# ROBUST AND STABLE ROBOTIC FORCE CONTROL

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Abstract: To perform many complex tasks, modern robots often require robust and stable force control. Linear, fixed-gain controllers can only provide adequate performance when they are tuned to specific task requirements, but if the environmental stiffness at the robot/task interface is unknown or varies significantly, performance is degraded. This paper describes the design of a robotic force controller that has a simple architecture yet is robust to bounded uncertainty in the environmental stiffness. Generic stability conditions for the controller are developed and a simple design methodology is formulated. The controller design is tested on an experimental robot, and is shown to perform favourably in the presence of large changes in environmental operating conditions.

## 1 INTRODUCTION

Traditionally, most industrial robots are designed to allow accurate and repeatable control of the position and velocity of the tooling at the device's end effector. However, if robots are to perform complex tasks in a wider range of applications in the future, it will be essential to accurately control forces and torques at the end effector/task interface. In addition, task constraints sometimes require position control in some degrees-of-freedom (DOF), and force control in others. Thus, to fulfil these extra demands, an important area of robotics research is the implementation of stable and accurate force control. However, this is often difficult to achieve in practice, particularly where robots are operating in unpredictable or disordered environments.

A large number of force control techniques of varying complexity have been proposed over the last twenty years (Zang & Hemami 1997; Whitney 1985). The most basic direct methods simply transform joint-space torques into a Cartesian-space wrench, either in an open-loop fashion (which do not require the explicit measurement of forces and torques) or using inner and outer closed loops for accurate control of joint torques and Cartesian forces, respectively. However, since most industrial robots have position control loops that are not easily modified, indirect methods are often preferred. These involve modifying either joint or Cartesian position demands in order to control forces by deliberately introducing position control errors and using the inherent stiffness of the manipulator in different Cartesian directions. Alternatively, it is possible to add an outer force control loop in systems that have a facility for real-time path modification (Bicker et al. 1994).

Two major problems in the implementation of practical controllers are stability and robustness. Stable force control is particularly difficult to achieve in 'hard' or 'stiff' contact situations, where the control loop sampling rate may be a limiting factor. In an attempt to improve stability various methods have been proposed, the simplest being the addition of compliant devices at the robot wrist (Whitney & Nevins 1979). Another solution is to employ 'active compliance' filters, where force feedback data is digitally filtered to emulate a passive spring/damper arrangement (Kim et al. 1992). However, both methods introduce a potentially unacceptable lag. Robustness is a problem where environmental uncertainty exists, and effective force control can only be achieved by employing an accurate environment stiffness detection technique and smooth switching between controller gains (Ow 1997). This slows down task execution, and can result in unstable contact when the effective stiffness at the robot/environment interface ($K_e$) varies significantly.

Recent increases in processing power of low-cost computers has led to an increased interest in 'intelligent control' techniques such as those


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employing fuzzy logic, artificial neural networks and genetic algorithms (Linkens & Nyongsa 1996).

Where attempts have been made to employ these techniques (specifically fuzzy logic) in explicit robot force controllers, simulation studies have demonstrated good tracking performance despite wide variations in environment stiffness, e.g. (Tarokh & Bailey 1997; Seraji 1998), and for specific contact situations, e.g. deburring (Kiguchi & Fukuda 1997). Improved performance using a hierarchical fuzzy force control strategy has also been demonstrated for various contact situations, such as peg-in-hole insertion (Lin & Huang 1998).

However, fuzzy techniques are not without problems. In addition to problems associated with dimensionality, i.e. large numbers of rules that must be evaluated in the inference process, the performance and stability of fuzzy systems are often difficult to validate analytically (Cao et al. 1998; Wolkenhauer & Edmunds 1997). Additionally, when compared to more 'traditional' control methods such as LQR (Frankin et al. 1994), the resulting fuzzy designs are more complex, have larger memory requirements and larger execution times (Bautista & Pont 2006).

Recent years have seen increased interest in the use of model following control (MFC) techniques. Due to its conceptually simple design and powerful robustness properties, this type of controller has been found to be particularly suited to industrial applications such as robotics and motion control (e.g. Li et al. 1998; Osypiuk et al. 2004). As such, it would seem that MFC-based techniques may prove to be applicable in the force control domain. This idea shall be explored in this paper, and a simple and stable MFC-based technique for force control is presented.

The paper is organised as follows. Section 2 presents a short overview of common difficulties in practical robotic force control. Following this, Section 3 gives a brief description of the MFC-based force controller, and generic stability conditions are developed. In section 4 this technique is applied to a robotic test facility and results are presented. Finally, conclusions and suggestions for further work are outlined.

