Semi-Autonomous Teleoperation of Multiple Cooperative Robots for Human-Robot Lunar Exploration*

Dongjun Lee and Mark W. Spong
Coordinated Science Laboratory
University of Illinois at Urbana-Champaign
1308 W. Main St. Urbana, IL 61801 USA
E-mail: d-lee@control.csl.uiuc.edu, mspong@uiuc.edu

Abstract

We propose a semi-autonomous teleoperation framework, developed in (Lee & Spong 2005), as a means for robotic missions to establish infrastructure and preparations for the sustained presence of humans on the Moon. This semi-autonomous framework consists of the two control loops: 1) local autonomous control and interagent communication on the Moon ensure secure cooperative manipulation of objects by the multiple slave robots regardless of communication delays and human commands; and 2) a bilateral teleoperation loop enabling a remote human operator (on the Earth, in lunar orbit, or on the Moon) to tele-control the grasped object via the delayed communication channels. This architecture will be useful for tasks requiring cooperative manipulation, such as construction of human habitats, assembly of solar photovoltaic panels, and cooperative handling of excavated rocks for in-situ resource utilization, to name a few. Simulation results are presented to highlight properties and capabilities of the proposed framework.

Introduction

It is anticipated that, within the next two decades, a sustained human presence on the Moon will be established (NASA 2004). One of the main purposes of this human presence on the Moon is to validate/develop technology and ways for human exploration on Mars or in space. For this, it is necessary to build infrastructure on the Moon for human presence, such as human habitats, in-situ resource utilization generators (ISRU), and solar photovoltaic (PV) tent arrays, to name a few (Huntsberger, Rodriguez, & Schenker 2000).

This lunar infrastructure should be ready before the start of human habitation. However, it would be prohibitely expensive, if not impossible, to send large numbers of human workers to create such infrastructure. At the same time, the state-of-the-art in robotics is such that a network of fully autonomous robots is not capable of carrying out complex tasks involving cooperative manipulation. The most viable scenario, therefore, is to utilize teams of semi-autonomous robots remotely controlled by a small number of humans.

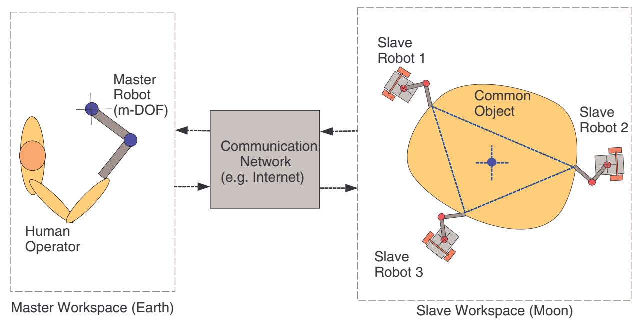

Figure 1: Teleoperation of multiple cooperative robots.

For such missions, a team of multiple cooperative robots would provide better manipulation dexterity, mechanical strength, robustness to single point failure, and safety (e.g. distributed kinetic energy) than using a single huge robot. Also, the robotic material handling and construction tasks required will be performed in a hostile, highly uncertain, and continuously changing environment (e.g. operation in an unmapped site, or sequential assembly of complex parts). Such uncertainty and unpredictability calls for both autonomous behavior and human teleoperation for successful task completion.

As a means toward this robotic mission for the human presence on the Moon, we propose the recently developed semi-autonomous multirobot teleoperation framework (Lee & Spong 2005; Lee, Martinez-Palafox, & Spong 2005). This semi-autonomous framework would enable an operator (on the Earth, on a lunar-orbit, or in a habitat on the Moon) to intelligently guide the cooperative manipulation among a team of multiple slave robots on the Moon over an unreliable and delayed communication network. See Fig. 1 for an illustration.

This semi-autonomous framework consists of the follow-

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ing two control loops: 1) a *local autonomous grasping control* loop which is located on the Moon close to the slave robots; and 2) a *bilateral teleoperation* loop which enables a human operator to tele-control the overall group behavior of the slave robots (and that of the grasped object) via the delayed communication network by operating a master force-reflecting device with a manageably small degrees-of-freedom (DOF). This teleoperation loop can also be replaced by the direct human interaction (i.e. mechanically coupled on site), when humans are coexisting and cooperating directly with the robots on the Moon.

With this semi-autonomous framework, we can achieve the following capabilities and properties:
1) *Abstraction*: A human can control the multiple slaves of possibly many-DOF by operating a master device of reasonably small-DOF;
2) *Haptic Feedback*: Through the bilateral teleoperation loop, the human operator can perceive the combined external forces acting on the grasped object and the slave robots on the Moon via delayed communication channels;
3) *Grasping Safety*: By controlling the cooperative grasping locally, the grasping can be maintained with high precision regardless of the communication delay and human command;
4) *Safe and Stable Interaction*: By enforcing energetic passivity (i.e. passive with the mechanical power as the supply rate (Willems 1972)) of the closed-loop system, its interaction with *any* passive environments/humans will be stable and safe (Colgate 1994).

The key enabling idea of the semi-autonomous teleoperation framework is the passive decomposition (Lee 2004; Lee & Li 2004), with which we can decompose the dynamics of the multiple slave robots into two decoupled systems while enforcing passivity: the *shape system* describing the cooperative grasping aspect; and the *locked system* abstracting the overall behavior of the multiple slave robots (and the grasped object).

