(1 - K_p K_\alpha) - K_p}{(K_e + K_v)^2 K_i} \Delta K_e \tag{14}$$

The relative error of term C can be written as:

$$\left|\frac{\Delta C}{C}\right| = \left|\frac{K_v(1 - K_p K_\alpha) - K_p}{Ke + K_p(1 + K_\alpha K_v)} \frac{\Delta K_e}{K_e + K_v}\right| = \left|H \frac{\Delta K_e}{K_e + K_v}\right| \tag{15}$$

From equation (15), we obtain the following result:

$$l = \lim_{K_\alpha \to \infty} |H| = 1 \tag{16}$$

which shows that if K_α is large enough, it has no more influence on the time response of the system. Only K_e influences the behavior of the system. This influence can be reduced by choosing K_v much larger than K_e, as stated in section 2.1.

Figure (6) represents the variation of $|H|$ as a function of K_α with $|H| = 0$ for $K_\alpha = K_0 = \frac{K_v - K_p}{K_v K_p}$:

Figure (6) shows the limit l when the gain K_α is superior to K_0. This case gives an information about the implementation of the virtual force control loop: the value of K_α has to be much greater than K_0 in order to limit the relative error $|\frac{\Delta C}{C}|$.

$$K_\alpha >> K_0 \tag{17}$$

This result is important to define a useful robust algorithm of the external force control for a robot manipulator without any information about the dynamic model of the robot and the environment.

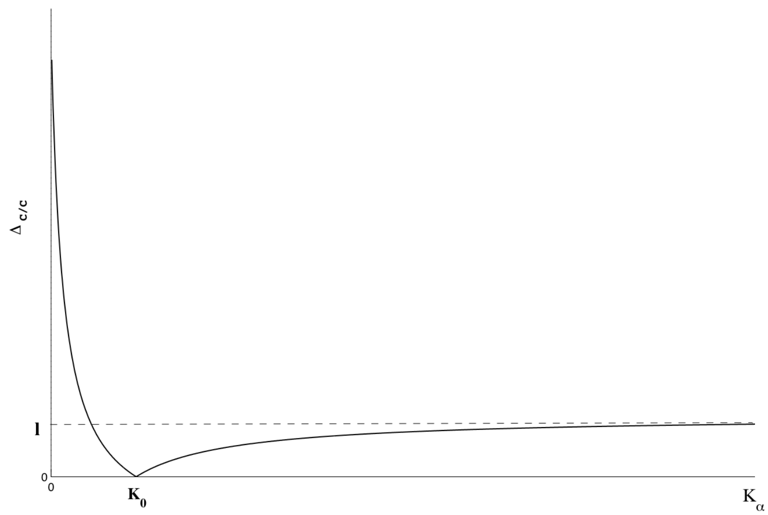


Figure 6: Variation of $|H|$ versus K_α

3 IMPLEMENTATION ISSUE

3.1 External position/force control scheme

Figure (7) presents the external position/force control scheme of a multi-joint manipulator as described in [9], [10]. The selection matrix **S** which selects position or force control for such or such component is diagonal and composed of 0's and 1's. FCL is the *Force Control Law*, PCL is the *Position Control Law*. The force control law we are using is an integral law.

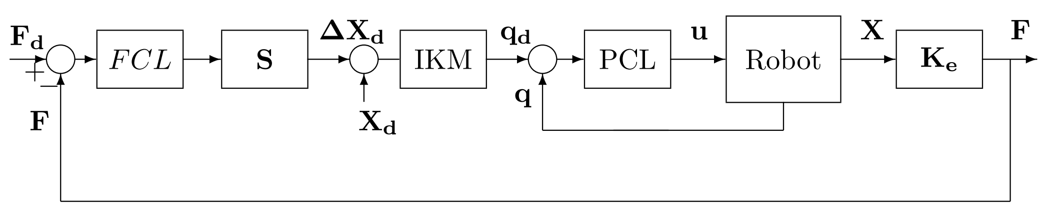


Figure 7: External force control scheme

3.2 External position/force control scheme with the virtual force loop

The external position/force control law with the virtual force loop is defined as in figure (8). The coefficients of the diagonal matrix $\mathbf{K_v}$ are defined greater than the estimated upper bounds of the coefficients of the diagonal matrix $\mathbf{K_e}$ along the directions where the manipulator exerts the efforts.

