Review on Bilateral Teleoperation with Force, Position, Power and Impedance Scaling

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***Abstract*— Scaling is a technique used to transfer the dynamic motion properties of a remote device (slave robot) to the operator (master robot) or vice versa. This is a challenging task in terms of force, position, power, and impedance scaling approaches when master and slave manipulators are dissimilar. Teleoperation using scaling methods is a popular topic in motion control field, and many research papers are written on different scaling methods. This paper gathers the most important and diffused bilateral scaling technologies. It also integrates a collection of some of the widely used scaling technologies with a historical overview and the improvements proposed by a range of researchers.**

Keywords—impedance scaling; power scaling; force scaling; position scaling; bilateral teleoperation

I. INTRODUCTION

The prefix “tele” is a Greek word to denote “at a distance”. Teleoperation means operating a machine at a distance using a set of commands communicated over a communication channel. Teleoperation provides the remote sense of the distant environment and makes the operator feel the similar conditions as those at the remote location. [1]

Most of the controllers that we come across in day today lives are unilateral controllers. As the name implies, communication is done unilaterally. Simple TV remote controller is an example for a unilateral controller. In a bilateral controller, master (operator) and slave (environment) sides are controlled bilaterally. The intention is to feel the environment at the distance while it is being controlled. Bilateral control system enables the slave side environment to be reflected in the master side and master side operating intention to be reflected in the slave side.

Humans have five sensors for vision, smell, sound, taste and touch. Though sound and visual sensors of the human can be stored and reproduced in a remote place, the sense of the nose (smell) and tongue (taste) cannot normally be transmitted nor stored in an electronic means. The fifth sensor, the touch can be transmitted and reproduced using the bilateral control concept. The target of bilateral control is the transmission of haptic information by electronic means from a remote location.

The bilateral control system is a popular and successful concept behind several engineering applications such as mine cleaning, space robots and medical surgeries. The aim in bilateral teleoperation concept is to provide a better haptic perception to the operator while performing a remote operation task. The operator should feel as if he is physically present at the remote environment (“telepresence”).

In microsurgery applications, the master and slave motion spaces are dissimilar, and hence scaling factors can be applied to extend human operator’s skills to small surgical areas [2]. The master manipulator’s movement and the applied force can be scaled down to perform micro level operations (macro manipulation at the master and micro manipulation at the slave or vice versa according to the assignment).

The principle of bilateral teleoperation is the realization of natural low of motion of two objects (Fig. 1). Force and position measurements are made at the slave and fed back to the master. The master manipulator is equipped with actuators to be able to exert forces on the operator. Basically the sense of touch is made by the sensation, position and the force acting on them. This information is gathered by different sensors [3].

The benefits of bilateral scaling in industrial environment are manifold. It definitely leads to cost reduction by integrating with accurate robot platforms and effective work handling. Scaling techniques are integrated in many practical applications to improve the existing drawbacks of control systems.

Bilateral teleoperation with scaling techniques is a useful and an increasingly researching topic in motion control field. A collection of existing scaling technologies with a historical overview and the improvements proposed by a range of researchers are covered in this paper. This review will benefit the future researchers and designers who wish to work in scaled bilateral experiments, and will allow them to understand the wider applicability of this concept.

This paper is categorized as follows. In the section II, the historical timeline of major scaled bilateral teleoperation systems are reviewed. Section III separately presents the available scaling techniques on control theoretic grounds. This discussion includes force, position, power and impedance scaling strategies proposed in various studies. In the section IV, the most significant bilateral scaling applications are summarized, and this paper is concluded in section V.