Then, by locally controlling the decoupled shape system, secure and possibly *fixtureless* cooperative grasping can be achieved regardless of the communication delay and human command. This fixtureless grasping would be useful when it is necessary to manipulate an object with unknown/irregular shape (e.g. rocks excavated on-site for ISRU).

Also, by teleoperating the locked system, a human can tele-control the overall behavior of the multiple slaves and the grasped object while perceiving the combined external forces on them. To passify the master-slave communication delays in this bilateral teleoperation loop, we utilize scattering-based (or wave-based) communication (Anderson & Spong 1989; Niemeyer & Slotine 2004; Stramigioli *et al.* 2002). The scattering formulation, first introduced in (Anderson & Spong 1989), has become the standard method for dealing with time delay in bilateral teleoperation tasks.

By exploiting the passivity property of the passive decomposition and scattering-based communication, the proposed semi-autonomous teleoperation scheme also enforces energetic passivity of the closed-loop system. Therefore, interaction safety and coupled stability are enhanced significantly.

The rest of this paper is organized as follows. We first provide the problem formulation in which we try to highlight the anticipated efficacy of the proposed semi-autonomous teleoperation for the robotic missions on the Moon. Then, the semi-autonomous teleoperation framework and its simulation results will be presented. Finally, we give a summary and some future research directions.

Problem Formulation

Semi-Autonomous Teleoperation Architecture

Let us consider the cooperative manipulation scenario in Fig. 1, which we can think of as being composed of two subtasks: 1) cooperative grasping by the network of slave robots and 2) manipulation of the grasped object.

The first requirement is for the grasping to be secure and tight regardless of communication delay. On the other hand, this cooperative grasping generally does not requires much intelligent decision processes, since, in many cases, its objective is to merely maintain a given kinematic relations among the robots' end-effectors.

In contrast, the manipulation of the grasped object often requires intelligent intervention (e.g. docking, peg-in-hole, assembly with contact force regulation), especially when the working environments are not well known or keep changing.

From this observation, the approach most likely to succeed is a semi-autonomous teleoperation architecture, where cooperative grasping (both the grasping shape and the internal force) is achieved autonomously by a *local* grasping controller situated on the Moon, while the overall motion of the multiple slaves and the grasped object is teleoperated by a human operator sitting on the Earth, a lunar-orbit, or in a habitat on the Moon, with some communication delays. The adverse effects of the communication delay are thus confined to the teleoperation loop and not do affect the grasping aspect. This teleoperation loop can be replaced by direct human intervention, when a human astronaut is coexisting with the slave robots on the Moon.

Communication and Control Architecture

We assume that there exists a centralized communication and computing (C&C) module for the slave robots, which communicates with all the slaves and computes control commands for them with negligible delays, while, at the same time, communicating with the master over the possibly delayed communication channel (see Fig. 2). Then, the control command for each slave robot provided by this centralized C&C module will be a combination of the (centralized) lo-

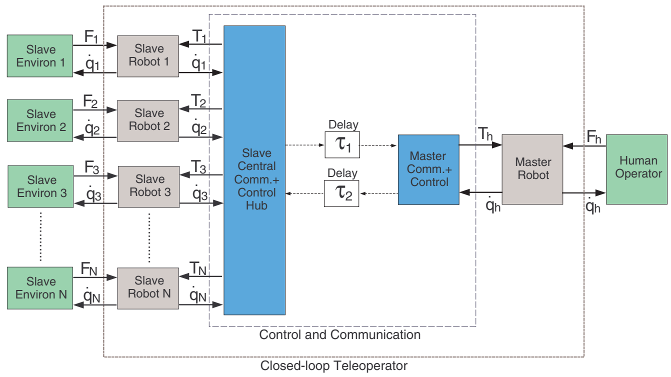

Figure 2: Communication and control (C&C) structure and power flow of the SMMS system.

cal autonomous grasping control, and the teleoperation control computed using the delayed information coming from the master site. Such a C&C structure would be achievable for many cooperative manipulation missions on the Moon, where the workspaces of the slaves are close to each other, thus, via wireless/wired communication, they can share a common centralized C&C module which may be situated in a separate post or on a single "smart" slave robot. It is also highly scalable with the number of slave robots.

Recent results have shown, (Imaida *et al.* 2004; Lee & Spong 2006b; 2006a), with the sorts of delays likely to be encountered in Earth-Moon communication, that the bilateral teleoperation loop can function well and the human will be able to tele-manipulate the grasped object without serious difficulty. It is particularly noteworthy that, in (Imaida *et al.* 2004), many useful manipulation tasks (e.g. contact force regulation, peg-in-hole task, slop-tracing, and slide-handle operation) could be achieved via the bilateral teleoperation between the Earth and a Satellite (ETS-VII), even when the round-trip delay was around 7sec.

In this work, we also assume that the master-slave communication delays are constants. This can be achieved by some signal buffering techniques [e.g. (Kosuge, Murayama, & Takeo 1996)]. Since the semi-autonomous framework is based on the scattering-based communication (Anderson & Spong 1989; Niemeyer & Slotine 2004; Stramigioli *et al.* 2002), these constant delays can still be unknown and asymmetric (i.e. the forward delay τ_1 can be different that the backward delay τ_2).

