The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Control Modeling of a Micro-Manipulator for Human Scale Tele-operation System

Nan Xiao and Shuxiang Guo

Abstract — **In this paper a human scale tele-operation system was introduced. The micro operator with 6 degrees of freedom is the most accurate part of the system. The micro operator is driven by 6 piezoelectric actuators. Because of the non-linear hysteretic restoring force, the accuracy of the micro operator couldn't get a very high level. Before compensation of the non-linear hysteretic restoring force, to describe the micro operator with a mathematic model is very important. In the paper, the authors build the micro operator's model with Bouc-Wen model. Then with a genetic algorithm the parameters in the mathematic model were identified. At last by experiments the identified parameters were tested and verified.**

Index Terms – human scale, micro operation, Bouc-Wen model, genetic algorithm

I. INTRODUCTION

In biology, micro-machining, and industry, researchers need to manipulate micro-objects in adverse environments, such as poisonous, corrosive, multidimensional, or remote environments. Therefore, three-dimensional high-speed micro-manipulation is needed as a fundamental technology for micro-mechatronics and bioengineering applications [1-6]. Recently, bioscience has made great progress with through advances in biotechnology, such as in genetic engineering, cell engineering, and developmental engineering. Such research requires micro- and nano-manipulation, mass production, and repetitive, high-speed, and high-precision processing. Consequently, human-scale nano tele-operating systems have been developed. For conventional robotics, numerous potential applications are insufficient [7]. The main problem is caused by the size of the objects to be manipulated. When the manipulated object is extremely small, such as a cell or embryo, the necessary system consists of fine mechanisms (macro/micro) and requires a complex fine-motion control system. Physical phenomena in the micro-world differ from those in the macro-world. Therefore, a manipulation system must be designed carefully. The key technologies include manipulation, micro systems, visualization, human interface, and automation technology. New approaches must be developed to address the challenge of high-speed micromanipulation.

Nan Xiao is with the Graduate school of Engineering, Kagawa University, 2217-20, Hayashi-cho, Takamatsu, Kagawa, Japan. s08d505@stmail.eng.kagawa-u.ac.jp
Shuxiang Guo is with the Intelligent Mech. Systems Eng. Depart. , Kagawa University, Japan. 2217-20, Hayashi-cho, Takamatsu, Kagawa, Japan, Harbin Engineering University, China, guo@eng.kagawa-u.ac.jp

In our research we build a human scale tele-operation system. It is a macro/micro manipulating system. The system is formulated by four main parts, as shown in figure 1. The first part is a microscope with a CCD camera. The second part is a macro movement stage. The macro movement stage is driven by stepping motors. This part has only two degrees of freedom it can generate displacement in horizontal direction. The third part is a micro movement stage. This part was driven by piezoelectric actuators and has three degrees of freedom. The macro/micro part can generate a minimal displacement of 20μm and a maximal displacement of 25mm. With these two parts, the manipulation object will be located under the microscope exactly. The forth part is a micro-manipulator with six degrees of freedom. The micro-manipulator is a Stewart Platform, and the parallel mechanism is driven by six piezoelectric actuators.

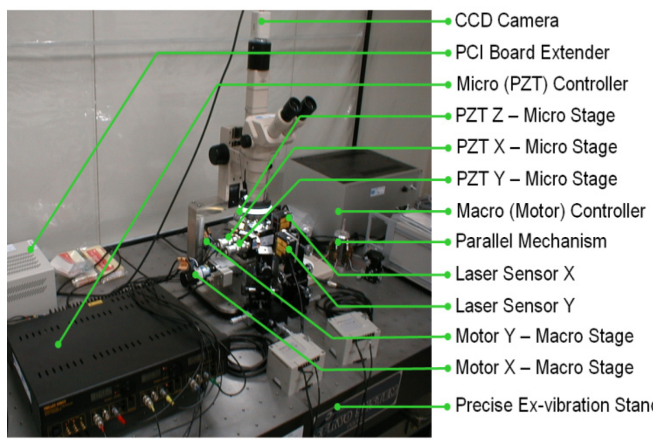

Fig.1 human-scale tele-operating system

The piezoelectric actuators show lots of excellent performance, such as fast reaction, high energy density and high resolution. However, these piezoelectric actuators have drawbacks, non-linear hysteretic between input voltage and displacement, non-linear hysteretic between displacement and output force. Researchers put much more attentions on modeling and identifying the hysteresis phenomenon to solve the non-linear hysteresis problems [8-14]. In order to make the parallel mechanism achieve a higher precision, the authors use Bouc -Wen model to describe the hysteresis and identified the parameters with genetic algorithm.

