力覚共有マウスを実現するためのマルチラテラル遠隔制御に関する設計法と国際間ゲームへの適用

森田 陽介[†1,a)]　小川 裕也[†1]　今村 孝[†2]　Kawaguchi Akira[†3]　三好 孝典[†1]　寺嶋 一彦[†1]

概要：本研究では，力位置帰還型マルチラテラル遠隔制御システムを使用しインターネットを介して複数の人が力覚を共有できるシステムを開発することを目的とする．本研究では，スキャッタリングマトリックスの新たな知見よりマルチラテラル遠隔制御システムを安定させるためにスキャッタリングマトリックスと位相制御フィルタを適用する．さらに，力覚共有マウスシステムに対する設計法を導出する．我々のシステムにおいて，トポロジーはネットワークで通常使用されるスター型のサーバ・クライアントシステムの形態を取り，クライアントとサーバ間の接続の成否にシステム全体が影響を受けない構成となっている．我々は，システムの有用性を確認するためにハプティックデバイスを使用しソウル-フロリダ-豊橋間で実験を実施し，位置がハプティックデバイスに印加された力によって制御された．実験より我々は，3つのクライアント間の力覚共有が通信遅延を含むマルチラテラルシステムで実現できることを確認した．

Design Method for Multilateral Tele-Control to Realize Shared Haptic Mouse and Its Application to Intercontinental Game

Yosuke Morita[†1,a)]　Yuya Ogawa[†1]　Takashi Imamura[†2]　Akira Kawaguchi[†3]
Takanori Miyoshi[†1]　Kazuhiko Terashima[†1]

Abstract: In this study, we aim to develop the system that many people can share a sense of force through the Internet, using a force-position multilateral tele-control system. We apply scattering matrix and phase control filter in order to stabilize the multilateral tele-control system with a new knowledge of scattering matrix. Additionally, we derive a design method for system " shared haptic mouse ". The unique characteristic of our design method is that stabilization is achieved by focusing on phase. In our system, topology takes the form of a commonly used star-shaped client/server system network topology and is configured such that the success or failure of specific connections between the client and server do not affect the entire system. We have conducted experiments between Stuttgart, New York, and Toyohashi using three haptic devices to verify the usefulness of this system, and successfully position was controlled by the force applied to the haptic device. Through experimentation, we verify that the shared haptic sensing between three clients is confirmed to have been realized in a multilateral system that included a communication delay.

1. Introduction

The challenge faced by tele-control on a network is finding a way to overcome the instability arising from the communication delays that arise between the master and slave, and while numerous solutions have been proposed by researchers to date. But the following three basic problems remain unsolved: 1) how to stabilize the master/slave connections in a non-passive system, 2) how to stabilize multilateral control in a system configured with $n : m$ connections, and 3) how to stabilize multilateral tele-control in an Internet environment, despite the indeterminate number of connections resulting from users

[†1] 現在，豊橋技術科学大学
Presently with Toyohashi Uniersity of Technology
[†2] 現在，新潟大学
Presently with Niigata Uniersity
[†3] 現在，ニューヨーク市立大学
Presently with City College of New York
[a)] y_morita.@syscon.me.tut.ac.jp

Fig. 1 Image of the shared haptic mouse which enables people in the world to share the force each other

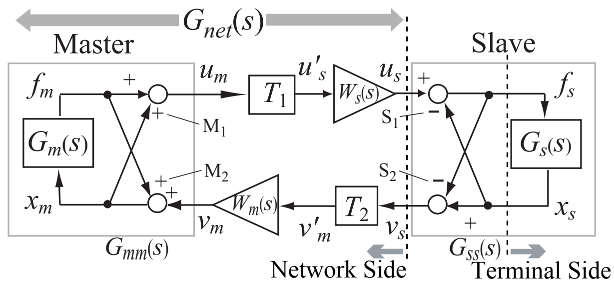


Fig. 2 Block diagram of bilateral tele-operation system using Scattering matrix

being able to connect and disconnect their systems freely.

The final image of this study is shown in **Fig. 1**. The mouse is moved by strings or wires stretched in four directions. This shared haptic mice used worldwide employ force sensors to measure the operating force applied by the operators, and the mice move in response to it's force. For example, if Operator A in the United States attempts to move the mouse to the right but Operator B in Japan and Operator C in Korea resist that movement, the mouse will not move. The mouse location is the same regardless where it is viewed around the world.

This paper presents new insights for scattering matrices, and upon solving the aforementioned problems for a certain class of models, derives a design method for a system " shared haptic mouse ". Typically, control design is often stabilized in terms of the norm or gain. However, the unique characteristic of our design method is that stabilization is achieved by focusing on phase. In the case of an Internet-based multilateral tele-control system with a large unspecified number of connections, it is difficult to design a gain-dependent control system, because the operating force response from a teleoperate site can range from 1 [N] for a single person to a response on the order of 10^6 [N] from several tens of thousands of people.