Plant Modeling

Let us consider the m-DOF master robot dynamics

$$M_h(q_h)\ddot{q}_h + C(q_h,\dot{q}_h)\dot{q}_h = T_h + F_h, \qquad (1)$$

where $q_h, T_h, F_h \in \Re^m$ are the configuration, the control (to be designed), and the human force, respectively. Also, $M_h(q_h) \in \Re^{m\times m}$ and $C_h(q_h,\dot{q}_h) \in \Re^{m\times m}$ are the inertia and Coriolis matrices s.t. $M_h(q_h)$ is positive-definite and symmetric and $\dot{M}_h(q_h) - 2C_h(q_h,\dot{q}_h)$ is skew-symmetric.

Let us denote the total DOF of N slave robots by $n := \sum_{i=1}^N n_i$ with n_i being the DOF of the i-th slave. Then, the group dynamics of the N-slave robots can be written in the following n-DOF robotic dynamics:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} = T + F, \qquad (2)$$

where $q := [q_1^T, ..., q_N^T]^T$, $T := [T_1^T, ...T_N^T]^T$, $F := [F_1^T, ..., F_N^T]^T \in \Re^n$, $M(q) := diag[M_1(q_1), .., M_N(q_N)]$, $C(q,\dot{q}) := diag[C_1(q_1,\dot{q}_1), .., C_N(q_N,\dot{q}_N)] \in \Re^{n\times n}$ with q_i, T_i, F_i, M_i, C_i being the configuration, the control, the environmental force, the inertia and the Coriolis matrices of the i-th slave robot, respectively. Then, similar to (1), $M(q)$ is symmetric and positive-definite and $\dot{M}(q) - 2C(q,\dot{q})$ is skew-symmetric.

In (1)-(2), we assume that the gravity term is locally cancelled out or contained in the external force terms, F_h, F. We also suppose that $n \geq m$ (i.e. DOF of the slaves is larger than that of the master). We also assume that suitable bilateral power/kinematic scalings have been already embedded in the dynamics (1)-(2) as in (Lee & Li 2003; 2005), with which different sizes/strengths between the master and slave environments can be matched.

Grasping Shape Function

We suppose that, for a given task objective, the internal grasping shape among the slave robots (2) can be specified by the $(n-m)$-dimensional function $q_E(q) \in \Re^{n-m}$, where $q \in \Re^n$ is the slave group configuration given in (2). Here, we assume that this q_E is smooth and its Jacobian is full-rank (i.e. q_E is a smooth submersion (Marsden & Ratiu 1999)). We call this function q_E *grasping shape function*. Then, a desired grasp shape can be achieved by enforcing the following condition

$$q_E(q(t)) \rightarrow q_E^d, \qquad (3)$$

where $q_E^d \in \Re^{n-m}$ is a constant vector describing the desired grasping shape. By designing the condition (3) s.t. a flexible object is surrounded and deformed by the slave robots, fixtureless cooperative grasping could be achieved.

As an example, let us consider three slave robots with their end-effectors confined on the (x,y)-plane as shown in Fig. 3. Then, we can define the following grasping shape function

$$q_E := \begin{pmatrix} x_1 - x_2 - Lcos(\phi_2 + \frac{\pi}{6}) \\ x_2 - x_3 + Lcos(\phi_2 - \frac{\pi}{6}) \\ y_1 - y_2 - Lsin(\phi_2 + \frac{\pi}{6}) \\ y_2 - y_3 + Lsin(\phi_2 - \frac{\pi}{6}) \\ \phi_1 - \phi_2 \\ \phi_2 - \phi_3 \end{pmatrix} \in \Re^6, \qquad (4)$$

where $(x_i, y_i, \phi_i) \in \Re^3$ are the translation and yaw angle of i-th agent's end-effector w.r.t. a common inertial frame $\mathcal{F}_o$.

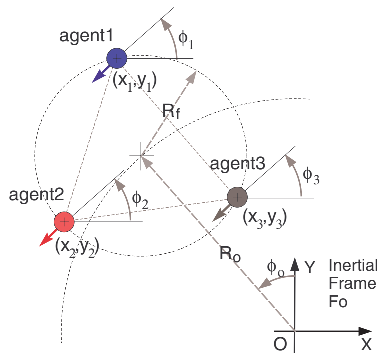

Figure 3: End-effectors of three slave robots on (x, y)-plane.

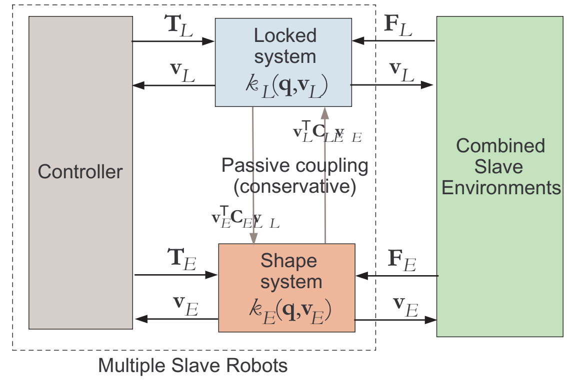

Figure 4: Circuit-network representation of the decomposed multiple slave robots (7)-(8).

