

ANALYSIS OF HUMAN DYNAMICS IN MICRO-TELEOPERATION SYSTEM

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Abstract: Microsurgery and microassembly are some high precision tasks that require the assistance of a micromanipulator. However, in order to manipulate micro objects it is inevitable to consider the scaling effect problem between the worlds with different physical characteristics. Some scaling methods have been proposed, but how the scaling gains affect the human operator performance is still a remaining problem. In this paper, when different transfer function parameters are selected, the effects on the performance and the dynamic characteristics of the human operator are analyzed.

Keywords: Micro-teleoperation, Scaling laws, Man-machine systems.

1 INTRODUCTION

In recent years, the expectation about microrobots has increased due to the development of micromotor and micromachining technology. The medical science is another field that makes use of these technologies in microsurgery technique [1]. However, to execute tasks like microassembling and microsurgery with high precision, the assistance of a micromanipulator is needed. In this case, to manipulate a micro object it is necessary to scale down the operator's movement and scale up the force from the environment, which is not an easy operation when the physical characteristics between the macro and the micro worlds are much different. Constant scaling [2] and impedance scaling [3][4][5] are the two scaling laws most commonly used to scale up and down the forces and movements between the master and slave. However, the proper design of the scaling gain to provide the human operator with a good maneuverability is still a remaining problem. The researches that have been done to evaluate the scaling laws did not take into consideration the human dynamic characteristics. It should be emphasized that the human dynamic characteristics play an important role in improving the performance of the master-slave manipulator system, which is a type of manually controlled man-machine system, because he/she is, in fact, a part of the system [6].

The aim of this paper is to analyze the effects on the performance and the dynamic characteristics of the human operator in a bilateral micro-teleoperation system, when different scaling methods are selected. It is useful to predict and evaluate the performance of the whole micro-teleoperation system. The behavior of the human operator to be involved in the position and force controller will also be discussed.

2 SCALING LAWS IN MICRO-TELEOPERATION SYSTEMS

In the micro-teleoperation task, the physical size of the environment and slave differs greatly from that of the master's, therefore it is necessary to scale up and down the informations (force and motion) exchanged between them. In this section, we will describe some scaling laws concerned to micro-teleoperation in real time.

2.1 Constant Scaling

Scaling up and down the physical quantities by a constant factor is the simplest way of scaling. It is not necessary that the motion and the force scaling gains have the same values. One consequence of this constant scaling [2], is that the operator can feel the micro world with its peculiar characteristics, like high viscosity and friction forces compared with the inertial forces. Because the human operator is not familiar with the forces that dominate the micro-world, he/she has some difficulties in maneuvering the master-slave manipulator.

2.2 Impedance Scaling

When the human operator manipulates a micro object, it is possible to apply the impedance scaling to reshape the environment in order to improve his/her maneuverability performance. The scaling method proposed by Colgate [3][4] aims to scale individually the microenvironment mass, damping and elastic

coefficient. It lies on the principle of the physical similarity laws, which indicates that the mass is proportional to the length cube and viscous forces vary as the area. Sakaki *et al.* [7] also studied the master-slave manipulation systems in different scale environments based on similarity transformation.

Another type of impedance scaling was proposed by Kaneko *et al.* [5], where not only geometrical scaling gains but also dynamic ones were adjusted for scaling transfer functions. Through this impedance scaling it is possible to reshape the dynamics of the microenvironment that the operator is going to experience, and present him an impedance which is shaped out of the real one.

Besides scaling the motion and force, a time scaling [8] was also proposed in order to compensate the high frequencies inherited to the micro world.

An evaluation of some scaling laws applied in a micro pick-and-place task was done by Tokashiki *et al.* [2]. Besides the Fitt's Law results, the master and slave position, velocity, and force were used in the evaluation. In their paper, however, the evaluated micro-teleoperation system did not take into consideration the human dynamics inside the control loop.

Yokokohji *et al.* [9] defined the ideal response of micro-teleoperation and proposed a new control scheme which can realize the ideal response. However, no quantitative evaluation about the effects of different scaling methods was proposed.

To evaluate the performance of the man-machine system like micro-teleoperation in more complex tasks, it is important also to analyze the human dynamic characteristics.

