Micro-Domain Force Estimation Using Hall-Effect Sensors for a Magnetic Microrobotic Station*

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Abstract

This paper introduces a novel micro-domain force estimation method for applications in a magnetic-haptic micromanipulation platform (MHMP). The MHMP employs the magnetic levitation technology in micro-domain worlds for ultra-high precision micromanipulation. In the MHMP, a microrobot that consists of a magnetic head and a body that includes electronic parts and an end-effector is manipulated by regulating an external magnetic field. The MHMP has been equipped with a haptic technology to allow a human operator to feel micro-domain environments and to intervene in dexterous tasks due to the poor knowledge from micro-worlds. To preserve a high feeling of a micro-domain environment for a human operator, the applied force/torque from the environment to the microrobot are required to be directly measured by specific sensors. Due to the size restriction, attaching force sensors to our microrobot is impractical. Therefore, we use a combination of Hall-effect sensor in the structure of the MHMP to estimate a single-axis force, eliminating the need for sensors on the microrobot. The Hall-sensors measure the magnetic flux and determine the location of the horizontally zero magnetic field gradient, B_{max} location. It was realized that the applied force from the environment to the microrobot is linearly proportional to the distance of the microrobot from the B_{max} location. The magnetic force which is equal to the environment force is calibrated using a cantilever deflection. The developed micro-domain force estimation method is verified experimentally, and it was demonstrated that this method has promising potential in estimating the environmental force applied to the microrobot in a non-contact way.

Key words : Magnetic Levitation, Micro-Domain Force Measurement, Hall-Effect Sensor, Micromanipulation

1. Introduction

In recent years, there has been an increasing interest in advancement of microrobotic systems in biological and biomedical applications. Such systems are employed for cell/scaffold micromanipulations⁽¹⁾, cell injections⁽²⁾, microsurgery⁽³⁾, and micro-drug delivery⁽⁴⁾. Untethered microrobotic systems are one of the most widely developing groups of microrobotic systems that have been extensively explored for biological and biomedical micromanipulations in recent decades. These untethered systems show promising approach in accommodating the on-board power supply limitations, the power required for the microrobot locomotion is transferred to the microrobot from a macro-domain power source.

A magnetic-haptic micromanipulation platform (MHMP)⁽⁵⁾ has been developed at the Maglev Microrobotics Laboratory, University of Waterloo for biological and biomedical micromanipulations, schematically shown in Fig. 1. The MHMP consists of three basic subsystems as follows: a magnetic untethered microrobot system (MUMS), a haptic device, and a bilateral teleoperation system. The MUMS uses the magnetic-based propulsion technol-

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Fig. 1 Schematic representation of the magnetic haptic manipulation platform (MHMP)⁽⁵⁾

ogy that produces a bio-compatible environment. The MHMP utilizes a commercial haptic interface as its master side that operates by a human operator. A bilateral macro-micro teleoperation technique has been employed for the telepresence of the human operator in the task's environment. During our previous studies, we developed the MHMP by which the human operator can feel the hard contact (high stiffness environment) during tasks if the microrobot confront a stiff environment. In the MHMP development process, we have equipped this platform to transfer the soft contact (small stiffness environment) feeling to the human operator. Thus, the applied force from the environment to microrobot is needed to be measured and then transferred to the human operator's hand.

Many methods for measuring force from the micro-Newton to milli-Newton range have been developed, such as atomic force microscopes⁽⁶⁾, microscales, piezoresistive cantilevers^{(7)–(12)} and capacitive force sensors⁽¹³⁾. These force measurement systems have been employed in the research field of microsystem and microassembly, as well as biomedical/biological research. However, attaching such measurement systems to the MHMP's microrobot is impracticable due to: 1) micro-scaled sensors is needed to be integrated with the microrobot for measuring forces; thus, the overall size and weight of the microrobot is largely increased, 2) to maintain free levitation, the microrobot needs to be equipped with an on-board wireless communication device to transfer the sensors' measurements, 3) the micro-sized force sensors are expensive and very sensitive to the physical parameters of an environment. This study proposes a novel micro-domain force estimation method eliminating the need of mounting a force sensor to the microrobot. The non-contact force estimation is carried out based on the magnetic flux measurements.