If we achieve the condition (3) with $q_E^d = 0$, the three robots in Fig. 3 will form an equilateral triangular with the side length of L, whose rotation is specified by the robot 2's yaw angle. Thus, fixtureless grasping of a flexible object could be achieved by choosing L to be small w.r.t. the object's size. In this case, the value of L would also determine the internal force generated by the object's deformation. Here, as the 6-DOF are constrained by the condition $q_E(t) = 0$, the overall motion of the three robots (total DOF$=9$) is then reduced to the remaining 3-DOF motion (i.e. translation/rotation of the triangle).

Semi-Autonomous Teleoperation Control

In this section, we highlight the main developments of the semi-autonomous teleoperation framework proposed in (Lee & Spong 2006b; Lee, Spong, & Martinez-Palafox 2005), to which we also refer readers for more details.

Decomposition of Multiple Slave Robots

Using the passive decomposition (Lee 2004; Lee & Li 2004), we first decompose the n-DOF dynamics of the multiple slave robots (2) into two decoupled systems while enforcing energetic passivity: the $(n-m)$-DOF *shape system* describing the cooperative grasping aspect, and the m-DOF *locked system* representing the overall motion of the multiple slaves with a fixed grasp shape. For more details on the passive decomposition, refer to (Lee & Li 2004; Lee, Spong, & Martinez-Palafox 2005).

The key idea of the passive decomposition is that the velocity $\dot{q} \in \Re^n$ of the multiple slaves (2) can be decomposed into the two components: the *shape system velocity* $v_E = \frac{d}{dt} q_E \in \Re^{n-m}$ representing the change in the $(n-m)$-DOF internal grasping shape q_E; and the *locked system velocity* $v_L \in \Re^m$ describing the remaining m-DOF overall motion of the total group with their internal shape fixed. In a vector form, this decomposition can be expressed by

$$\begin{pmatrix} v_L \\ v_E \end{pmatrix} = S(q)\dot{q}, \qquad (5)$$

where $S(q)$ is a (non-singular) decomposition matrix.

For example, consider the three robots (total DOF$=9$) in Fig. 3 with q_E in (4). Then, $v_E = \dot{q}_E$ represents the rate of changes of the triangle's size and shape (i.e. 6-DOF internal grasping shape), while v_L (to be shown to have the form (12)) describes the translational-velocity and yaw-rate of the triangle itself (i.e. 3-DOF overall group motion).

We also define compatible transforms s.t.

$$\begin{pmatrix} T_L \\ T_E \end{pmatrix} := S^{-T}(q)T, \text{ and } \begin{pmatrix} F_L \\ F_E \end{pmatrix} := S^{-T}(q)F. \qquad (6)$$

Then, using (5)-(6), the slaves' dynamics (2) can be partially decoupled s.t.

$$\underbrace{M_L(q)\dot{v}_L + C_L(q,\dot{q})v_L}_{\text{locked system dynamics}} + \underbrace{C_{LE}(q,\dot{q})\dot{q}_E}_{\text{coupling}} = T_L + F_L, \qquad (7)$$

$$\underbrace{M_E(q)\ddot{q}_E + C_E(q,\dot{q})\dot{q}_E}_{\text{shape system dynamics}} + \underbrace{C_{EL}(q,\dot{q})v_L}_{\text{coupling}} = T_E + F_E. \qquad (8)$$

We call the $(n-m)$-DOF system in (8) *shape system* which explicitly describes the grasping aspect having $q_E(t)$ as its configuration. Also, we refer the m-DOF dynamics in (7) as *locked system* which represents overall dynamics of the multiple slave robots with a fixed grasping shape $q_E(t)$. Here, F_L and F_E represent the combined effects of the environmental forces on the overall motion of the slave robots, and the internal grasping force, respectively.

Proposition 1 *(Lee & Spong 2005) The partially decomposed dynamics* (7)-(8) *have the following properties:*
1) $M_L(q)$ and $M_E(q)$ are symmetric and positive definite.
2) $\dot{M}_L(q) - 2C_L(q,\dot{q})$ and $\dot{M}_E(q) - 2C_E(q,\dot{q})$ are skew-symmetric.
3) $C_{LE}(q,\dot{q}) + C_{EL}^T(q,\dot{q}) = 0$.

Thus, if we cancel out the coupling terms $C_{LE}(q,\dot{q})\dot{q}_E$, $C_{EL}(q,\dot{q})v_L$ in (7)-(8), the locked and shape systems will have dynamics reminiscent of usual robotic dynamics. Note that those coupling terms in (7)-(8) are only functions of the velocity and configuration. Thus, the decoupling can be achieved by using only the position and velocity feedback without requiring acceleration feedback which is often unavailable in many practical robotic systems (e.g. robots with angle encoders).

The unique and powerful property of the passive decomposition is that this decoupling control is intrinsically passive as shown by (from item 3 of proposition 1):

$$v_L^T C_{LE}(q,\dot{q})v_E + v_E^T C_{EL}(q,\dot{q})v_L = 0. \tag{9}$$

This equality implies that the decoupling control does not generate (or dissipate) any mechanical power (i.e. energetically conservative), thus, will not violate passivity. See Fig. 4 for a circuit representation of the locked and shape systems, and their energetically conservative couplings in (7)-(8).