3 MAN-MACHINE SYSTEMS

Early researches have already shown that it is important is to consider the human dynamic characteristics when designing and evaluating man-machines systems. The major part of the analytical theory on manual control of vehicles was developed in the 60's.

One of the important results was the Crossover Model proposed by McRuer *et al.* [6]. It was shown that near the crossover frequency, which corresponds to $|H(s)G(s)|=1$, the following equation was satisfied.

$$H(s)G(s) \cong \frac{w_c e^{-t_e s}}{s} \quad ; \text{ near } w_c \tag{1}$$

e^{-t_e} (0.1•0.4s) : Time lag due to human responses

w_c (0.5•0.8 Hz) : Crossover frequency

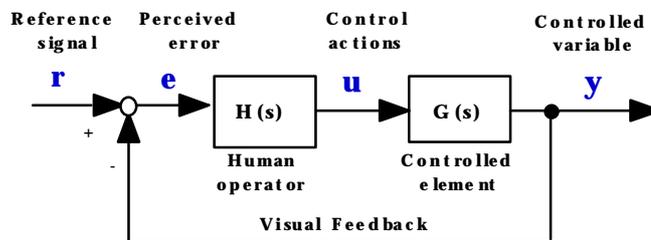


Fig. 1 Block diagram including the human operator

We can deduce from the above equation that according to the manipulated machine characteristics, the human operator can modify his/her own dynamic characteristics. As a result, the slope of $|H(s)G(s)|$, near the crossover frequency, lies very close to -20dB/decade amplitude ratio.

4 FORMULATION

To analyze the effects of different scaling methods on the performance and the dynamic characteristics of the human operator, a master-slave manipulator system is utilized. As this is an initial research, first, only the position control task is considered. The reason is because the evaluation of position control task is much simpler and it also can be useful to make a comparison between former researches on man-machine systems.

4.1 Control Scheme

The control strategy applied here is based on the impedance shaping proposed by Kaneko *et al.* [5]. The aim of this control scheme is to reshape the environment impedance.

The dynamic equation of the master-slave manipulator can be written as:

$$M_m \ddot{x}_m + B_m \dot{x}_m = F_m^{cmd} + F_m \quad (2)$$

$$M_s \ddot{x}_s + B_s \dot{x}_s = F_s^{cmd} - F_s \quad (3)$$

, where,

M_m, B_m •Master inertia and dumping coefficients

M_s, B_s •Slave inertial and dumping coefficients

$x_m, \dot{x}_m, \ddot{x}_m$ •Master position, velocity and acceleration

$x_s, \dot{x}_s, \ddot{x}_s$ •Slave position, velocity and acceleration

F_m^{cmd}, F_s^{cmd} ,•Master and slave driving forces

F_m •Operational force (Force applied to the master arm by the operator)

F_s •Slave force (Force exerted against the environment by the slave)

The slave force F_s , occurs when the slave interacts with the environment, and it can be represented as follows:

$$F_s = Z_e(x_s - x_e) \quad (4)$$

$$Z_e = M_e s^2 + B_e s + K_e \quad (5)$$

, where,

Z_e •Environment impedance

x_e •Environment position

M_e, B_e, K_e •Environment inertia, dumping and elastic coefficient

s •Complex frequency (Laplace Transformation).

We selected the Motion-Force Transmission Method (Fig. 3) to control the master-slave manipulator. In this method, the master is controlled by a force controller, and the slave by a position controller. Namely, the master is driven to make the master force F_m , follow the slave force F_s , and the slave is driven to make the slave position x_s follow the master position x_m . The master and slave driving forces are given as follows:

$$F_m^{cmd} = -K_f(\mathbf{a}(s)F_s - F_m) - \mathbf{a}F_s \quad (6)$$

$$F_s^{cmd} = K_p(\mathbf{b}(s)x_m - x_s) - K_v \dot{x}_s \quad (7)$$

, where,

K_p, K_v •Position and velocity feedback gain

K_f •Force feedback gain

$\mathbf{a}(s), \mathbf{b}(s)$ •Force and position scaling gain

In order to improve the master-slave manipulator's maneuverability, the gains of the both position and force controllers (k_p, k_v, k_f) were selected, while retaining stability. In that way, assuming that the environment position $x_e = 0$, the impedance shaped from the real one can be represented as:

$$\frac{x_m}{F_m} \approx \frac{1}{\mathbf{a}\mathbf{b}k_p Z_e} (k_p \gg 0, k_v \gg 0, k_f \gg 0) \quad (8)$$

4.2 Scaling Laws

In our experiments the following two scaling laws were adopted.