## 2 FORCE CONTROL

Prior to examining the robust approach, it is beneficial to outline the force control problem under consideration and describe a conventional solution. A typical conventional force control scheme is shown in Figure 1. The combined stiffness at the end effector/task interface in the direction of the applied force is $K_e$. This varies between a minimum value, determined by the objects in the environment with which the robot is in contact, and a maximum value, limited by the stiffness of the arm and torque sensor. The latter is dominant when the robot is touching a surface of very high stiffness, i.e. in a hard contact situation. Designing a fixed-gain conventional controller to meet a chosen specification for a specific value of $K_e$ is, in principle, a relatively straightforward task. A problem arises when $K_e$ is unknown or variable, as shown in Figure 2. For example, consider the case where the system is tuned to achieve a specified performance at an upper limit of $K_e$ - at low $K_e$ the system will be overdamped with a relatively high settling time. Conversely, if the system had been tuned for the desired performance at the lower limit of $K_e$, significant overshoot and oscillatory behaviour would have occurred at higher stiffness values.

In practical robotic systems these effects often have serious consequences, mainly in relation to system stability. In particular, the finite and relatively low sampling rates of many industrial robot control systems can result in unstable behaviour, a situation exacerbated by the presence of noise, non-linearities and other factors. For this reason, force controllers of the type described usually require some form of environment stiffness detection technique to enable the controller gains to be switched accordingly. The main problem with this process is that it is time consuming, often involving 'guarded moves' to contact in order to enable sufficient data to be collected for the algorithm to work. Such methods can also be unreliable in the presence of transducer noise, and are not very effective in situations where $K_e$ is variable or rapidly changing.

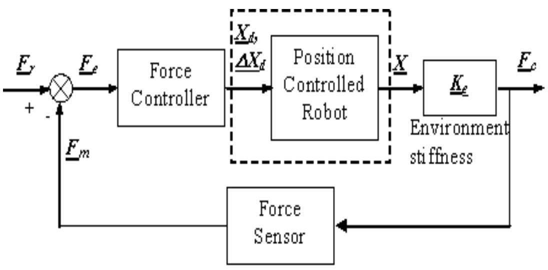


Figure 1: Robot force control.

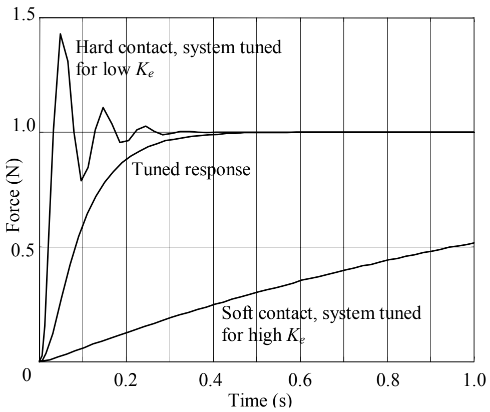


Figure 2: Effect of environmental stiffness.

# 3 ROBUST FORCE CONTROL

## 3.1 Principle

In this section we present the proposed robust force controller. It is loosely based around the robust PID strategy discussed in detail by Scokzowski et al. (2005). The original strategy is based upon a two-loop MFC, containing a nominal model of the controlled plant and two PID controllers. The block diagram of a basic MFC controller is shown in Figure 3.

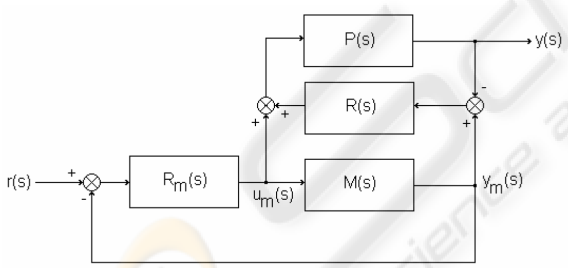


Figure 3: Robust PID based on MFC.

In this type of control, the model compensator $R_m(s)$ is tuned to a nominal model of the plant M(s); the actual plant P(s) contains bounded uncertainties. The auxiliary controller R(s) acts on the difference between the actual process output and the model process output to modify the model control signal $u_m(s)$, which is also fed to the plant.

As shown in Figure 1, when adding an outer force control loop, it is common to use a velocity signal as the input to the robot. In this case the model M(s) is simply the second order motion control loop dynamics augmented by a free integrator, and a known value of environment stiffness. The bounded uncertainty in the plant is then just the environment stiffness $K_e$, varying between $Ke_{max}$ and $Ke_{min}$.

If the two loop controllers R(s) and $R_m(s)$ are simple proportional gains, as shown in Figure 4, then the MFC structure is considerably simplified. The model loop gain Kp can be tuned for $Ke_{max}$, (a relatively trivial task) whilst the auxiliary loop gain Kp' can be tuned to provide an additional control signal should the actual value of $K_e$ be less than $Ke_{max}$. In the following section we will consider the stability criteria for this controller structure and provide a bound on the maximum value for Kp'.

