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Brief paper

Passive position error correction in Internet-based teleoperation☆

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ABSTRACT

During the last two decades, important advances have been made in the field of bilateral teleoperation. Different techniques for performing stable teleoperation in non-ideal conditions have been developed, especially in a passivity framework. Until recently, however, no robust solutions for addressing this problem with variable delays and other drawbacks of packet-switched networks have been developed. The requirement of maintaining passivity in these circumstances degrades performance, due to the loss of energy that it involves. In this paper an arrangement is proposed which is capable of eliminating position errors, while maintaining passivity of an Internet-like channel. The behaviour of this new controller is studied by Lyapunov analysis, compared to previous methods, and validated through numerical simulations.

1. Introduction

Teleoperated systems follow a master–slave scheme, in which a slave manipulator reproduces the movements of a master manipulator commanded by an operator. In bilateral teleoperation (Hokayem & Spong, 2006) force feedback is provided to the operator, enabling him to feel the contacts with the environment. Modern bilateral teleoperation stems from Anderson and Spong (1989), where it was shown that if master and slave exchange power variables (such as force and velocity), the communications channel is not passive in the presence of time delays and may destabilize the whole system. The proposed solution was reformulated in Niemeyer and Slotine (1991) as the transmission of a pair of *wave variables*, which preserves passivity of the communications channel for constant time delays. Position error may arise due to different reasons (initial mismatch, contacts with the environment, numerical errors, …); and, since only the master velocity is transmitted – not its position – there is no way to recover from this error. Several improvements have been proposed to overcome this problem. In Niemeyer and Slotine (1997b) it was suggested to transmit the integrals of the wave variables, which encode position and momentum information. A modification of the wave commands (Niemeyer & Slotine, 1997a) was also proposed. In Yokokohji, Tsujioka, and Yoshikawa (2002) a similar method was presented, introducing the idea of using the energy produced by this solution to reduce the position error that appears after a communication blackout. In Chopra, Spong, Ortega, and Barabanov (2006) a modified architecture was proposed in which additional position signals were transmitted and proportional controllers were added on each side. A condition for stability of these controllers for constant time delays was given. In Secchi, Stramigioli, and Fantuzzi (2006) a method for compensating position errors in port-Hamiltonian bilateral teleoperation with constant time delays was proposed. The slave controller is modified by adding a virtual tank, which stores the energy dissipated in the resistive element. The state of the controller is augmented with a variable corresponding to the rest length of its elastic element, which is changed in order to compensate for the position error, while the required energy is extracted from the tank. In a recent extension (Secchi, Stramigioli, & Fantuzzi, 2008) this arrangement was modified to compensate for the errors caused by packet losses in the network, as well as by dissipation in the impedance controller. In Aziminejad, Tavakoli, Patel, and Moallem (2008) different wave transformation arrangements, resulting in admittance-type and hybrid-type teleoperation architectures, were examined. Some approaches that are not based on scattering have also appeared: in Nuño, Basáñez, and Ortega (2007)

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a scheme encoding position and integral of force was proposed, and in Chopra, Spong, and Lozano (2008) and Nuño, Ortega, and Basáñez (2010) the passivity-based architecture was extended to guarantee state synchronization of master/slave robots. Some common assumptions of these methods, such as constant time delays, or that the data arrives in the same order it is transmitted, limit their application.

The contribution of this paper is the development of a controller for improving position tracking in bilateral teleoperation via packet-switched networks. It is suited for the worst case scenario, i.e. for arbitrary time-varying delays, disordered packets and data losses; and, since it is based on passivity, it does not induce instability. The structure of this paper is as follows: first, preliminary considerations are made in Section 2. Then, the controller is presented in Section 3. The overall stability of the setup and the controller's ability to reduce the position error are analyzed in Section 4. Simulation results are shown in Section 5 along with some comments, and conclusions are presented in Section 6.

2. Preliminaries

Wave variables are the input and output terms (u, v) into which the power flow through a network element's port can be separated:

$$u = \frac{1}{\sqrt{2b}}(F + b\dot{x}), \qquad v = \frac{1}{\sqrt{2b}}(F - b\dot{x}). \tag{1}$$

Here, F and $\dot{x}$ are power variables (force and velocity), and b represents an impedance. Notice that (u^2, v^2) have units of power and, if h is the fixed sampling interval, u^2h, v^2h represent energy packets.