The components of the diagonal matrix $\mathbf{K}_\alpha$ are computed by using the result obtained in equation (17). A bounded estimation of the static gain of the manipulator for a given position in contact with

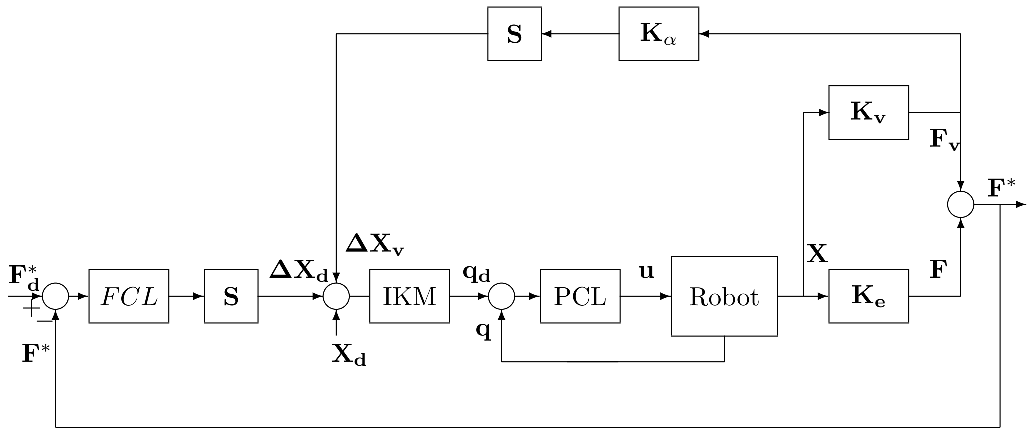
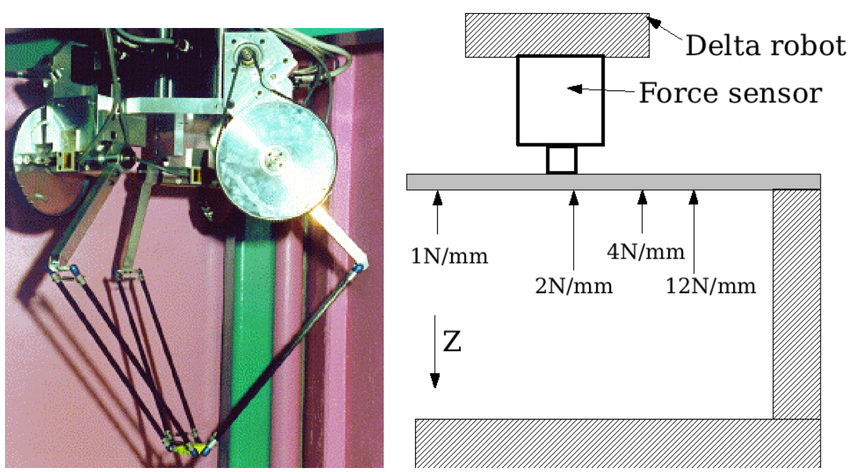


Figure 8: External virtual force control scheme

the environment allows us to determine the components of $\mathbf{K}_\alpha$, each of them verifying an equation of type (17).

4 EXPERIMENTAL RESULTS

The experimental setup is a fast DELTA parallel robot manipulator (cf. figure (9.a)). A six-axis force sensor is mounted on the end-effector plate.



(a) (b)

Figure 9: The Delta robot and experimental environment

The force sensor is in contact along the $\mathbf{z}$ axis with an aluminum plate which is fixed at one end (cf. figure 9.b). We have identified 4 different stiffnesses along this plate in order to validate the virtual loop (cf. figure (10). The set of identified stiffnesses is the following: $K_{e_z} = [1, 2, 4, 12]\, N/mm$. All trials are performed with the force sensor already in contact with the plate ($F_z = 2N$) in order to avoid the shock disturbance upon contacting.

The desired force component $F_{d_z} = 50N$ is applied as a step. The PCL is a PID controller. The FCL uses an integral term tuned to obtain the best response time with the maximally flat response for the stiffness component $K_{e_z} = 4N/mm$. The sampling rate of the controller is $T_e = 0,5ms$. The coefficients of the PCL and FCL are maintained constant during the trials.

The four types of lines in figure (10) (solid, dotted, etc.) correspond to the four different stiffnesses. We use the same rules in figures (11), (12),(13),(14).

