Robust Telecontrol with Output Feedback

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Abstract. Close loop control systems with time delay on either the feedforward or feedback channels have been under investigation for a long time. Teleoperated close loop systems belong to this class of systems. Different from the classical teleoperated structure where the close loop is located close to the plant, and the communication channels are only either used for sending command signals and/or monitoring output responses, the teleoperated close loop system has the controller located in the command center and the communication channels form part of the close loop system..The new technologies on wireless communication used with sensors and actuators, are making possible the construction of .less expensive wireless teleoperated close loop systems in the industry. It is obvious that time delay on both channels is the must important parameter that limit the stability and performance of the teleoperated close loop system. Therefore, one important issue is to design a robust close loop teleoperated system that kept stability and performance in a wide range of time delay. In this work an Hoo optimization technique was applied in the design of a close loop telecontroled system with uncertaint time delay. The results show that the designed robust controlled system under the Hoo technique allows a significant extention of performans and stability for a wider range of time delay.

Keywords: Robust Telecontrol, Time Delay, Hoo Design

1 Introduction

Telerobotics is a technology for operating and monitoring movil or fixed robots from a distance. We can found multiple examples of applications as in nuclear plants, and medicine. Design of a teleoperated system requires tracking of reference commands, regulation with respect to output disturbances, immunity to sensor and communication channels noise, and performance and stability robustness to parameter variations. All these features can only be satisfied by use of feedback. There exist two feedback telecontrol schemes that satisfy the above requirements, the one that has the feedback control loop in the same site as the plant, and the scheme where the controller is at the command center with the direct and the feedback communication channels as part of the close loop. The former scheme is the must applied, but there exists applications where the second one is the only option, as in bilateral telerobotics, [1], [2] or because of dangerous environments that limit the use of electronic

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hardware. Another powerful reason is the advent of the new inexpensive wireless telecommunication technology use with sensors and actuators making it possible to built this type of feedback loops in industrial environments. Therefore, study and design of telecontrol feedback loops has become indispensable. A main problem present in the second scheme is the presence of time delay in the control loop that may seriously jeopardize the system performance and stability. There exist several methods and techniques that can extend, the performance and stability of the telecontroled system, to ample values of the time delay. The robust Hoo optimization [3], [4], has proved to be a good method to improve the system performance when there exist model and parameter uncertainty. Here, by taking the time delay as an uncertaint parameter, we apply such method to the telecontrol of a three degree of freedom robot manipulator. The controlled system shows robustness to ample changes on time delay in the communication channels as compared with other simpler schemes, besides it was able also to attenuate the noise present in the sensors and induced in the communication channels. The paper is divided as follows: Section II is dedicated to the description of the controlled system, and the modeling of the time delay taken as a multiplicative uncertainty. Then Section III, briefly presents the Hoo design problem. Section IV shows how the weighting matrices are chosen for this design, and the results obtained. Finally, in Section V some conclusions are given.

2 Multivariable modeling of the time delay

The structure of the telecontrol system considered for this case is shown in Fig.1.

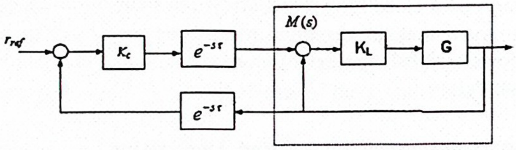

Fig.1.- Structure of the telecontroled system.

The robot was taken as three by three multivariable system G(s) to which a robust local regulator KL(s) has previously been designed and applied to form the regulated system M(s). The output vector is composed of the three angular positions of the rotational arms of the robot. Each of the two multivariable communication channels were modeled as a diagonal matrix with time delay $e^{-s\tau}$ as entries. The six time delays were taken as unknown, independent, but bounded, that is $\tau_i<\tau_{ci}$ for i = 1,2,...,6. In order to facilitate the analysis and design the six uncertaint time delay were taken as a single value τ bounded by τ_c where $\tau_c = \max_i(\tau_{ci})$. Kc(jw) is the multivariable controller for design. Fig.2 shows an equivalent system more appropriate for analysis and design where the direct and feedback time delays are put in a single expression.

