BILATERAL CONTROL AND FORCE FEEDBACK ON ROBOTS: AN ANALYSIS

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ABSTRACT

Telerobotics is perhaps one of the earliest aspects of robotics. Literally meaning robotics at a distance, it is generally understood to refer to robotics with a human operator in control or human-in-the-loop. Any highlevel, planning, or cognitive decisions are made by the human user, while the robot is responsible for their mechanical implementation. In essence, the brain is removed or distant from the body. An emphasis is taken on bilateral control and force feedback, which is a vital research field today.

BILATERAL CONTROL AND FORCE FEEDBACK

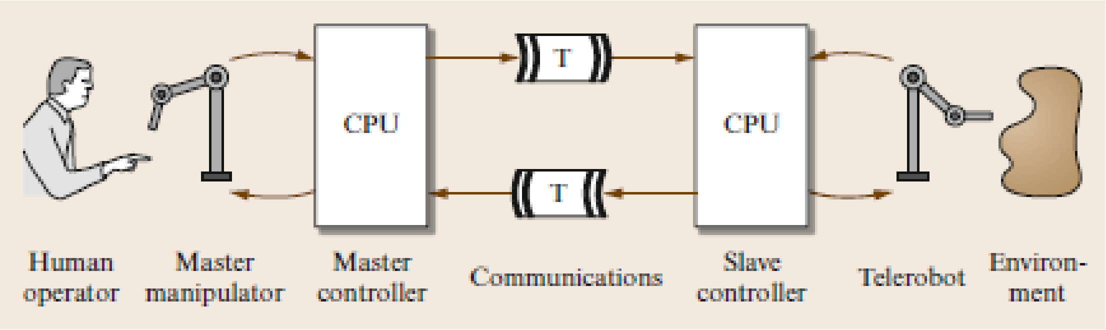

Fig. 1. Bilateral teleoperator

In pursuit of telepresence and to increase task performance, many master–slave systems incorporate force feedback. That is, the slave robot doubles as a sensor and the master functions as a display device, so that the system provides both forward and feedback pathways from the user to the environment and back. Figure 1 depicts the common architecture viewed as a chain of elements from the user to the environment. The bilateral nature of this setup makes the control architecture particularly challenging: multiple feedback loops form and even without environment contact or user intervention, the two robots form an internal closed loop. The communications between the two sites often inserts delays into the system and this loop, so that stability of the system can be a challenging issue. To present force information without stability problems, it is possible to use alternate displays, such as audio or tactile devices. Meanwhile, the combination of vibro tactile methods with explicit force feedback can increase high-frequency sensations and provide benefits to the user. Tactile shape sensing and display also extends the force information presented to the user. In the following we discuss explicit force feedback. We first examine the basic architectures before discussing stability and some advanced techniques.

POSITION/FORCE CONTROL

Two basic architectures couple the master and slave robots: position–position and position–force. We assume that the robot tips are to be connected by the equations, giving the control laws for translation. Control of orientation or joint motions follows equivalent patterns.

Position–Position Architecture

In the simplest case, both robots are instructed to track each other. Both sites implement a tracking controller, often a proportional-derivative (PD) controller, to fulfill these commands:

$$\mathbf{F_m = -K_m(x_m - x_{md}) - B_m(\dot{x}_m - \dot{x}_{md})}$$
$$\mathbf{F_s = -K_s(xs - x_{sd}) - B_s(\dot{x}_s - \dot{x}_{sd})}$$

If the position and velocity gains are the same (**K**m = **K**s = **K**, **B**m = **B**s = **B**), then the two forces are the same and the system effectively provides force feedback. This may also be interpreted as a spring and damper between the tips of each robot. If the two robots are substantially different and require different position and velocity gains, the master–slave forces will be scaled and/or distorted. Note we have assumed the slave is under impedance control and back-drivable. If the slave is admittance controlled, i. e., it accepts position commands directly, the second part of is unnecessary. Also note that by construction the user feels the slave's controller forces, which include forces associated with the spring–damper and slave inertia in addition to environment forces.

Indeed while moving without contact, the user will feel the inertial and other dynamic forces needed to move the slave. Furthermore, if the slave is not back-drivable, i.e., does not easily move under environment forces, the environment force may be entirely hidden from the user. Naturally this defeats the purpose of force feedback. In these cases, a local force control system may be used to render the slave back-drivable. Alternatively, a position–force architecture may be selected.