Suppose we want to use a packet-switched network as communications channel. In Munir and Book (2002) it was shown that the UDP protocol is more suitable for control purposes than TCP/IP; however, it fails to guarantee the order of arrival of the data packets, which can also be lost on the way. These problems – variable time delay, disordered packets and data losses – can destabilize the system if not properly treated. In order to preserve passivity, a lost packet should be replaced by a null packet, so that no additional energy is injected into the system. Even if there is no loss of packets, an empty sampling instance can appear due to increasing delay; in this case the same strategy should be adopted. The drawback of this "null packet" strategy is that it eliminates more energy than the "previous packet" one, thus degrading performance. In order to improve performance while maintaining passivity, the solution presented in Chopra, Berestesky, and Spong (2008) will be adopted. It consists of five modules: Subtractor, Interpolator, Buffer, Compressor and Expander, which are collectively labeled as SIBCE in Fig. 1. When a packet is lost, the interpolator produces a "null packet" instance, but the data contained in the lost packet will be recovered as soon as the next one arrives. When that happens, the energy will be distributed among the number of new samples, producing n samples of value $\hat{u} = \frac{\sum u - (\sum u)_{previous}}{t - t_{previous}} = \frac{\sum_{i=1}^{n} u_i}{n}$. The interpolator creates new samples guaranteeing that their energy (E') is not higher than that of the original samples (E), thus preserving passivity of the communications channel for arbitrary delays and losses:

$$E' = n\hat{u}^2 h = \frac{\left(\sum_{i=1}^{n} u(i)\right)^2 h}{n} \leq E = \sum_{i=1}^{n} u^2(i)h. \tag{2}$$

Assumption 1. From these results, detailed in Chopra et al. (2008), it can be assumed that for the scheme depicted in Fig. 1, and for the delay buffer in the channel from u_m to v_{s1}, the following holds:

$$E(k) - E(1) \leq \left[\sum_{i=1}^{k} u_m^2(i) - \sum_{i=1}^{k} v_{s1}^2(i)\right] h \tag{3}$$

where $E(k)$ is the energy stored at time $t = kh$ inside this delay buffer. A similar relation holds for the delay buffer in the channel from u_s to v_m.

3. Passive position error correction

3.1. Exploiting the energy margin

The previous section's arrangement is energy-dissipating: in order to assure passivity, the energy coming out of the interpolator is equal to *or less* than the incoming energy. Thus, a measurable *Energy Margin* (EM) is being generated. The correction proposed here consists of reusing this energy margin, injecting it back to the system. This recovered energy is transformed into a correction of the wave variable that is proportional to the position error. The energy of the resulting term is monitored so that it is not increased by a quantity larger than the available EM. In this way, passivity of the communications channel is guaranteed. A diagram of the teleoperation setup is depicted in Fig. 1, where this control action is labelled as "EM" and applies a correction v_{s4} on the wave variable v_{s3} (which is obtained after a possible correction v_{s2} is introduced on v_{s1} by a "Wave Trimmer" module, WT, to be described later). It is assumed, with no loss of generality, that the master device generates the position setpoint that must be followed by the slave device. The correcting algorithm is as follows:

- At each sampling instance a packet is created at the master side, containing the following data, $\left[\sum_{i=1}^{k} u_m(i), E_{ms}(k), x_m(k), k\right]$:
  . The sum of all the wave variables generated at the master side until that moment, $\sum_{i=1}^{k} u_m(i)$.
  . The energy of all the previously sent wave variables, $E_{ms}(k) = \sum_{i=1}^{k} u_m^2(i)h$.
  . The value of the position command, $x_m(k)$.
  . The sampling instance, k.
- This packet is sent through the communications channel to the slave side, where it is read. The position error is then calculated as:

  $$e(k) = x_{md}(k) - x_s(k) \tag{4}$$

  where subscript d denotes a delayed signal, i.e. $x_{md}(k) = x_m(k - n_d)$, where n_d is the number of sampling instances that the packet is delayed (n_d is not constant, but we choose to write n_d instead of $n_d(k)$ for ease of notation). Then, a control term proportional to this position error is obtained as $v_s'(k) = K_{EM}e(k)$, where the constant K_{EM} is a design parameter. This term is the provisional wave correction and will be added to the value of the received wave variable, v_{s3}, provided that there is some energy margin available. The provisionally modified wave is $v_s''(k) = v_{s3}(k) + v_s'(k)$.
- In order to assure passivity of the communications channel, its outgoing energy must be equal to or less than the incoming energy. The energy injected by the modified wave variable is $(v_s''(k))^2h$, this is:

  $$E'(k) = [v_{s3}(k) + K_{EM}(x_{md}(k) - x_s(k))]^2 h,$$

  while the energy margin is defined as:

  $$EM(k) = \left[E_{ms}(k - 1 - n_d) - \sum_{i=1}^{k-1} v_{s3}^2(i)\right] h. \tag{5}$$

  If the injected energy does not make the energy balance from v_{s3} to v_s larger than the energy margin, the wave