The design class targeted by this paper is a model in which a one-input one-output linear passive system is connected in series to each of the output terminals of an n-input n-output linear passive system, as will be described later, and the entire system is non-passive. Although it is limited as perceived, this model is useful for the purpose of this paper, which is to realize a shared haptic mouse.

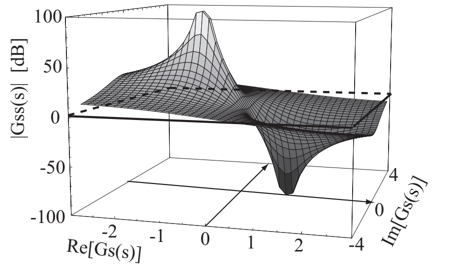
This paper is organized as follows. Section 2 presents new insights into scattering matrices, which are used in Section 3 to demonstrate the stability of the shared haptic sensation mouse. Section 4 shows the experimental results, which are summarized in the Conclusion.

2. Characteristics of the Scattering Matrix

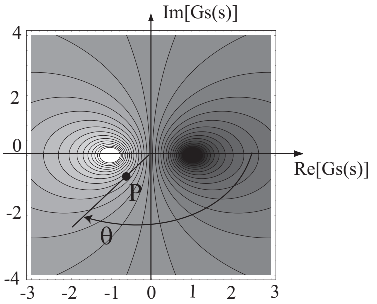
In order to clarify the characteristics of the scattering matrix, we consider force and position feedback-type bilateral control that includes a time delay. In **Fig. 2**, $G_m(s)$ is the master, $G_s(s)$ is the slave, $f_m(t)$ is the force applied by the operator, $f_s(t)$ is the force received by the slave, $x_s(t)$ is the device location computed by the slave, and $x_m(t)$ is the location received by the master. The scattering matrix is the cross-coupled portion of the drawing. Herein, the inner side is of the scanning matrix is referred to as the network side and the outer side is referred to as the terminal side.

Spong et al. were the first researchers to incorporate a scattering matrix into tele-control[1]. They demonstrated that a scattering matrix is passive regardless of the time-invariant delay T and that if the non-linear systems of $G_m(s)$ and $G_s(s)$ have passivity, the system will be stable. This configuration is commonly known as the Cayley transform, but the achievement of Spong et al. can also be considered to be the introduction of the concept of time delay.

However, it is unlikely that real-world stability problems can be solved with passivity alone. In digital control, for example, due to S/H, the phase delay will reach -180 [deg] at the Nyquist frequency, and even the motion of a spring-mass-damper system or a point mass, which is the most basic system in mechanics, will result in a second-order delay system and therefore be non-passive. To solve this problem, Miyoshi et al. have previously proposed a bilateral control system stabilization method for the non-passive linear $G_s(s)$ and $G_m(s)$ systems[2]. In the present study, a norm compensator that suppresses norms of 1 or greater that have been generated due to non-passivity in the communication circuit is used to ensure stability.



(a) |Gss(s)| according to Re[Gs(s)] and Im[Gs(s)] (3D View)



(b) |Gss(s)| according to Re[Gs(s)] and Im[Gs(s)] (Density Plot)

Fig. 3 Magnitude of $G_{ss}(s)$ according to $Re[G_s(s)]$ and $Im[G_s(s)]$ on complex plane

2.1 Characteristics of Gain in Network-Side

In Fig. 2, the system is disconnected at u_s and v_s on the slave side, when the transfer function $G_{ss}(s)$, where the input to the scattering matrix is u_s and the output from the scattering matrix is v_s, is expressed by the following equation using $G_s(s)$.

$$G_{ss}(s) = \frac{V_s(s)}{U_s(s)} = \frac{G_s(s)-1}{G_s(s)+1} \tag{1}$$

It is apparent that the magnitude of the gain, when represented on an $G_s(s) = a(\omega) + b(\omega)i$ complex plane, is represented by **Fig. 3** and Proposion 1, and in terms of the relationship with passivity.

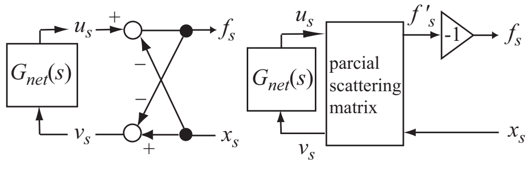
Proposition1

When $\theta(\omega) = \angle G_s(j\omega)$, in $-\pi \leq \theta < -\pi/2,\ \pi/2 < \theta \leq \pi$, upper bound $\overline{|G_{ss}|}(\omega)$ of $|G_{ss}(j\omega)|$ is given as $\overline{|G_{ss}|}(\omega) = \sqrt{\dfrac{1-\cos\theta(\omega)}{1+\cos\theta(\omega)}}$. Moreover, $\overline{|G_{ss}|}(\omega) = 1$,in $-\pi/2 \leq \theta \leq \pi/2$.

