Networked Haptic Cooperation among Multiple Users via Virtual Object Coordination to Averaged Position of Peer Copies

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This paper proposes a distributed haptic control architecture whose coordination gain at each user site is independent of the number of cooperating peers. In the proposed architecture, users interact through manipulating a shared virtual object (SVO) together. The distributed copies of the SVO are controlled through virtual couplers. At each peer, the gain of the force feedback loop is maintained constant regardless of the number of interacting users by coordinating the local SVO copy to the averaged motion of the other SVO copies. The motion of the SVO representative is computed by averaging the motion of all other SVO copies. A preliminary investigation contrasts the proposed controller to traditional distributed virtual coupling control. The comparison is performed via MATLAB simulations of an exemplary cooperative manipulation performed by three users. The results illustrate that the proposed controller: (1) can render a lighter SVO with decreased position coherence among the distributed SVO copies for the same stiffness of coordination; (2) achieves similar position coherence among the distributed SVO copies for the same SVO mass.

I. INTRODUCTION

Networked haptic cooperation among multiple users has promising applications in immersive online computer games [6] and cooperative industrial design [10]. However, the need to involve as many participants as possible brings about the challenges of: (1) synchronizing the SVO among the haptically cooperating users; and (2) maintaining the cooperation stable. Particularly threatening both for synchronization and for stability are adverse network effects like delay, jitter and packet loss, which introduce destabilizing phase lags in the force control loop. Several network and control approaches have been developed to synchronize the SVO among multiple cooperative participants.

One approach mitigates the network challenges through offering users information about the current network conditions via decorators [18]. Decorators are graphical cues that inform the cooperating participants about network delay and jitter. Enriched color schemes [19] and subsequent development of three categories of decorators [2] allow the visualization of more complex network information. Further performance improvements are obtained by combining decorators: with a prediction scheme of the SVO behavior based on interpolation of data from a history buffer [4]; or with dead-reckoning [11], [8]. High cooperation performance for network delays up to 80 ms can also be achieved by compensating for delayed or lost updates using the dead-reckoning-based prediction scheme in [13].

Another approach smoothes network jitter through fixed and adaptive buffers in [3]. The impetus for this approach is provided by the larger negative impact that jitter has on networked haptic cooperation compared to long and constant network delay [15], [12]. Embedded in the S-SCTP transport protocol [20], the fixed buffer leads to faster completion of the cooperation task in the presence of delay and jitter. The adaptive buffer better prevents overall packet loss in the presence of long delay and severe jitter [21], and better reduces the additional delay due to buffering [13].

When networked haptic cooperation among multiple participants is controlled via distributed architectures, stability is endangered not only by network effects, but also by: (1) the distribution of the SVO mass among the SVO copies of all interacting users; and (2) the variation of the coordination gain of each SVO copy with the number of cooperating participants. Yet, distributed controllers are often preferred to centralized schemes because they improve the perception of rigid contacts [9]. Existing schemes for distributed control of networked haptic cooperation [9], [16], [17]: (1) divide the SVO mass equally among all local SVO copies; and (2) coordinate each SVO copy to all other SVO copies. Such typical mass distribution may lead to unstable interaction if the number of users becomes large enough to render the mass of the local SVO copies smaller than the minimum mass [5]. The coordination of each SVO copy to the other SVO copies may lead to instability because the impedances of the many controllers compound and may exceed the Z-width [7] of the

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users' haptic interfaces, i.e., the maximum impedance that the interfaces can stably display to their respective users. However, little research addresses these difficulties. Recent work in [1] introduces a framework for computing virtual coupling parameters that guarantee stable cooperation among multiple users for a-priory assigned connectivity between a fixed number of operators and a centralized SVO. The extension of the framework in [1] to the cooperative manipulation of a distributed SVO may constitute the focus of upcoming investigation.

This paper introduces a distributed haptic control architecture whose coordination gain at each user site is independent of the number of participants involved in the cooperation. In the proposed architecture, users interact through manipulating a SVO together. The distributed copies of the SVO are controlled through virtual couplers. At each participant, the gain of the force feedback loop is maintained constant regardless of the number of interacting users by coordinating the local SVO copy to an SVO representative. The motion of the SVO representative is computed by averaging the motion of all other SVO copies. A preliminary investigation contrasts the proposed controller to traditional distributed virtual coupling control. The comparison is performed via MATLAB simulations of an exemplary cooperative manipulation performed by three users. The results illustrate that the proposed controller: (1) can render a lighter SVO with decreased position coherence among the distributed SVO copies for the same coordination stiffness; (2) achieves similar position coherence among the distributed SVO copies for the same SVO mass.