- Constant Scaling

$$F_s = (M_e s^2 + B_e s + K_e)(x_s - x_e) \quad (9)$$

$$F_m = \mathbf{a}F_s \quad (10)$$

$$x_s = \mathbf{b}x_m \quad (11)$$

Where the scaling gains $\mathbf{a} = 100$. and $\mathbf{b} = 1/100$.

- Impedance Scaling

$$F_m = \mathbf{a}(s)F_s \quad (12)$$

$$x_s = \mathbf{b}(s)x_m \quad (13)$$

Where $\mathbf{a} = 100$ and $\mathbf{b} = (s+2)/100$, $\mathbf{b} = (s+5)/100$ were selected as the force scaling and position scaling, respectively.

5 EXPERIMENT

5.1 Experimental Apparatus

A planar 2 D.O.F linear direct drive motor system was used as the master, and the slave, as well as the environment were simulated by the computer. The human operator manipulates the master holding a grip with a force sensor attached to it. The visual information about the slave is projected from the roof and the operator looks at the image on a screen board right above the master arm. The human operator's movement is detected by the master encoder (250000x4[pulse/m], with resolution of 1[μm]) and the operational force is measured by a 6-axis-torque-sensor (Nitta Corp. IFS-67M25A25-140, with resolution of 0.6[g]).

5.2 Experiment Task

A micro object with mass M_e (0.002[Kg]) is fixed to a base, which is connected to it via a damper B_e (20[Ns/m]) and spring K_e (50[N/m]). The micro object is fixed to the slave arm, so there is no need to grasp it. The model adopted in the experiments is shown in Fig. 2. The goal of the task is to move the slave arm via the master arm in order to pursuit a random reference signal presented close to the micro object. The random reference signal was constructed adding various sinusoids with different amplitudes and frequencies (0.01•10Hz, cut off frequency at 0.3Hz). Two young male students were selected for the experiments. After repetitive sessions of training, they performed the experiment tasks for three different scaling parameters. According to McRuer *et al.* [6] the man-machine open-loop transfer function, near the crossover frequency, assumes a first-order form. Consequently when the human operator controls a first-order controlled element, it is enough for him/her to behaviour like a proportional gain. The master-slave system considered here, is a forth-order system, but at frequencies up to 100 Hz, the fourth and the third terms are negligible compared with the second and first terms. As a result, selecting $(s+a)$ as the impedance scaling gain seems to be a reasonable choice. In all the cases the visual magnifying was set up to 100 times.

5.3 Experimental Results

5.3.1 Pursuit Error

As a first step to evaluate the maneuverability of the micro-teleoperation system, the pursuit error was calculated by the Integrated Square Error (ISE).

$$ISE = \sum_{i=1}^N \left[\int_0^{T_i} e_i^2(t) dt / \int_0^{T_i} r_i^2(t) dt \right] \quad (14)$$

After learning to manipulate the micro-teleoperation system, the subjects were told to pursuit the reference signal in ten trials. One constant scaling gain and two impedance scaling gains were selected in this task. The results of the ISE and the standard deviation are shown in Fig. 2. In the case of subject 1, it is evident that the performance of the operator is improved due to the impedance scaling. On the other hand, only when $\mathbf{b} = (s+5)$ was selected, the subject 2 obtained a significant high score. From these results, it is clear which scaling method gives better performance. However, it is not easy to speculate the reasons why it happend. A reasonable explanation could be found from the human dynamic characteristics.

5.3.2 Master-Slave Manipulator and Human Dynamic Characteristics

To identify the human transfer function, the non-parametric spectrum analysis was adopted. As the task was based on visual feedback, the identification was done considering a closed-loop control system. To identify the $H(s)G(s)$ transfer function, the reference signal r , the error e , and the master force F_m were measured (see Fig. 1). First, we estimate the cross spectral density $P_{ry}(s)$ between r and y , and also $P_{ru}(s)$ between r and u . Then the ratio between the two cross spectral densities was calculated to obtain the transfer function.