Proposition 1 means that the upper bound of the gain of the scattering matrix, as seen from the network side, can be uniquely determined by the phase of the terminal side. In other words, the scattering matrix is a component that can control the network-side gain with the phase on the terminal side.

2.2 Characteristics of Phase in Terminal-Side

Consider **Fig. 4** (a), which is an extracted right portion of Fig. 2. If the transfer function $G_{net}(s)$ is connected to v_s and u_s, the transfer function of the scattering matrix,



(a)Physical Matrix (b)Partial Matrix

Fig. 4 Phase of scattering matrix according to $Re[G_{net}(s)]$ and $Im[G_{net}(s)]$ on complex plane

as seen from the terminal side, is expressed by the following equation which is similar to Eq. (1).

$$\frac{F_s(s)}{X_s(s)} = \frac{G_{net}(s)-1}{G_{net}(s)+1} \tag{2}$$

At this time, we obtain the follow Proposition.

Proposition2

When $r(\omega) = |G_{net}(j\omega)|$ $(r(\omega) \leq 1)$, lower bound $\underline{\angle\Delta}(\omega)$ of phase of $\frac{F'_s(j\omega)}{X_s(j\omega)} = -\frac{F_s(j\omega)}{X_s(j\omega)}$ in scattering matrix is given as $\underline{\angle\Delta}(\omega) = -\arctan\dfrac{2r(\omega)}{1-r(\omega)^2}$. Moreover, upper bound $\overline{\angle\Delta}(\omega)$ is given as $\overline{\angle\Delta}(\omega) = \arctan\frac{2r(\omega)}{1-r(\omega)^2}$.

Where the phase of the sign-inverted f'_s is shown virtually in Fig. 4 (b). Assuming that a portion of the scattering matrix has been extracted, the portion from x_s to f'_s is hereinafter referred to as a " partial scattering matrix " (PSM). The reason for considering the negative sign is indicated in paragraph 2.3 and 3.3.

In the scattering matrix, if the H_∞ norm is less than or equal to 1, it is known that the output thereof will be passive, which is consistent with the results of the abovementioned Proposition. In other words, if $r \leq 1$, the phase is within the range of $-\pi/2$ to $\pi/2$, and the passivity in a linear system is shown. **Fig. 5** shows a three-dimensional (3D) graph of the $\angle\frac{F'_s(j\omega)}{X_s(j\omega)}$ at the time of change of $a(\omega) = Re[G_{net}(s)]$, and $b(\omega) = Im[G_{net}(s)]$. As $r = \sqrt{a^2+b^2}$ expands outward centered about the origin, it can be confirmed that the range of possible phases expands. The angle also changes according to the phase of $G_{net}(s)$ itself, but does not fall below the lower bound.

Proposition 2 means that the lower limit of the phase of the scattering matrix, as seen from the terminal side, can be adjusted by modifying the gain on the network side. In other words, the scattering matrix is a component that can use the network-side gain to control the phase of the terminal side.

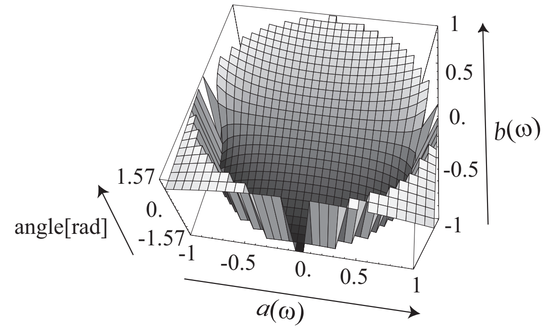


Fig. 5 Phase of scattering matrix according to $Re[G_{net}(s)]$ and $Im[G_{net}(s)]$ on complex plane

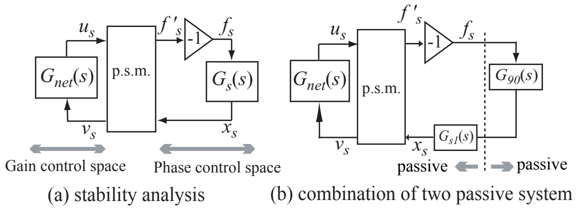


Fig. 6 Stability condition between gain control domain and phase control domain with scattering matrix

2.3 Stability Condition of Closed Loop Including Scattering Matrix

Consider the stability in **Fig. 6** (a). Here, the square is a PSM, $G_{net}(s)$ has a certain gain $r(\omega)$ (at any arbitrary phase), and $G_s(s)$ has a phase of $\theta(\omega)$ (at any arbitrary gain). In this situation, the follow Lemma can be derived.

