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Robot Force and Impact Control with Feedforward Switching

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Abstract: This paper proposes the use of a proportional force controller with feedforward and active damping. It is demonstrated that with the adequate selection of the parameters both velocity control in free motion and force tracking in constrained motion can be achieved. Nevertheless, the most important contribution of the article is the switching of the feedforward term in function of the state variables in order to smooth the impact. Optimal switching criteria from the point of view of energy dissipation have been deduced and verified by simulations.

1. INTRODUCTION

A major problem in robot force control is the abrupt change from free to constrained motion. The transition from one phase to the other, also called impact, is probably the most critical part of the task. The difference in the dynamics of the system is very important in the two phases. This is emphasised by the fact that in the typical industrial applications of force control the environment is very stiff, making the system underdamped with very high frequency of oscillations.

During the impact is high peaks of force may occur and cause irreversible damage to the robot, the environment or the tool. Even if that doesn't happen, smaller peaks of force deteriorate gradually the mechanics of the robot.

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All these drawbacks could be easily avoided designing an overdamped controller if the characteristics of the environment were known. Unfortunately it is often not the case. For this reason, any a priori selected parameters of the regulator may not be adequate, and additional actions could be necessary if the system appears to be underdamped when the contact is achieved.

Another inconvenient of the impact is the fact that it is extremely brief and may last just a few sampling periods. As consequence an adaptive controller, for example, may be too slow to protect the system.

Some authors propose to apply a controller whose only purpose is to smooth the impact. It would be applied just during the transient phase and its objective should be the fast dissipation of the energy rather than the tracking of a reference value. It should be replaced by another controller once the transition is finished in order to reach the force reference.

The impact control has been extensively researched and very diverse solutions have been proposed. The most complete compilation from different sources as well a very exhausting analysis of the impact control has been made by

B. Brogliato (1999). It should be noticed that, as stated for example by Brach in 1991 or Brogliato in 1999 there are two ways to treat the impact: the rigid and the flexible model. The former doesn't consider what is happening during the contact phase, just before and after it. It is assumed that the duration of the impact is infinitely short. The relation between the velocities in the moment of the contact and after the rebound is given by the coefficient of restitution. In the flexible model the impact is treated analytically considering the robot and/ or the environment as elastic bodies. This model will be used in this article.

Following will be mentioned some methods for impact control proposed by different researchers. With the rigid model, Brogliato et al. proposed in 1997 two methods for limiting the number of rebounds and assuring in this way the stability of the system. There are more works based on the flexible model than on the rigid one. Volpe and Khosla proposed three methods for impact control in 1993b. All three are oriented to avoid contact loss rather than the protection against peaks of force. Hyde and Cutkosky proposed in 1994 the modulation with pulses of the feedforward. These pulses are computed to suppress the transitory harmonics. Ferreti and al. in 1998 applied during the impact a feedforward determined empirically combined with the force regulator, in order to avoid contact losses. From the enumerated sources, it can be deduced that the techniques for impact are control are very heterogeneous. They don't use the same model. Some are thought to try to avoid contact losses regardless of the possible peaks of force. Others are limited to guarantee the convergence of the system alter a finite number of rebounds. Some consider the characteristics of the environment are completely known.

It should be emphasized that the application of a regulator only for the impact implies the necessity of another controller for tracking the reference force. As consequence, a switching between controllers becomes necessary. This may create problems if switching criteria are not well established, like limit cycles or sliding regimes.

This article proposes a unique controller valid both for force and impact control. During the impact, the feedforward term is switched depending of the state variables in order to dissipate faster the energy of the system. The optimal switching criteria are deduced and verified in simulations.

The variation of the parameters of the controller in function of the state has been proposed previously to this article. A compilation of several sources has been made by Armstrong et al. in 2006. Possibly the first interesting contribution that should be mentioned has been published by Franke in 1987. Regarding application of the parameter variation in force control, it was first introduced by Xu, Hollerbach and Ma in 1994 and 1995. They proposed a non linear PD controller. Both the proportional and derivative constant varied between a minimum and a maximum value according to a non linear law that had into account the signs of the force error and its derivative. H. Seraji gave some interesting contributions in this direction in 1997 and 1998.

The switching of the parameters has been introduced in force control by B. Armstrong et al. in 1997, 2000, 2001 and 2006. This is the most similar work to this article. The authors switch the gain matrix according to the state of the system. The essential idea is the same, but a different mathematical methodology was used. In the work of B. Armstrong and al. LMI has been used to demonstrate the validity of the method. The technique worked until the difference between the parameters exceeded a value that had to be found empirically. The main advantage of the method exposed in this article is that it does not require any empirical adjustments. As it will be explained later, it does not limit the value of the parameters. For extreme values the performance is better. Another difference between the work of Armstrong et al. and the one exposed in this article is that the former switches the feedback parameters and the latter the feedforward.