This paper is organized as follows. Section I has already introduced the need for measuring the micro-domain force for a microrobotic platform. Section II explains the principal of magnetic propulsion used in the development of the MHMP. Section III describes the contribution of the proposed force measurement systems for the MHMP. Section IV explains the rule of Hall-effect sensors in force estimation. Finally, Section V discusses the calibration of the force estimation method and experimental verifications.

2. Background

This section, firstly, demonstrates the overall structure of the Magnetic-Haptic Micromanipulation platform (MHMP) and describes the functionalities of its components. Then, the concept of non-contact manipulation using magnetic propulsion are reviewed and mathemat-

ically represented.

2.1. Description of Magnetic-Haptic Micromanipulation platform (MHMP)

The magnetic-haptic micromanipulation platform (MHMP) has been developed at Maglev Microrobotics Laboratory, University of Waterloo, and introduced in Ref. (5) with promising potential for extensive micromanipulation applications. This platform includes two sites— a master and a slave— that can communicate with each other by analog and/or Ethernet connections. The Ethernet/UDP communication channel provides fast data transferring for this real-time system, and enables the human operator in the master site to conduct remotely a task in the slave site connected to the Internet; Fig. 1 presents a schematic diagram of the MHMP.

The slave site includes the magnetic microrobotic station (MMS) and a scaled bilateral teleoperation system (SBTS). The MMS is a magnetic untethered microrobotic system (MUMS) that consists of two main separated components: a magnetic drive unit (MDU) and a microrobot. The MDU produces and regulates the magnetic field for propelling the microrobot in a non-contact way; Section 2.2 reviews the principle of magnetic propulsion and the magnetic force model produced by the MDU. The MDU has been equipped with three high precision laser micrometers to determine the position of the microrobot in three axes; the laser sensors provide the accuracy of 2-8 μm [the highest accuracy at the center region of micrometer's working space and the lowest at the boundaries]. The MDU uses three PID controllers to stabilize the microrobot's motion inside a cubic workspace. The controllers for horizontal axes provide 1.5 μm as the root-mean-square, RMS, of the position error. A 16-bit analogue card is used to capture the laser reading in the working range of ± 5 volt that causes 0.45 μm measurement error. Considering the hardware errors, the accuracy of positioning the microrobot can be estimated as 4-12 μm in the working envelope of the MHMP as $20 \times 20 \times 30 \text{ mm}^3$ ⁽⁵⁾. The MHMP's microrobot is made of two main components: a magnetic head, a body that carries electronic parts, and an end-effector.

The bilateral macro-micro teleoperation technique is employed in the SBTS for the telepresence of a human operator in the micro-domain world. The SBTS implements macro-micro scaling for both position and force to make a micro-domain task more comfortable for the human operator. The gain-switching control scheme⁽¹⁴⁾ is utilized as a strategy of the SBTS for the MHMP to improve the transparency of position-error-based teleoperation for two cases: 1) free motion, and 2) bump into a hard contact. However, the transparency and fidelity of the SBTS can be improved if the SBTS's controller is fed with the measurements slave-side force sensors, 4-channel bilateral teleoperation⁽¹⁵⁾.

The master site includes the haptic station. This station consists of a haptic Phantom omni device (HPOD) and a server computer. The human operator can control the microrobot's position by moving the HPOD's stylus. In addition, the HPOD provides force-feedback to the human operator's hand. A Linux server computer is employed to communicate with the slave site. This server sends the position command from master site to slave site and also receives the calculated force-feedback from the slave site through analog and/or Ethernet/UDP. More details of the MHMP can be reviewed in Ref. (5).

2.2. Principle of Magnetic Propulsion and Modeling

The magnetic propulsion originates from the interaction of a magnetic material with the external magnetic field. Placing the permanent magnet with an inherent magnetization $\mathbf{M}$ in an external magnetic field $\mathbf{B}$ raises the total potential energy and proceeds a force exerted on the unit volume of a permanent magnet, as in Ref. (5),

$$f = +\nabla (\mathbf{M} \cdot \mathbf{B}) \quad (1)$$

This external magnetic field also applies magnetic torque $\tau = \mathbf{M} \times \mathbf{B}$ to the unit volume of the permanent magnet. This magnetic torque tends to orient the permanent magnet parallel

Fig. 2 Basic components of the magnetic drive unit (MDU)

to the external magnetic field's vector. Therefore, the forces and torques experienced by the permanent magnet can be controlled by regulating the external magnetic field. More details of controlling the magnetic forces and torques have been reviewed in Ref. (5), (16), (17).

