

Development master arm of 2-DOF planar parallel manipulator for In-Vitro Fertilization

Kitti Thamrongaphichartkul¹, Supachai Vongbunyong^{1,*} and Lalana Nuntakarn²

¹ Innovation and Advanced Manufacturing Research Group, Institute of Field Robotics, King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Rd., Bang Mod, Thung Khru, Bangkok 10140, Thailand

² Ramathibodi Hospital, Department of Obstetrics and Gynecology, Reproductive Endocrinology and Infertility Unit, Mahidol University, 272 Rama VI Rd., Thung Phaya Thai, Ratchathewi, Bangkok 10140, Thailand

* Corresponding Author: supachai.von@kmutt.ac.th, 081-431-1968

Abstract. Micromanipulator is a mechanical device used for manipulating miniature objects in the order of micron. It is widely used in In-Vitro Fertilization (IVF) in which sperms will be held in a micro-needle and penetrate to an oocyte for fertilization. IVF needs to be performed by high skill embryologists to control the movement of the needle accurately due to the lack of tactile perception of the user. Haptic device is a device that can transmit and simulate position, velocity and force in order to enhance interaction between the user and system. However, commercially available haptic devices have unnecessary degrees of freedom and limited workspace which are inappropriate for IVF process. This paper focuses on development of a haptic device for using in IVF process. It will be used as a master arm for the master-slave system for IVF process in order to enhance the ability of users to control the micromanipulator. As a result, the embryologist is able to carry out the IVF process more effectively with having tactile perception.

1. Introduction

Currently infertility can be found in 8-10% of couples globally [1]. A number of couples require Assisted Reproductive Technology (ART) treatment for conception. In-Vitro Fertilization (IVF) is a conventional method that allows sperms and an oocyte to fertilize in a petri dish. With this method, proper sperms and oocyte can be carefully selected, for instance sperm with high mobility. This is currently considered one of the most effective treatments for infertility and genetic abnormality. Intracytoplasmic Sperm Injection (ICSI) is a procedure in which the sperm is injected into an oocyte in order to be fertilized. ICSI process is performed by using manual micromanipulator (see figure 1) where a micro needle and a holding pipette are equipped and controlled. ICSI consists of 3 steps: (1) selecting a single sperm by using micro needle; (2) holding the oocyte by using holding pipet, and (3) controlling the position micro needle to penetrate into the oocyte and injection sperm into oocyte.

In general, embryologists with the ICSI expertise manually use a micromanipulator for accurately manipulating sperm and oocyte. The movement need to be scaled down due to the small size of the subjects which are in the order of microns (sperms are 3-5 microns and oocytes are 100 microns see figure 2), the success rate of the current and manual ICSI process are between 50-80% [2]. This is because important physical variables – i.e. position, velocity and tactile perception – are uncontrollable.



From this difficulty, haptic devices can be considered one of the tools that potentially improve this procedure.



Figure 1. Micromanipulator (RI Intragal-3)



Figure 2. Sperm is deposited into the egg in research

Haptic devices are the devices that are able to simulate an augmented force by providing some feedback to the users. Therefore, the users can perceive the virtual environment and manipulate the virtual objects in more intuitive ways. Research in field of haptic interface, e.g. [5-10] and [12], works on how to design force feedback devices. One of the most notable and commercially available haptic devices is Sensable PHANTOM Omni [13] (see figure 3). It is a motorized device that generates tactile feedback that allows the users to perceive virtual forces and virtual objects. [10] presents a haptic device that is designed based on 5-bar linkage mechanism. This mechanism has 2-DOF which is necessary for controlling a micromanipulator in the direction along x- and y-axes. A number of research works show that haptic devices used with robotic system in ICSI process is able to improve the success rate of 90% and survival rate of 90.7% (n = 120) [4]. In addition, the authors of [6] design a new end-effector to sense the contact force with strain gauge and developed a haptic device for transmit force to the embryologists in ICSI process. As a result, the embryologists can feel injection force and contact of membrane through the device.



Figure 3. PHANTOM 6-DOF Master Device



Figure 4. Slave arm is added on micromanipulator

In this research, the manual micromanipulator is enhanced by equipping an added-on system that allows semi-automatic control of the existing manual manipulator. The system primarily consists of (1) a master arm which is a haptic device and (2) a slave arm which is connected to the micromanipulator's control joystick. The slave arm is previously presented in [12] (see figure. 4).

In this article, the master arm with haptic interface is presented. The master arm is haptic device connecting between the embryologist and micro environment. It can help the embryologist to manipulate the subjects by enabling tactile perception. Virtual fixture is enabled in order to guide the user to work easily. In addition, the workspace is designed and customized to be more user-friendly than commercially available haptic devices.