Lemma1 When $G_{net}(s)$ has an arbitrary phase and $G_s(s)$ has an arbitrary gain and prescribed phase $\theta(\omega) = \angle G_s(j\omega)$ $(-\pi \leq \theta(\omega) \leq -\pi/2)$, stability condition of the closed loop system is $|G_{net}(j\omega)| \leq \sqrt{\frac{1+\cos\theta(\omega)}{1-\cos\theta(\omega)}}$. Moreover, when $G_s(s)$ consists of $G_{s1}(s) \times G_{90}(s)$, the stability condition of Fig. 6 (b) is $|G_{net}(j\omega)| \leq \sqrt{\frac{1+\sin\theta(\omega)}{1-\sin\theta(\omega)}}$, and closed loop is fed back with two passive components. Where phase lag of $G_{90}(s)$ exceeds -90 [deg] and $\theta(\omega) = \angle G_{s1}(j\omega)$ $(-\frac{\pi}{2} \leq \theta(\omega) \leq 0)$.

This Lemma holds special significance for tele-control stabilization because, in an environment where the network side phase has indeterminacy due to an indefinite communication delay, and in an environment where the terminal-side gain also has indeterminacy due to an indefinite number of accesses and parameter fluctuations, stability can be improved in both directions by manipulating $|G_{net}(j\omega)|$.

3. Stabilization Method in Multilateral Systems

3.1 Server Model

This paragraph describes the stabilization of a multi-

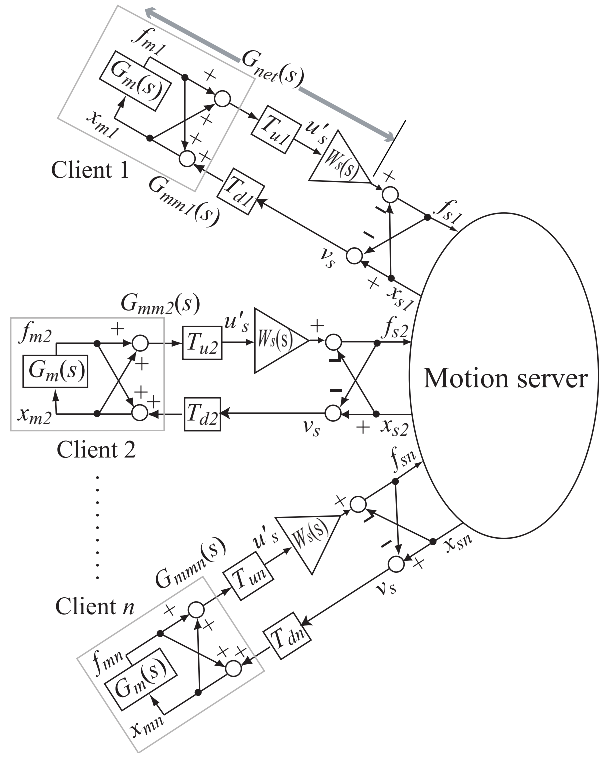


Fig. 7 Block diagram of shared haptic mouse with multilateral control system

lateral system having the topology of **Fig. 7**. That is, n shared haptic mice (hereinafter referred to as clients) existing worldwide are coupled via a network and scattering matrix to a motion server, and each exerts mechanical interference on the others. Because of the complex intertwining of non-passive systems with different communication delays T_{ui},T_{di} $(i = 1, 2, \ldots, n)$ existing for each network, stabilization is not easy to realize.

To date, as methods used to stabilize multilateral systems, Katsura et al.[3], have proposed a relaying topology to implement the haptic sensing. However, with this topology, all haptic sensing will be interrupted if the network is cut even at just one location. Therefore, in practice, shared haptic sensing via the Internet would not possible. In contrast, because the topology proposed in this study takes the form of a commonly used star-shaped client/server system network topology and is configured such that the success or failure of specific connections between the client and server do not affect the entire system, the number of connections can be increased very easily. Behzad et al.[4] have proposed dual-user teleoperation systems, and allowed interaction between both users. However, this system can be applied only two operators. Duc et al.[5] have proposed a control method that is besed on bilateral tele-operation system, and conducted the experiment using one master robot and two

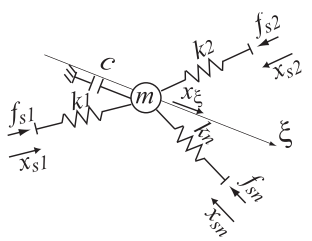


Fig. 8 Physical model of multilateral tele-control system

slave robots. However, this system applied by one master and many slave, that is, operator is only one person. Kanno et al.[6] have proposed multilateral tele-operation based on wave-variables. With this system, small position tracking errors occur due to wave variables and local PD control , whereas, our method does not have any error in steady state because it does not use any feedback signal for stabilization. Ohnishi et al.[7] have proposed centralized controller for multilateral control system. However, this system has the constrain in which each operator's position has to be consistent with each other. On the other hand, our proposed system does not have any constraint for each client.