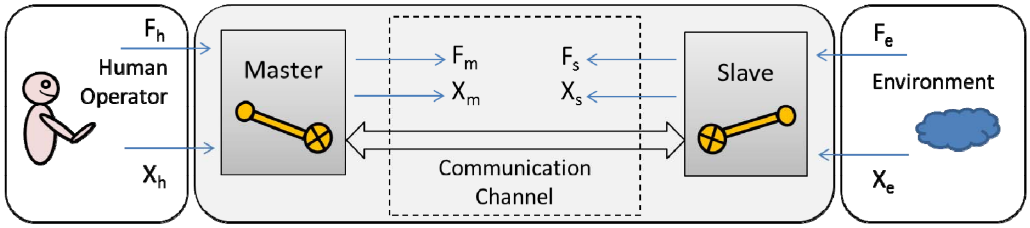

Fig. 1. Bilateral teleoperation system. The human operator applies a force of F_h on the master manipulator and moves it by X_h. These force and position measurements are transmitted to the slave manipulator over a communication channel. The reaction force caused by the environment F_e and the movement of the slave manipulator X_e are fed back to the master.

II. History of Scaled Bilateral Teleoperation

The first successful bilateral teleoperation using master-slave manipulators was recorded in 1940s when R. Goertz and his team developed a mechanical pantograph applying the bilateral teleoperation concept. These manipulators were built to handle nuclear material of a nuclear reactor [4]. Since that invention by R. Goertz, the bilateral teleoperation techniques were developed rapidly using different scaling approaches.

Since the inception of modern bilateral teleoperation in 1940s, the operationaliy of the bilateral controller was developed using different scaling techniques. The applicability of bilateral scaling concept was developed from the deep sea explorations (1950s) to today's haptic related industrial applications, and since then the concept of bilateral scaling has evolved greatly and contributed to many sectors ranging from robot assisted surgery to hazardous material handling.

In 1962, Cornell Aeronautical Laboratory studied a master-slave robotic system as a man-amplifier to scale up the soldiers' lifting and carrying capabilities [5]. The same master-slave system was developed by General Electric Co from 1960 to 1971, and it was called the Hardiman [6,7]. Hardiman was a prototype man-amplifier (exoskeleton) worn by a human operator. However, man-amplifiers did not meet with much initial success because it required too much concentration of the part of the operator.

Supervisory control for teleoperation was proposed by Sheridan [8] in 1970 as a combined concept of teleoperation and automatic control. This concept was used for teleoperation in space or in undersea operations with time scaling techniques to solve the problem of transmission time delay [9].

In 1988, Raju [10] presented the impedance scaled teleoperation techniques and suggested impedance adjustments of the teleoperation system to improve the haptic performance. The extensions of impedance scaling were proposed by Sakaki [9] and Colgate [7,11] in early 1990s. In parallel to these studies, the integration of force, position and impedance scaling techniques resulted in sophisticated teleoperation activities such as robot assisted minimally invasive surgeries and micro assembly [12,13]. As a result of these advanced teleoperation approaches, a popular telesurgery application callled "Da Vinci surgical system" [14] was developed by Intuitive Surgical Inc. It is a laparoscopic assist device that enables surgeons to perform complex surgeries in a minimally invasive fashion [15].

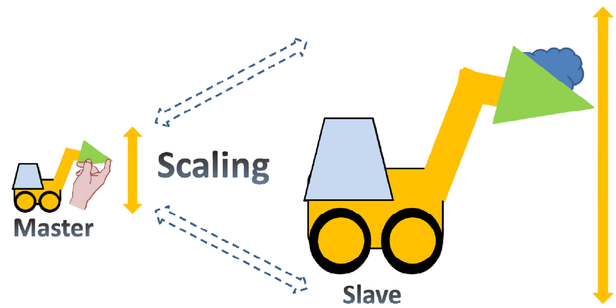

Fig. 2. Bilateral force and position scaling concept with dis-similar master and slave models

III. Developments in Bilateral Scaling Techniques

In bilateral teleoperation, normally it is expected the environment to be sensed as it is. However, sensing the environment as it is at the operator might not be practical depending on the task performed by the slave manipulator. For example, as shown in Fig. 2, if the operator tries to lift a heavy object using the control force and position applied at the master manipulator, those force/position measurements should be scaled up when they are reproducing at the slave manipulator. Similarly, the feedback of force/position measurements from the environment should be scaled down when it is transmitted towards the operator to ensure the comfort of the operator.

