Bilateral Matched-Impedance Teleoperation with Application to Excavator Control

S.E. Salcudean, K. Hashtrudi-Zaad, S. Tafazoli
S.P. DiMaio, and C. Reboulet†
Department of Electrical and Computer Engineering
University of British Columbia
Vancouver, BC, V6T 1Z4, Canada
tims@ece.ubc.ca , *keyvanh@ece.ubc.ca*

† Département de Commande des Systèmes et Dynamique du Vol de l'Office National d'Etudes et Recherches Aérospatiale
2 avenue Edouard Belin
31055 Toulouse, France

Introduction

This paper addresses issues of transparency and implementation of dual-hybrid teleoperation. A method for automatically adjusting the master and slave impedances to match stiff and soft environments and to interpolate between them is presented and evaluated using simulations. The application of this technique to the force-feedback control of a mini-excavator is also presented and discussed, including supporting experimental results.

Since its introduction in the 1940s, the field of teleoperation has expanded its scope to include manipulation at different scales and in virtual worlds. Teleoperation has been used in the handling of radioactive materials, sub-sea exploration and servicing. Its use has also been demonstrated in space, construction, forestry, mining, and microsurgery.

The goal of teleoperation is to achieve "transparency" by mimicking human motor and sensory functions. When manipulating a tool, transparency is achieved if the operator cannot distinguish between maneuvering the master controller and maneuvering the actual tool. Transparency can be defined as a perfect match of the environment impedance to that transmitted to the operator's hand [1].

Studies have shown that to achieve transparency as defined by impedance matching, fixed controllers require a four-channel architecture that communicates the sensed forces and

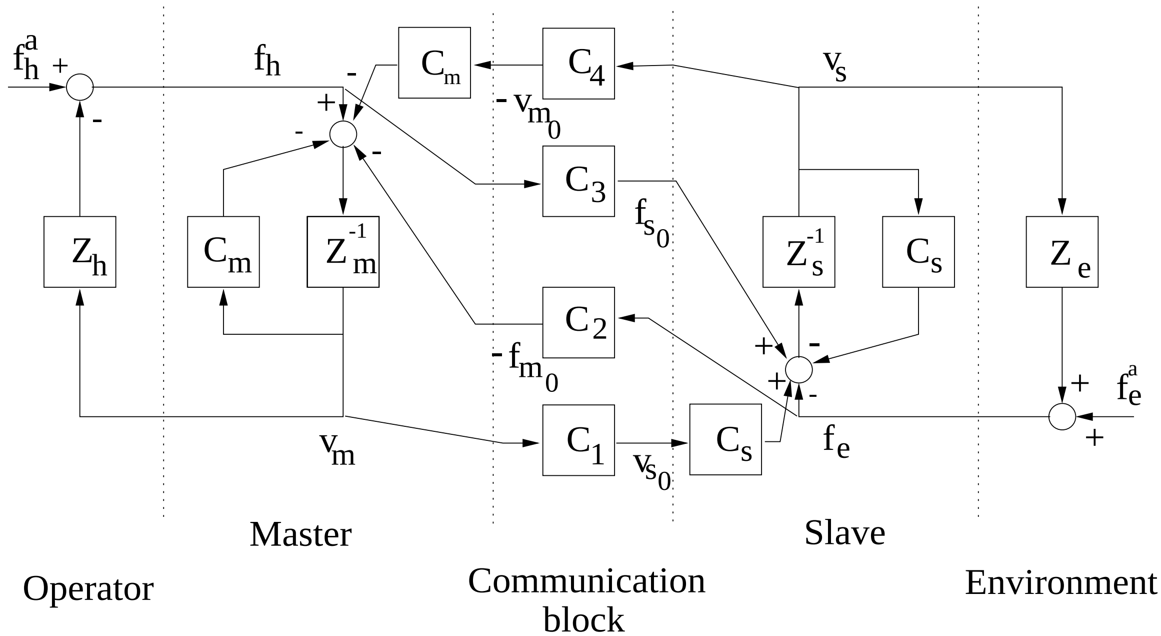

Figure 1: Four-channel teleoperation system.

positions from the master to the slave, and vice-versa [1, 2]. Recently, it has been proven that the use of local force feedback at the master or slave side allows the elimination of one of the force channels without affecting transparency [3]. The design of fixed transparent controllers is still an open research problem. Many approaches have been proposed (see [4] for a limited survey), but none produce robust, satisfactory performance.

As an alternative approach, a transparent bilateral impedance control architecture was proposed in [5]. Since then, only a few adaptive controllers that build upon this architecture have been reported [6, 7, 8, 9]. As shown in [6], this is partly due to the difficulties encountered in developing environment impedance estimators that converge fast enough for contact tasks. The design problem is compounded further by the presence of communication delays.

Dual-hybrid teleoperation is a recent control approach that allows stable bilateral teleoperation under moderate time delays [10]. It requires a qualitative model of the environment and provides the user with kinesthetic feedback by splitting the master and slave domains into dual force-controlled and position-controlled subspaces without closing feedback loops through the teleoperator communication block.

In this paper, the concept of dual-hybrid teleoperation is interpreted in the context of the four-channel architecture. It is shown that, for very high or very low environment impedances, an accurate impedance estimate is not necessary, as this is likely outside the dynamic range of the master and/or the human sensory system. A simple method of adjusting the master and slave impedances to match the environment and hand impedances is presented. The effectiveness of this "matched-impedance" teleoperation approach is shown using a haptic interface and a simulated slave. In related work, a simple scheme for damping adjustment in bilateral teleoperators is presented in [11].