The physical model of the motion server is shown in **Fig. 8**. An operating force f_{si} [N] is provided as an input via a spring k_i [N/m] to a mass point having a mass m [kg]. With the spring end position x_{si} [m] at this time as the output, f_{si} and x_{si} belong to a local coordinate system X_i that forms an angle from the global coordinate system ξ to $T_{\xi i} = \cos\phi_i$. Here, $T_{\xi i}$ indicates the direction of force added by the i-th client, and is assigned arbitrarily. For example, if $T_{\xi 1} = 1$ and $T_{\xi 2} = -1$, they will be placed opposite each other. For the purpose of simplification, the mass point S_O is assumed to move only in the direction of the x_ξ [m] coordinate system, and in proportion to the speed in the ξ direction, during which the mass point encounters the resistance of the coefficient of viscosity c [N/(m/s)]. x_{si} is determined under the influence of all inputs $f_{s1}, f_{s2}, \ldots, f_{sn}$.

At this time, the model is expressed by Eq. (3).

$$\begin{cases} T_{\xi 1}f_{s1} + T_{\xi 2}f_{s2} + \ldots + T_{\xi n}f_{sn} = m\ddot{x}_\xi + c\dot{x}_\xi \\ k_{s1}(x_{s1} - T_{\xi 1}x_\xi) = f_{s1} \\ \vdots \\ k_{sn}(x_{sn} - T_{\xi n}x_\xi) = f_{sn} \end{cases} \tag{3}$$

We will get input-output relation by applying laplace transformation method to above equation.

$$\begin{aligned} X_{si}(s) &= \\ &\frac{ms^2+cs+k_i}{k_i s(ms+c)}{T_{\xi i}}^2 F_{si}(s) + \sum_{j=1(j\neq i)}^{n} \frac{1}{s(ms+c)} T_{\xi i}T_{\xi j}F_{sj}(s) \\ &= \frac{1}{k_i}F_{si}(s) + \sum_{j=1}^{n}\frac{1}{s(ms+c)}T_{\xi i}T_{\xi j}F_{sj}(s) \\ &(i = 1, 2, \ldots, n) \end{aligned} \tag{4}$$

The second term represents the value of x_ξ determined by f_{sj}, and the first term represents the relative position of x_{sj} from there. This function is not positive definite, and is therefore non-passive.

This is converted to the block form of **Fig. 10**.

$$X_s(s) = \frac{1}{ms+c}G_{sO}(s)F_s(s) \tag{5}$$

$$G_{sO}(s) = \begin{bmatrix} \frac{m}{k_1}s + \frac{c}{k_1} + \frac{{T_{\xi 1}}^2}{s} & \frac{T_{\xi 1}T_{\xi 2}}{s} & \cdots & \frac{T_{\xi 1}T_{\xi n}}{s} \\ \frac{T_{\xi 2}T_{\xi 1}}{s} & \frac{m}{k_2}s + \frac{c}{k_2} + \frac{{T_{\xi 2}}^2}{s} & \cdots & \frac{T_{\xi 2}T_{\xi n}}{s} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{T_{\xi n}T_{\xi 1}}{s} & \frac{T_{\xi n}T_{\xi 2}}{s} & \cdots & \frac{m}{k_n}s + \frac{c}{k_n} + \frac{{T_{\xi n}}^2}{s} \end{bmatrix}$$

Where, $X_s(s) = [x_{s1}(s), x_{s2}(s), ..., x_{xn}(s)]^T$, $F_s(s) = [f_{s1}(s), f_{s2}(s), ..., f_{sn}(s)]^T$, $G_{si}(s) = \frac{1}{ms+c}$, and $G_{sO}(s)$ is positive real and passive system as follows.

$$\frac{G_{sO}(j\omega) + {G_{sO}}^T(-j\omega)}{2} = diag\left\{\frac{c}{k_1}, \frac{c}{k_2}, \cdots, \frac{c}{k_n}\right\} \geq 0$$

3.2 Client-Side Model

In contrast, the master model $G_m(s)$ is an admittance control system that is assumed to consist of a force sensor capable of detecting the operating force and is attached to a linear slider capable of positioning a servo motor, as shown in **Fig. 9** (a). The operator transmits the operating force f_m via the sensor, and the server transmits the position reference x_m to the linear slider. Here, if $G_{servo}(s)$ is the transfer function for positioning the linear motor, the $G_m(s)$ transfer function is as given by Fig. 9 (b) and Eq. (6). Additionally, K_h[N/m] is the spring constant of the reaction force generated according to the rigidity of the operator's hand when the slider is moved, and D_h[N/(m/s)] is damper coefficient between the slider and the operator's hand. These quantities are determined by the mechanical properties of the operator's arm [2].

Although the sign of the scattering matrix in Fig. 7 is positive, this is not intended to indicate positive feedback. When the slider is moved in the positive direction, the resistive force generated by the operator's hand is in the negative direction.