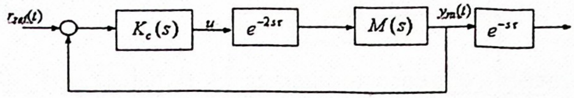

Fig.2. Equivalent system

From an analysis of the above system the loop gain L(s) is obtained as:

$$L(s) = e^{-2s\tau} M(s) K_c(s)$$

and the output sensitivity matrix function So(s) that relates the vector measured output with the disturbances at the output of the plant is given by:

$$S_o(s) = \left(I + e^{-2s\tau} M(s) K_c(s)\right)^{-1} \tag{1}$$

It is clear from the above expression how the time delay enters and affects the performance and stability of the close loop system by changing the corresponding characteristic equation. Another useful expression for design is the complementary sensitivity matrix function T(s) = I - So(s) given as:

$$T(s) = \left(I + e^{-2s\tau} M(s) K_c(s)\right)^{-1} e^{-2s\tau} M(s) K_c(s) \tag{2}$$

and, from Fig. 2 the achieved output of the system to a reference command is given as:

$$e^{-s\tau} y_m(s) = T(s) r_{ref}(s) \tag{3}$$

indicating that the actual output will show a τ. secs. direct delay with respect to a command signal and not 2τ. secs., as it could be expected.

Generally speacking, random delays are present in every communication channel with magnitudes depending on the characteristics of the channel. Stochastic analysis has been the general tool applied to analyse system with random delays, here we use the Hoo optimization method based on the "worst case", policy in order to design a controller that assert stability and performance in a wide range of time delay values. While the results may be conservative, this can be seen as an advantage if seen from the security point of view. The model uncertainty of an actual plant P(s) may be represented by normalising the plant with respect to a nominal plant Pn(s), as:

$$P(s) = P_n(s)(I + \Delta(s)) \tag{4}$$

where $\Delta(s)$ is a non-structured multiplicative uncertainty such that $\|\Delta(s)\|_\infty < \beta$. In a block diagram the above equation is represented as in Fig.3

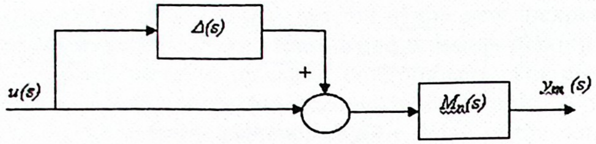

Fig.3. Multiplicative uncertainty modeling.

Now, back to the equivalent system of Fig. 2, if the actual plant P(s) is taken as $e^{-2s\tau}M(s)$ and M(s) is taken as the nominal plant, we will obtain the following identity:

$$e^{-2s\tau}M(s) = M(s)(I + \Delta(s)) \tag{5}$$

From Eq.(5) the following non-structured multiplicative uncertainty is derived:

$$\Delta(s) = e^{-2s\tau}I - I \tag{6}$$

Clearly, the parametric uncertainty of the time delay τ has been incorporated in the multiplicative uncertainty Δ(s). Hence, a class of uncertainty Δ_m is defined such that for every time delay $\tau < \tau_c$ there is a $\Delta \in \Delta_m$ and β so that $\|\Delta(jw)\|_\infty < \beta$. In this case

$\|\Delta(j\omega)\|_\infty = \max_\omega \left|e^{-2j\omega\tau} - 1\right|$. Fig. 4 shows several frequency response curves of the above multiplicative uncertainty for different values of the time delay.

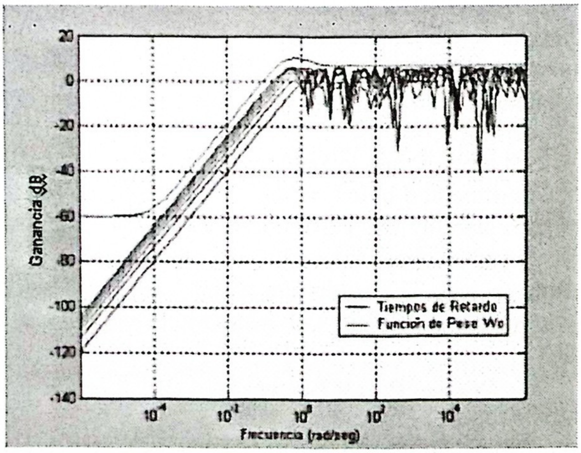

Fig. 4. Frequency response of the multiplicative uncertainty $\Delta(jw)$.

3 Design Problem

The objective of the design is to compute a controller by only using output feedback such that the controlled system remains stable on ample values of the time delay and satisfies the following design specifications:

-Tracking of a step reference signal with a steady state error less than 2%

-Sensor and communication channels noise attenuation.

-No actuator saturation.

In order to apply Hoo optimization design method to derive a controller to satisfy the above specifications we use the augmented system shown in Fig. 5.