One area of application of force-feedback teleoperation is the control of excavators, where it is expected that significant productivity gains can be realized by enabling the operator to feel the forces on the excavator bucket via an active joystick [12, 13]. Therefore, experimental results with a Takeuchi mini-excavator were carried out and are also presented. The results show that the machine can indeed be controlled in impedance or force mode and a simple leveling task is performed while the machine and joystick are controlled in matched-impedance teleoperation mode.

The paper is organized as follows. First, transparency and dual-hybrid teleoperation are discussed. Then, the matched-impedance teleoperation approach is introduced and simulation results are presented. Experiments with an excavator controlled in impedance mode are described next. Finally, conclusions are drawn and future work is discussed.

Transparency and Dual-Hybrid Teleoperation

Consider the teleoperation system described schematically in Fig. 1. Lumped linear time-invariant models are assumed throughout.

The operator and environment dynamics are modeled by Thevenin equivalents having impedances Z_h and Z_e, and exogenous force inputs f_h^a and f_e^a, respectively:

$$\begin{aligned} f_h &= f_h^a - Z_h v_m \\ f_e &= f_e^a + Z_e v_s \ , \end{aligned}$$

where v_m and v_s are the master and slave velocities, f_h is the force applied by the operator on the master, and f_e is the force applied by the slave on the environment.

The master and slave manipulators are assumed to be controlled in impedance mode with dynamics given by:

$$\begin{aligned} Z_m v_m &= C_m(v_{m0} - v_m) + f_h + f_{m0} \\ Z_s v_s &= C_s(v_{s0} - v_s) + f_{s0} - f_e \ , \end{aligned} \tag{1}$$

where Z_m and Z_s are the master and slave mechanical impedances, C_m and C_s are the master and slave compensators acting on velocity errors and v_{m0}, f_{m0}, v_{s0} and f_{s0} are commanded velocity and forces.

A "four channel" architecture is assumed [1], with forces and position signals being communicated between the master and the slave, as follows:

$$\begin{aligned} v_{s0} &= C_1 v_m \\ f_{m0} &= -C_2 f_e \\ f_{s0} &= C_3 f_h \\ v_{m0} &= -C_4 v_s \ . \end{aligned} \tag{2}$$

The master, communication and slave blocks described in Fig. 1 form a two-port network terminated by the operator and environment one-port network models. The dynamics of this two-port network can be described in hybrid matrix form as follows [5]:

$$\begin{bmatrix} f_h \\ -v_s \end{bmatrix} = \begin{bmatrix} Z_{m0} & G_f^{-1} \\ G_p & Z_{s0}^{-1} \end{bmatrix} \begin{bmatrix} v_m \\ f_e \end{bmatrix} ,$$

where Z_{m0} and G_p are the master impedance and position gain, respectively, with the slave in free motion, and G_f^{-1} and Z_{s0}^{-1} are the inverse force gain and slave admittance, respectively, with the master fully constrained.

If the environment has no exogeonous component, or $f_e = Z_e v_s$, the impedance transmitted to the operator's hand $f_h = Z_{th} v_m$ is given by

$$Z_{th} = Z_{m0} - G_f^{-1}(Z_e^{-1} + Z_{s0}^{-1})^{-1} G_p \ . \tag{3}$$

In terms of the parameters in (1) and (2), (3) becomes

$$Z_{th} = [I - (C_2 Z_e + C_m C_4)(Z_s + C_s + Z_e)^{-1} C_3]^{-1} \times$$

$$[(C_2 Z_e + C_m C_4)(Z_s + C_s + Z_e)^{-1} C_s C_1 + (Z_m + C_m)] \ .$$

In the scalar case, the hybrid parameters can be obtained as in [1],

$$\begin{aligned} Z_{m0} &= \frac{(Z_m + C_m)(Z_s + C_s) + C_s C_1 C_m C_4}{Z_s + C_s - C_3 C_m C_4} \\ G_f^{-1} &= \frac{(Z_s + C_s) C_2 - C_m C_4}{Z_s + C_s - C_3 C_m C_4} \\ G_p &= -\frac{C_3 (Z_m + C_m) + C_s C_1}{Z_s + C_s - C_3 C_m C_4} \\ Z_{s0}^{-1} &= \frac{1 - C_2 C_3}{Z_s + C_s - C_3 C_m C_4} , \end{aligned}$$

and

$$Z_{th} = \frac{A + B Z_e}{C + D Z_e}$$

with

$$\begin{aligned} A &= (Z_s + C_s)(Z_m + C_m) + C_1 C_s C_4 C_m \\ B &= (Z_m + C_m + C_1 C_s C_2) \\ C &= (Z_s + C_s - C_3 C_4 C_m) \\ D &= (1 - C_2 C_3) \ . \end{aligned}$$

The teleoperation system is *transparent* if (i) the slave follows the master (*i.e.*, $G_p = -n_p I$ for position control and $G_p = -n_p I/s$ for velocity control (the master position controls the slave velocity), where n_p is a scaling factor, and (ii) if Z_{th} is equal to Z_e for any environment impedance Z_e [5, 14] (or, alternatively, $Z_{th} = Z_{t0} + Z_e$, where Z_{t0} is a "tool" impedance, usually taken to be Z_m [14]).

In special cases, such as identical master and slave dynamics, it is possible to design *fixed controllers* that provide *perfect* transparency [1], even when the slave manipulator is controlled by the master in velocity mode [14]. However, controller design is difficult (all teleoperation "channels," C_sC_1, C_2,C_3 and C_mC_4, must be nonzero) and the stability robustness is quite poor. Recent studies showed that by using master or/and slave local force feedback, the forces transmitted through the communication channel may be reduced without affecting transparency. This may result in a class of perfectly transparent three-channel control architectures in which one of the force feedforward channels is cancelled ($C_2 = 0$ or $C_3 = 0$) [3]. As an alternative, techniques using environment identification have been proposed [6, 7, 8, 9] based on the architecture presented in [5]. Such schemes rely on the identification of the environment impedance and its duplication at the master. At least with conventional identification approaches, it was found that environment identification converges slowly has high sensitivity to delays, and therefore is unsuitable when the environment changes fast, as is the case when manipulating stiff constrained objects [6].