The switching of the parameters for impedance control has been published in 2005 by the authors of this article.

The article is organized as follows: the second section is dedicated to the description of the system, i.e. the model of the physical process and the controller. Some equations used later are deduced. The third section is dedicated to the deduction of the switching criteria and the simulations' results. The final section summarises the conclusions of the article.

It must be emphasized that this article is dedicated to a one degree of freedom non-elastic robot.

2. DESCRIPTION OF THE SYSTEM

This section is dedicated to the description of the model used to deduce the equations. It consists of the physical process and the controller. The former has two elements: the robot and the environment. This article contemplates the case of a rigid (non-elastic) robot. It can be modelled by a mass and a viscous damping:

$$u = ms^2 x + bsx \tag{1}$$

Where u is the control action, m the mass of the robot, b the viscous damping and x the position of the robot.

The environment is represented by its interaction force with the robot. It can be expressed in the following way:

$$f = K_e(x - x_e) + B_e sx \tag{2}$$

Where f is the interaction force, K_e the stiffness, B_e the damping and x_e the coordinate of the environment.

Regarding the controller, a proportional regulator with feedforward and active damping has been used. The control action is given by the expression:

$$u = K_p(F_{ref} - f) + ff + b_a v \tag{3}$$

Where K_p is the proportional constant, F_{ref} the force reference, ff the feedforward term, b_a the active damping and v the velocity of the robot.The schema of the system is represented in the figure 1.

The system is second order with positive coefficients, thus it is always stable. The acceleration will be

$$\begin{aligned}\ddot{x} &= \frac{1}{m}(K_p(F_{ref} - f) + ff - (b + b_a)\dot{x} - f) = \\ &= \frac{1}{m}(K_p F_{ref} + (K_p + 1)K_e x_e + ff - \\ &-(b + b_a + (K_p + 1)B_e)\dot{x} - (K_p + 1)K_e x\end{aligned} \tag{6}$$

The final position:

$$x_\infty = \frac{K_p F_{ref} + (K_p + 1)K_e x_e + ff}{(K_p + 1)K_e} \tag{7}$$

And the final force:

$$\begin{aligned}K_e(x_\infty - x_e) &= K_e \frac{K_p F_{ref} + (K_p + 1)K_e x_e + ff}{(K_p + 1)K_e} - \\ -K_e x_e &= \frac{K_p F_{ref} + ff}{(K_p + 1)}\end{aligned} \tag{8}$$

It seems logical to assign the value to the feedforward

$$ff = F_{ref} \tag{9}$$

Then the reference force will be reached:

$$F_\infty = F_{ref} \tag{10}$$

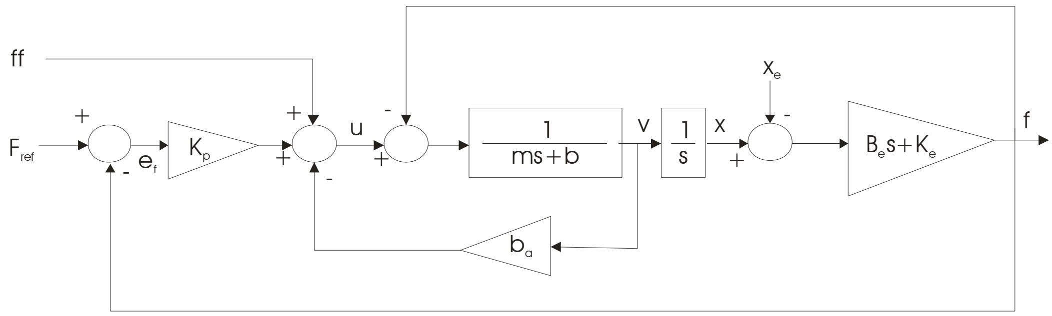

Figure 1. Diagram of the system.