II. DISTRIBUTED CONTROL OF MULTIPLE PEERS

This section overviews the traditional and the proposed distributed control architectures in the context of cooperative manipulation of a SVO by three peers. In contrast to [14], which enables direct user-to-user interaction in addition to cooperative manipulations through distributing the users across the network, this section decreases the minimum mass of the SVO that the users can stably manipulate together through coordinating the local SVO copy to the averaged motion of the other SVO copies.

A. Traditional Virtual Coupling-Based Peer Control

The dynamics of traditional distributed control of networked haptic cooperation between two peer users based on virtual coupling coordination are presented in detail in [16], and are schematically depicted in Figure 1. As illustrated in Figure 1, the virtual environment of each peer includes a copy of the SVO, considered to be a cube in a rigid enclosure that forces it to move only horizontally. In this figure, $m_{\mathrm{HD}i}$ and $b_{\mathrm{HD}i}$ are the mass and damping of the haptic interfaces; $m_{\mathrm{O}i}$ and $b_{\mathrm{O}i}$ are the mass and damping of Peer i's SVO copy; $K_{\mathrm{VC}i}$, $B_{\mathrm{VC}i}$ and $F_{\mathrm{VC}i}$ are the stiffness, damping and interaction force at the contact between Peer i and its local SVO copy, respectively; K_{T} and B_{T} are the stiffness and damping of the virtual coupler that coordinates the two local SVO copies; $F_{\mathrm{T}ij}$ is the controller force that comands Peer i's SVO copy to follow Peer j's SVO copy; $x_{\mathrm{O}i}$ and $\dot{x}_{\mathrm{O}i}$ are the position and velocity of Peer i's SVO copy; $x_{\mathrm{O}i_n}$ and $\dot{x}_{\mathrm{O}i_n}$ are the position and velocity commands sent by Peer i's SVO copy to Peer j-th virtual environment; lastly, $F_{\mathrm{h}i}$ is the force applied by the i-th user to their haptic interface. The network delay is considered to be T_d, both in the forward and return paths.

The direct extension of the traditional peer-to-peer scheme to haptic cooperation among three users is illustrated in Figure 2. In this control approach, the three SVO copies are connected through six virtual couplers, two at each peer site. The mass of the SVO is equally divided among the three cube copies. The damping of the SVO is inherited by all three cube copies. The dynamics of haptic cooperation among three peers coordinated via traditional peer control are a straightforward extension of the dynamics presented in [16].

B. Virtual Coupling-Based Peer Control to Averaged Position

In the proposed distributed control architecture, each local SVO copy is commanded to follow the averaged motion of all other SVO copies. For cooperation between two users, the proposed architecture is equivalent to the traditional architecture. Cooperation among three users via the proposed architecture is shown in Figure 3. As before, the virtual environment of each peer includes a local copy of a rigid virtual cube in a rigid enclosure that allows it to move only horizontally. In Figure 3, $F_{\mathrm{T}i}$ is the control force that commands Peer i's SVO copy to follow the averaged motion of the other two SVO copies; and $x_{\mathrm{O}i_d}$ and $\dot{x}_{\mathrm{O}i_d}$ are the position and velocity commands applied to Peer i's SVO copy.

In this control approach, the three SVO copies are connected through three virtual couplers, one at each peer site. As before, the mass of the SVO is equally divided among the three cube copies. The damping of the SVO is inherited by all three cube copies. The dynamics of haptic cooperation among three peers coordinated via the proposed peer control to averaged position are:

- for the peer haptic devices:

$$F_{\mathrm{h}1} - F_{\mathrm{VC}1} = m_{\mathrm{HD}1}\ddot{x}_1 + b_{\mathrm{HD}1}\dot{x}_1 \tag{1}$$

$$F_{\mathrm{h}2} - F_{\mathrm{VC}2} = m_{\mathrm{HD}2}\ddot{x}_2 + b_{\mathrm{HD}2}\dot{x}_2 \tag{2}$$

$$F_{\mathrm{h}3} - F_{\mathrm{VC}3} = m_{\mathrm{HD}3}\ddot{x}_3 + b_{\mathrm{HD}3}\dot{x}_3 \tag{3}$$