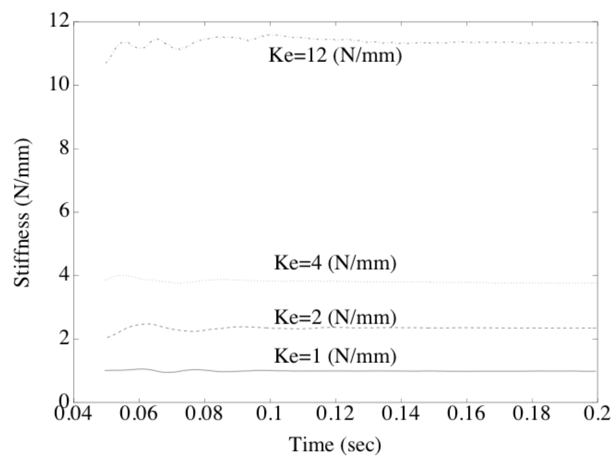


Figure 10: Indentification of the stiffnesses

The result of the first experimentations with the classical external force control law are presented in figure (11). We observe a different time response for each stiffness.

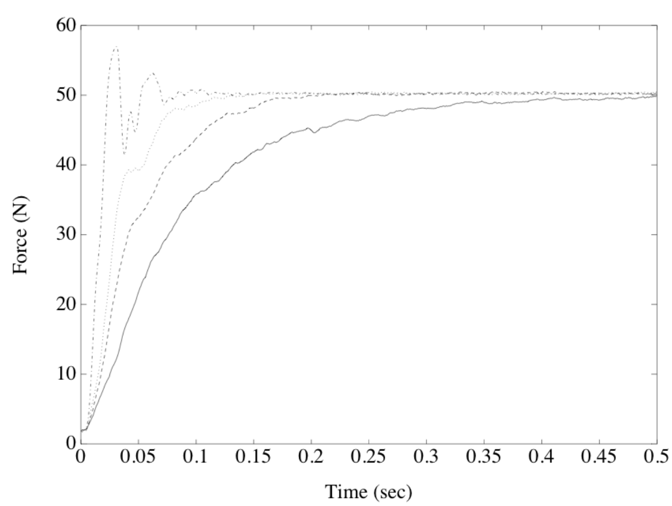


Figure 11: Classical external position/force control loop with different stiffness values.

We have implemented the virtual control loop on the DELTA robot controller according to the scheme of figure (5). The matrix component $K_{v_z} = 30N/mm$. We have chosen the matrix $\mathbf{K}_\alpha = \mathbf{I}$, in order to respect the constraint equation (17). The experimentation results with the virtual control loop added on the external force control law are presented in figure (12).

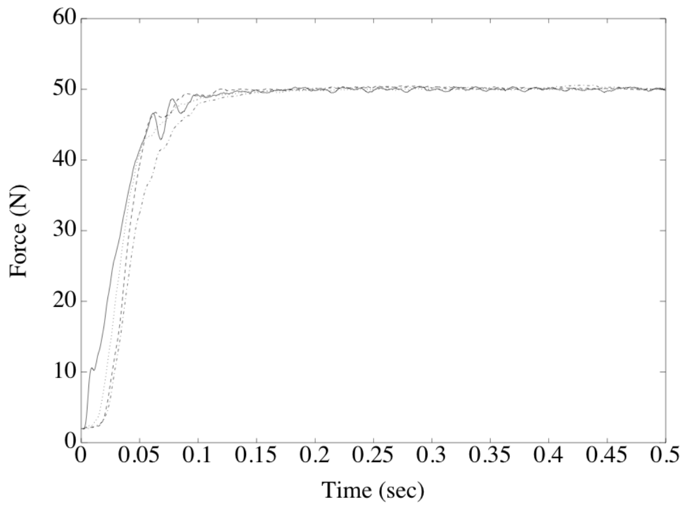


Figure 12: External position/force control loop with virtual loop and different stiffness values

We observe on these curves some identical time responses versus the variation of the environment stiffness. The relative error of the stiffness variation with the classical external control law is: $\frac{\Delta K_e}{K_e} = 11$. It is getting: $\frac{\Delta K_e}{K_e + K_v} = 0,35$ with the virtual control loop. The virtual desired force component $F^*_{d_z}$ (figure (13)) is computed in real time according to equation (8). These different curves show the adaptation of the final value of F^* versus the environment stiffness.