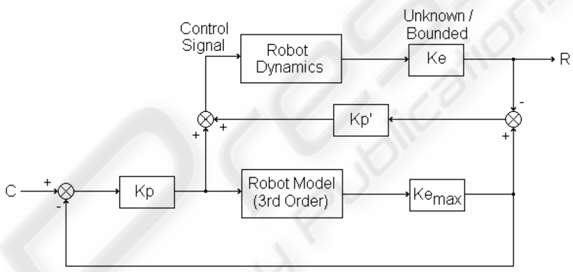


Figure 4: Robust force controller.

## 3.2 Design for Stability

If the 'model loop' controller $R_m(s)$ is tuned for stability using a nominal design method on the plant P(s) augmented by the maximum environmental stiffness gain $Ke_{max}$, then we know that the stability of the overall control strategy is restricted by the roots of the equation:

$$1 + R(s)M(s)[1 + \Delta(s)] = 0 \tag{1}$$

Where Δ(s) denotes the model perturbations (uncertainty). The objective is to find for a given plant and bounded uncertainty in the stiffness gain a maximum bound on |R(s)| that will maintain stability. In the case where the uncertainty exclusively resides in the environment stiffness gain $K_e$, then if the original loop is tuned for $Ke_{max}$ then M(s)[1+Δ(s)] in (1) reduces to:

$$M(s)[1 + \Delta(s)] = P(s) = G(s)K_{e\max} \tag{2}$$

The robot dynamics have the form (due to the free integrator in the forward path):

$$G(s) = \frac{\omega_n^{\ 2}}{s^3 + 2\xi\omega_n s^2 + \omega_n^{\ 2} s} \tag{3}$$

And the controller R(s) in this case is a single gain, Kp*'*, using (2) and (3) we can re-write equation (1) as follows:

$$s^3 + 2\xi\omega_n s^2 + \omega_n^{\ 2} s + \omega_n^{\ 2} Kp' Ke_{\max} = 0 \tag{4}$$

Applying the Routh-Hurwitz stability criterion (Pippard 1997) for a cubic equation, we know that the system is stable if all the co-efficients in the left of (4) are positive, and the following criterion is satisfied:

$$2\xi\omega_n\omega_n^{\ 2} \geq \omega_n^{\ 2} Kp' Ke_{\max} \tag{5}$$

Re-arranging (5) gives a stability limit for the controller gain $Kp'_{max}$ as follows:

$$Kp'_{\max} = \frac{2\xi\omega_n}{Ke_{\max}} \tag{6}$$

Thus if the gain Kp' is chosen between the limits:

$$Kp < Kp' < Kp'_{\max} \tag{7}$$

The controller will be stable for unknown environment gains in the range $0 < K_e < K_{emax}$; as for all gains below $Ke_{max}$, the stability criteria of (5) holds.

# 4 EXPERIMENTAL TESTING

## 4.1 Test Facility

A research facility, previously described in detail (Short 2003), has been developed in the form of a planar robot arm and PC-based open architecture controller. The robot joints are actuated by brushless servomotors (with digital servoamplifiers), and the control loop for each axis is closed via a multitasking DSP embedded in a Delta Tau® Programmable Multi-Axis Controller (PMAC) motion control card, installed into the PC

Each axis has an individual PID controller with feedforward control to enable accurate velocity and position profile following. A six-axis force/torque sensor was developed in-house for the project, and used in this study. The robot arm is shown in Figure 5. For this work, a one-axis version of the system was employed by attaching the sensor to the wrist of the second link, which was then locked at 90° to the first link.

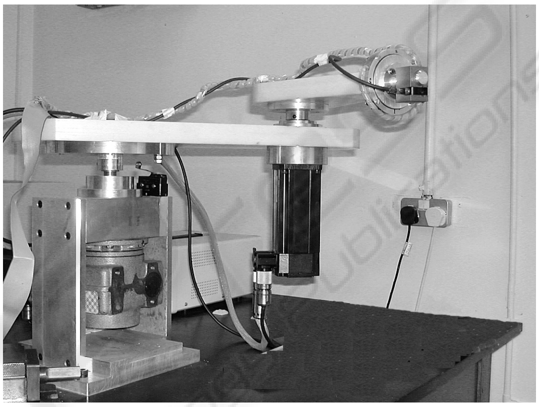

Figure 5: Test facility.

In this paper, we apply the controller proposed in the previous section to this facility. The controller was coded in C and added into the control library. Each experiment involved a contact situation, where the robot first approached a surface then applied a force of 25 N. The contact surface was varied in each experiment, and we used two surfaces; hard (steel) and soft (plastic). In order to reliably detect the contact surface, the end effector was fitted with a Baumer Electric® photoswitch which was calibrated to signal with high accuracy when an object was 5mm away. The robot thus approached the contact surface at a slow jog speed until this signal was made, then switched to force control mode. The sample rate was 200 Hz in each experiment. In the following section we describe the parameters that were used.