- for the copies of the shared virtual object:

$$F_{\mathrm{VC}1} - F_{\mathrm{T}1} = m_{\mathrm{O}1}\ddot{x}_{\mathrm{O}1} + b_{\mathrm{O}i}\dot{x}_{\mathrm{O}1} \tag{4}$$

$$F_{\mathrm{VC}2} - F_{\mathrm{T}2} = m_{\mathrm{O}2}\ddot{x}_{\mathrm{O}2} + b_{\mathrm{O}2}\dot{x}_{\mathrm{O}2} \tag{5}$$

$$F_{\mathrm{VC}3} - F_{\mathrm{T}3} = m_{\mathrm{O}3}\ddot{x}_{\mathrm{O}3} + b_{\mathrm{O}3}\dot{x}_{\mathrm{O}3} \tag{6}$$

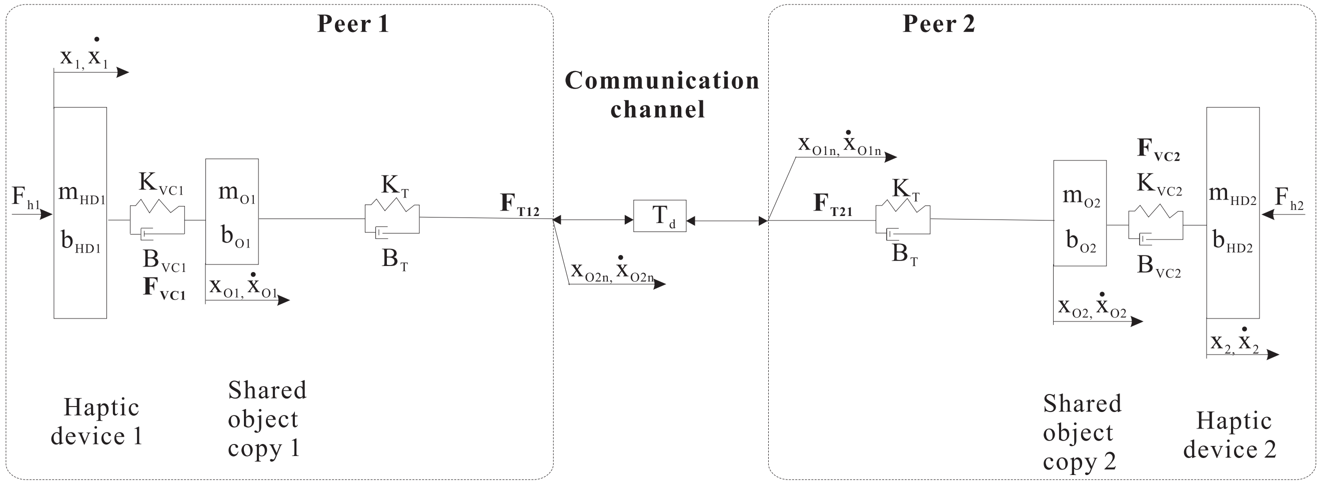

Fig. 1. The traditional peer-to-peer scheme with virtual coupling controller for haptic cooperation between two networked users [16].

where:

$$F_{\text{VC1}} = K_{\text{VC1}}(x_1 - x_{\text{O1}}) + B_{\text{VC1}}(\dot{x}_1 - \dot{x}_{\text{O1}}) \tag{7}$$

$$F_{\text{VC2}} = K_{\text{VC1}}(x_2 - x_{\text{O2}}) + B_{\text{VC1}}(\dot{x}_2 - \dot{x}_{\text{O2}}) \tag{8}$$

$$F_{\text{VC3}} = K_{\text{VC3}}(x_3 - x_{\text{O3}}) + B_{\text{VC3}}(\dot{x}_3 - \dot{x}_{\text{O3}}) \tag{9}$$

$$F_{\text{T1}} = K_{\text{T}}(x_{\text{O1}} - x_{\text{O1}_d}) + B_{\text{T}}(\dot{x}_{\text{O1}} - \dot{x}_{\text{O1}_d}) \tag{10}$$

$$F_{\text{T2}} = K_{\text{T}}(x_{\text{O2}} - x_{\text{O2}_d}) + B_{\text{T}}(\dot{x}_{\text{O2}} - \dot{x}_{\text{O2}_d}) \tag{11}$$