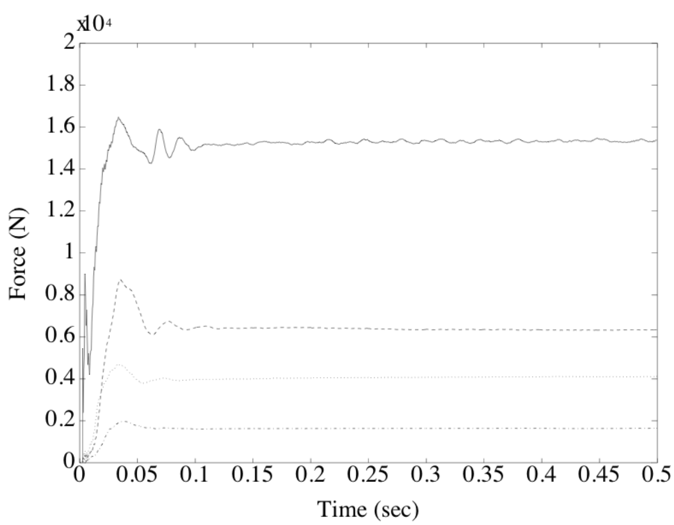
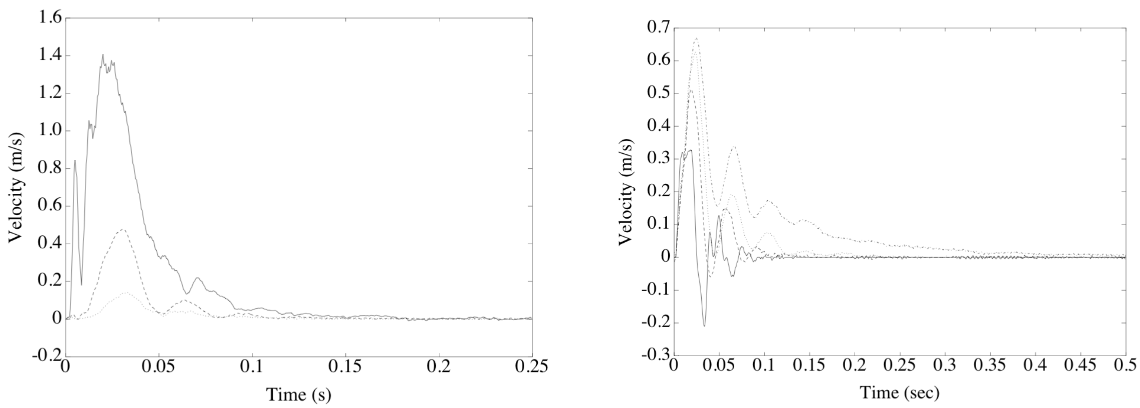


Figure 13: Virtual desired force F^*_d

The velocities of the end-effector with the classical force control law (cf. figure (14.b) and virtual environment loop (cf. figure (14.a) are very different. The maximum velocity (cf. figure (14.a) obtained with $K_e = 1N/mm$ is higher than the maximun velocity with the classical external control law. This is due to the fact that the virtual environment tends to keep the response time constant whatever the environment stiffness value. This advantage could become a major drawback if the difference between $\mathbf{K_e}$ and $\mathbf{K_v}$ is too large in comparison to the maximum capabilities of the actuators. A risk of actuator saturation is then possible.



(a) (b)

Figure 14: Velocities of the end-effector of the DELTA robot

5 CONCLUSIONS

We have presented in this paper one of the main problems we encounter in robot force control: the unknown environment. We proposed a solution to increase the robustness of the force control schemes: the virtual environment control loop, which can easily be implemented on an industrial robot with an open controller, since no precise knowledge of the robot and environment parameters (dynamics, amplifier gains, stiffness, etc.) is needed. We have described, in the case of a basic virtual environment, this method and shown its advantages and limitations. We chose to implement it with the external position/force control law that is often presented as a very convenient solution. Very interesting results have been obtained with a fast parallel DELTA robot which prove the efficiency of the virtual environment approach. We believe that this method could be pertinently used for some medical applications (echography, skin harvesting, etc.), where variations of the stiffness are for instance due to the elasticity of the skin.

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