Control Design

Once we achieve the decomposition (7)-(8), control design becomes fairly straightforward. We design the locked and shape controls T_L, T_E in (7)-(8) to be

$$\begin{pmatrix} T_L \\ T_E \end{pmatrix} := \underbrace{\begin{pmatrix} C_{LE}(q,\dot{q})\dot{q}_E \\ C_{EL}(q,\dot{q})v_L \end{pmatrix}}_{\text{passive decoupling}} + \underbrace{\begin{pmatrix} T_L' \\ T_E' \end{pmatrix}}_{\text{teleoperation and grasping}}, \tag{10}$$

where the decoupling control is intrinsically passive as shown in (9), and $T_E' \in \Re^{n-m}$ and $T_L' \in \Re^m$ will embed the local autonomous grasping control and the bilateral teleoperation control as below.

Under the control (10), the closed-loop shape system dynamics is given by

$$M_E(q)\ddot{q}_E + C_E(q,\dot{q})\dot{q}_E = T_E' + F_E.$$

Since this is similar to the usual robot dynamics, we can utilize many control schemes to achieve the regulation objective (3) (i.e. $q_E(t) \to q_E^d$) for the cooperative grasping. One example is the following proportional-derivative (PD) control with feedforward (FF) cancellation:

$$T_E'(t) := -K_v^E \dot{q}_E(t) - K_p^E(q_E(t) - q_E^d) - \widehat{F}_E(t), \tag{11}$$

where $\widehat{F}_E(t)$ is the estimate of $F_E(t)$, q_E^d is the desired constant grasping shape in (3), and K_v^E, K_p^E are the damping and spring gains.

The FF (feedforward) term $\widehat{F}_E(t)$ in (11) would be necessary for such applications where high grasping precision is crucial or the contact force is so large that excessively large PD-gains are required to compensate for it. This FF-term, however, does not generally ensures passivity, as it might generate unbounded energy (e.g. with corrupted force sensing). Thus, to enforce passivity, this

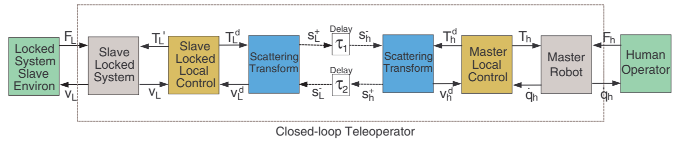

Figure 5: Symmetric teleoperation architecture.

FF-term may need to be implemented in some passivity-enforcing implementation structures (e.g. (Lee & Li 2005; Hannaford & Ryu 2002)) s.t. its energy generation can be always limited. This is especially true when model uncertainty and sensing inaccuracy are substantial (Lee & Li 2005). However, the PD-control in (11) is itself intrinsically passive, thus, does not require any special implementation.

Similarly, with the control (10), the closed-loop dynamics of the locked system is given by

$$M_L(q)\dot{v}_L + C_L(q,\dot{q})v_L = T_L' + F_L.$$

This is again similar to the usual robotic dynamics. Thus, we can easily construct a bilateral teleoperation loop between this locked system and the master device (1), considering them just as two usual robotic systems.

In particular, we use the scattering-based teleoperation (Anderson & Spong 1989; Niemeyer & Slotine 2004; Stramigioli *et al.* 2002) to couple this locked system and the master device (1), in which, instead of the power conjugate variables, scattering-variables (i.e. incident/reflected powers) are communicated. With this scattering-based approach, the communication delays can be passified and stable bilateral teleoperation can be ensured. To mitigate the wave-reflections which can severely corrupt the realism, we use the symmetric teleoperation architecture as shown in Fig. 5 with proportional-integral (PI) control used as the local controls (i.e. after the scattering-transforms). This scattering-based teleoperation can deal with unknown and/or asymmetric time-delays.

With these designed controls, we can achieve the followings: 1) passivity of the closed-loop system is enforced (with the special implementation, if the FF-control in (11) is used), thus, interaction safety and stability are substantially enhanced; 2) due to the locked-shape decoupling, the secure grasping can be ensured (i.e. (3) is achieved) regardless of the human teleoperation command and communication-delays; and 3) the teleoperation loop provides the human with extended physiological proprioception (Childress 1998) so that s/he can tele-manipulate the grasped object and the overall behavior of the multiple slave robots over the delayed communication network.

In (Lee, Spong, & Martinez-Palafox 2005), a robustness analysis was also performed for this semi-autonomous scheme against model parametric uncertainty. It shows that 1) passivity (i.e. interaction safety and stability) is ensured regardless of the model uncertainty; and 2) performance degradation due to the model uncertainty can be made arbitrary small by increasing the control gains.

Simulation

Here, we present some simulation results to highlight the property/capability of the semi-autonomous teleoperation scheme. For the simulation, we consider three slave end-effectors on the (x, y)-plane in Fig. 3. For simplicity, we model them as identical 3-DOF point-masses, whose motions are specified by $(x_i, y_i, \phi_i) \in \Re^3$ (i.e. translation and yaw angle) w.r.t. a common inertial frame $\mathcal{F}_o$. The master-device is also assumed to have 3-DOF point mass dynamics.