$$F_{\text{T3}} = K_{\text{T}}(x_{\text{O3}} - x_{\text{O3}_d}) + B_{\text{T}}(\dot{x}_{\text{O3}} - \dot{x}_{\text{O3}_d}) \tag{12}$$

$$x_{\text{O1}_d} = \frac{(x_{\text{O2}_n} + x_{\text{O3}_n})}{2}, \dot{x}_{\text{O1}_d} = \frac{(\dot{x}_{\text{O2}_n} + \dot{x}_{\text{O3}_n})}{2} \tag{13}$$

$$x_{\text{O2}_d} = \frac{(x_{\text{O1}_n} + x_{\text{O3}_n})}{2}, \dot{x}_{\text{O2}_d} = \frac{(\dot{x}_{\text{O1}_n} + \dot{x}_{\text{O3}_n})}{2} \tag{14}$$

$$x_{\text{O3}_d} = \frac{(x_{\text{O1}_n} + x_{\text{O2}_n})}{2}, \dot{x}_{\text{O3}_d} = \frac{(\dot{x}_{\text{O1}_n} + \dot{x}_{\text{O2}_n})}{2} \tag{15}$$

III. SIMULATIONS

This section compares the proposed controller to the traditional peer-to-peer scheme with virtual coupling control [16] via MATLAB simulations of an exemplary cooperative manipulation involving three peer users. In the exemplary manipulation, all users apply constant forces to the shared virtual cube. User 1 and User 3 push the cube to the right with equal forces whose sum equals the force with which User 2 pushes the cube to the left. In the first set of simulations, the stiffness of all virtual couplers is fixed and the SVO mass is decreased until the cooperation becomes unstable. In the second set of simulations, the SVO mass is fixed and the stiffness of all virtual couplers is increased until instability arises. To separate the effect of the coordination scheme from the effect of communications, a network delay equal to one step of the force feedback loop ($T_d = 0.001$s) is considered in simulations, and network jitter and packet loss are neglected.

Hereafter:

- S_{13} identifies the traditional distributed control with virtual coupling coordination among all pairs of SVO copies [16];
- S_{23} identifies the proposed distributed control with virtual coupling coordination of each local SVO to the averaged position of the other SVO copies.

The following parameters are used in all simulations: $F_{h1} = 5$N, $F_{h2} = -10$N, $F_{h2} = 5$N; $m_{\text{HD}i} = 0.5$kg, $b_{\text{HD}i} = 5$Ns/m; $b_{\text{O}i} = 5$Ns/m; $K_{\text{VC}i} = 2000$N/m, $B_{\text{VC}i} = 3$Ns/m; $B_{\text{T}i} = 30$N/m. The shared virtual cube and all peers are initially at rest, at positions $x_{\text{O}i} = 0$m, $x_{\text{HD1}} = x_{\text{HD3}} = -0.15$m, and $x_{\text{HD2}} = 0.15$m, respectively.

The position coherency performance of the two controllers is evaluated via the standard deviation of the positions of all SVO copies Δ:

$$\Delta = \sqrt{\frac{1}{N}\sum_{1}^{N}(x_{\text{O}i} - \overline{x}_{\text{O}})^2}, \tag{16}$$

where $\overline{x}_{\text{O}} = \frac{\sum_{i=1}^{N} x_{\text{O}i}}{N}$ and N is the number of participants to the cooperative manipulation.

Figure 4 shows the user trajectories during the exemplary cooperative manipulation of a maximally light SVO ($m_{\text{O}min} = 0.142$kg) coordinated via traditional control with stiffness $K_{\text{T}} = 2000$N/m. Figure 5 depicts the user trajectories during the exemplary cooperative manipulation of a maximally light SVO ($m_{\text{O}min} = 0.076$kg) coordinated via the proposed control for the same stiffness $K_{\text{T}} = 2000$N/m. The results are summarized in Table I. For the same virtual coupling stiffness, the minimum mass for which the cooperation remains stable is much lighter when the proposed