This article is organized as follows. System overview which is an architecture of our system is in Section 2. Design method of the master arm is in Section 3. Final design and implementation is described in Section 4. The section 5 describes an experiment. The discussion and conclusion are described in Section 5 and Section 6, respectively

2. System Overview

In this section the system used for operating haptic application is explained. The system overview is shown on the connection diagram on figure 5. The main components are users, a master arm, a controller, and a semi-auto micromanipulator.

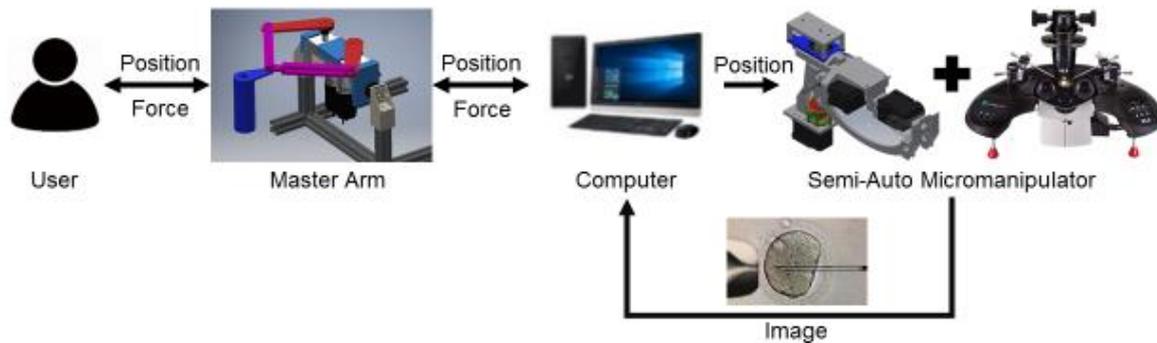


Figure 5 System components in research

2.1. User

User is an embryologist with micromanipulator expertise that can control position of the micro needle and micro pipette via the master arm. User can sense the force between the micro needle and the oocyte.

2.2. Master Arm

The master arm is a haptic device used for implementing force feedback while manipulating the micro needle and the micro pipette. The user can control them without using conventional joystick directly (see figure 6).



Figure 6. Joystick used for controlling a micro needle.

2.3. Controller

The controller consists of 2 control layers, which are implemented on different architectures. The high level system is operated on the computer (C#) for creating haptic interface with user. The low level system based on C++ on a microcontroller for controlling the hardware and mechanisms.

2.3.1. High Level System. At the High level control layer, EMGU Library is used for processing images in order to detect the micro needle and the micro pipette shown in figure 7. The result is used to simulate the impact force that will be emulated on the master arm.

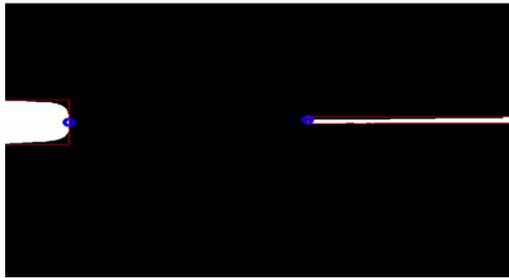


Figure 7. Image obtained after image processing

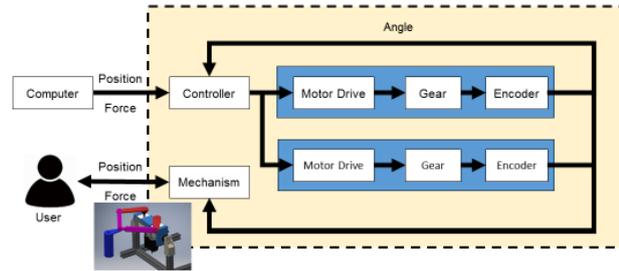


Figure 8 Low level system

2.3.2. *Low Level System.* Use microcontroller STM32F746 to implement a hardware interface because it has QEI module that is capable of reading encoders and running the control loop at 1 kHz. Figure 8 shows the low level system in this research.

2.4. *Semi-Auto Micromanipulator.*

Manual micromanipulator is a device in which the user can use to manipulate small objects by controlling the joystick. The hand movement of the user is scaled down to the movement in the order of microns. The slave arm is an added-on mechanism with 3 DOF that is used to control the joystick (see figure 4). It is designed by the authors and presented in [12]. It is equipped on the micromanipulator by clamping between the base of the slave arm and the base of micromanipulator (see figure 9).