Bilateral scaling mainly consists of position, force and impedance scaling methods and sometimes time scaling. Many researchers and organizations in teleoperation arena have developed the theories and models using one of position, force, impedance and time scaling methods or a hybrid of them. Some significant researches in scaled bilateral teleoperation are discussed briefly in the following sections under different scaling approaches.

A. Power scaling

In 1960s, Mosher [6] used power and impedance scaling bilateral manipulators for strength increasing "man-amplifiers" called Hardiman. A similar manipulator named "extender" [16] was introduced by Kazerooni in 1980s. In his design, the operator is intimately connected to the powered limb of the extender and communicates with the extender via both power and information.

Later, in early 1990s, Colgate [7] presented a condition for robust stability in power scaled bilateral teleoperation system. Assuming passive environment, Colgate described his approach in terms of scattering matrices [17]. In this approach, the passivity is assumed when an LTI n-port network with a scattering matrix $S(j\omega)$ is satisfied the condition of $\| S(j\omega) \|_{\infty} \le 1$.

If the scattering matrices of human operator and the environment are S_h and S_e respectively, then the corresponding scattering matrix can be represented as,

$$S_{he}(s) = \begin{pmatrix} S_h & 0 \\ 0 & S_e \end{pmatrix} \tag{1}$$

The scattering matrix for the master slave teleoperation system (Fig. 3) is given by (2). Where, subscripts *1* and *2* denote port 1 and port 2, and *m* and *s* stand for master and slave of the teleoperation system respectively.

$$S_{ms}(s) = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \tag{2}$$

The scattering matrix of the two-port teleoperation system, is given in terms of the hybrid matrix $H(s)$ (discussed in Impedance scaling section in (9)) by simple loop transformation.

$$S(s) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} (H(s)-1)(H(s)+1)^{-1} \tag{3}$$

Again, in 1993, in a conceptually similar approach, Colgate presented the bilateral power scaling using effort and flow variables [18]. This approach can be modeled as an ideal bilateral manipulator is assumed (Fig. 3) connecting a 1-port operator and 1-port environment. This system is viewed as an effort-flow pair being exchanged at each port (in the case of mechanical systems it is the force-velocity pair).

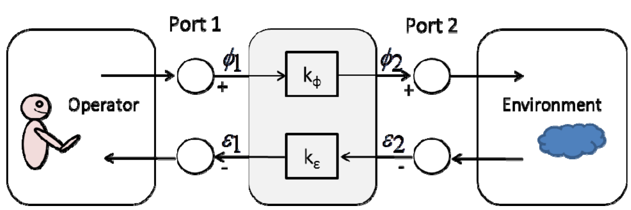

Fig. 3. One DOF teleoperator system with an ideal power scaling bilateral manipulator. Where, ϕ is a flow variable and ε is an effort variable. k_ϕ and k_ε are dimensionless static scaling factors [18].

The power transferred from the operator to the master manipulator and from the environment to the slave manipulator is defined by the bilateral control law. If the effort variables (currents, velocities) are scaled with respect to each other, then it is necessary that the flow variables (voltages, forces) to be at the inverse scale to satisfy power balancing equation.

$$\phi_1 \varepsilon_1 = -\frac{k_\varepsilon}{k_\phi} \phi_2 \varepsilon_2 \tag{4}$$

The ratio k_ε / k_ϕ is defined as the "power scaling factor".

B. Impedance scaling

1) Scaling with two-port architecture

Further to the power scaling approach discussed in previous section, Colgate introduced impedance shaping bilateral control system in [18,19]. In this design, the master/slave impedances were dynamically reshaped to create an appropriate dynamic behavior of the system.