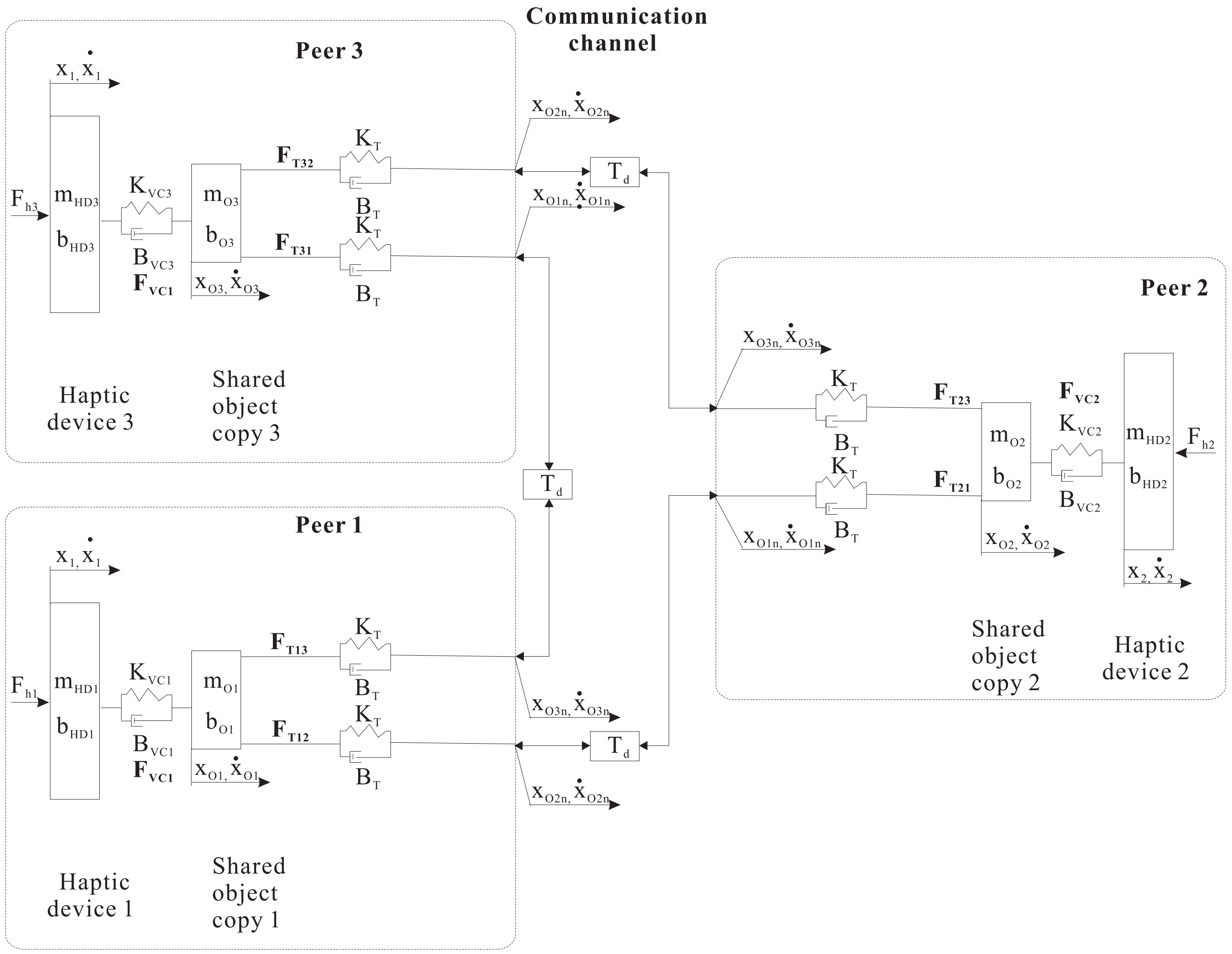

Fig. 2. Traditional distributed control of haptic cooperation among three networked users (coordination of local SVO copy to all other SVO copies).

controller is employed.

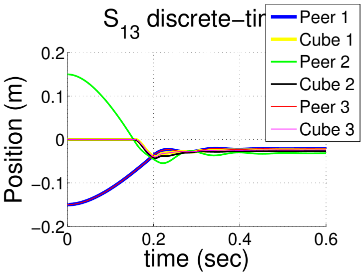

Fig. 4. Maximally light SVO ($m_{\mathrm{O}min} = 0.142$kg) manipulated via traditional control of three users (S_{13}), $K_{\mathrm{T}} = 2000$N/m.