The paper is organized as follows. Section II gives the modeling method of the micro operator. In section III a genetic algorithm is given to identify the parameters in the model. Then the fitness function is given in details. In section IV, we introduce our experiment system then give the identified parameters and the experimental results. The conclusion was obtained in section V.

II. MODELING OF PIEZOELECTRIC ACTUATORS IN PARALLEL MECHANISM

Figure 2 shows the parallel mechanism in our system. It is a parallel mechanism with 6 DOF. The parallel mechanism consists of four parts. The first part is the end plate to which the moving part of the operating hand is fixed. The second part consists of six linkages. The third part consists of six piezoelectric actuators. They have the same maximum displacement. They can enlarge in only one direction when the piezoelectric actuator extends. And the fourth part is the base plate used to fix the position of the six piezoelectric actuators. The parallel mechanism has the characters of high precision and fast response.

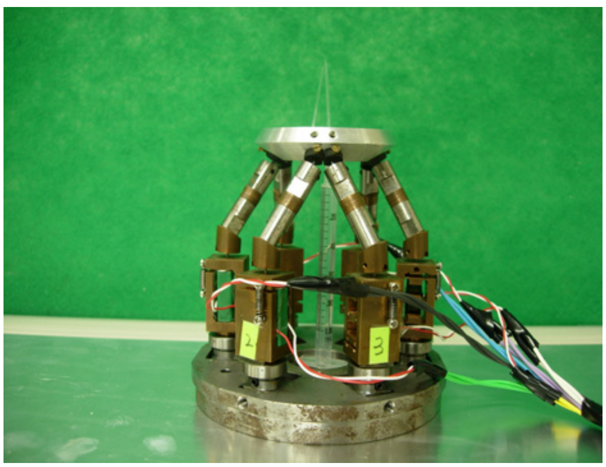

Fig. 2 The parallel mechanism

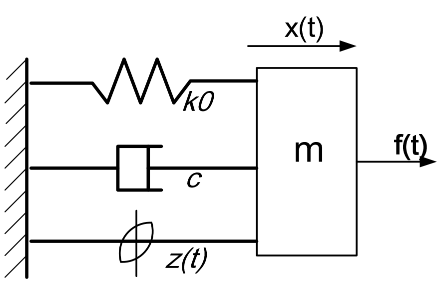

Fig.3 Model of the piezoelectric actuators in PM

Define the center of the base-platform is the origin of the coordinate. And define the position of the center on the upper-platform $Y(t)$ as the system output:

$$Y(t) = \xi i + \psi j + \zeta k = F\{y_i(t)\} \qquad (i = 1 \sim 6)$$

where $y_i(t)$ is the output of the six piezoelectric actuators. From this equation it can be know that the system output can be mapped to the displacement of the six piezoelectric actuators [21-23].

In the parallel mechanism, each piezoelectric actuator has only one degree of freedom. We could describe these actuators with a sample model as shown in figure 3. By figure 3, the governing equation of one piezoelectric actuator could be obtained easily.

$$m_i\ddot{x}_i(t) + c_i\dot{x}_i(t) + k_i x_i(t) + z_i(t) = F_i(t) - f_{0i}(t) \qquad (1)$$
$$y_i(t) = x_i(t) \qquad (i = 1 \sim 6)$$

where m is the mass of the piezoelectric actuator, $x_i(t)$, $\dot{x}_i(t)$ and $\ddot{x}_i(t)$ are the displacement, velocity and acceleration of the piezoelectric actuator, $y_i(t)$ is the output displacement of one piezoelectric actuator, c_i is the viscous damping coefficient, k_i is the stiffness, $f_{0i}(t)$ is the disturbance generated by the load. In the system the load include two parts, one is the load of extern object, and one is generated by the mechanism such as the affect of the displacement of other actuators. In this paper, the disturbance $f_{0i}(t)$ is described as:

$$f_{0i}(t) = (0.1 + 0.2\sin(50\pi t) + 0.2\sin(100\pi t)) \times 10^{-6}$$

The hysteretic restoring force of the piezoelectric actuator $z(t)$ is given by Bouc-Wen model [15]:

$$\dot{z} = A_i\dot{x} - \beta_i\dot{x}_i |z|^n - \gamma_i |\dot{x}_i| z |z|^{n-1} \qquad (i = 1 \sim 6) \qquad (2)$$

where A_i, β_i, γ_i and n is the parameters of the model. One can control the shape of the hysteresis circle by adjust A_i, β_i and γ_i, control the smooth of the hysteresis circle by adjust n.

For convenience, we modified system governing equations to Eq. (3) and Eq. (4) by the theory proposed in [16] [17], they also can describe the characteristic with Eq. (1) and Eq. (2). Here as an approximately calculation parameter n in Eq.2 is set to 1.

$$m_i\ddot{x}_i(t) + c_i\dot{x}_i(t) + k_{0i}x_i(t) = k_i(d_i u_i - h_i) - f_{0i}(t) \qquad (3)$$

$$\dot{h}_i(t) = \alpha_i d_{ei}\dot{u}_i(t) - \beta_i |\dot{u}_i(t)| h_i(t) - \gamma_i\dot{u}_i(t) |h_i(t)| \qquad (4)$$

where $h_i(t)$ is a state variable, d_i is the piezoelectric coefficie nt, $u_i(t)$ is input voltage on the piezoelectric actuator of the s ystem.

III. PARAMETERS IDENTIFICATION

There are seven piezoelectric actuators on the parallel mechanism, for each actuator has eight parameters to be identified.

$$p_i = \{m_i, c_i, k_i, d_i, \alpha_i, \beta_i, \gamma_i\} \qquad (i = 1 \sim 6)$$

We adopt a genetic algorithm (GA) to identify these parameters of the non-linear system. The genetic algorithm proposed by Holland[18] is a searching technique used in computing to find exact or approximate solutions to optimization and search problems. The resolutions of GA are approximate values but not fully equal to the true values.

A. Process of genetic algorithm

The process of GA is shown in figure 4. Before start the process we have to fix the range of parameters and to decide a fitness function. In this paper we decided these ranges by tests and experiment. For example, to estimate the magnitude of the parameters at firstly, m can be measured approximately and the maximum displacement of the piezoelectric actuators is given so the range of the piezoelectric coefficient d can be estimated. The parameters' ranges of six actuators are shown in table 1. A scalar value could be obtained from the fitness function and with these values we can know the fitness of a group of parameters to the system. In next section we will give the fitness function. With 50 individuals and real-coded [17], an initial population was generated. Based on the fitness value, individuals with highly adaptable are selected. These individuals are crossed then a new generation was got. Here we made the crossover rate to 0.7. Then some individual got mutation with a mutation rate at 0.125. At last the new individuals were inserted to the old population by their fitness value. This is a generation. In this paper we run this for 100 times. The best individual was kept as the output result.

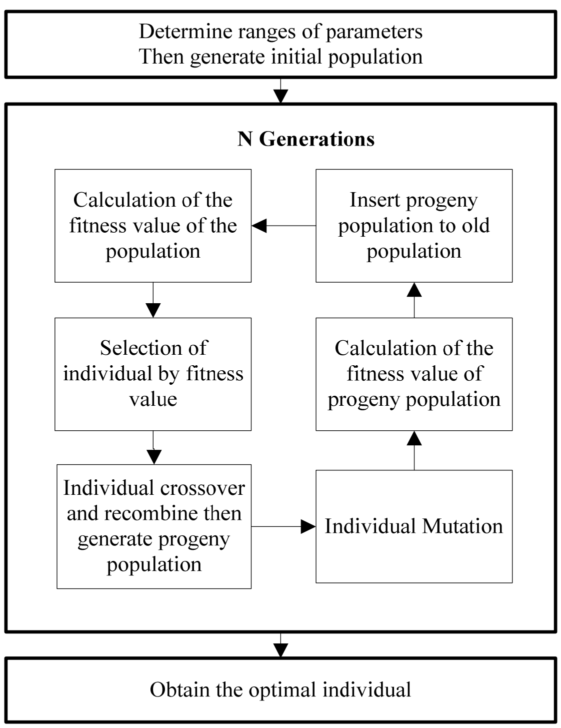

Fig.4 Process of genetic algorithm

Table 1 Ranges of parameters

m (g)	c (Nm/s)	k (N/m)	d (m/V)
2~5	1e-2~1e-3	0~10	1e-6~1e-7
α	β	γ	
0~1	0~1	0~1	

B. Fitness function

Fitness function responses the fitness of the parameters to the system. How to decide an appropriate and efficient fitness function is very important.