$$H(s)G(s) = \frac{P_{ry}(s)}{P_{ru}(s)} \quad (15)$$

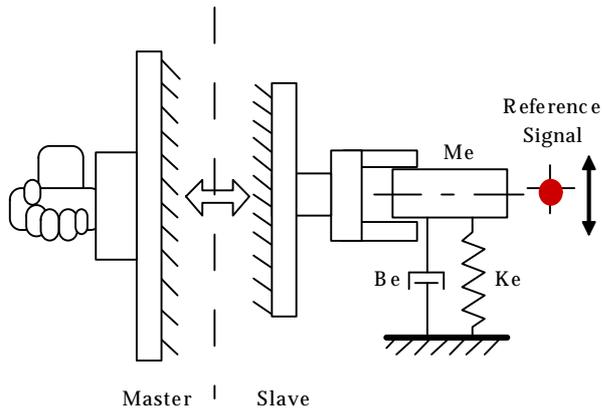


Fig. 2 Model of Experiment Tasks

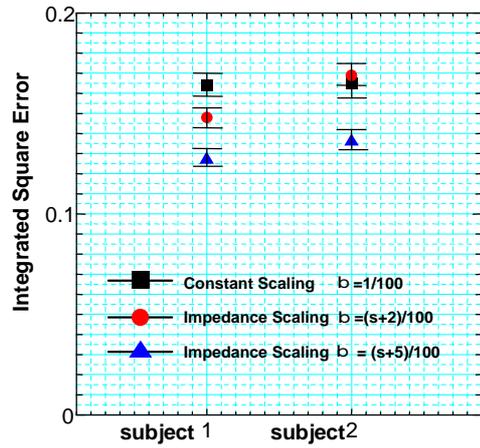


Fig. 3 Pursuit Error

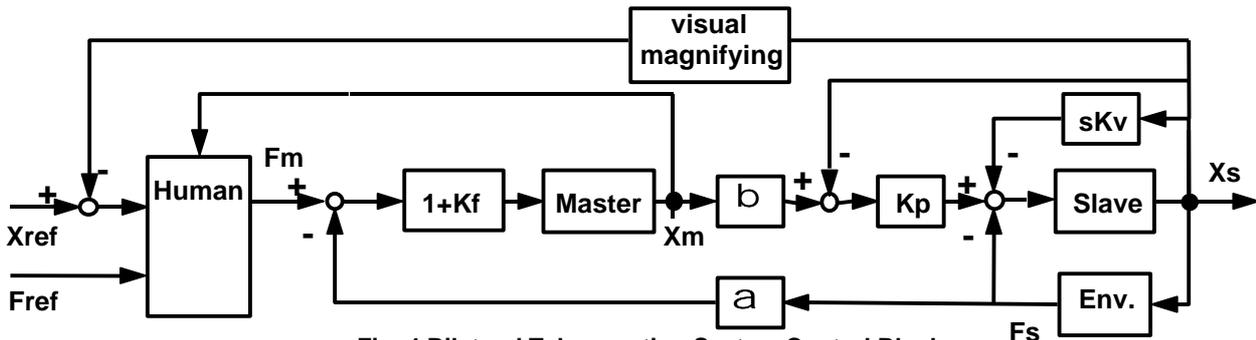


Fig. 4 Bilateral Teleoperation System Control Block

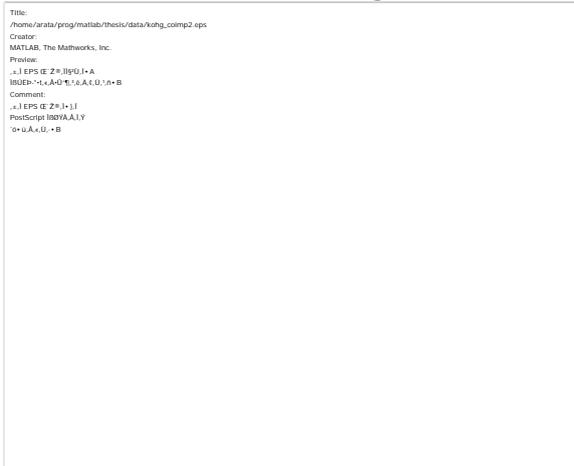


Fig. 5 H(s)G(s) Identification (subject 2)