The impedance scaling factor $k_\varepsilon k_\phi$ of Fig. 3. can be derived from the relationship between the impedance felt by the operator and the impedance of the environment.

$$Z_o(\phi 1) = k_\varepsilon k_\phi Z_e(\phi 2) \tag{5}$$

The impedance scaling approach can be modeled assuming an LTI two port teleoperation network. Similar studies are available in [10, 20-22]. Considering the two-port network arrangement in Fig. 4, following mechanical equations can be derived.

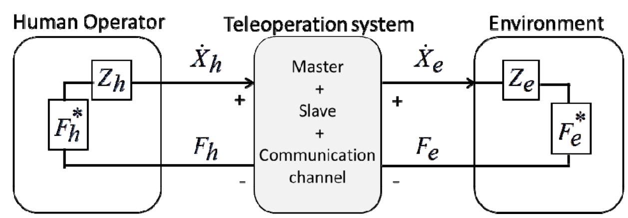

Fig. 4. Two-port network representation of teleoperator system. Where, Z_h, $\dot{X}_h$, F_h and F_h^*, and Z_e, $\dot{X}_e$, F_e and, F_e^* represent impedance, velocity, force and the exogenous force input generated by the operator and the environment, respectively.

Let the effort variable be the position X and flow variable be the force F of the mechanical system model. Then, the operator and the environment impedances becomes $Z_h(s)$ and $Z_e(s)$ respectively.

$$Z_h(s) = \frac{F_h(s)}{-\dot{X}_h(s)}, \quad Z_e(s) = \frac{F_e(s)}{\dot{X}_e(s)} \tag{6}$$

The impedance matrix $Z(s)$ and admittance matrix $Y(s)$ can be obtained as follows [10].

$$\begin{pmatrix} F_h(s) \\ F_e(s) \end{pmatrix} = \underbrace{\begin{pmatrix} z_{11}(s) & z_{12}(s) \\ z_{21}(s) & z_{22}(s) \end{pmatrix}}_{Z(s)} \begin{pmatrix} \dot{X}_h(s) \\ -\dot{X}_e(s) \end{pmatrix} \tag{7}$$

$$\begin{pmatrix} \dot{X}_h(s) \\ -\dot{X}_e(s) \end{pmatrix} = \underbrace{\begin{pmatrix} y_{11}(s) & y_{12}(s) \\ y_{21}(s) & y_{22}(s) \end{pmatrix}}_{Y(s)} \begin{pmatrix} F_h(s) \\ F_e(s) \end{pmatrix} \tag{8}$$

Above system model can be represented by its hybrid matrix $H(s)$ [22], given that the force response is sensed at the slave manipulator.

$$\begin{pmatrix} F_h(s) \\ -\dot{X}_e(s) \end{pmatrix} = \underbrace{\begin{pmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{pmatrix}}_{H(s)} \begin{pmatrix} \dot{X}_h(s) \\ \dot{F}_e(s) \end{pmatrix} \tag{9}$$

The elements of hybrid matrix $H(s)$ can be reduced to a set of scaling facets. This interpretation has become the basis for several theoretical contributions such as the scattering approach and 4-channel model, especially to address the communication delays of the channel.

$$H(s) = \begin{pmatrix} \text{Input Impedance} & \text{Force Scale} \\ \text{-Velocity Scale} & \text{Output Admittance} \end{pmatrix} \tag{10}$$

a) Scaling with wave-variable architecture

Wave variable approach described in [23, 24,25,26] is a similar approach to the scattering matrix based method. This concept is developed in the analysis and design of teleoperation systems with time delays. As shown in Fig. 5, instead of exchanging master-slave force and velocity signals, wave variables (a_1 , a_2 , b_1 and b_2) are transmitted.

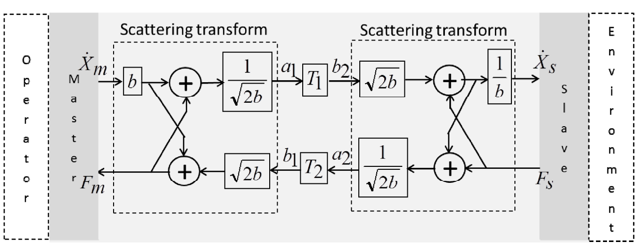

Fig. 5. Scattering-wave variable architecture for bilateral teleoperation. Where, $\dot{X}_m$ and F_m , and $\dot{X}_s$ and F_s , represent velocity and force variables of master and lave manipulators, respectively.