For directions in which Z_e is known, the environment impedance does not need to be identified. In particular, in directions in which Z_e is known to be small (*e.g.,* free motion), the master should act as a force source/position sensor and have low impedance, whereas the slave should behave as a position source/force sensor and have high impedance. Thus C_m, Z_m should be small, whereas C_s should be large, implying that positions are sent to the slave, and forces are returned to the master, with $C_3 = C_4 = 0$. Under these conditions, $G_f^{-1} \approx C_2$, $G_p \approx -C_1$, and $Z_{th} \approx Z_m + C_m$ and is small (as small as $Z_m + C_m$ can be made while maintaining stability of the master). Note that not much changes in the above if C_2 is set to zero, since the returned forces are small.

The dual situation applies in directions in which Z_e is known to be large (*e.g.,* constrained motion). In those directions, the master should act as a force sensor/position source and have high impedance, with forces being sent to the slave and positions being returned to the master. Thus C_m should be large, and C_s, Z_s should be small, implying that forces are sent to the slave and positions are returned to the master, with $C_1 = C_2 = 0$. Under these conditions, $G_f^{-1} \approx 1/C_3$, $G_p \approx 1/C_4$, and $Z_{th} \approx (Z_m + C_m)$ and is large (as large as $Z_m + C_m$ can be made while maintaining stability of the master). Note that not much changes in the above if C_4 is set to zero, since the returned velocities are small.

Although not considered from a transparency perspective, this concept of "dual-hybrid teleoperation" has been introduced, studied and demonstrated experimentally in [10]. It has been shown that when the geometric constraints for a teleoperation task are known, the master and slave workspaces can be split into dual position-controlled and force-controlled subspaces ($C_2 = 0$ if Z_e is small, $C_4 = 0$ if Z_e is large), and information can be transmitted unilaterally in these orthogonal subspaces while still providing useful kinesthetic feedback to the operator [10]. The drawback of the method is the need to define the dual subspaces for specific tasks. This can be done using high-level software for typical manufacturing tasks, as described in [10] and references therein, but is more difficult in unstructured environments such as encountered in construction, mining and forestry. Note that in the dual-hybrid teleoperation approach, feedback loops need not be closed through the teleoperator communication block, making this method very attractive when time delays are present.

Matched-Impedance Teleoperation

The goals of dual-hybrid teleoperation are met if both forces and velocities are transmitted between the master and the slave, and the master and slave target impedances are adjusted in a dual manner to "match" the impedances of the environment or hand.

Consider first the scalar case and assume that the master and slave can be controlled in impedance mode to realize controlled master and slave target impedances $(Z_m + C_m)(\gamma_m)$ and $(Z_s + C_s)(\gamma_s)$ in (1), parametrized by real-valued vectors γ_m and γ_s. The parameters γ_m and γ_s are such that the impedances $(Z_m + C_m)(\hat{\gamma}_m)$ and $(Z_s + C_s)(\hat{\gamma}_s)$ are as high as possible, and $(Z_m + C_m)(\check{\gamma}_m)$ and $(Z_s + C_s)(\check{\gamma}_s)$ are as low as possible, while maintaining stability for all environments likely to be encountered. The meaning of "high" and "low" could be defined in an appropriate manner. The control parameters may affect Z_m and Z_s through the use of local force feedback, not illustrated in Fig. 1. Suppose the master and slave target impedances are adjusted as follows:

$$
\begin{array}{lrcl}
\text{If } |f_e| > G|v_s| & & \text{and} & |f_e| > f_{min} \\
& \lambda_s & = & \dfrac{G|v_s|}{|f_e|} \\
& \gamma_s & = & \check{\gamma}_s + \dfrac{1}{2}\lambda_s(\hat{\gamma}_s - \check{\gamma}_s) \\
& \gamma_m & = & \hat{\gamma}_m + \dfrac{1}{2}\lambda_s(\check{\gamma}_m - \hat{\gamma}_m) \\
\text{If } G|v_s| > |f_e| & & \text{and} & G|v_s| > f_{min} \\
& \lambda_s & = & \dfrac{|f_e|}{G|v_s|} \\
& \gamma_s & = & \hat{\gamma}_s + \dfrac{1}{2}\lambda_s(\check{\gamma}_s - \hat{\gamma}_s) \\
& \gamma_m & = & \check{\gamma}_m + \dfrac{1}{2}\lambda_s(\hat{\gamma}_m - \check{\gamma}_m) \\
\text{Else} & \gamma_s & = & \dfrac{1}{2}(\check{\gamma}_s + \hat{\gamma}_s) \\
& \gamma_m & = & \dfrac{1}{2}(\check{\gamma}_m + \hat{\gamma}_m)\ ,
\end{array}
\qquad (4)
$$

where G is a scaling parameter that can be thought of as the magnitude of a nominal environment impedance or can be set as the ratio of the maximum expected slave environment force to the maximum expected slave velocity. As seen from (4), G is the minimum amount of information needed from the environment to design the controller. The threshold force f_{min} is needed to avoid an ill-defined λ when both the velocity and force are small. Note that since the impedance matching or adaptation in (4) directly incorporates the instant values of the velocity and force without adding dynamic to the controller, it does not produce additional time delay in the teleoperation system.