From Eq. 3 and Eq.4 we can obtained:

$$x_i(k) = x_i(k-1) + \Delta t(\frac{1}{m_i}(-c_i x_i(k-1) - k_i x_i(k-2) + k_i(d_i u_i(k-2) - h_i(k-2)) - f_{0i}(t))) \tag{5}$$

$$h_i(k) = h_i(k-1) + \Delta t(\alpha_i d_i \dot{u}_i(k-1) - \beta_i \,|\, \dot{u}_i(k-1) \,|\, h_i(k-1)) - \alpha_i \dot{u}_i(k-1) \,|\, h_i(k-1) \,|) \quad (i = 1 \sim 6) \tag{6}$$

Define the error ε as:

$$\varepsilon = x_i - \hat{x}_i$$

where x_i is the displacement of one piezoelectric actuator, $\hat{x}_i$ is the displacement calculated by Eq.(5) and Eq.(6).The parameters were given by GA. The displacement x_i and input voltage u_i can be measured. And $\dot{u}_i$ can be obtained by signal processing.

We define the fitness fun $F(m_i, c_i, k_i, d_i, \alpha_i, \beta_i, \gamma_i)$ as:

$$F(m_i, c_i, k_i, d_i, \alpha_i, \beta_i, \gamma_i) = (\frac{\sum_{j=1}^{N} \varepsilon_j^2}{N})^{-1} \quad (i = 1 \sim 6) \tag{7}$$

where N is the number of samples. It can be seen from Eq. (7), the fitness get bigger when the calculated results get close to the measurement.

IV. EXPERIMENT AND RESULTS

A. Experiment system

Figure 5 shows the displacement measurement devices of the piezoelectric actuators on the micro manipulator. We use these devices to identify the parameters. A sine signal was generated by DA board as the piezoelectric actuator's input $u_i(t)$. The input signal is from 0V to 8V and with a frequency of 1Hz. The signal was sent to the piezoelectric actuators' power amplifier and AD board at the same time. By piezoelectric actuator's power amplifier the input voltage was transformed to 0~120V which is the rated voltage of the piezoelectric actuator. In our research strain gages are used to measure the piezoelectric actuators' displacement $x_i(t)$. For each piezoelectric actuator we fixed two strains on it, one for displacement measurement and another one for temperature compensation. As shown in figure.6. A strain gage with highly accuracy was used to measure the strain then the signal was sent to the work station by an AD board. A measure error occurred although the strain gage have highly precision, and the measure error is included in the disturbance $f_{0i}(t)$. We set the AD board with a sampling frequency of 3k Hz.