The following expression can be deduced from the diagram on the figure:

$$K_p(F_{ref} - f) + ff - f = (ms^2 + bs)x \tag{4}$$

After the substitution of (2) in (4) and a few elementary operations the following expression is obtained:

$$\begin{aligned}&K_p F_{ref} + (K_p + 1)K_e x_e + ff = \\ &= (ms^2 + (b + (K_p + 1)B_e)s + (K_p + 1)K_e)x\end{aligned} \tag{5}$$

Note that in free motion the interaction force is zero and the equation (4) becomes:

$$K_p F_{ref} + ff = (ms^2 + bs)x \tag{11}$$

The position of the robot will be:

$$x(s) = \frac{K_p F_{ref} + ff}{ms^2 + bs} \tag{12}$$

And the velocity:

$$v(s) = sx(s) = \frac{K_p F_{ref} + ff}{ms + b} \qquad (13)$$

The final values of the position and the velocity:

$$\begin{aligned} x_\infty &= \infty \\ v_\infty &= \frac{K_p F_{ref} + ff}{b} \end{aligned} \qquad (14)$$

Thus, in the stationary state in free motion the robot moves at constant speed. This is equivalent to a velocity control. It is better suited than position control because in some cases the exact coordinate of the environment is unknown. Since K_p, F_{ref} and ff are used for force control in constrained motion, the adjustment of the velocity in free motion can be made by adding some active damping.

3. SWITCHING THE FEEDFORWARD

As stated above, the feedforward values may be switched in order to dissipate faster the energy of the system and damp the impact.

To deduce the switching criteria the following Lyapunov function is used:

$$\begin{aligned} V &= \frac{1}{2}((x - x_\infty)^2 + \dot{x}^2) = \\ &= \frac{1}{2}((x - \frac{K_p F_{ref} + (K_p + 1)K_e x_e + ff}{(K_p + 1)K_e})^2 + \dot{x}^2) \end{aligned} \qquad (15)$$

Its derivative:

$$\begin{aligned} &\dot{V} = (x - x_\infty)\dot{x} + \dot{x}\ddot{x} = \\ &(x - \frac{K_p F_{ref} + (K_p + 1)K_e x_e + ff}{(K_p + 1)K_e})\dot{x} + \\ &+ \frac{1}{m}(K_p F_{ref} + (K_p + 1)x_e + ff - \\ &-(b + b_a + (K_p + 1)B_e)\dot{x} - (K_p + 1)K_e x)\dot{x} \end{aligned} \qquad (16)$$

The partial derivative of the previous expression with respect to the feedforward:

$$\frac{\delta \dot{V}}{\delta ff} = \dot{x}(1 + \frac{1}{m}) \qquad (17)$$

It can be assumed that when this expression is positive, the term associated to the feedforward generates energy. Otherwise, it dissipates it. This implies the following switching criteria:

$$ff = \begin{cases} ff_{\min} & if \quad \dot{x} > 0 \\ ff_{\max} & if \quad \dot{x} < 0 \end{cases} \qquad (18)$$

It should be emphasized that the switching is to be performed only during the transitory phase. After, the feedforward should be set according to (10) to reach the reference value.

The switching criteria have been verified by means of simulations. These were made at first assigning smaller and smaller values to ff_{min}, while keeping ff_{max} constant. Next, the contrary was made: ff_{min} was kept constant, while the values of ff_{max} were increased in several successive experiments. Testing the two cases separately, the effectiveness of the switching criteria is verified. Otherwise, the positive results in one case could compensate the negative ones of the other, giving a false appearance of the validity of the method.

The data for the simulations were the following: K_p=10, b_a=0, m=1kg, b=10 Ns/m, K_e=10^6 N/m, B_e=10 N/m. These values are realistic. The stiffness is very high making the system highly underdamped.

The simulations results are represented in the following figures.

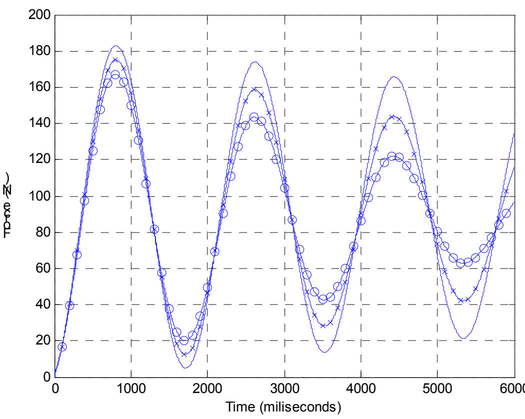

Fig. 2. Diagram of the force when switching ff_{min}. Full line: ff_{min} =100 (no switching) , crosses: ff_{min} =50, circles: ff_{min} =0.

