A control structure for bilateral telemanipulation

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Abstract. A framework for considering the stability of bilateral telemanipulator systems is considered. The approach adapts the work of Lawrence[3] to use a state-space formulation thus simplifying the identification of the stability conditions from the eigenvalues of the feedback system. Both numerical and symbolic stability conditions are considered.

Keywords: bilateral telemanipulator, control, stability

1 Background

Telemanipulator theory forms the basis for applications that include remote handling, surgical robots, exoskeletons and haptic systems[5]. In many cases, to avoid the complexity of the control system, the system operates as a strict master-slave system where position coordinates are generated by the master and the slave is servoed to follow these positions. In such cases the operator must rely on visual feedback when contact is made between the slave and the remote environment. Better control can be achieved when position and force information available at the slave is directed back to the master. One example is the OOEC Magpie[1] which is a foot operated assisted dining device that give direct mechanical feedback of forces encountered by the eating utensil to the operator's foot. A similar principal applies to orthotic devices such as the Wilmington Robotics Exoskeleton (WREX)[4] where there is a close coupling between the orthosis and the arm.

In more complex telemanipulator systems some form of closed-loop control around the actuator mechanisms is needed. In most cases this is based on position feedback control of small permanent magnet motors. Where there is backdrivable transmission between the motor and the linkage joint it is possible to estimate the external forces applied to the linkage[6], and these forces can then be reflected into the associated master or slave.

Lawrence[3] identified four connections that can be made between the master and slave of a backdrivable linkage telemanipulator system that can then allow permutations of position, force, impedance or admittance to be reflected into the master and slave systems.

2 Simplified structure of a master-slave telemanipulator

A variation of the Lawrence[3] control structure is shown in Fig 2 It consists of

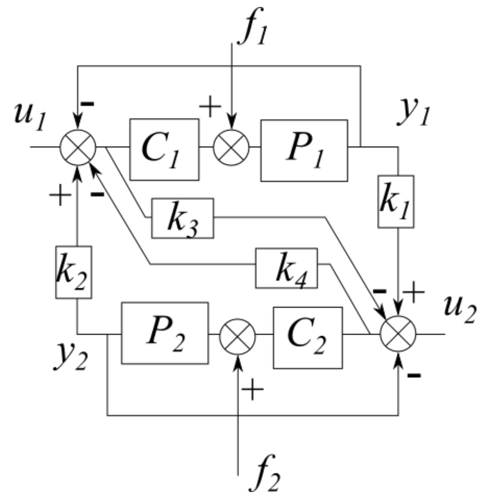

Fig. 1. Bilateral telemanipulator as a coupled control system. The upper system (C_1 P_1) will be considered as the master and the lower as the slave although in general the master and slave can be exchanged without loss of generality

two control systems that are assumed to be backdrivable. Thus the upper part of the figure (the master) consists of a plant P_1 that is assumed to contain the robot linkage and transmission, and the controller C_1 is assumed to also include the characteristics of the actuator. Evidently with this structure in a unity closed-loop feedback system as shown it is possible to show that the position gain y_1/u_1 is given as

$$y_1 = (1 + P_1C_1)^{-1}P_1C_1u_1$$

Thus under a restricted set of conditions P_1C_1 can be considered to dominate with respect to unity and the output will try to match the input. These conditions require a high controller gain without local instability so are likely to be realised when the system is tuned with an algorithm such as Zeigler-Nichols. In a similar argument the gain due to the 'disturbance' f_1 can be expressed in the form

$$y_1 = (1 + P_1C_1)^{-1}P_1f_1$$

and in this case with the same restricted set of conditions the admittance of the mechanism, the position response to the disturbance force f_1, can be considered to be C_1. The controller gain can be seen to relate directly to the impedance (stiffness) of the closed-loop system and inversely to the admittance.

The four gains k_1, k_2, k_3, k_4 in the controller structure shown in Fig 2 can be considered in two parts. Gains k_1 and k_2 simply set the position demand, master to slave and slave to master. To assess the effect of the remaining two gains k_3 and k_4 it should be noted that the gains k_1k_4 supplement the controller C_1 and the gains k_2k_3 supplement the controller C_2. With this adaption the impedance of the master can be considered to be set by $C_1(1 + k_4k_1)$ and the stiffness of the slave is set by $C_2(1+k_2k_3)$. Alternatively the two controller gains k_1, k_3 can be chosen to be an estimate of f_1 and scaled to be a force demand of the slave with a similar argument for the gains k_2, k_4[6].