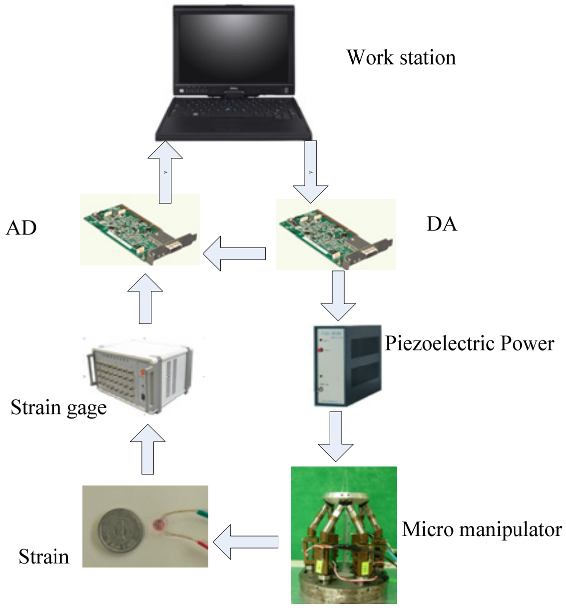

Fig.5 Displacement measurement devices

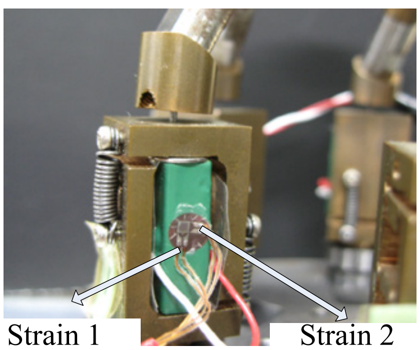

Fig.6 strains on the piezoelectric actuator

B. Experimental result

By these measurement devices we got the input signal $u_i(t)$ and the output displacement $y_i(t)$ (i=1~6). In GA, we set the maximum generations to 100. For actuator 1, we got a curve to trace the performance of GA as shown in figure 7. From the figure we can see, after 70 generations, the max fitness value get to a steady value. So we get a group of parameters with a maximum fitness as the optimal parameters output.

By the same way the parameters of actuator 2~5 can be identified. We put these parameters in Table 2. The error between the actual displacement and the calculation displacement is:

$$\varepsilon_i = | y_i - \hat{y}_i | \qquad (i = 1 \sim N)$$

where N is the number of displacement sample x_i , in our research N=18000. If the maximum of the actual displacement

is $y_{\max_i}$ we governed Δ_i as:

$$\Delta_i = \varepsilon_i / y_{\max_i} \qquad (i = 1 \sim N)$$

The number of the sample which $\Delta_i < 5\%$ is n, we define an fitness rate σ as:

$$\sigma = n / N \times 100\%$$

With σ we can judge how a group of identified parameters close to actual ones. We put these σ in the last row of table 2.

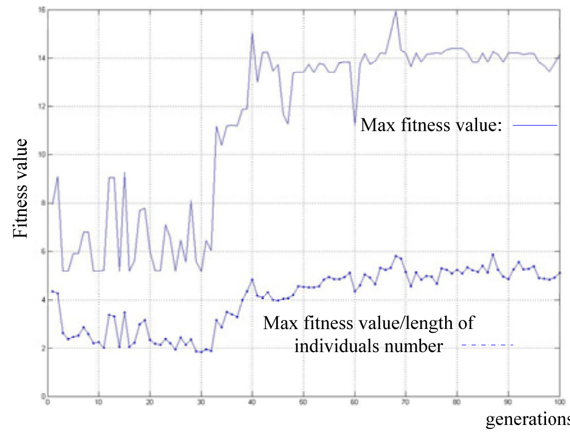

Fig. 7 GA performance tracing of actuator 1

Table 2 Identified parameters

	A1	A2	A 3	A4	A5	A6
m (kg)	2.90e-3	2.95e-3	2.90e-3	3.00e-3	3.10e-3	3.00e-3
c (Nm/s)	3.1e-2	2.8e-2	2.9e-2	3.0 e-2	2.9e-2	3.0e-2
k (N/m)	0.82	1.7	1.0	1.7	1.7	1.3
d (m/V)	1.70e-6	1.73e-6	1.70e-6	1.70e-6	1.68e-6	1.78e-6
α	0.3	0.1	0.2	0.3	0.3	0.5
β	0.8	0.7	0.7	0.8	0.8	0.7
γ	0.7	0.3	0.9	0.8	0.8	0.7
σ	95.8%	98.1%	99.5%	95.7%	98.9%	99.5%

As shown in figure 8, there six group of curves. From A to F are corresponding to piezoelectric actuator 1 to 6. In each group there are two figures. The left one is the relationship between time and displacement. The curve with red and solid line is the actual displacement data which is measured by strain gages. The curve with blue dash line is the calculation data with the identified parameters. The figure in the right is the relationship between input voltage and the displacement. The curve with red and solid line is the actual displacement and the curve with blue and dash line is the calculation data.