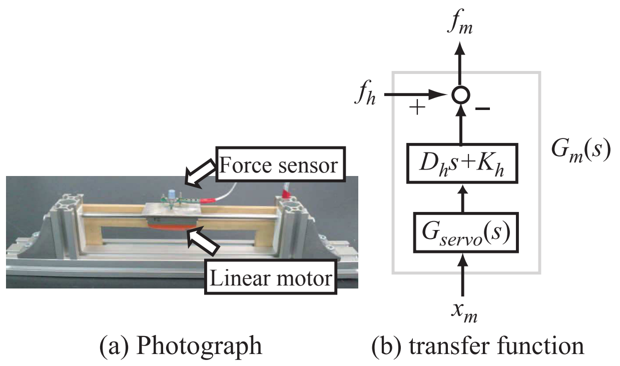


Fig. 9 Photograph and block diagram of client system

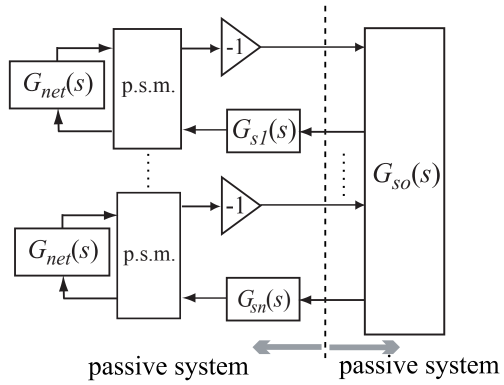


Fig. 10 Block diagram of multilateral tele-control system

$$
\begin{aligned}
F_m(s) &= (D_h s + K_h) G_{servo}(s) X_m(s) \qquad (6)\\
&\simeq (D_h s + K_h) X_m(s)
\end{aligned}
$$

3.3 Server-Side Stability

Fig. 7 can be rewritten in Fig. 10 from Eq. 5. Herein, $G_{sO}(S)$ and $G_{si}(s) = \frac{1}{ms+c}$ correspond to $G_{90}(s)$ and $G_s(s)$ in Fig. 6 (b) respectively, and $G_{net}(S)$ is the transfer function of network side in Fig. 7

In Eq. (5), in a case where k_i is large and m and c are small, the $1/s$ term becomes dominant, and at 0 [rad/s], $G_{sO}(s)$ may become approximately -90 [deg]. In other words, if estimated on the phase-delayed side, a phase delay of approximately -90 [deg] can be estimated over the entire frequency band. On the other hand, because $G_{si}(s)$ is a first-order delay system, the phase becomes $-\frac{m}{c}\omega$ and approximately 0 [deg] at low frequencies. Accordingly, from Lemma 1, $G_{net}(s)$ that realizes stability for whole system, must exist and have sufficient conditions for stabilization.

$$
\begin{aligned}
|G_{net}(j\omega)| &= \sqrt{\frac{1+\sin(\arctan(-\frac{m}{c}\omega))}{1-\sin(\arctan(-\frac{m}{c}\omega))}}\\
&= \sqrt{\frac{\sqrt{m^2\omega^2+c^2}-m\omega}{\sqrt{m^2\omega^2+c^2}+m\omega}}
\end{aligned}
$$

Additionally, in Fig. 2, assuming that that the H_∞ norm of the transfer function from v'_m to u_m is less than or equal to 1 and is stable, the gain does not change with the time-invariant delay T_1 and T_2, and therefore $||\frac{U_m(s)}{V'_m(s)}||_\infty \le 1$. From the above, it is shown that the entire system can be stabilized by introducing a filter $W_s(s)$ configured as

$$
0 \le |W_s(j\omega)| \le \sqrt{\frac{\sqrt{m^2\omega^2+c^2}-m\omega}{\sqrt{m^2\omega^2+c^2}+m\omega}} \qquad (7)
$$

$W_s(s)$ is a filter that functions to control the phase delay of the scattering matrix, generate the phase margin on the terminal side, and to stabilize the system. Therefore, it is referred to as a phase control filter (PCF) below.

Actually, although the multilateral system is MIMO system, the stability condition will remain intact. When the j-th $\frac{x_{yj}}{f_{sj}}$ becomes passive by using PCF written in Eq. (7), whole the left part of Fig. 10 also becomes passive because passive diagonal matrix is constructed.

Thus, although the number of clients n, the delay time T_{ui} and T_{di}, the operator rigidity K_h and D_h, and most other parameters are indeterminate, the server-side system reduces to the combination of two passive system in which one is $G_{sO}(s)$ and the other one consists of $W_s(s)$, scattering matrix, and $G_{si}(s)$.

3.4 Client-Side Stability

In Eq. (6), $G_m(s)$ is passive regardless of the values of K_h and D_h, and therefore Proposition 1 prescribes that $|G_{mm}(j\omega)| \le 1$. $G_m(s)$ is also stable because the loop in the scattering matrix physically has negative feedback. Accordingly, by setting the PCF $W_m(s) = 1$, the assumption provided in the previous paragraph is satisfied.