We consider the grasping shape function in (4). Then, following (Lee, Spong, & Martinez-Palafox 2005), the locked system velocity in (7) can be found to be

$$v_L = \begin{pmatrix} \frac{1}{3}(\dot{x}_1 + \dot{x}_2 + \dot{x}_3) \\ \frac{1}{3}(\dot{y}_1 + \dot{y}_2 + \dot{y}_3) \\ \frac{1}{3}(\dot{\phi}_1 + \dot{\phi}_2 + \dot{\phi}_3) + \omega_1 + \omega_3 \end{pmatrix} \in \Re^3, \qquad (12)$$

where $\omega_1 := -\frac{L}{3}[\dot{x}_1 sin(\phi_2 + \frac{\pi}{6}) - \dot{y}_1 cos(\phi_2 + \frac{\pi}{6})]$ and $\omega_3 := -\frac{L}{3}[\dot{x}_3 sin(\phi_2 - \frac{\pi}{6}) - \dot{y}_3 cos(\phi_2 - \frac{\pi}{6})]$. This v_L (12) becomes the translation velocity and rotating rate of the triangle when $q_E(t) = 0$. Using this v_L and $\frac{d}{dt}q_E$, we can construct the decomposition matrix $S(q)$ in (5).

To show the robustness of the proposed framework, we impose 10% uncertainty for the inertias. With this, the locked and shape systems can not be perfectly decoupled from each other by the decoupling control in (10), as the accuracy of the decomposition depends on the system's inertia structure. We impose 1sec master-slave round-trip delay. This delay, which would be much less than that in usual Moon-Earth teleoperation, is chosen here just for the concept illustration. Of course, we can incorporate a longer delay with slowing down the task operation speed. We also model humans as a PD-control loop, whose set point is given by the delayed average motion of the slaves (i.e. $\frac{1}{3}\sum_{i=1}^{3}(x_i(t-\tau_2), y_i(t-\tau_2), \phi_i(t-\tau_2)) \in \Re^3$ with τ_2 being the backward delay).

For the simulation, we use the local grasping control (11) with high-enough PD-gains and omit the FF-term (i.e. $-\hat{F}_E(t)$ in (11)). Without this FF-term, the grasping control (11) becomes intrinsically passive, thus, any special passivity-ensuring implementation is not necessary.

First, we include a circular deformable object to validate the cooperative manipulation capability. To achieve the fixtureless grasping using the flexibility of the object, we set L in (4) s.t. three slave robots will try to lie on a circle whose radius is 80% of that of the object. We model the contact force between slaves and the object by spring and damper. We also assume frictionless contact, i.e. no torque is exerted on the slave robots' rotations.

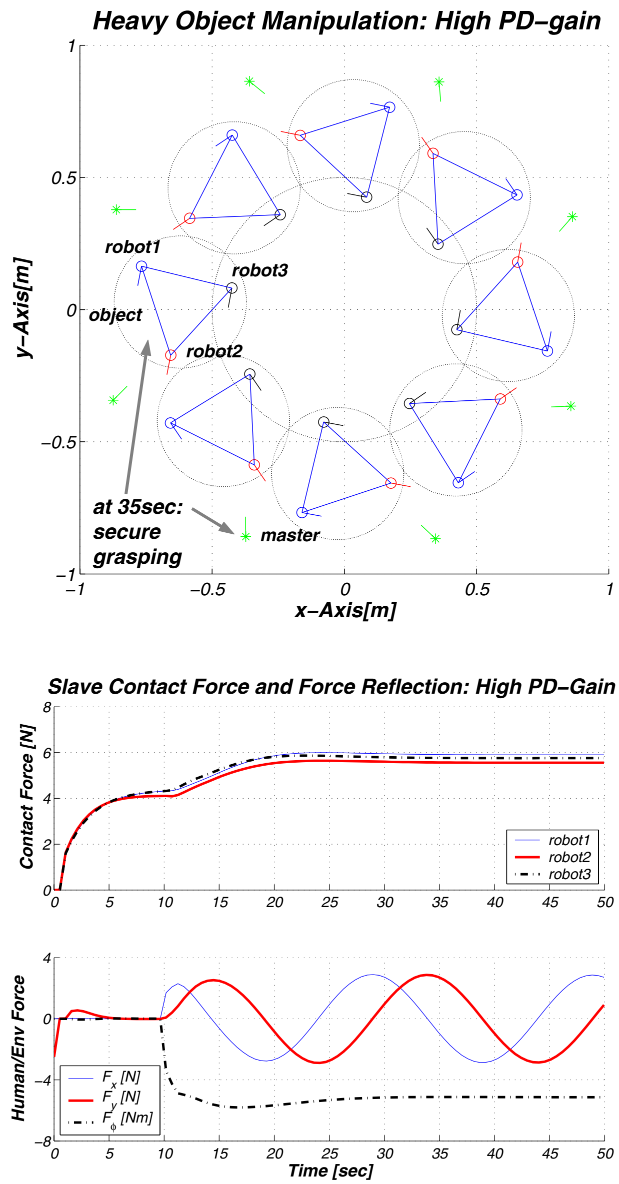

Figure 6: Cooperative manipulation of a heavy object: [top figure] snapshots of the simulation, where eight circles of radius $0.25m$ show the grasped object with no deformation, while the small circles (or asterisks, resp.) and their stems represent the positions and headings of the slave robots (or the master system, resp.). While the human operator teleoperates the grasped object to revolve along the circle counterclockwise, the secure grasping is maintained without any fixture as shown by that the equilateral grasping shapes among the slaves are preserved; [middle figure] contact force profiles of the three slave robots during the manipulation; [bottom figure] human force profile shows that the human operator could perceive the combined inertial forces of the grasped object and the slave robots.