Wave variables can be expressed as inwave or incident wave $\overrightarrow{W}(s)$ and outwave or reflected wave $\overleftarrow{W}(s)$. The travelling waves are defined using an algebraic transformation expressed as follows,

$$a_1 = \frac{F_m + b\dot{X}_m}{2\sqrt{b}}, \; a_2 = \frac{F_e - b\dot{X}_e}{2\sqrt{b}} \tag{11}$$

$$b_1 = \frac{F_m - b\dot{X}_m}{2\sqrt{b}}, \; b_2 = \frac{F_e + b\dot{X}_e}{2\sqrt{b}} \tag{12}$$

where, b is the characteristic impedance of the transmission line which serves as a tuning parameter to tradeoff between speed of motion and level of forces. The relationship between incident wave and reflected wave is given by,

$$\overleftarrow{W}(s) = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \underbrace{\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix}}_{S(s)} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = S(s)\overrightarrow{W}(s) \tag{13}$$

Several control strategies are introduced in the wave domain due to the intrinsic passivity of the wave formulation. These strategies are useful to maintain the passivity when performed directly in the power variables domain. Different types of representations of a network can be transformed to each other, as long as the matrices are not ill-conditioned [27]

2) Transparency in impedance scaling

In order to perform different force/position (velocity) scaling tasks, the bilateral teleoperation system has to be transparent. When the transparency is high, the system represents the environmental impedance with high accuracy at the master side. The transparency can be achieved when the operator impedance $Z_h(s)$ and the environment impedance $Z_e(s)$ are equal.

$$Z_h(s) = Z_e(s) \tag{14}$$

When this condition is satisfied, the accurate environment impedance is transferred to the operator. This yields the hybrid matrix and scattering matrix to become,

$$H(s) = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad S(s) = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \tag{15}$$

Susa et al. [28] following a similar hybrid matrix based approach showed that the scaling factors and controller gains can be incorporated to achieve ideal reproducibility and operationality in a micro-macro bilateral system. Ideal reproducibility and operationability of the micro-macro teleoperation system is achieved by the proposed impedance scaling based hybrid matrix, according to,

$$\begin{pmatrix} h_{11}(s) & h_{12}(s) \\ h_{21}(s) & h_{22}(s) \end{pmatrix} = \begin{pmatrix} \frac{M_{nm}^2}{C_f} s^2 & \beta \frac{M_{nm}}{M_{ns}} \\ \alpha \frac{M_{nm}}{M_{ns}} & 0 \end{pmatrix}, \tag{16}$$

where, master and slave nominal masses are approximated by M_{nm} and M_{ns} respectively, α and β denote position and force scaling ratios of the system respectively, and C_f represents force control gain.

3) Scaling with four-channel Lawrence architecture

In 1995, Salcudean [29] suggested a four channel data transmission structure to achieve the transparency of bilateral teleoperation system under position and rate control. The four channel general teleoperator architecture (Fig. 6) introduced by Lawrence [30,31] is adopted here for the proposed design.

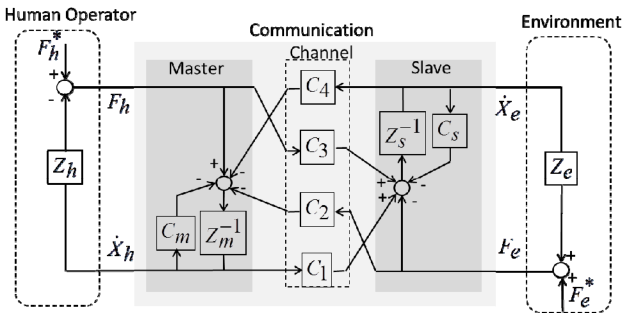

Fig. 6. General four-channel bilateral teleoperation system block diagram. C_m and C_s are the transfer functions of the local controllers, and C_1 - C_4 are remote compensators.