The magnetic untethered microrobotic system (MUMS), as the heart of micromanipulation platform, is made up of two separated subsystems: a magnetic drive unit (MDU) and a microrobot. The drive unit is advanced to generate the magnetic field for propelling the microrobot in an enclosed environment, shown in Fig. 2 schematically. The drive unit consists of six-pair of electromagnets, a disc pole-piece for connecting the magnetic poles, and a yoke. The effectiveness of this structure for the 3D position controlling of the microrobots was reported in^{(5), (16), (17)}. The maximum magnetic field in z-direction produced by the MDU is in the range of 0.1-0.2 Tesla inside the workspace. The resolution of the generated magnetic field by MDU is 0.19 μ T.

In this study, we model the microrobot's head with magnetization $\mathbf{M}$ as a single dipole permanent magnet, and it is assumed that $\mathbf{M} = [0 \ 0 \ M]$. Furthermore, For a small permanent magnet (PM), the magnetization can be taken as a constant and as uniformly distributed throughout the volume. Therefore, the induced magnetic force due to the external magnetic field can be represented by

$$f = M (\nabla B_z) \quad (2)$$

This mathematical relation demonstrates the changes of magnetic force with the gradients of the z-component of the magnetic field. In theory, the permanent magnet placed in an external magnetic field is inclined to move toward the minimum total potential energy location; i.e. B_{max} point - B_{max} point signifies the location of the maximum magnetic field on the horizontal plane which the PM is hanged on. If the PM is in a steady state condition, its weight is balanced by the vertical magnetic force, and the horizontal forces equal zero, since no horizontal force occurs in the B_{max} position. Hence, the PM can be manipulated by regulating the gradients of B and controlling the B_{max} location. Figure 3 demonstrates the changes of B_{max} locations by the variations of the coils' currents of the electromagnets. This figure also represents the capability of the MDU in producing a unique B_{max} location in the horizontal plane. Based on experimental measurements and numerical analyses, we developed the

Fig. 3 Surface and contour plot of magnetic flux density z-component obtained by experimental measurement, (a) and (b) demonstrate the B_z in the horizontal plane with the coils' currents with two various patterns P_1 and P_2 , respectively. The contour plot of the B_{max} location place under surface plot with the coils' currents of two various patterns P_1 and P_2 , respectively.

MDU's magnetic force model^{(5),(17)} as

$$f_x = M \frac{\partial B_z}{\partial x} = x/4 (\alpha_x + 3\alpha_y) (I_1 + I_3 + I_4 + I_6) + x\alpha_x (I_2 + I_5) + \sqrt{3}/4y (\alpha_x - \alpha_y) (I_1 - I_3 + I_4 - I_6) - \sqrt{2}/2\beta_y (I_1 - I_3 + I_4 - I_6) \quad (3)$$

$$f_y = M \frac{\partial B_z}{\partial y} = y/4 (3\alpha_x + \alpha_y) (I_1 + I_3 + I_4 + I_6) + y\alpha_y (I_2 + I_5) - \sqrt{3}/4x (\alpha_x - \alpha_y) (I_1 - I_3 + I_4 - I_6) - 1/2\beta_y (I_1 + 2I_2 + I_3 - I_4 - 2I_5 - I_6) \quad (4)$$

$$f_z = M \frac{\partial B_z}{\partial z} = (\alpha_z z + \beta_z) (I_1 + I_2 + I_3 + I_4 + I_5 + I_6) \quad (5)$$

where α_x , α_y , α_z , β_y , and β_z and are magnetic field parameters, determined by experimental measurement and the linear least square curve fitting. The parameter I_i presents electromagnet number i 's coil current, the electromagnets' arrangements is shown in Fig. 2.