In the first $10sec$, the three slaves approach to the object and grasp it cooperatively without a rigid fixture, while the human stabilizes the object on the top of the circle with $\phi_o = \phi_2 = 0$ in Fig. 3. Then, the human operates the master device to make the grasped object revolve along the circle counterclockwise with the periodicity of $w = 0.05$Hz. Snapshots on the (x, y)-plane, slave contact force, and human force profiles are shown in Fig. 6. In the snapshots, the eight circles of radius $0.25m$ represent the grasped object without deformation, while the small circles and their stems represent the positions and headings of the slave robots, respectively. Similarly, the asterisks and their stems show the positions and headings of the master system.

While the human operator drives the grasped object along the circle, the slave robots can maintain a secure cooperative grasping without any fixture, as shown by the preservation of the equilateral grasping shapes among the slaves in Fig. 6. During the teleoperation, the human operator can also perceive the combined inertial force of the grasped object and the slave robots as shown by the human force profile in the bottom of Fig. 6. With the FF-term (i.e. $-\hat{F}_E(t)$ in (11)), this grasping security could be improved even with smaller PD-gains (results not shown in here for brevity). A movie of this simulation is also available at `http://decision.csl.uiuc.edu/∼d-lee/heavy.avi`.

The next simulation is performed to validate the force reflection capability. Once the human stabilizes the slave triangular formation with $\phi_o(t) = \phi_2(t) = 0$ in Fig. 3, we impose an external force on the center of the grasped object, which is along the x-axis and increasing during $10 - 20sec$ with the rate of $0.3N/sec$. Human and slave contact forces are shown in Fig. 7.

As shown in Fig. 7, the human operator is able to perceive the external force acting on the object. This external force is reflected through the dynamics of the slave robots and the bilateral teleoperation control loop over the delayed communication. As this external force increases during $10 - 20sec$, the robot 2's contact force decreases while those for the robots 1 and 3 increase. This is due to the flexibility of the object: the external force deforms the object so that its center is pulled away from the robot 2 and pushed toward the robots 1 and 3, while the grasping shape is still rigidly maintained. It is also worthwhile to mention that a human can perceive external forces acting on individual slave robots, too.

Conclusion and Future Works

In this paper, we propose a semi-autonomous teleoperation framework as a way to achieve many robotic cooperative manipulation missions for the sustained human presence on the Moon. The proposed framework ensures secure cooperative grasping of a common object by a team of multiple robots on the Moon, while enabling a human operator (from the Earth, a lunar orbit, or a habitat on the Moon) to bilaterally telemanipulate the motion of the grasped object over the delayed communication channels. We believe that this framework would be particularly useful for robotic missions on the Moon, where the cooperative manipulation capability is necessary. Some examples include cooperative construction of human habitat, assembly of solar PV panel, and handling of excavated rocks for in-situ resource utilization.

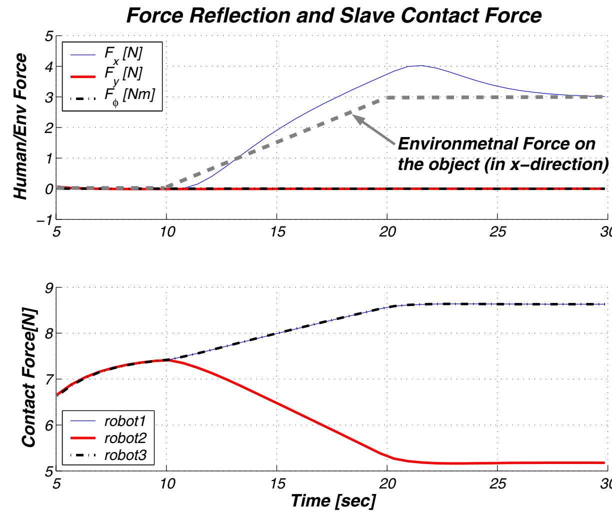

Figure 7: Human/contact forces with external force on the grasped object: [top figure] profiles of the human force (F_x, F_y, F_ϕ) and the linearly increasing external force acting on the grasped object (dotted line). This external force is reflected to and perceived by the human operator; [bottom figure] contact forces of the three slave robots, where the decrease in the robot 2's force is due to the flexibility of the object, i.e. the external force deforms the object so that its center is pulled away from the robot 2, while the grasping shape is rigidly maintained.

Among many possible future directions, we think that the following two topics would be particularly important and rewarding: 1) cooperative teleoperated transport; and 2) virtual motion constraints generation for a given mission objective.

In the cooperative teleoperated transport, the multiple mobile manipulators (i.e. manipulator on a top of mobile platform) will carry a common object to a certain desired location (e.g. transport of minerals for in-situ resource utilization), while the grasped object is tele-controlled by a remote human operator. For this problem, we will search for a decomposition similar to the one presented in this paper, which needs to address nonholonomic constraints of the mobile platforms (i.e. no side-slip condition) on the top of the coordination requirement (i.e. holonomic constraints) among the slave robots.