Then, when $|f_e| \gg G|v_s|$ (*i.e.*, the slave is in contact with a high-impedance environment), the slave will have low impedance and will track force commands. As the force decreases in size relative to velocity, the slave impedance increases. When $G|v_s| \gg |f_e|$ (*i.e.*, the slave is in free motion), the slave it will have high impedance and will track position commands. The dual situation applies to the master. Qualitatively speaking, by (4), the environment is emulated at the master and the operator at the slave. As Hogan has discussed in [15], in the interaction between two objects, one acts as impedance and the other as admittance. In our case, if the slave is an impedance (admittance), the environment will act as an admittance (impedance), and since the master emulates the environment, it should act as an admittance (impedance).

In terms of system stability, no analysis has been performed. In the above, it is assumed that $(Z_m + C_m)(\gamma_m)$, $(Z_s + C_s)(\gamma_s)$, and the bilateral teleoperation system are all stable for all $\gamma_m \in [\check{\gamma}_m, \hat{\gamma}_m]$, $\gamma_s \in [\check{\gamma}_s, \hat{\gamma}_s]$ and for all hand and environment impedances likely to be encountered.

Evaluation of Matched-Impedance Teleoperation using a Virtual Slave

The above impedance adjustment technique was evaluated by using a teleoperation system consisting of a magnetically levitated (Maglev) master and a virtual slave. On the one hand, a virtual slave and virtual environments were selected as a simple means of applying known and programmable environment impedances. This approach also allows easy monitoring of the control variables in 4. On the other hand, an actual force-feedback hand controller was used because the variability of hand impedance with grasp and applied forces would make it difficult to simulate the operator.

The Maglev master has a handle actuated in parallel by six voice coils. The handle, whose position is sensed by an optical sensor, is actively levitated by a real-time controller [16]. The levitated handle can be accurately modelled as a single mass ($Z_m = m_m s = 0.6kg$).

The virtual slave, implemented on a real-time system, simulated another mass ($Z_s = m_s s = 6$ kg). The motion of the virtual slave was displayed on a graphics workstation as the displacement of the bucket of an excavator Fig. 2.

PD controllers $C_m = b_m + k_m/s$ and $C_s = b_s + k_s/s$ were implemented at the master and slave, with $Z_m + C_m = m_m(s^2 + 2\zeta_m s\omega_m + \omega_m^2)$ and $Z_s + C_s = m_s(s^2 + 2\zeta_s s\omega_s + \omega_s^2)$

Figure 2: Photograph of the simulation setup.

parametrized by characteristic frequencies ω_m and ω_s lying in prespecified intervals between "soft" and "stiff" extremes. The damping ratios ζ_m and ζ_s were kept fixed.

Scaled positions and forces were sent from the master to the slave, and vice versa, according to the four-channel controller of 2, with $C_1 = 100$, $C_2 = 10$, $C_3 = 1/10$, and $C_4 = 1/100$.

The impedance adjustment described in (4) was implemented with $\gamma_m = \omega_m$ and $\gamma_s = \omega_s$.

Fig. 3 displays the outcome of an experiment in which the master was moved up and down along the vertical axis, while the environment the slave encountered had five different stiffness levels, depending on the depth of the slave. For $x_s \geq 0$m, the environment stiffness was 0. For $0 > x_s \geq -0.1$m, the environment stiffness was 10 N/m. For $-0.1\text{m} > x_s \geq -0.2$m, the environment stiffness was 100 N/m. For $-0.2\text{m} > x_s \geq -0.3$m, the environment stiffness was 500 N/m. For $-0.3\text{m} > x_s$, the environment stiffness was 1000 N/m. The characteristic frequency ω_s of $Z_s + C_s$, the environment force acting on the slave f_e, the slave velocity v_s, and the scaled master and slave positions $100x_m$ and x_s and are being displayed.

Position tracking in free motion (t less than 10 s), and force tracking in constrained motion (t larger than 14 s) have been observed, with tracking errors of the order of 2 %. The "softening" of the slave impedance as the slave penetrates the environment can be verified. The impedance adjustment law (4) provides high stiffness in free motion, with good position tracking, and high compliance in constrained motion, with good force tracking. The

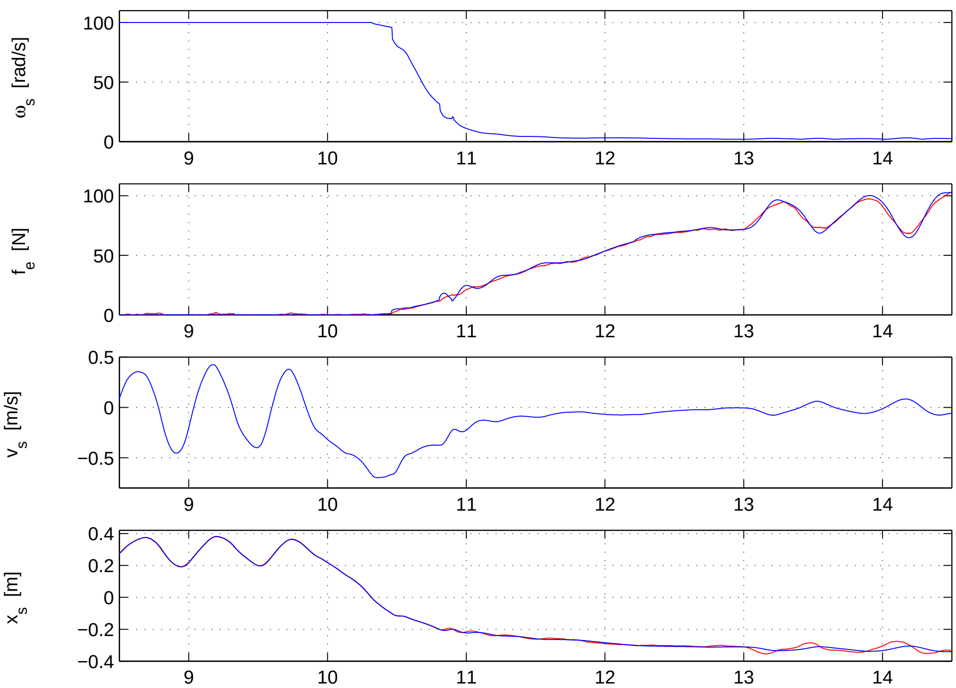

Figure 3: Matched-impedance simulation results. Correspondences between desired/commanded (red) and actual (blue) force and position trajectories are shown.