3.5 Boundary Condition for PSF $W_s(s)$

When considering a stable steady state in this configuration, as shown in Fig. 2, the cross-coupled signals at points S_1 and M_1 are positive and negative signals that cancel. Furthermore, the signals at points S_2 and M_2 also cancel. Accordingly, when $W_s(0) = 1$ and $W_m(0) = 1$, it is ensured that $f_m = f_s$ and $x_s = x_m$, and the force and position on the master and slave are in agreement.

4. Experimental Results of the Multilateral System

Some experiments were conducted by connecting a total of three one-degree-of-freedom haptic devices to a server as clients. **Fig. 11** shows the experimental landscapes between Toyohashi, Newyork, and Stuttgart. In this ap-

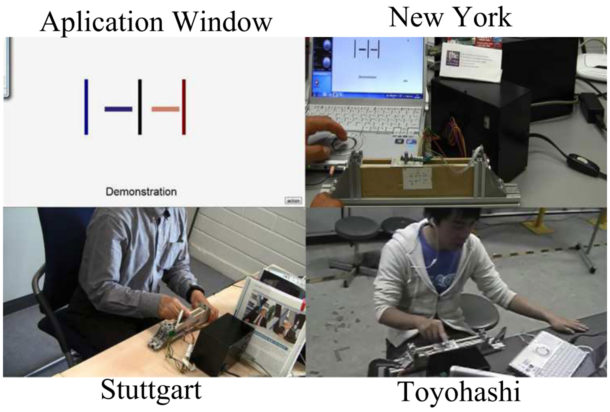


Fig. 11 Photograph of experimental landscapes using 3 clients

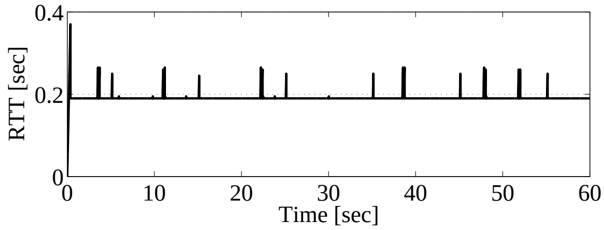
plication window, vertical bar means player, left player is Stuttgart operator, center player is Toyohashi operator, and right player is New York operator. Additionally, each client was considered to reside on the same axis and the operating force f_{si} is applied as an input to a spring mass damper system at the server. In this experiment, the force applied to each haptic device by an operator is transmitted as the respective client force f_{mi} through a communication delay T_{ui} to the server. The resultant force of this client is computed by the server to derive a position x_{si}. The position x_{si} computed by the server is transmitted through a communication delay T_{di} to each client, and the position of each haptic device is controlled. In the case of resistance by another operator, the position does not change as intended even when force is applied, and the operator is able to tactually perceive the operating force of the other operators.

Round trip time (RTT) during Toyohashi and New York, and Toyohashi and Stuttgart is shown **Fig. 12**. As for Fig. 12, variation of RTT was almost constant. For this result, we verified good network condition.

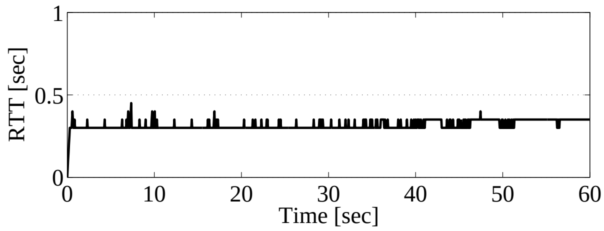
Table 1 shows the main experimental conditions. Additionally, even though the PCF value has been adjusted and a compensator has been added to increase the phase margin on the terminal side, remarks related to this issue are omitted here. Where P_{li} is establishment of the packet loss [%] mesured by experiment. Note that the client numbers and the haptic device numbers correspond to each other. In this experiment, client number 1 is New York, number 2 is Stuttgart, and number 3 is Toyohashi.

Experimental results of the client force f_{mi} (= force applied to a haptic device) and the position x_{si} output from a server (= position of each client) are shown in **Fig. 13** for the case of operating all haptic devices.