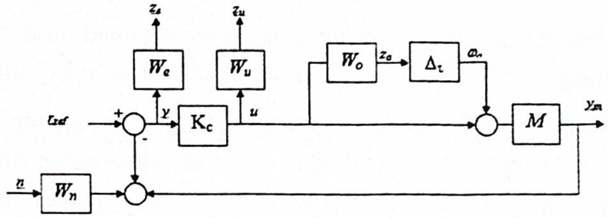

Fig. 5. Augmented system

Here the *Wi(jw) i=1,2,..4* are weighting 3x3 matrices where *Wo(jw)* is designed to normalize the multiplicative uncertainty, that is if $\Delta \in \Delta_m$, then $\|W_o(j\omega)\Delta(j\omega)\| < 1$, *Wu(jw)* models or normalizes the control signals amplitude under different performance conditions such that actuators saturation be avoid, *Wn(jw)* emulates sensor noise, and *We(jw)* gives as output the vector signal $z_e(t)$ that indicates the system performance when subject to reference, and noise inputs as well as modeling uncertainty. The external signals to the system are: the referente and noise signals , $r(t)$, and $n(t)$, and $w_a(t)$ signal that represents the way the uncertainty affects the system. $y(t)$ is the input to the controller that for this case is the error signal of the system, $u(t)$ the control signal, and $ym(t)$ is the measured output signal. The output signals taken for design are $z_u(t)$ the normalized control signal, $z_e(t)$ the normalized error signal, and finally $z_a(t)$ the equivalent weighting response to model uncertainty. From a simple analysis of the diagram of Fig.5 the following transfer function matrix between the external vector signal $\overline{w} = \begin{bmatrix} w_a^T & r^T & n^T \end{bmatrix}^T$ and the output vector signal $\overline{z} = \begin{bmatrix} z_a^T & z_e^T & z_u^T \end{bmatrix}^T$ of the augmented system is derived:

$$\Im_{wz} = \begin{bmatrix} -W_a S_o KM & W_a S_o K & -W_a S_o K W_n \\ -W_e S_o M & W_e S_o & -W_e S_o W_n \\ -W_u S_o KM & W_u S_o K & -W_u S_o K W_n \end{bmatrix} \tag{7}$$

Hence, the design H_∞ optimization problem is stated as follow: *Compute a controller Kc(jw)) such that the close loop system became robust stable in ample* *values of the communication channels time delays, with robust performance with respect to design specifications, and*

$$\min_{K(s)} \left\| \Im_{wz} \right\|_{\infty}$$

4 Weighting Matrices

Next, we describe how the weighting matrices are obtained for design purpose.

The weighting matrix $W_o(j\omega)$ is chosen such that its maximum singular value for all frequencies $\overline{\sigma}(W_o(j\omega))$ covers the family of frequency responses of the multiplicative uncertainty corresponding to different values of the time delay in order to satisfy the condition $\left\| W_o(j\omega)\Delta(j\omega) \right\| < 1$. The matrix transfer function obtained, in this case, to satisfy the above condition was:

$$W_o(s) = \frac{2.2387(s + 0.089 \times 10^{-3})(s + 2)}{(s + 0.4)(s + 1)} I_3 \qquad (8)$$

which frequency response is shown in Fig. 4. Wn(jw), the noise weighting function, models the frequency spectrum of the noise present in the system. It was found that the servopotenciometer, used for position sensing, were the source of high intensity noise at low frequencies as compared with the communication channel noise, so, a high-pass filter model was proposed with 35 dbs attenuation up to two octabs from the bandwith of the nomial plant Mn(s), (0.42 rad/sec), and with a 6 dbs constant attenuation at high frequencies. Then, the corresponding weighting transfer matrix obtained was:

$$W_n(s) = \frac{2(s + 4)}{s + 80} I_3 \qquad (9)$$

The weighting matrix Wu(jw) was mainly applied in such a way as to avoid as much as possible the actuators saturation under different performance. The control input *u(t)* in this particular case represents the angular movements of the robot, so Wu(jw) was taken as a scalar attenuation of 1/170 in all control channels. As with respect to the error weighting matrix We(jw), this models the performance of the system to referente and disturbance inputs of low frequency. Therefore, in order to obtain a good time responce to step inputs, an integrator is a good option. Here instead of using this model an approximation was used by the application of a lag filter in the three channels of the error vector. As a rule this last weightig matriz is the main function for tuning the controller. Thus, after several simulations, it was obtained the following matrix:

$$W_e(s) = \frac{10\left(s/5 + 1\right)}{\left(s/0.0021 + 1\right)} I_3 \tag{10}$$

The final step of the Hoo design is to find out if the controlled system satisfies the nominal and robustness conditions which are:

For robust stabilty we look for:

$$\left\| -W_a S_c K_c M \right\|_\infty < 1 \tag{11}$$

For a good tracking, and rejection of referente and disturbance respectively as well of high noise attenuation we need:

$$\left\| \begin{matrix} W_e S_M & -W_e S_M W_n \\ W_u S_c K_c & -W_u S_c K_c W \end{matrix} \right\|_\infty < 1 \tag{12}$$

which is the condition for a good nominal performance.