3. The Concept of Environmental Force Estimation

The previous section discussed the principle of microrobot's free levitation and the mathematical force model experienced by the microrobot inside the magnetic field produced by the MDU. In a condition that the microrobot is in contact with an environment that applies force (f_e) to the microrobot, the microrobot is not stabilized at the B_{max} location. The magnetic field produced by the MDU exerts force to the microrobot to move it toward the B_{max} location, meanwhile the environment applies equal and opposite direction force (f_e) to the microrobot. Thus, the microrobot becomes stable at a location that the magnetic field gradient is not equal to zero in the horizontal motion plane, shown schematically in Fig. 4 [This study focuses on the investigation of environmental force measurement in y-direction; however, the motion study in x- and z-direction can be performed in the similar way, the reference axis is shown in Fig. 2]. In the steady state condition, the magnetic force applies to the microrobot equals to the environmental force that can be estimated by using Eq. 5 as

$$f_y = f_e = y_r/4 (3\alpha_x + \alpha_y) (I_1 + I_3 + I_4 + I_6) + y_r\alpha_y (I_2 + I_5) - \sqrt{3}/4x_r (\alpha_x - \alpha_y)$$

Fig. 4 The schematic representation of the force estimation concept

$$(I_1 - I_3 + I_4 - I_6) - 1/2\beta_y (I_1 + 2I_2 + I_3 - I_4 - 2I_5 - I_6) \quad (6)$$

where x_r and y_r determine the position of the microrobot in the horizontal plane relative to the reference coordinate defined in Fig. 2. Since, it is a single-axis force estimation, y-direction, we assumed the $x_r = 0$ and keep the vertical position of the microrobot z_r equals to z_0 . The microrobot real position can be represents as $y_r = y_{Bmax} + \Delta y$, Fig. 4. This relation can then be replaced in Eq. 6 as

$$f_y = f_e = (y_{Bmax} + \Delta y)/4 (3\alpha_x + \alpha_y) (I_1 + I_3 + I_4 + I_6) + (y_{Bmax} + \Delta y)\alpha_y (I_2 + I_5) - 1/2\beta_y (I_1 + 2I_2 + I_3 - I_4 - 2I_5 - I_6) \quad (7)$$

re-arranging this equation as

$$f_y = f_e = \overbrace{[\Delta y/4 (3\alpha_x + \alpha_y) (I_1 + I_3 + I_4 + I_6) + \Delta y\alpha_y (I_2 + I_5)]}^{A_1 \neq 0} + [y_{Bmax}/4 (3\alpha_x + \alpha_y) (I_1 + I_3 + I_4 + I_6) + y_{Bmax}\alpha_y (I_2 + I_5) - 1/2\beta_y (I_1 + 2I_2 + I_3 - I_4 - 2I_5 - I_6)] \quad (8)$$

the term A_1 is the non-zero part of this force equation, since the magnetic force at the B_{max} location is zero. Therefore, the force equation can then be derived as

$$f_y = f_e = \Delta y/4 (3\alpha_x + \alpha_y) (I_1 + I_3 + I_4 + I_6) + \Delta y\alpha_y (I_2 + I_5) \quad (9)$$

We assume that the environmental forces apply to the microrobot in y-direction and keep $x_r = 0, z_r = z_0$ [environmental force in the x-direction is zero, $f_x = 0$, and the microrobot's weight is the only force in the z-direction]. Therefore, using Eq. 3 and 5 results in

$$I_1 + I_2 + I_3 + I_4 + I_5 + I_6 = C_1 \quad (10)$$

$$I_1 + I_4 - I_3 - I_6 = 0 \implies I_1 + I_4 = I_3 + I_6 = C_2 \quad (11)$$

where C_1 and C_2 are constants for motions in the y-direction; replacing these two relation in Eq. 9 re-presents the force model as

$$f_y = f_e = \Delta y \underbrace{\left[\frac{3}{2}\alpha_x C_2 + \frac{1}{2}\alpha_y (2C_1 - 3C_2) \right]}_C = C\Delta y \quad (12)$$

This equation demonstrates that the magnetic force applies to the microrobot is linearly proportional to the distance of the microrobot from the B_{max} location. Thus, by determining the B_{max} location and the constant C in Eq. 12, the environmental force in the steady-state condition can be estimated. The next section reviews a method to obtain the B_{max} location.

Fig. 5 The Hall-effect sensors are attached to a measurement stick and installed on the bottom of pole-piece⁽¹⁸⁾

4. B_{max} Position Determination

In Ref. (18), we have proposed a novel technique to determine the microrobot's position by measuring the magnetic flux produced by the MDU. The MDU aligns the magnetic field in such a way that only one B_{max} emerges in the horizontal plane below the pole-piece. The position of B_{max} can be controlled by tuning the electromagnets' produced magnetic fluxes [changing the electromagnets' coil current alters produced magnetic flux]. Thus, the B_{max} 's horizontal shifts are took place by the produced magnetic flux. If the relation is reversed, the B_{max} horizontal position can be estimated by measuring the magnetic flux. This reverse concept can be employed to determine the B_{max} location.