interpolation between these two extremes achieves a compromise between position and force tracking when the slave moves through a compliant environment (such as digging with an excavator), when both tracking of forces and positions are desired. In addition, less chattering in contact tasks is observed than when using a simple force thresholding technique. This is because following contact, the manipulator needs to build up enough speed before it is switched back into position control.

Experiments with a Teleoperated Excavator

A position-based impedance controller for excavator-type manipulators has been previously developed by the authors [17]. The controller structure is briefly reviewed in this section, and experimental results are presented for position and force tracking in a contact regime.

Machine Instrumentation

Figs. 4 and 5 show a photograph and the schematic of the instrumented Takeuchi TB035 mini-excavator used for the experiments. This work is concerned only with movement of the

Figure 4: Photograph of the UBC mini-excavator performing a leveling task on a piece of lumber.

backhoe links (boom, stick, and bucket) in the vertical plane. The pilot system for the main valves of the arm cylinders has been modified for computer control by employing ON/OFF valves operated in differential pulse-width modulation mode (DPWM) [18, 19]. A VME-based computer running the VxWorks real-time operating system is being used to control the machine.

Position Control

The position of the bucket tip and the orientation of the bucket link relative to the horizontal plane are the task space variables (R_t, Z_t and α in Fig. 5) being controlled. Since the hydraulic cylinders behave like velocity sources, the range of attainable arm impedances is better when a position-based impedance control scheme is used [20]. Therefore, inner-loop cylinder position controllers were implemented. Cylinder extensions are determined from the joint angles using a polynomial mapping [21].

Experiments showed that simple PD control with different feedback gains for extension and retraction regimes and with deadband compensation (for the main valve spool) results in satisfactory cylinder position tracking performance [22]. With these position controllers, the cylinders can be modeled as velocity sources with the linear closed loop dynamics $l(s) = P(s)l_d(s)$, where $l = [l_{boom},\ l_{stick},\ l_{bucket}]^T$ is the vector of actual cylinder extensions, l_d is the vector of desired cylinder extensions, and $P(s)$ is the diagonal transfer function matrix which can be identified experimentally as reported in [22].

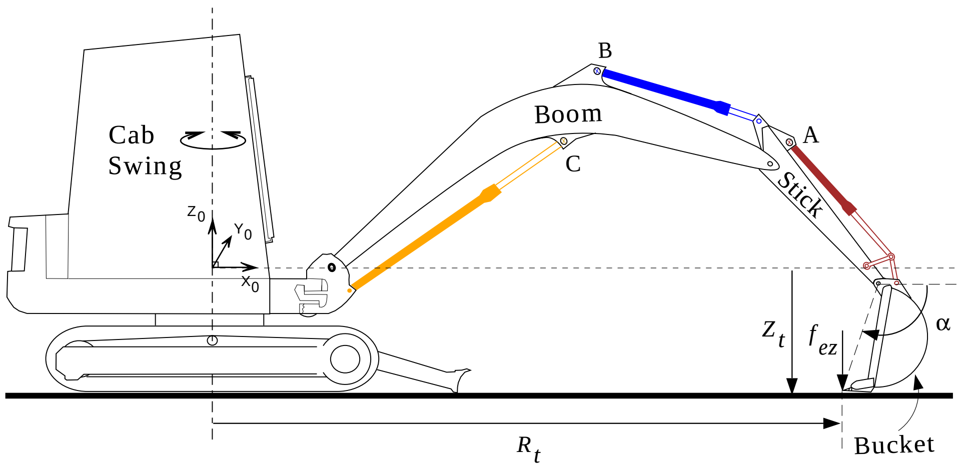

Figure 5: Mini-excavator schematic. Load pins are installed at A, B, and C to measure cylinder forces, and resolvers are installed to measure the boom, stick, and bucket angles.

Impedance Control

A desired (target) task-space impedance C_s is assumed. Using a linearized model for manipulator dynamics, the following position-based impedance controller

$$\begin{aligned} l_d &= \widehat{P^{-1}}[J^T(sZ_s + sC_s - sZ_r)J]^{-1} \\ &\quad [J^T sC_s x_0 + J^T f_0 - f_c + J_c\tau_g] \;, \end{aligned} \tag{5}$$

was developed and applied to the cylinders to implement the slave dynamics (1), where Z_r is the excavator arm mass impedance, $\widehat{P^{-1}}(s)$ is a stable approximation to the inverse of $P(s)$, J is the manipulator Jacobian, J_c is the cylinder Jacobian, $f_0 = f_{s0}$, $x_0 = \frac{v_{s0}}{s}$, f_c is the cylinder force vector (sensed by load pins), and τ_g is the gravity joint torque, which can be evaluated as a function of joint coordinates q and a set of inertial parameters ψ which were previously identified using a least-squares fit of joint angle and cylinder force data [18, 21] [1].