## 4.2 Controller Design

From a previous identification exercise, the parameters of the robot arm model and the environment stiffness limits were determined to be as follows (Short 2003):

$$\omega_n = 244\,rad/s,\ \xi = 1,$$
$$K_{e\max} = 168\ N/mm, \quad K_{e\min} = 11\ N/mm \qquad (8)$$

Using these parameters, the nominal loop gain Kp was tuned to a value of 0.02 to give the desired transient performance – a 95% rise time of approximately 2 seconds with minimal (ideally zero) overshoot. Using (6), $Kp'_{max}$ was determined to be 2.9. We therefore chose a value of Kp' = 1.5 for the experiments.

## 4.3 Experimental Results

Figure 6 shows the response of the system when applying a force to the hard (steel) surface. The very small negative force indicated before contact with the surface was made (at approx 1s) was due to a small drift in the calibration of the force sensor whilst moving in free space. Figure 7 shows the soft (plastic) case. We also show, for completeness, the contact situation for a single loop controller tuned for high $K_e$ in the soft contact case. This is shown in figure 8.

These figures demonstrate the effectiveness of the approach. Comparing Figures 7 and 8, the compensation added by the extra loop can clearly be seen; in Figure 7 we see an almost identical transient to Figure 6. Additionally, in Figure 6 the controller demonstrates no signs of instability as Kp' was kept below the maximum amount. We also measured the integral of time by absolute error ITAE (Franklin et al. 1994) for the responses shown in Figures 6, 7 and 8. This is shown in Table 1. From this the closeness of the proposed robust controller transient responses can be seen (R). The response of the normal (N) controller is also shown in the table. The poor quality of control is clearly highlighted by this vastly increased value.

Table 1: ITAE measures for contact situations.

| System | ITAE |
|---|---|
| (R) Low $K_e$ | 23.61 |
| (R) High $K_e$ | 23.95 |
| (N) Low $K_e$ | 666.5 |

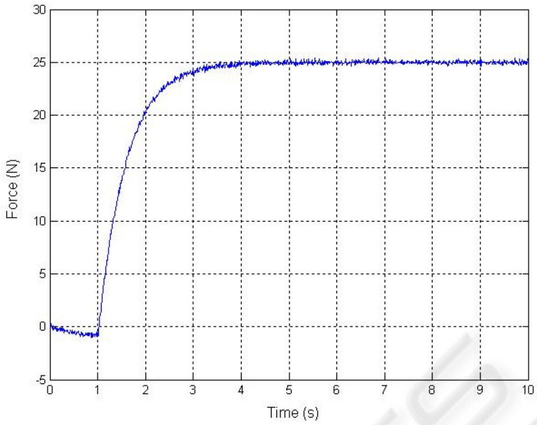


Figure 6: Hard contact situation.


Figure 7: Soft contact situation.

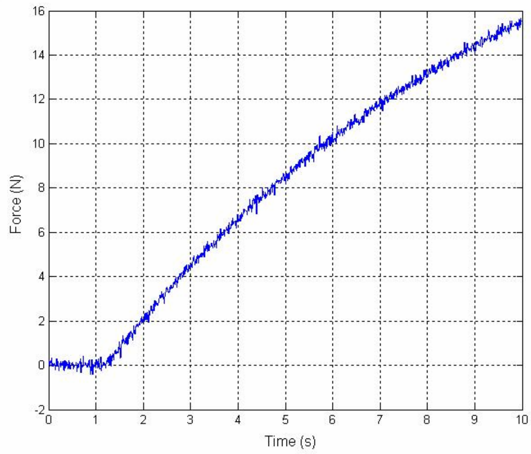


Figure 8: Soft contact situation (normal controller).

## 5 CONCLUSIONS

In this paper a distinct method for robotic force control has been proposed and tested using an experimental test robot. The method has been shown to improve system performance where a high degree of environmental uncertainty exists, without the need for a stiffness detection routine. The method is conceptually simple and extremely easy to implement; its simplicity also lends itself to easy analytical analysis.

The practical realisation of robotic force control remains a problematic area of research. However, the potential of simple, stable controllers to overcome fundamental difficulties associated with applications where environmental uncertainty exists has been demonstrated.

However, work is required to further validate the control method. This will include analysis of situations where PD controllers are used as the loop compensators, and forces are applied in Cartesian coordinates. We will also consider the effects of model mismatch (which is inevitable if the methodology is to be applied to industrial robots). Further work will also consider implementation on a 6-DOF manipulator to confirm its performance in a range of industrial tasks, and to contrast the approach with other methodologies.

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