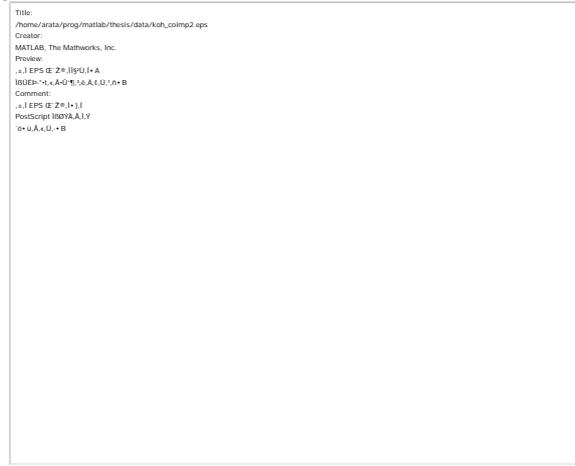


Fig. 6 H(s) Identification (subject 2)



Fig. 7 H(s)G(s) Identification (subject 2)



Fig. 8 H(s) Identification (subject 2)

The different pursuit errors in the position control task performed by subject 2, can be explained by the $H(s)G(s)$ and $H(s)$ transfer functions. As shown in Fig. 3 no significant difference in the performance is found for $b = 0.01$ and $b = (s + 2)/100$. It can be verified from the $H(s)G(s)$ transfer function frequency response in Fig.5, i.e. the both scaling gains resulted in almost the same crossover frequencies. On the other hand, for $b = (s + 5)/100$, the crossover frequency is shifted to the right as shown in Fig. 7, which improves the maneuverability of the master-slave system. As the results, the pursuit error was much decreased.

In this way, the dynamic characteristics of the man-machine system provide us with the information about the maneuverability of the system. Therefore, by analyzing not only the master-slave system but also the human dynamic characteristics, it is possible to estimate the performance for each task.

6 CONCLUSION

In this paper, different transfer function parameters were selected and the effects on the performance and the dynamic characteristics of the human operator were analyzed to evaluate the micro-teleoperation system. As a result, the impedance scaling produced a better performance, which can be explained by the shift in the crossover frequency. It was also shown that the identification of the human operator characteristics over the frequency domain was useful to predict and improve the maneuverability of the micro-teleoperation system.

Future work must be done to analyze the micro-teleoperation system performance in respect to force controlled task.

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REFERENCES

- [1] Mitsuishi, M., Kobayashi, K., Watanabe, T., Nakanishi, H., Watanabe, H., and Kramer, B., Development of an Inter-World Tele-Micro-Surgery System with Operational Environment Information Transmission Capability, *IEEE Int. Conf. on Robotics and Automation*, pp. 3081-3088, 1995.
- [2] Tokashiki, H., Akella, P., and Tanie, K., Scaled bilateral telemanipulation: An Experimental investigation of scaling laws, SPIE, vol. 2351, *Telemanipulator and Telepresence Technologies*, pp. 214-224, 1994.
- [3] Colgate, J. E., Power and Impedance Scaling in Bilateral Manipulation, *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp.2292-2297, 1991.
- [4] Colgate, J. E., Robust Impedance Shaping Telemanipulation, *IEEE Trans. Robotics and Automation*, vol. 4, pp. 374-384, 1993.
- [5] Kaneko, K., Tokashiki, H., Tanie, K. and Komoriya, K., Impedance Shaping based on Force Feedback Bilateral Control in Macro-Micro Teleoperation System, *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp.710-717, 1997.
- [6] McRuer, D. T. and Jex, H. R., A Review of Quasi-Linear Pilot Models, *IEEE Trans. Human Factors in Electronics*, HFE-8, 3, 231-208, 1967.
- [7] Sakaki, T. and Tachi, S., Impedance Scaling of a Tele-Existence Master-Slave Manipulation System by Using Similarity Transformation, *Proc. of the Second Int. Symposium on Measurement and Control in Robotics*, pp. 295-302, 1992.
- [8] Kobayashi, H. and Nakamura, H., A Scaled Teleoperation, *IEEE Intl. Workshop on Robot and Human Communication*, pp. 269-274, 1991.
- [9] Yokokohji, Y., Hosotani, N., and Yoshikawa, T., Analysis of Maneuverability and Stability of Micro-Teleoperation Systems, *IEEE Int. Conf. on Robotics and Automation*, Vol. 1, pp.237-242, 1994

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