With the choice of $Z_s = Z_r$, the slave impedance control law of equation (5) is simplified and is shown in Fig. 6. As it is seen, the error between the force command f_0 and the calculated bucket-tip force $J^{-T}(J_c^T\tau_g - f_c)$ is passed through the target impedance filter C_s. The resultant Cartesian position disturbance is added to the position command x_0 to yield the desired cylinder extension l_d. The implemented impedance is in fact a second-order impedance C_s plus the inertia of the excavator arm (stiffness and damping control).

[1] Details of the control design and stability analysis can be found in [17, 22].

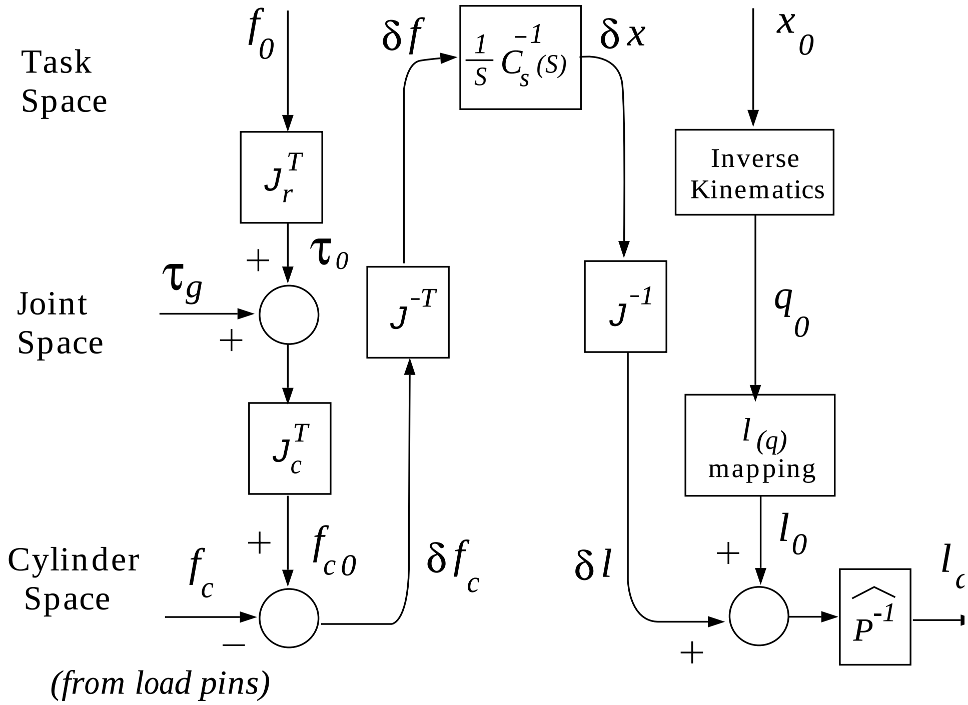

Figure 6: The implemented position-based impedance controller.

Impedance Control Experiments

First, experiments were carried out to illustrate the effectiveness of the task-space impedance control of the excavator. For a prototype leveling task, the operator would move the bucket radially back and forth while exerting a normal force on the ground. The radial position R_t of the bucket tip, the bucket orientation α, and the vertical forces f_{ez} against the ground should be controlled. The impedance controller (5) was implemented with $\widehat{P^{-1}} = I$ along the elevation axis Z_t, and $Z_s = Z_r$ and $C_s = 400s + 10,000 + 10,000/s$, where SI units are used throughout.

A piece of lumber was laid on the ground in front of the excavator arm at an approximate elevation $Z_t = -1$, as shown in Fig. 4. A desired trajectory as shown with dash-dot lines (black) in Fig. 7 was commanded, and the desired force was set to zero. Only the bucket tip was in contact with the wood, in accordance with the kinematics and Jacobian calculations used in the controller. Fig. 7 shows the bucket tip position and force trajectories for both position control (red solid lines) and impedance control (blue dashed lines). It can be seen that in the impedance mode the bucket trajectory does comply with the environment constraint, and transient and steady-state forces are small. In contrast, in position control mode, interaction forces are significantly higher, and because the arm does not comply with

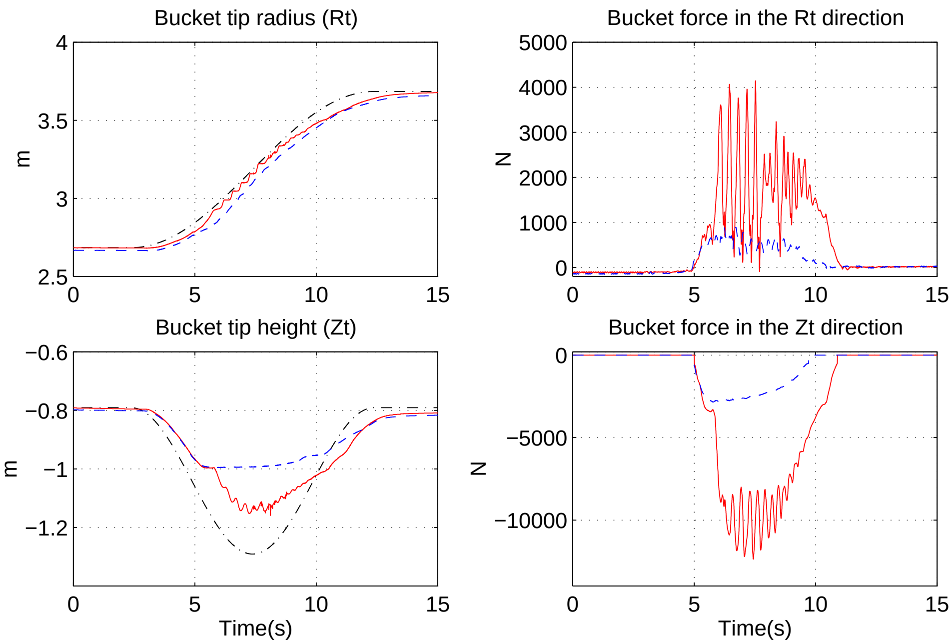

Figure 7: Leveling experiment: desired tranjectories plotted in dash-dot lines (black), position control results plotted in solid lines (red), and impedance control results plotted in dashed lines (blue).