The other topic for future research is how to generate virtual holonomic/nonholonomic constraints for the locked system and for the individual robots according to a given mission objective. When imposed on the locked system, these constrains may be used by a human operator as a virtual-rail for guided assembly or as a virtual-wall to protect coexisting humans/objects from the grasped object. On the other hand, if imposed on the individual robots, these constrains may be used to prevent unwanted collisions between the robots and environments or among the robots themselves, or to control their individual motions according to a given mission plan. In order to achieve these virtual constraints, we may extend the ideas presented in (Lee & Li 2005), where potential field and velocity field are utilized as virtual constraints for the usual master-slave system. In the cooperative teleoperated transport, we may be able to generate these virtual constraints not by using the motor actuation but by the real mechanical constraints (i.e. no side-slip of wheels) just as like in the Cobot (Peshkin & Colgate 1999).

References

Anderson, R. J., and Spong, M. W. 1989. Bilateral control of tele-operators with time delay. *IEEE Transactions on Automatic Control* 34(5):494–501.

Childress, D. S. 1998. Control strategy for upper-limb prostheses. *Proceedings of the 20th Annual International Conf. of the IEEE Engineering in Medicine and Biology Society* 20(5):2273–2275.

Colgate, J. E. 1994. Coupled stability of multiport systems - theory and experiments. *Transactions of the ASME, Journal of Dynamic Systems, Measurement and Control* 116(3):419–428.

Hannaford, B., and Ryu, J. 2002. Time domain passivity control of haptic interfaces. *IEEE Transactions on Robotics and Automation* 18(1):1–10.

Huntsberger, T.; Rodriguez, G.; and Schenker, P. S. 2000. Robotics challenges for robotic and human mars exploration. In *Robotics*, 340–346.

Imaida, T.; Yokokohji, Y.; Doi, T.; Oda, M.; and Yoshikawa, T. 2004. Ground-space bilateral teleoperation of ets-vii robot arm by direct bilateral coupling under 7-s time delay condition. *IEEE Transactions on Robotics and Automation* 20(3):499–511.

Kosuge, K.; Murayama, H.; and Takeo, K. 1996. Bilateral feedback control of telemanipulators via computer network. In *Proceedings of IEEE/RSJ International Conf. on Intelligent Robots and Systems*, 1380–1385.

Lee, D. J., and Li, P. Y. 2003. Passive bilateral feedforward control of linear dynamically similar teleoperated manipulators. *IEEE Transactions on Robotics and Automation* 19(3):443–456.

Lee, D. J., and Li, P. Y. 2004. Passive decomposition for multiple mechanical systems under coordination requirements. In *Proceedings of the IEEE Conference on Decision and Control*, 1240–1245.

Lee, D. J., and Li, P. Y. 2005. Passive bilateral control and tool dynamics rendering for nonlinear mechanical teleoperators. *IEEE Transactions on Robotics* 21(5):936–951.

Lee, D. J., and Spong, M. W. 2005. Bilateral teleoperation of multiple cooperative robots over delayed communication networks: theory. In *Proceedings of IEEE International Conf. on Robotics & Automation*, 362–367.

Lee, D. J., and Spong, M. W. 2006a. Passive bilateral teleoperation with constant time-delay. *IEEE Transactions on Robotics*. To appear. Preprint available at http://decision.csl.uiuc.edu/∼d-lee/LeeSpongDelayTRO04.pdf.

Lee, D. J., and Spong, M. W. 2006b. Passive bilateral teleoperation with constant time-delays. In *Proceedings of IEEE International Conf. on Robotics & Automation*. Accepted. Preprint also available at http://decision.csl.uiuc.edu/∼d-lee/ICRA06a.pdf.

Lee, D. J.; Martinez-Palafox, O.; and Spong, M. W. 2005. Bilateral teleoperation of multiple cooperative robots over delayed communication networks: application. In *Proceedings of IEEE International Conf. on Robotics & Automation*, 368–373.

Lee, D. J.; Spong, M. W.; and Martinez-Palafox, O. 2005. Bilateral teleoperation of multiple cooperative robots over delayed communication network. *IEEE Transactions on Robotics*. Submitted. Preprint also available at http://decision.csl.uiuc.edu/∼d-lee/LSMTRO04.pdf.

Lee, D. 2004. *Passive Decomposition and Control of Interactive Mechanical Systems under Coordination Requirements*. University of Minnesota: Doctoral Dissertation. Also available at http://decision.csl.uiuc.edu/∼d-lee/Dissertation.pdf.

Marsden, J. E., and Ratiu, T. S. 1999. *Introduction to mechanics and symmetry*. New York, NY: Springer, 2 edition.

NASA. 2004. *The Vision for Space Exploration*.

Niemeyer, G., and Slotine, J. J. E. 2004. Telemanipulation with time delays. *International Journal of Robotics Research* 23(9):873–890.

Peshkin, M., and Colgate, J. E. 1999. Cobots. *Industrial Robot* 26(5):335–341.

Stramigioli, S.; van der Schaft, A.; Maschke, B.; and Melchiorri, C. 2002. Geometric scattering in robotic telemanipulation. *IEEE Transactions on Robotics and Automation* 18(4):588–596.

Willems, J. C. 1972. Dissipative dynamical systems part1: general theory. *Arch. Rational Mech. Anal.* 45(22):321–351.