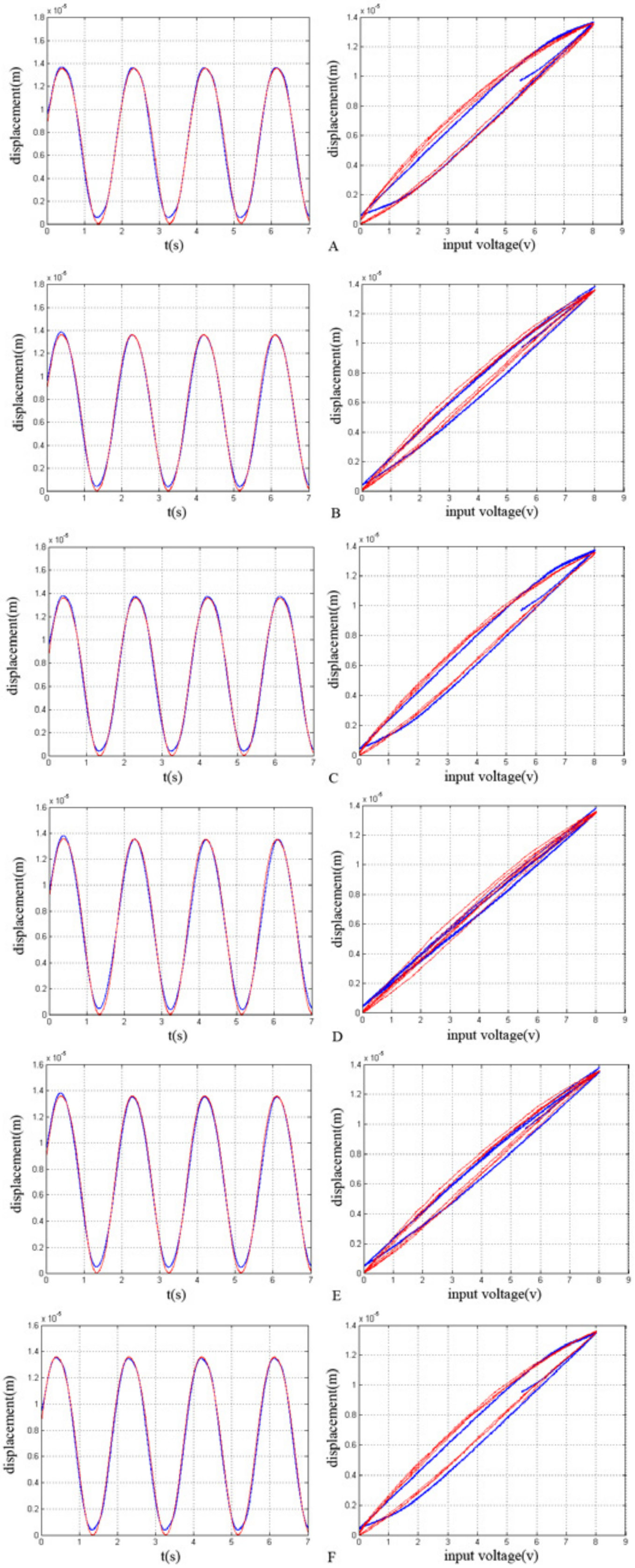

Fig. 8 Time vs. Displacement (left) Input voltage vs. Displacement (right)

Calculation data is with blue dash and actual data is with red solid.

Although the same piezoelectric actuators are use, from the input voltage-displacement curve we can find that each piezoelectric actuator has different non-linear hysteretic force. That caused by the processing of the micro manipulator and the difference performance of the piezoelectric actuators.

V. CONCLUSION AND FUTURE WORK

In this paper, a human scale tele-operation system was introduced. A micro operator was designed. In the micro manipulator there are six piezoelectric actuators. To improve the precision of the micro manipulator, we built the model for this micro operator with a Bouc-Wen hysteretic model. By using a genetic algorithm the parameters in the micro operators' model were identified. From the experimental results, we can see the identified data fits the actual data well.

In six groups, the max fitness rate gets to 99.5%, but the minimum fitness is only 95.7.0%. In order to get a higher fitness rate, it had better to run the genetic algorithm with much more generations or to improve the fitness function. However, the model of the micro operator could be used in the human scale tele-operation system.

In the future, we will improve the genetic algorithm to identify parameters with higher accuracy. Then with the model we will design control methods for the micro operator to improve the performance.

ACKNOWLEDGMENT

This research is supported by Kagawa University Characteristic Prior Research Fund 2010.

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