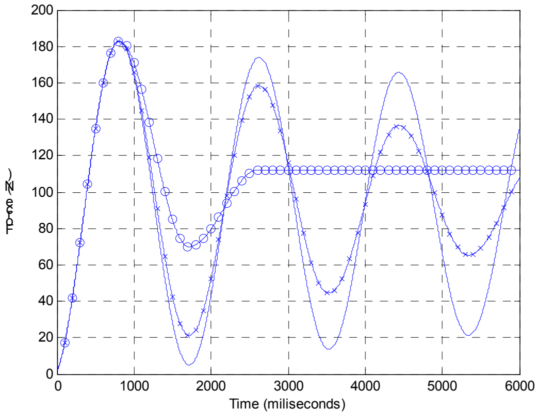

Fig. 3. Diagram of the force when switching ff_{max}. Full line: ff_{max} =100 (no switching), crosses: ff_{max} =200 , circles: ff_{max} =500.

It can be appreciated in the simulations that both decreasing of ff_{min} and increasing of ff_{max} improve the damping of the system. The former reduces the maxima and the latter the minima, because ff_{min} is active when penetrating the environment, and ff_{max} when retiring.

It may be also appreciated that for the value ff_{max} =500, the system enters into a sliding regime after the second maximum, i.e. it switches infinitely from ff_{max} to ff_{min}. This is potentially a harmful effect because the system keeps switching infinitely instead of tracking the reference value. The analysis of the conditions of appearance of sliding regimes will not be treated in this article. The most straightforward way to avoid them is not to switch if they happen. In the following figure is represented the value of the feedforward when switched between 100 and 500. A sliding regime can be appreciated.

4. SLIDING REGIME ANALYSIS

According to (18), the feedforward switches when the velocity changes its sign. In this case

$$S : \dot{x} = 0 \tag{19}$$

is called the switching surface.

A sliding regime occurs when switching causes the system to remain on S that becomes in this case a sliding surface.

It can be stated that if any of the following statements is true, the system is moving away from the surface:

$$\dot{x} > 0 \quad and \quad \ddot{x} > 0 \tag{20}$$

$$\dot{x} < 0 \quad and \quad \ddot{x} < 0 \tag{21}$$

In the first case, S is positive and increasing and in the second case it is negative and decreasing. In both cases the distance from the surface is increasing. In the contrary cases:

$$\dot{x} > 0 \quad and \quad \ddot{x} < 0 \tag{22}$$

$$\dot{x} < 0 \quad and \quad \ddot{x} > 0 \tag{23}$$

The system is leaning towards the surface.

Following be analysed the case when switching from ff_{min} to ff_{max}. The other case is completely symmetric and it will not be treated in this article due to the lack of space.
According to (18) the system switches to ff_{max} when velocity goes to negative from positive. Obviously, this may happen only if velocity is decreasing, i.e. the acceleration is negative. Before the switching, the case (22) is true. After the switching, since velocity is negative, cases (21) or (23) are possible. If (23) is true, the system will move away from the surface and it will not enter a sliding regime. If (23) is true, the system will be returned back to the surface and switch infinitely between the (22) and (23). That corresponds to a sliding regime. In order to avoid it, the acceleration must be negative after switching to ff_{max}. According to (6):

$$\begin{aligned} &\ddot{x} = \frac{1}{m}(K_p(F_{ref} - f) + ff_{\max} - (b + b_a)\dot{x} - f) < 0 \Leftrightarrow \\ &\Leftrightarrow ff_{\max} < K_p(F_{ref} - f) + (b + b_a)\dot{x} - f \end{aligned} \tag{24}$$

Since near the surface $\dot{x} \approx 0$, this is equivalent to:

$$ff_{\max} < K_p(F_{ref} - f) - f \tag{25}$$

Since all the elements are known or measurable the appearance of sliding regimes may be predicted. In this case switching is not to be performed. Another possibility is to assign to ff_{max} a value to that satisfies (25).

5. CONCLUSIONS

The article is dedicated to the force and impact control. The controller that has been used is a proportional force control with feedforward and active damping. First, some characteristics of the controller are deduced. It has been demonstrated that it is adequate for velocity control in free motion and force tracking in constrained motion.

The most important part of the article is the application of the switching of the feedforward for the attenuation of the impact. Switching criteria are deduced in order to dissipate the energy as fast as possible.

The criteria have been verified by means of simulations. The switching was performed between two values. In most cases, the simulations have demonstrated the improvement in the impact control when the minimal value of the feedforward is decreased as well as when the maximal value is increased. Nevertheless, in some cases, for extreme values of the feedforward, the system may enter a sliding regime. Fortunately, these cases are predictable and may be avoided.

The proposed method always guarantees an improvement of the damping of the system unless the system enters a sliding regime. It needs just a few sampling periods to be effective. There is no reason it could be not used in combination with other impact control methods. The values to assign to the feedforward are straightforward: the maximum value should be as big and the minimal value as small as possible regardless of the characteristics of the environment.

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