A combination of Hall-effect sensors has been installed on the MDU's structure to measure the magnetic flux. Since the generated magnetic flux of electromagnets penetrates to the MMS's workspace through the pole-piece, Hall-effect sensors are attached to the pole-piece to measure the produced magnetic flux. In Ref. (18), we have extensively investigated the optimal arrangement of Hall-effect sensors. In order to estimate the B_{max} position in one axis, it is found that at least two hall sensors should be installed on the specified axis on the pole-piece. The difference of magnetic flux measured by these two sensors can be mapped to the B_{max} position; Fig. 5 shows the two Hall-effect sensors in the y-direction attached to the pole-piece.

The MDU has been used to manipulate the microrobot along the y-axis; meanwhile the magnetic flux is measured by the Hall-effect sensors and is recorded. Figure 6 presents the measured flux differential versus the microrobot's position on the y-direction. This figure also shows the best fitted curves to experimental measurements as

$$y_{B_{max}} = 0.044v_d + 0.0069 \quad (13)$$

where v_d is the flux differential in voltage measured by the Hall-effect sensors (Two hall sensors' outputs have been amplified via operational amplifier). The performance of Hall-effect-based B_{max} location estimation method in y-axis has been presented in Fig. 7. As shown in this figure, the Hall-effect sensors measurements coupled with the mathematical Eq. 13 provides accurate position estimation when the microrobot is close to the center of the working envelope, an accuracy of 0.3 mm as the root-mean-square (RMS) of the position error.

5. Experimental Validation And Force Calibration

Section 3 discussed the environmental force model -equals to the magnetic force in the steady-state condition-, which is linearly the function of the distance of the microrobot from the B_{max} location, Eq. 12. Section 4 discussed the technique for estimating the B_{max} location in the y-direction, Eq. 13. Replacing the B_{max} location, Eq. 13, in the force model relation, Eq. 12, results in the following derivation of the force

$$f_y = f_e = C\Delta y = C(y_r - y_{B_{max}}) = C(y_r - 0.044v_d - 0.0069) = C_r y_r + C_v v_d + C_0 \quad (14)$$

Fig. 6 The changes of B_{max} location in y-direction versus variation of magnetic flux differential, position-voltage relation

Fig. 7 The performance of using hall-effect sensors in estimating the microrobot's position

where C_r , C_v , and C_0 are constant coefficients that can be determined by a series of experimental measurements. Since Eq. 14 has three coefficients, these coefficients can be determined by defining at least three equations. Depending on the number of calibration points, the coefficients of the Eq. 14 can then be determined as

$$\begin{bmatrix} C_r \\ C_v \\ C_0 \end{bmatrix} = \begin{bmatrix} y_{r_1} & v_{d_1} & 1 \\ y_{r_2} & v_{d_2} & 1 \\ \vdots & \vdots & 1 \\ y_{r_{n-1}} & v_{d_{n-1}} & 1 \\ y_{r_n} & v_{d_n} & 1 \end{bmatrix}^{\dagger} \begin{bmatrix} f_{y_1} \\ f_{y_2} \\ \vdots \\ f_{y_{n-1}} \\ f_{y_n} \end{bmatrix} \quad (15)$$

where the subscript i denotes the number of the calibration point, and $\dagger$ is the generalized inverse or pseudo-inverse operation of a matrix. To obtain calibration points, a high precision force measurement setup has been designed based on the tip deflection of a cantilever, Fig. 8 shows this setup. The microrobot used for this study includes a cylindrical permanent magnet, the radius of 5 mm and the height of 10 mm, as the head of the microrobot with a needle-base end-effector. The weight of this microrobot is 11 gr. The aluminum cantilever is $50 \times 5 \times 0.05 \text{ mm}^3$ and made by Aluminum alloy 1100. The laser sensor measures the tip deflection of the cantilever with the accuracy. The force applied to the tip of the cantilever can be obtained by

$$P = \frac{3EI\delta}{l^3} \quad (16)$$

where E , I , l , and δ are modulus of elasticity, area moment of inertia, length, and elastic deflection, respectively. The accuracy analyses demonstrated that the cantilever-based force measurement method provides the error of less than $0.64 \mu\text{N}$ in measuring the applied force to the cantilever's tip. However, this error can be reduced by increasing the accuracy of deflection measurement and physical properties of the cantilever. In the experimental measurement,

