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Direct Force Control of a Robot in Contact with an Uneven Surface

Abstract: Our case of study is a robot in contact with an uneven planar surface. The robot's contact task consist of exerting a desired force on normal direction to the surface while a desired trajectory is tracked along the surface. For accomplish the task, we use a PID-type admittance controller. The uneven characteristic of the surface is modeled via ramp and sinusoidal disturbances, which are added to the position on normal direction to the surface. We analyze the capabilities of the force control to reject disturbances, and we propose a method for tunning the force controller that ensures an acceptable force error when disturbances emerge in the system. Then, analyzing the relative stability of the force control system, we provide a sub-optimal method to tune the control gains, and to estimate the maximum velocity of the end effector. Furthermore, a method to select the stiffness in the force control system is given. The analysis and methods are verified by simulations

Keywords: Robotics, Force Control, Stability

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1 Introduction

Force control is essential when robots are in contact with the environment since the interacting force has to be bounded or regulated on a desired value. Direct force control techniques are capable to achieve the regulation of the force avoiding damage on the environment and in the robot itself [4]. However, these control techniques may not work properly when extra dynamics such as sensor dynamics, filters and delays, emerge in the system [2].

In order to have a force control system that includes dynamics commonly omitted in the design of the controller but unavoidable in practical applications, our research group presented a more accurate force control system in [1]. This model includes the dynamics of filters and delays, and its respective values.

In this note, we design a direct force control for the control system mentioned above. The direct force control is based on a PID-type admittance control. Firstly, the PID control is tuned, and we compare the performance between P, PD and PID. Then, we model the uneven characteristic of the surface via ramp and sinusoidal disturbance. Considering disturbances, and acceptable limits in the regulation error, we propose a method to tune the direct force control that achieves a sub-optimal performance. Furthermore, we study the variation in the stiffness, and a method to find the stiffness that satisfy the acceptable force errors is presented.

2 Force Control System

Fig. 1 presents the block diagram of the force control system to be studied in this paper. The elements of the control system are: $G_c(s) = K_p + K_d s + \frac{K_i}{s}$ is the controller, $G_T(s) = e^{-Ts}$ represents the delay due sensor communication, $G_{LP}(s) = \frac{1}{\tau_{LP}s+1}$ is a low-pass filter used to suppress noisy in measurements, τ is a time constant characterizing the time-response of the robot, v is the control signal, and $e = f_d - f$ is the force error.

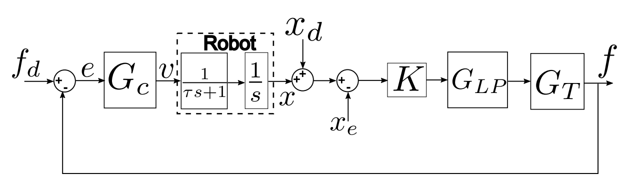

Fig. 1. Block diagram of force control system

For analyze the force, we are using the elastic model,

$$f = K(x - x_e) \quad (1)$$

where $K > 0$ is the stiffness of the surface, x is the end-effector x-coordinate, and x_e is the position/location of the planar surface. Fig. 2 presents a single-degree-of-freedom model [3], widely use for analysis of the interaction force. The goal is to find a control input v that ensures a desired force f_d is exerted on the environment.

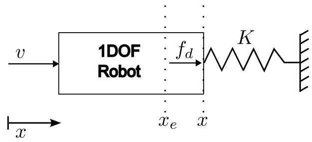

Fig. 2. 1-DOF system in contact with elastic environment

3 Control Design

Firstly, using the *pidTuner* of Matlab, we tuned the controller P, PD and PID to have same settling time $t_s \approx 0.8$ seconds and overshoot of 15%. We test a step input of 50 [N] at 30 seconds. Fig. 3 shows the time response, one can see that the settling-time and overshoot are similar but the PD controller is faster than P and PID.

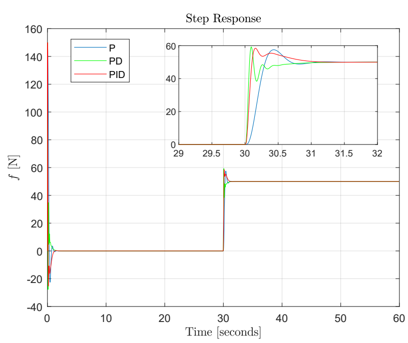

Fig. 3. Simulation results:force f with P, PD, and PID

Since the PD controller provide a faster response, the robustness of $G_c(s)$ ($K_i = 0$) when a ramp disturbance $X_d(s) = \frac{M}{s^2}$ appears is tested. The magnitude of the ramp M is related with the velocity of the end-effector. The steady state error $e_{ss} = \frac{M}{K_p}$ is computed, and the curves in Fig. 4 are obtained. The curves are a tuning tool, whenever the magnitude M is known, the control gain that provides the indicated (in the vertical axis) force error can be selected. The curves can be limited by the gain margin and the maximum admissible error. Then, we can fine the control gain that minimize the force error, and the maximum magnitude M that preserve the desired performance. For example, assuming a acceptable error of 3.5 [N] and a maxim gain of 0.002, the maximum M is $2M$, see Fig. 4.

Fig. 5 presents, the simulation when the PID controller is used, and the stiffness is varying. one can observe that the bigger the stiffness K, the more oscillations. The smaller K, the slower response. Then, we can find the stiffness value that improves performance in terms of damping and overshoot

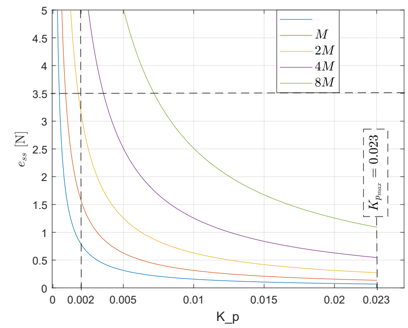

Fig. 4. Sub-optimal tuning of K_p in terms of e_{ss} and ramp value M

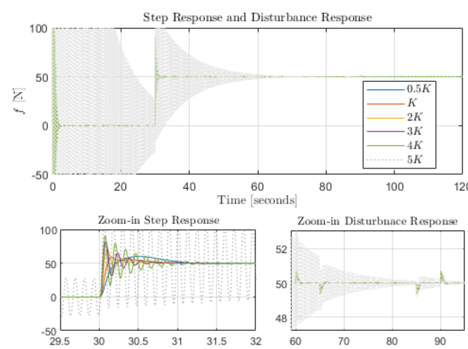

Fig. 5. Step input of 50 [N], PID is fixed and stiffness K varies

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