In the experiment of Fig. 13, three haptic devices were



(a) Between Toyohashi and New York



(b) Between Toyohashi and Stuttgart

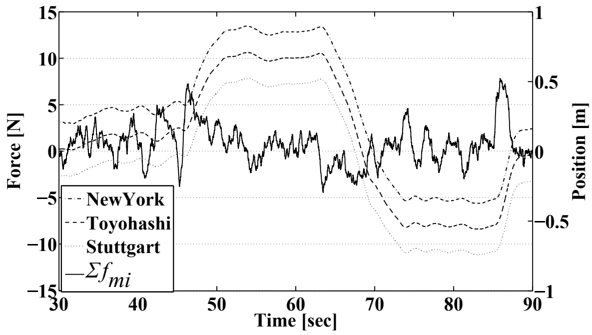
Fig. 12 Experimental results of round trip time

Table 1 Typical parameters of experiments

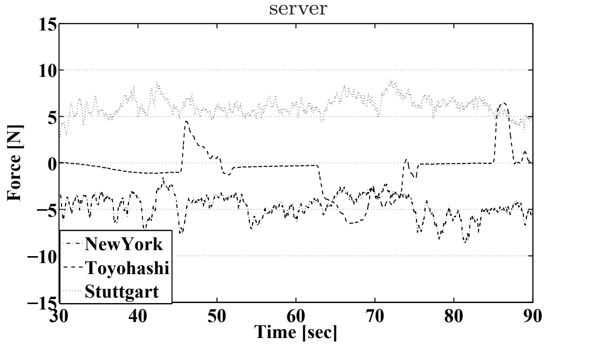
	unit	value		unit	value
$T_{u1}+T_{d1}$	[ms]	190.8	T_ξ	-	1
$T_{u2}+T_{d2}$	[ms]	323.0	k_i	[N/m]	200
$T_{u3}+T_{d3}$	[ms]	0	m	[kg]	0.775
P_{l1}	[%]	0.03	c	[N/(m/s)]	1.58
P_{l2}	[%]	0.00			
P_{l3}	[%]	0			

operated. Fig. 13 (a) shows the resultant force of each client and the position output from the server, and Fig. 13 (b) shows the force of each operator. After approximately 30 seconds, the operators of New York and Stuttgart began jostling so that the positions of their haptic devices did not change. At about 45 seconds, the operator of Toyohashi applied a force in the positive direction, and then at about 63 seconds, applied a force in the negative direction.

From Fig. 13, it can be seen that during the interval from the beginning of operation at the time of 30 seconds until the start of the Toyohashi operation, the force applied by New York operator and the force applied by Stuttgart operator were balanced, and thus there was almost no position change. Additionally, because the forces of New York operator and Stuttgart operator were balanced, during the time intervals from 45 to 51 seconds and from 63 to 73 seconds, it was confirmed that the force applied by Toyohashi and the resultant force Σf_{mi} change in the same direction, and that the each position and the resultant force Σf_{mi} also change in the same direction. Furthermore, during the time intervals from 76 to 85 seconds, each position fluctuates slightly, but the balanced force relationship keeps its position stable.



(a) Relationship between force and position calculated by server



(b) Applied force of 3 position

Fig. 13 Experimental results of haptic games

From the above, the shared haptic sensing between multiple clients is confirmed to have been realized in a multilateral system that included a communication delay.

5. Conclusion

In this paper, we have presented new insights concerning scattering matrices and, using the characteristics thereof, have demonstrated the stability of a client/server multilateral system that has a communication delay. Additionally, through experimentation, we have demonstrated the effectiveness of our proposed system, which has the advantage of maintaining stability over the entire system and the shared haptic sensing between multiple clients is confirmed to have been realized in a multilateral system, when there are three clients connected between Stuttgart, New York, and Toyohashi.

6. Acknowledgments

This work was supported by the Martin Buss in Technische University Munich and JSPS KAKENHI Grant Number 24360090.

参考文献

[1] R.Anderson, M.Spong, "Bilateral Control of Teleoperators with Time Delay", *IEEE Transactionson Automatic Control*, Vol.34, No.5, pp.494-501, 1989.

[2] Takanori Miyoshi, Kazuhiro Terasima and Martin Buss, "A Design Method of Wave Filter for Stabilizing Non-passive Operating System", *IEEE International Conference on Applications*, 4-6, 2006.

[3] Takumi Ishii, Seiichiro Katsura "Articuled Multilateral Control for Haptic Broadcasting System", *IEEE Industrial Electronics on Society*, 7-10, 2010.

[4] Behzad Khademian, and Keyvan Hashtrudi-Zaad "A Four-Channel Multilateral Shared Control Architecture for Dual-User Teleoperation Systems", *IEEE Intelligent Robots and Systems*, pp.2660-2666, 2007.

[5] Nam Duc Do, and Toru Namerikawa, "Cooperative Control Based on Force-Reflection with Four-channel Teleoperation System", *IEEE Conference on Decision and Control and European Control Conference*, pp.4879-4884, 2011.

[6] Kanno Takahiro, and Yasuyoshi Yokokohji, "Multilateral Teleoperation Control over Time-Delayed Computer Networks using Wave Variables", *IEEE Haptics Symposium*, pp.125-131, 2012.

[7] Daisuke Yashiro, Dapeng Tian, and Kouhei Ohnishi, "Centralized Controller based Multilateral Control with Communication Delay", *IEEE International Conference on Mechatronics*, pp.991-996, 2011.