Fig. 8 Force measurement setup-using cantilever tip deflection

Fig. 9 The microrobot is commanded toward the cantilever's tip: a) real position of the microrobot b) flux differential in voltage

the cantilever is placed with zero distance from the microrobot, and the microrobot is then commanded toward the cantilever's tip in several steps and then moved backward to detach from the cantilever's tip. As shown in Fig. 9, the microrobot starts pushing moderately the cantilever's tip at the time of 32.3 second by increasing the magnetic flux differential [the flux differential changes in voltage (v_d) versus the real position of the microrobot (y_r) is presented in Fig. 9.b], and the deflection measurement records first displacement of the cantilever's tip at time of the 32.7 second. The microrobot is detached from the cantilever's tip at the time 321 second, since the microrobot is commanded to move to the position -0.5 mm. Although the releasing process has softly taken place, a small vibration occurs in the cantilever as seen in Fig. 10 which presents the deflection of the cantilever's tip and the measured force by Eq. 16.

To calculate the force by using Eq. 14, the flux differential in voltage and the real position of the microrobot are instantaneously recorded during the experimental measurements, previously demonstrated by Fig. 9.b. Using Eq. 15 and the obtained calibration points, the unknown coefficients of Eq. 14 can then be determined as $C_r = -5.47 \times 10^{-3}$, $C_v = 2.42 \times 10^{-5}$, and $C_0 = 4.09 \times 10^{-6}$. The force applied to the cantilever's tip can be calculated by the Hall-effect sensors method by replacing the derived coefficients in Eq. 14, shown in Fig. 11 the comparison of the two force measurement methods: measuring the deflection of the cantilever and the Hall-effect-based measurement. As shown in this figure, the Hall-effect-based method

Fig. 10 The microrobot is commanded toward the cantilever's tip: a) cantilever's tip deflection b) force estimated based on the measured deflection

Fig. 11 The comparison of the two force measurement methods: measured by the deflection of the cantilever and calculated by the Hall-effect-based method

can accurately estimate the deflection force. To validate the performance of Hall-effect-based method corresponding to the cantilever-based technique, the root-mean-square (RMS) of the force error, calculated force obtained by Hall-effect-based method minus the measure force obtained by the cantilever-based technique, has been calculated as $0.63 \mu\text{N}$. Thus, the non-contact force estimation technique, Hall-effect-based method, provides high accuracy relative to the measured force by the cantilever-based routine. Since the cantilever-based technique has the accuracy of $0.64 \mu\text{N}$, the accuracy of Hall-effect-based method can be calculated as $1.27 \mu\text{N}$.

The concept of Hall-effect-based force measurement, in Section 4, is based on the distance of real position of the microrobot and the estimated B_{max} location, Fig. 12 demonstrates the change of B_{max} location versus the microrobot's real position, when the microrobot pushes the cantilever. As expected, by increasing the cantilever's deflection, the distance of the microrobot's position from the B_{max} location becomes larger. As shown, when the microrobot is in contact with cantilever, there is discrepancy between the microrobot's position and the estimated B_{max} location, and whenever the microrobot is detached from the cantilever, the microrobot's position and the estimated B_{max} are very closed to each other, Fig. 13 presents the

Fig. 12 The microrobot's position versus estimated B_{max} location- the cantilever is placed with zero distance from the microrobot

Fig. 13 Changes of force in respect to the distance of the microrobot from the B_{max} location

linear relation of applied force to the microrobot by measuring the distance of the microrobot from the estimated B_{max} .

6. conclusion

In this study, a novel micro-domain force measurement methodology is proposed for a magnetic-haptic micromanipulation platform (MHMP). The MHMP consists of a micro magnetically levitated slave robot and a macro-master haptic robot. The MHMP enables a human operator to control the micro slave robot by manoeuvring the macro-master haptic robot. To allow the human operator the feeling of a micro-domain task, the micro-domain force estima-

tion method is developed to measure the environmental force in a single-axis direction. This method uses magnetic flux measurement and the microrobot's position information to calculate the environmental force. No force sensor is attached to the microrobot to measure the force, that keeps the microrobot's size restriction and makes the microrobot inexpensive and disposable for biological applications.

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