the constraint, the machine cab tilts up during position control [17]. Note that in spite of the environment friction in R_t direction, which is proportional to the normal force f_{ez}, position tracking in this degree of freedom is satisfactory. The target impedance used in the above-explained experiment was quite conservative. Since the impedance setting actually adds to the arm inertia, it is desirable to choose the mass term in C_s as low as possible so that the impact forces are low. Experiments showed that the mass component in C_s can be easily set to zero. Employing off-line identification, the environment impedance ($Z_e = B_e + K_e/s$) coefficients were found to be in the range of $B_e < 500(Ns/m)$ and $10^5 < K_e(N/m)$. On the other hand, the target impedance parameters that still preserve stability in contact were found to be in the approximate range of $B_d > 3000(Ns/m)$ and $10^4 < K_d < 10^5(N/m)$. Thus, one is able to choose a target stiffness about 10 times lower than that of the environment.

Bilateral Matched-Impedance Control Experiments

Experiments on a tele-excavation setup comprising a maglev joystick [16] as the master haptic interface and the mini-excavator as the slave manipulator have been conducted to evaluate the impedance-matching control approach. The task to be carried out is the same leveling task discussed above. For safety, and due to the much larger workspace of the excavator than that of the haptic interface, the excavator had to be controlled in velocity mode. The master and slave stiffnesses were adjusted according to

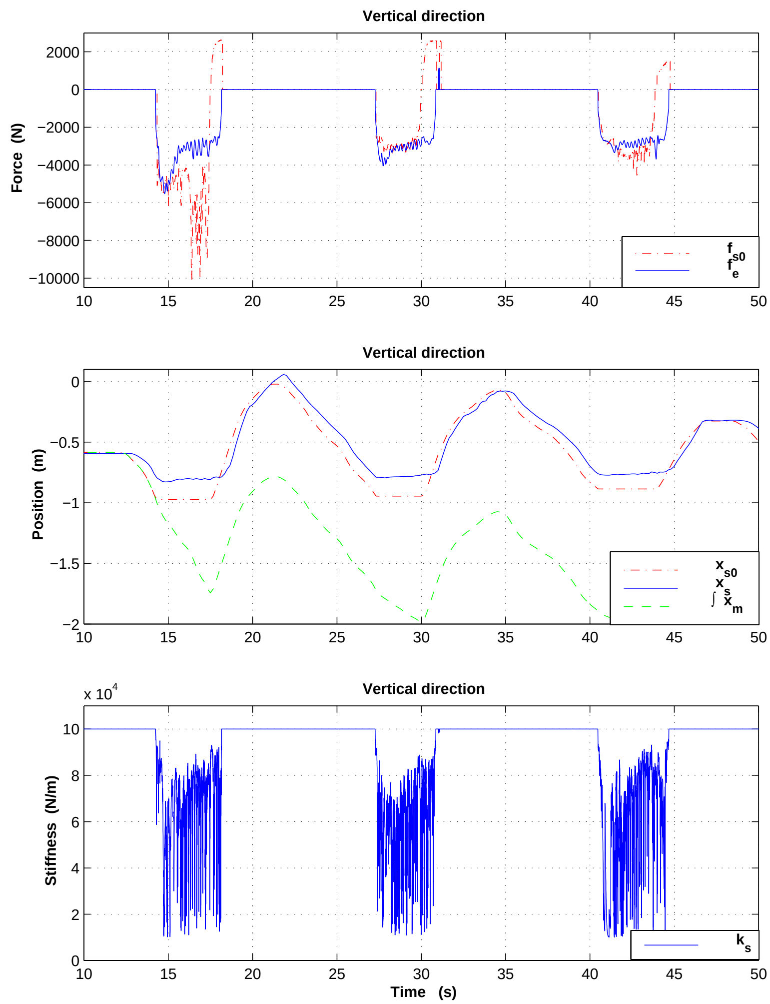

Figure 8: Mini-excavator vertical bucket tip position and force tracking in matched-impedance teleoperation.

$$k_s = \check{k}_s + \frac{1}{\lambda+1}(\hat{k}_s - \check{k}_s) \quad (6)$$

$$k_m = \hat{k}_m + \frac{1}{\lambda+1}(\check{k}_m - \hat{k}_m) \quad (7)$$

while keeping the master damping ratio constant at $\zeta_m = 0.7$ and the slave target impedance damping at $b_s = 5000(Ns/m)$. Here, $\lambda(v_s, f_e) = \frac{|f_e|}{G|v_s|}$, $\lambda(0,0) = 0$, and $k_m \in [\check{k}_m, \hat{k}_m] =$ [841, 5887] N/m, $k_s \in [\check{k}_s, \hat{k}_s] =$ [10000, 100000] N/m are the ranges of master and slave stiffnesses. This is essentially the same as the adjustment law as in (4). Practically, (6)–(7) are implemented as

$$k_s = \check{k}_s + \sigma(\hat{k}_s - \check{k}_s) \quad (8)$$
$$k_m = \hat{k}_m + \sigma(\check{k}_m - \hat{k}_m), \quad (9)$$

where $\sigma(v_s, f_e) = \frac{G|v_s|}{G|v_s|+|f_e|}$ and $\sigma(0,0) = 1$.