Thus it can be seen that forces or positions from the master can be reflected into the slave, and vice versa.

2.1 A simplified state-space representation of a bilateral telemanipulator.

If we assume each 'plant' is a mass and damper so $\dot{x} = Ax + B\epsilon$ and $y = Cx$. This assumption provides a minimal system that uses Newton's second law along with the damper to provide a channel for the energy dissipation.

If each system has two states and decoupled we can generate a combined state matrix

where $x = [x_1\ \dot{x_1}\ x_2\ \dot{x_2}]^T$ and $\epsilon = [\epsilon_1\ \epsilon_2]^T$

For example the figure without the gain terms k_1 to k_4 could be considered as

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & -b_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -b_2 \end{pmatrix} \qquad B = \begin{pmatrix} 0 & 0 \\ c_1 & 0 \\ 0 & 0 \\ 0 & c_2 \end{pmatrix} \tag{1}$$

The output matrix C then selects outputs y_1 and y_2

$$C = \begin{pmatrix} 1\,0\,0\,0 \\ 0\,0\,1\,0 \end{pmatrix}$$

A gain matrix can be identified from

$$\begin{bmatrix} 1 & -k_4 \\ -k_3 & 1 \end{bmatrix} \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \end{bmatrix} = \begin{bmatrix} -1 & k_2 \\ k_1 & -1 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$

That is $\epsilon = Ky$ where

$$K = \begin{pmatrix} -\frac{k_1\,k_4-1}{k_3\,k_4-1} & -\frac{k_2-k_4}{k_3\,k_4-1} \\ -\frac{k_1-k_3}{k_3\,k_4-1} & -\frac{k_2\,k_3-1}{k_3\,k_4-1} \end{pmatrix}$$

The feedback gain and original system can be combined to for a new state-space system of the form.

$$\dot{x} = (A - BKC)x + BKr$$

So the revised A matrix is

$$A' = \begin{pmatrix} 0 & 1 & 0 & 0 \\ \frac{c_1\,(k_1\,k_4-1)}{k_3\,k_4-1} & -b_1 & \frac{c_1\,(k_2-k_4)}{k_3\,k_4-1} & 0 \\ 0 & 0 & 0 & 1 \\ \frac{c_2\,(k_1-k_3)}{k_3\,k_4-1} & 0 & \frac{c_2\,(k_2\,k_3-1)}{k_3\,k_4-1} & -b_2 \end{pmatrix} \tag{2}$$

We can crosscheck see it is still stable by setting the k gains to 0 and testing the eigenvalues, which require negative real part of the expression $-\frac{b_1}{2} \pm \frac{\sqrt{{b_1}^2 - 4\,c_1}}{2}$ Setting any one of the gains k_1, k_2, k_3, k_3 to be non zero makes no change to the eigenvalues and hence to the system stability.

The eigenvalues of the full system2 where all the gains k_1, k_2, k_3, k_3 are set, can be computed in Matlab but are too large to be of any value.

2.2 A strict symmetrical bilateral telemanipulator

By setting the master and slave to have identical components as well as ensuring $k_2 = k_1$ and $k_4 = k_3$ we get a symmetrical bilateral telemanipulator. In this case the eigenvalues relatively simple, that is

$$\lambda = -\frac{b_1}{2} \pm \frac{1}{2}\sqrt{4\,C_1 \frac{1+k_1}{k_3-1} + {b_1}^2}$$
$$\lambda = -\frac{b_1}{2} \pm \frac{1}{2}\sqrt{4\,C_1 \frac{k_1-1}{k_3+1} + {b_1}^2}$$

The four values come about because k_1 and k_3 range from 0 to ∞ Evidently setting $k_3 = \pm 1$ would result in an unstable response.

Essentially need the C_1 term to be negative. C_1 itself must be positive so k_1 must be less than 1 and k_3 greater than 1. This strict arrangement is of limited value.

2.3 A simplified identical bilateral telemanipulator

A further simplification is to make the master and slave identical so that the controllers c_1 and c_2 are the same proportional gain, and both plants have a the same damping term. Under these conditions the eigenvalues are considerably simpler and the four values can be computed as.