Position–Force Architecture

In the position–position architecture, the user is presented with the slave's controller force. While this is very stable, it also means the user feels the friction and inertia in the slave robot, which the controller is actively driving to overcome. In many scenarios this is undesirable. To avoid the issue, position–force architectures place a force sensor at the tip of the slave robot and feedback the force from there. That is, the system is controlled by

$$\mathbf{F_m = F_{sensor}\ ,}$$
$$\mathbf{F_s = -K_s(x_s - x_{sd}) - Bs(xs - \dot{x}_{sd})}$$

This allows the user to only feel the external forces acting between the slave and the environment and presents a more clear sense of the environment. However, this architecture is less stable: the control loop passes from master motion to slave motion to environment forces back to master forces. There may be some lag in the slave's motion tracking not to mention any delay in communications. Meanwhile the loop gain can be very high: a small motion command can turn into a large force if the slave is pressing against a stiff environment. In combination, stability may be compromised in stiff contact and many systems exhibit contact instability in these cases.

PASSIVITY AND STABILITY

The two basic architectures presented in previous section, clearly illustrate one of the basic tradeoffs and challenges in force feedback: stability and performance. Stability issues arise because any models of the system depend on the environment as well as the user. Both these elements are difficult to capture and, if we assume we want to explore unknown environments, impossible to predict. This issue makes a stability analysis very difficult. A common tool that avoids some of this issue is the concept of passivity. Although passivity provides only a sufficient (not a necessary) condition for stability, it incorporates the environmental uncertainly very well. Passivity is an intuitive tool that examines the energy flows in a system and makes stability assertions if energy is dissipated instead of generated. Three rules are of importance here. First, a system is passive if and only if it can not produce energy. That is the output energy from the system is limited by the initial and accumulated energy in the system. Second, two passive systems can be combined to form a new passive system.

Third, the feedback connection of two passive systems is stable. In the case of telerobotics, we generally assume that the slave robot will only interact with passive environments. Without the human operator, stability can therefore be assured if the system is also passive, without needing an explicit environment model. On the master side the operator closes a loop and has to be considered in the stability analysis. In general, the master robot will be held by the user's hand and arm. A variety of models and parameters describe the human arm dynamics, mainly in the form of a mass–damper–spring system. In we find a summary of model parameters used by different authors. For an impedance-controlled haptic interface, common to most systems, the worst-case scenario for stability is the situation when the operator is not holding the haptic device. Thus we may elect to ignore the human operator in the analysis, assuming the human force equals zero (**F**human = 0). A system then found to be stable will also be stable if the operator is interacting with the device. We choose a sign convention, such that the power at every boundary is positive if flowing to the right. For example, at the first boundary, the positive power flow is the product of master velocity times applied (human) force

$$\mathbf{P}_{\mathbf{left}} = \mathbf{x}_{\mathbf{m}}^{\mathbf{T}}\mathbf{F}_{\mathbf{human}}$$

Meanwhile at the last boundary, the positive power flow is the product of the slave velocity times the environment force (which ultimately opposes the human force)

$$\mathbf{P}_{\mathbf{right}} = \mathbf{x}_{\mathbf{s}}^{\mathbf{T}}\mathbf{F}_{\mathbf{env}}$$

To simplify the analysis, we can examine the passivity of each two-port element and then deduce the overall passivity. The master and slave robots are mechanical elements and hence passive. The controllers of a position–position architecture mimic a spring and damper, which are also passive elements. So without delay, a position–position architecture is passive. While powerful to handle uncertainty, passivity can be overly conservative. Many controllers are overdamped if every subsystem is passive. In contrast, the combination of an active and a passive sub system may be passive and stable and show less dissipation. From network theory, the Llewellyn criterion specifies when a possibly active two-port connected with any passive one-port becomes passive.

This two-port is then labeled unconditionally stable, as it will be stable in connection to any two passive one-ports. The Llewellyn criterion may hence be used as a more general stability test for telerobotic systems or components. Passive controllers are also limited as they cannot hide the dynamics of the slave robot. In the above position–position architecture, the user will feel the forces associated with the slave inertia. In contrast the position–force architecture hides the slave inertia and friction from the user. As such, when the user inserts kinetic energy into the master without feeling any resistance, the system itself creates and injects the kinetic energy for the slave. This violates passivity and provides another insight as to why the architecture suffers from potential stability problems.

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