Fig. 8 shows the excavator force command f_{s0} (dotted-red), the actual excavator force f_e (solid-blue), the vertical command x_{s0} (dotted-red), the actual excavator position x_s (solid-blue), the integral of the Maglev position $\int x_m$ (dashed-green), and the slave stiffness k_s (solid-blue), while the leveling task is performed. The slave commanded position is the integrated master position (*i.e.*, $x_{s0} = \int v_m$). In free motion, σ is around unity and the slave is practically controlled in position mode. At the same time, the master is soft. As soon as the excavator makes contact, the environment forces build up, the slave velocity decreases, and therefore σ becomes close to zero, resulting in low slave and high master impedances. In this case, more weight is put on the slave force than on the slave position command, and consequently the slave is practically controlled in force mode. The oscillation visible in the excavator force command profile at about $t = 17(s)$ is due to the Maglev flotor reaching its nonlinear workspace region.

A slight complication occurs since the maglev–excavator system is operating in velocity mode. As seen in Fig. 8, while in contact, the slave position set–point command continues to build up with time as long as the master is deflected outside its nominal position deadband, causing a large position command x_{so} to push the bucket harder into the ground. An upward force command generated by the operator lifting the master may not be able to compensate for the large position command x_{s0} unless the master position integration is stopped. As a result, the environment unilateral constraint is mapped into a bilateral constraint for the master. To avoid this problem, if σ is close to zero (*i.e.*, while in contact), the slave position command signal x_{s0} is frozen if the master position x_m and the contact force f_e oppose each other.

Conclusions

A new bilateral teleoperation controller has been presented in this article. The master and slave manipulators are controlled in impedance mode, with their target impedances adjusted in a dual manner to match high or low impedance environments. The adjustment rules presented use the relative sizes of forces and velocities to simply interpolate between low and high impedance controllers. The method was justified by the success of dual-hybrid teleoperation and has been demonstrated to work using a simulator driven by a maglev force-feedback joystick. Experimental results using the same maglev force-feedback joystick to control an excavator have also been presented, demonstrating through a typical leveling task that this method can work well in practice.

The comparison of forces to velocities in deciding the master and slave impedances seems to be an effective method for dealing with extreme environment conditions, namely, free motion or hard constraint. No chattering was noticed during contact tasks.

Future work should seek a better interpretation of the impedance adjustment rules described here, both for single robot impedance control and bilateral teleoperation. Integration of conventional environment identification schemes with these adjustment rules should also be pursued. Extensions to velocity control should be clarified, and issues of stability should be addressed.

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Authors' Biographies:

Septimiu E. Salcudean received his B.Eng. and M.Eng. from McGill University, and his PhD. from U.C. Berkeley, all in Electrical Engineering. From 1986 to 1989 he was a Research Staff Member in Manufacturing Research at the IBM T.J. Watson Research Center. He then joined the Department of Electrical and Computer Engineering at the University of British Columbia, Vancouver, Canada, where he is now a Professor. He spent one year at ONERA in Toulouse in 1996-1997. Dr. Salcudean is interested in the optimization-based design and control of haptic interfaces and tele-manipulation systems. He is pursuing applications to medical diagnostic and surgery and the control of heavy-duty hydraulic machines such as excavators. He is an Editor of the IEEE Transactions on Robotics and Automation.

Keyvan Hashtrudi-Zaad was born in Tehran, Iran, in 1967. He received his B.Sc. and M.A. Sc. degrees in Electrical Engineering from Sharif University of Technology, Tehran, Iran, and Concordia University, Montreal, Canada, in 1991 and 1994, respectively. He is currently a Ph.D. candidate of the Department of Electrical and Computer Engineering of the University of British Columbia, Vancouver, Canada. His research interests include bilateral teleoperation control, environment impedance identification, adaptive robot control, control of flexible robots and singular perturbations. He is a student member of IEEE and ASME.

Shahram Tafazoli received the B.Sc. and M.Sc.(with honors) degrees in Electrical Engineering from Sharif University of Technology, Tehran, 1989 and 1991, respectively. He received his Ph.D. degree in Electrical and Computer Engineering from the University of British Columbia (UBC), Vancouver, in January 1997. He was the Vice Chairman of the IEEE Control Systems Society, Vancouver Chapter, in 1995. Dr. Tafazoli has been collaborating with the Robotics and Control Laboratory of UBC as a Research and Development Consultant. Currently, he is the president and technical director of Motion Metrics Inc., a startup company emerged from his consulting projects. He is also a part-time instructor in the UBC Electrical and Computer Engineering Department. His research interests include position and force control of robotic manipulators, parameter identification, on-line monitoring, teleoperation, and computer vision. He has an application emphasis on the control, dynamic payload monitoring, and fault diagnosis of heavy-duty hydraulic manipulators such as excavators, log loaders, and mining shovels.

Simon P. DiMaio was born in Cape Town, South Africa and received the B.Sc. degree in Electrical Engineering from the University of Cape Town in 1995. He completed the M.A. Sc. degree at the University of British Columbia, Canada, in 1998, where he is currently working toward the Ph.D. degree in Electrical Engineering. His research interests include robotics, control, virtual environments and human-machine interfaces.

Claude Reboulet is a graduate of the Ecole Nationale Supérieure d'Electronique, d'Electrotechnique, Informatique et d'Hydraulique of Toulouse. He received his "Habilitation à Diriger des Recherches" from Universit é Paul Sabatier in 1998. His current research include kinematics, mechanical design, parallel robots, teleoperation, control of robotics systems and UAVs. He is Deputy-Director of the System Control and Flight Dynamics Department of ONERA (Office National d'Etudes et Recherches Aérospatiales).