Finally, for robust performance the controlled system must satisfy the following condition:

$$\left\| \mathfrak{J}_{wz} \right\|_\infty < 1 \tag{13}$$

From application of the Robust Toolbox of MATLAB, we obtain the following results: A high order controller Kc(jw) which was reduced to a lower order controller (10^{th} order), without much deterioration of the performance and stability conditions of the controlled system. The controller shows a high gain at low frequencies (20dbs) with a cross frequency around 0.08 rad/sec, and with a roll-off of -20 dbs/dec at intermediate frequencies. The frequency responses of equations (11), and (12) are shown in Fig.6 below. It is clear from this graph that the conditions for robust stability and nominal performance were well satisfied by the design.

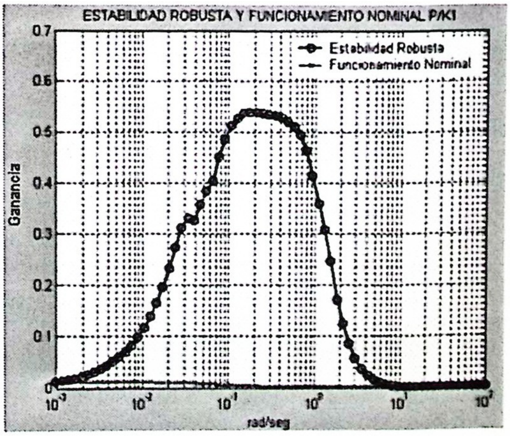

Fig. 6. Robust stability and Nominal performance requirement.

Robust performance condition Eq. (13), was examined by computing the corresponding structural singular value μ of the equation. When this value is less than one, then the system becomes robust on performance. For this design a value of $\mu = 0.79$, was obtained, meaning that the controlled system stands up to 126% non structured modeling variations.

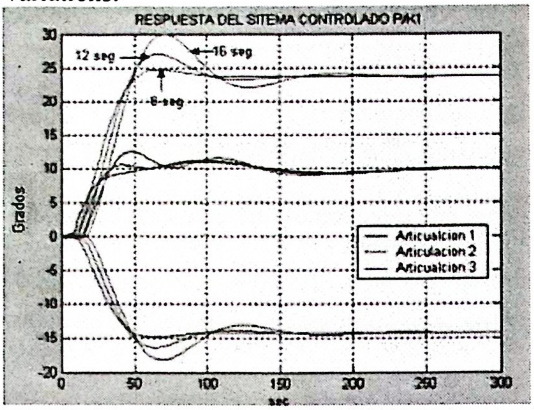

Fig. 7. Step responses of the controlled system.

The time response of the controlled system to step reference inputs of 10, -15, and 25 degrees respectively, on the three joints of the robot are shown in Fig.7 for different values of the time delay.

Steady state errors of up to 6% were obtained for all values of the time delay. Therefore more subtle tuning is needed to reach the specifications on this performance. The specification on noise attenuation was ample satisfied as can be seen in Fig.8 below

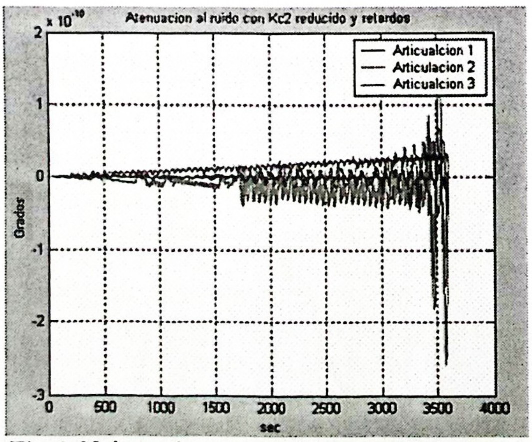

Fig. 8. Noise at the outputs of the controlled system.

Before the Hoo design was applied, a PI controller design was carried out on each of the loops of the telecontrolled system. It was found that for such controllers the system became unstable when a 3.4 secs time delay was present in the communication channels while for the Hoo design this time was extended almost 7 times to 21 secs., and good time responses were obtained for up to 16 secs. as can be seen in Fig.7. Therefore, the design condition of extending the stability and performance of the system, to ample values of the time delay in the communication channels was reached.

5 Conclusions

Due to the new technologies on integrated circuits for wireless communication the cost, and size of the main elements, transmitters and receptors, of the communication system have been reduced and now it is possible to consider the application of feedback structure of close loop telecontrol systems. As is well know the main problem of such structure is the introduction of uncertainty on the time delays present in the communication channels. There exist control design techniques that can extend the performance and stability of this system to ample values of the time delay. Hoo is one of such techniques. Here, it has been applied to a close loop telerobotic system and has proved to introduce significant improvement with respect to extend the performance and stability to ample values of time delay in the communication channels, as compared with other controllers. Also, the controlled system shows great noise attenuation and exelent disturbance rejection .

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