The revised A matrix becomes

$$A' = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -\frac{c_1\,(k_1\,k_4-1)}{k_3\,k_4-1} & -b_1 & -\frac{c_1\,(k_2-k_4)}{k_3\,k_4-1} & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{c_1\,(k_1-k_3)}{k_3\,k_4-1} & 0 & -\frac{c_1\,(k_2\,k_3-1)}{k_3\,k_4-1} & -b_1 \end{pmatrix}$$

so the eigenvalues are

$$\lambda = -\frac{b_1}{2} \pm \frac{1}{2}\sqrt{\frac{4\,c_1 + 2\,c_1\,\beta - {b_1}^2 - 2\,c_1\,k_1\,k_4 - 2\,c_1\,k_2\,k_3 + {b_1}^2\,k_3\,k_4}{k_3\,k_4 - 1}}$$

where

$$\beta = \pm\sqrt{{k_1}^2\,{k_4}^2 - 2\,k_1\,k_2\,k_3\,k_4 + 4\,k_1\,k_2 - 4\,k_1\,k_4 + {k_2}^2\,{k_3}^2 - 4\,k_2\,k_3 + 4\,k_3\,k_4}$$

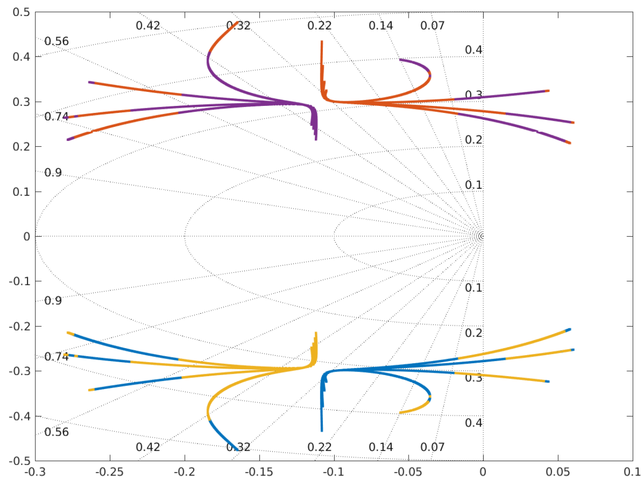

Fig. 2. Movement of eigenvalues towards the positive real axis. Test conditions are $m_1 = m_2 = 1$, $b_1 = .2$ $b_2 = .24$, $c_1 = c_2 = .1$, $k_1 = 2$, k_3 is set to the values -1.5 0 1 and 1.5. k_4 is varied between -0.1 and 0.5. Note that for values of k_3 below 1.5 the eigenvalues all move across into the positive half plane. Thus unusually a higher gain results in a more stable system, however this is at the expense of the forward position gain of the master-slave system.

3 Numerical simulation

Further insight is possible by numerical simulation. It is first assumed that the master and slave are independently stable via the linear controllers c_1 and c_2. Although the numerical simulation could enforce the master and slave to have identical plant and controller gains, a slightly less restrictive condition is investigated where the master and slave are simply close (in the sense of the damping values b_1 and b_2 having similar values. The simulations are all done with k_1 set to 2 so there is a position magnification of 2.

4 Discussion

In reality exoskeletons and telerobotics are non-linear thus further complicating the stability analysis. Local stability can be considered by linearising around a set of operating points however it is unlikely that a completely general stability condition can be set, in particular once other nonlinear effects start to manifest, in particular the discontinuous forces that result from the slave making contact with the environment. It is possible that gain scheduling via Linear parameter-varying control, or passivity estimators[2] may allow changing the gains to ensure stability of complete system across all operation modes.

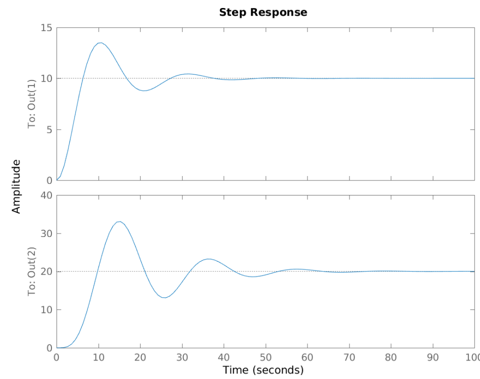

Fig. 3. Step response of the numerical system with only the position forward gain k_1. The response in this case can be seen to be stable with the master acting as a second order system and the response from the slave following a forth order response.

5 Conclusions

This paper outlines the control considerations for a bilateral force reflecting feedback mechanisms, in particular the eigenvalues of a simple telemanipulator with no attempt to convey slave forces back to the operator, and a force feedback approach that uses the controller error term as an indication of impedance. The paper outlines a convenient state-space representation of a simple master-slave telemanipulator that facilitates analysis.
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