Figure 6 illustrates the user trajectories during the exemplary cooperative manipulation of a SVO with mass $m_{\mathrm{O}min} = 0.142$kg coordinated via the maximally stiff traditional control $K_{\mathrm{T}} = 31500$N/m. Figure 7 plots the user trajectories during the exemplary cooperative manipulation of the SVO with mass $m_{\mathrm{O}min} = 0.142$kg coordinated via the maximally stiff proposed control $K_{\mathrm{T}} = 33800$N/m. ($m_{\mathrm{O}min} = 0.076$kg) coordinated via the proposed control for the same SVO mass $m_{\mathrm{O}} = 0.15$kg. The results are presented

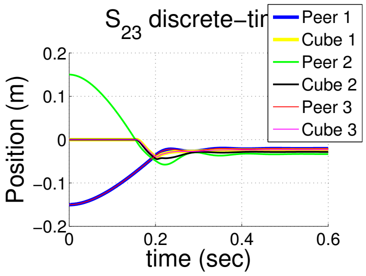

Fig. 5. Maximally light SVO ($m_{\mathrm{O}min} = 0.076$kg) manipulated via proposed control of three users (S_{13}), $K_{\mathrm{T}} = 2000$N/m.

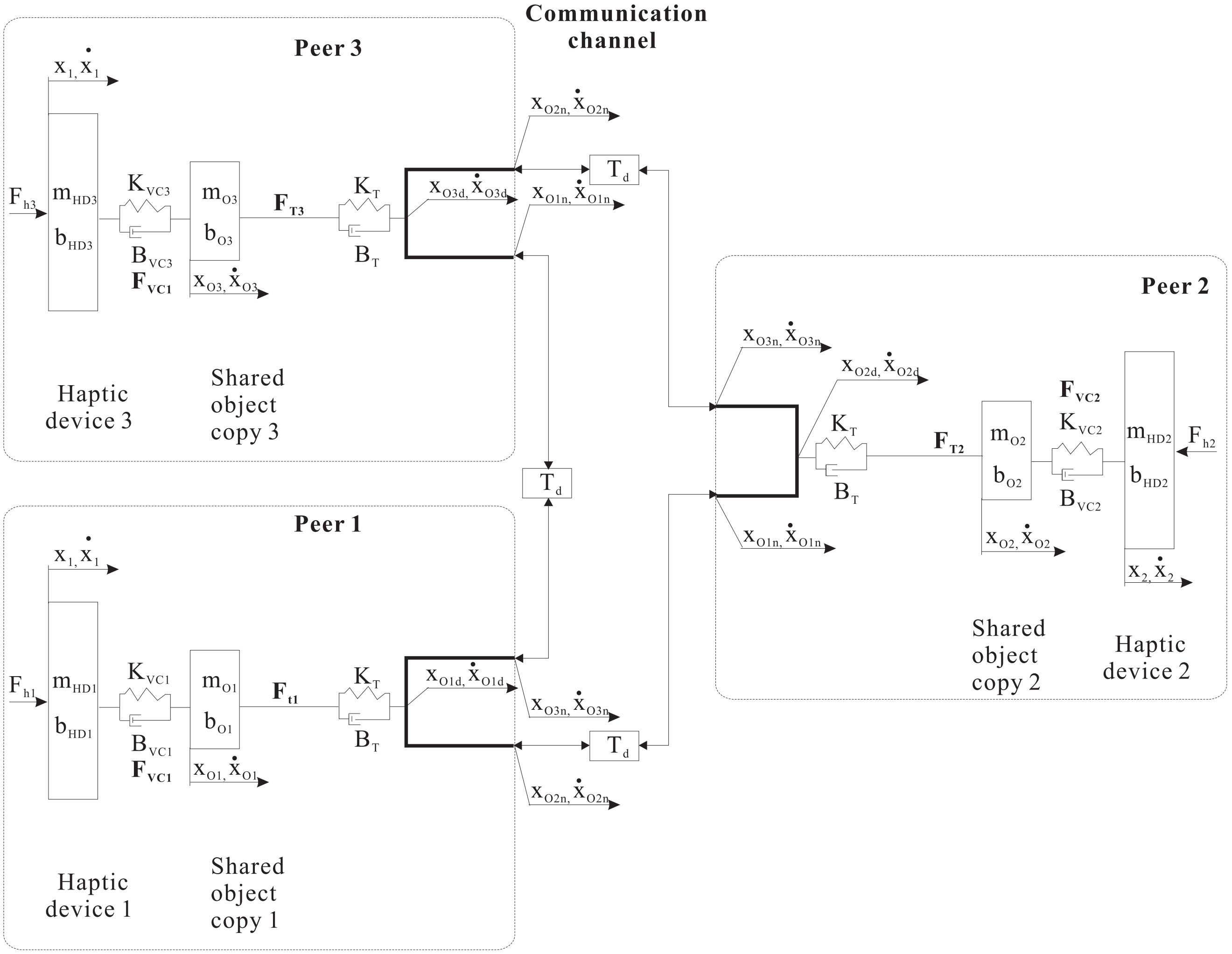

Fig. 3. Proposed distributed control to averaged position of haptic cooperation among three networked users (coordination of local SVO copy to averaged position of other SVO copies).

	N	m_{O} (kg)	$m_{\mathrm{O}i}(kg)$	x_{O1} (m)	x_{O2} (m)	$x_{\mathrm{O3}}(m)$
S_{13}	3	0.142	0.0473	-0.0242	-0.0267	-0.0242
S_{23}	3	0.076	0.0252	-0.0234	-0.0283	-0.0234

TABLE I
MINIMUM SVO MASS FOR FIXED VIRTUAL COUPLING STIFFNESS $K_{\mathrm{T}} = 2000$ N/M.

in Table II. For the same SVO mass, the proposed controller maintains the interaction stable for higher coordination stiffness.

The position coherence performance of the traditional and proposed control approaches are shown in Table III. The proposed coordination of the local SVO copies to the averaged position of the other SVO copies achieves position coherency similar to traditional SVO coordination when users manipulate the same SVO. Position coherency decreases

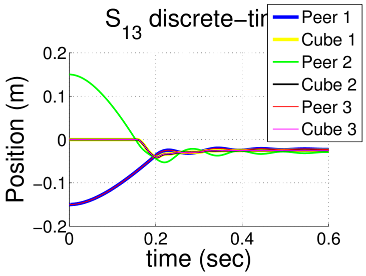