As for the proposed design, the transmitted impedance felt by the operator, Z_t can be expressed using the block transfer function as below.

$$Z_t = \frac{[(Z_m + C_m)(Z_s + C_s) + C_1 C_4] + Z_e (Z_m + C_m + C_1 C_2)}{(Z_s + C_s - C_3 C_4) + Z_e (1 - C_2 C_3)} \quad (17)$$

For a fully transparent teleoperator system, $Z_t = Z_e$ equation should be satisfied for any Z_e. Based on these grounds, a mixed position/rate model was introduced in [29]. In this approach, the scaling between the master and slave velocity and force was realized by the hybrid matrix $H(s)$, according to,

$$H(s) = \begin{pmatrix} Z_m(s) & G(s) \\ -\frac{1}{G(s)} & 0 \end{pmatrix}. \quad (18)$$

Where, $Z_m(s)$ is the master impedance and $G(s)$ is a stable transfer function.

The four-channel architecture proposed by Lawrence was used in different bilateral scaling designs and teleoperation theories. Few of the most important improvements suggested for four-channel bilateral teleoperator systems can be found in [32-35].

C. Force/position scaling

When the master and the slave manipulators operate on macro-micro architecture or vice versa, thus it is vital to select matching scaling factors to achieve the desired performance. The steady state condition of the bilateral controller can be governed by,

$$H(s) = \begin{pmatrix} Z_m(s) & G(s) \\ -\frac{1}{G(s)} & 0 \end{pmatrix}. \quad (18)$$

where, α and β are the position and force scaling factors respectively. F_m and X_m, and F_s and X_s represent force and position quantities of the master and slave manipulators, respectively.

Force and position scaling can perform transformations from the motor space to the modal space through the scaling gain matrix approach. However, in real time, actual manipulation scenarios, the scaling gain in the control should be changed arbitrary by operators for more precise operations. Kosugi et al., in [36], suggested a variable scaling gain concept to change the scaling gain arbitrary to achieve this condition. Conceptually similar force and position scaled problems are addressed in [37-40]

IV. Applications of Bilateral Scaling Techniques

Many of the real world teleoperation systems or teleoperation applications do not use one-to-one force and position following approaches. Scaling in terms of force, position, power, impedance and sometimes time provides humans to apply their skills in a various industrial missions. These applications range from extending human operator's skills in minimally invasive surgeries to outer orbit space applications. Few of the most significant applications are summarized in Table 1.

TABLE I. Common Scaled Bilateral Teleoperation Applications

Field	Applications	Selected references
Space	Moon/Mars exploration, Satellite	[41-43]
Underwater	Unmanned underwater vehicles	[44,46]
Telesurgery	Minimally invasive surgery, micro-surgery	[2, 11-14]
Military	Unmanned Air Vehicles, Unmanned Ground Vehicles, Land-mine field clearing vehicle	[45,46]
Security	Bomb deactivation, hazardous material handling	[46,47]

V. CONCLUSION

Although, bilateral teleoperation with scaling techniques is a highly researching area in motion control field, a fewer number of books and resources are available for new researchers. In this review, a collection of some of the widely used scaling technologies with a historical overview and the improvements proposed by a range of researchers are briefly discussed.

As we discussed and stated above, a number of scaling approaches in bilateral teleoperations have been developed for different application areas. Many different control strategies have been presented to efficiently handle the teleoperation tasks. There are effective and promising studies to address the issues related to force, position, power and impedance scaling formulations. However, so far, the time scaling in bilateral teleoperation is not a matured research area. Time delay introduced by the communication channel can cause deterioration in system response and make the system unstable easily. Consequently, it is vital to focus the future bilateral scaling experiments on robust time scaling and compensation methods.

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