Fig. 6. Maximally stiff ($K_{\mathrm{T}} = 31500$N/m) traditional control of haptic cooperation among three users (S_{13}), $m_{\mathrm{O}min} = 0.15$ kg.

when users move together a lighter SVO.

IV. CONCLUSION

This paper has proposed a distributed haptic control architecture whose coordination gain at each user site is inde-

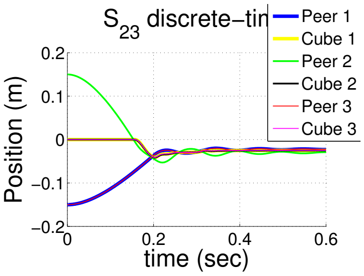

Fig. 7. Maximally stiff ($K_{\mathrm{T}} = 33800$N/m) proposed control of haptic cooperation among three users (S_{23}), $m_{\mathrm{O}min} = 0.15$ kg.

	N	K_{T} (N/m)	$m_{\mathrm{O}i}\,(kg)$	$x_{\mathrm{O}1}$ (m)	$x_{\mathrm{O}2}$ (m)	$x_{\mathrm{O}3}\,(m)$
S_{13}	3	31500	0.05	-0.025	-0.0251	-0.025
S_{23}	3	33800	0.05	-0.0249	-0.0252	-0.0249

TABLE II
MAXIMUM VIRTUAL COUPLING STIFFNESS FOR FIXED SVO MASS $m_{\mathrm{O}} = 0.15$ KG.

pendent of the number of cooperating participants. In the proposed architecture, users interact through manipulating a SVO together. The distributed copies of the SVO are controlled through virtual couplers. At each peer, the gain of the force feedback loop is maintained constant regardless of the number of interacting users by coordinating the local SVO copy to the averaged motion of the other SVO copies. MATLAB simulations of an exemplary cooperative manipulation performed by three users illustrate that the proposed controller: (1) can render a lighter SVO with decreased position coherence among the distributed SVO copies for the same stiffness of coordination; (2) achieves similar position coherence among the distributed SVO copies for the same SVO mass.

Upcoming work focuses on the analytical investigation of the stability of the proposed controller, and on its experimental validation.

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	Δ (m) for fixed K_{T}	Δ (m) for fixed m_{O}
S_{13}	1.2e-3	0.047e-3
S_{23}	2.3e-3	0.14e-3

TABLE III
POSITION COHERENCY OF THE TWO DISTRIBUTED CONTROLLERS.