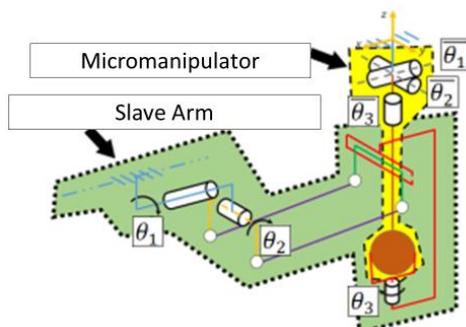


Figure 9. Mechanism of slave arm

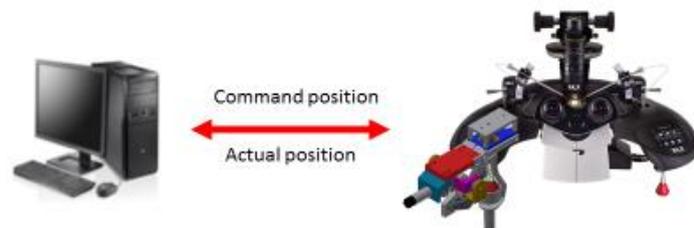


Figure 10. Communication between computer and slave arm

In this research, our system is capable of upgrading a manual micromanipulator to a semi-automatic micromanipulator by adding on the slave arm. It can change the traditional control method to computer control method. The command of position can be sent from the computer to the micromanipulator (see figure 10).

3. Design

As shown in figure 11, a five-bar linkage planar parallel mechanism [10] presents the conceptual design of the master arm. This is a simple yet effective mechanism that allows the movement of 2 DOF which is sufficient for the intended function in this research. The end-effector is located at point P_3 and moves on the x-y plane. At point P_1 and P_2 , motor and encoder for driving θ_1 and θ_2 are located. The force at the end-effector is related to torque applied by motor at joint 1 and joint 2.

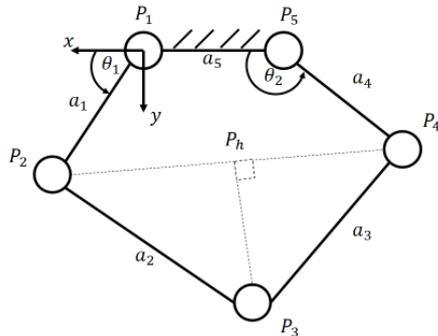


Figure 11. 5-bars linkage mechanism

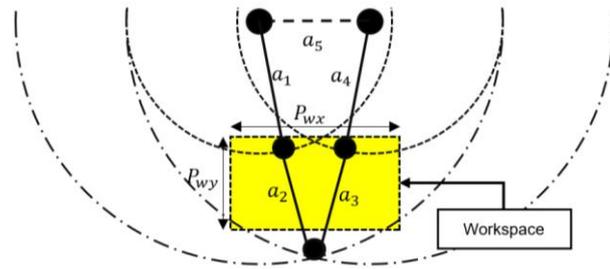


Figure 12. 5-bars linkage mechanism design

3.1. Linkage Design

The mechanism's length is designed by specifying the operating workspace. A graphical method is used to find the length of each link (see figure 12). The determined workspace is $P_{wx} = 100$ and $P_{wy} = 100$.

Therefore, the lengths of linkages are $a_1 = 90$, $a_2 = 130$, $a_3 = 130$, $a_4 = 90$ and $a_5 = 60$. Simulation of the end-effector was done by using a commercial mathematic simulation software. The positions in the designed workspace are shown in figure 13.

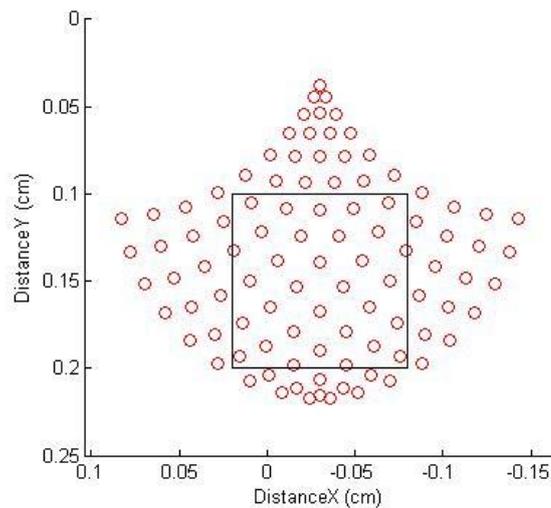


Figure 13 5-bars linkage mechanism simulation

3.2. Forward Kinematics

Forward kinematics is derived in order to describe both the position of end-effector P_3 and the position of the each linkage [10]. In figure 13, P_1 is used as the origin. The end-effector's position $P_3(x_3, y_3)$ is given by equations (1) and (2)

$$x_3 = x_h \pm \frac{\|P_3 - P_h\|}{\|P_2 - P_4\|} (y_4 - y_2) \quad (1)$$

$$y_3 = y_h \mp \frac{\|P_3 - P_h\|}{\|P_2 - P_4\|} (x_4 - x_2) \quad (2)$$

3.3. Jacobian

Jacobian is a method to transform force at end of effector (P_3) to torque of motor at joints 1 and 2 [10]. See equation (3).

$$J = \begin{bmatrix} \frac{\partial x_3}{\partial \theta_1} & \frac{\partial x_3}{\partial \theta_5} \\ \frac{\partial y_3}{\partial \theta_1} & \frac{\partial y_3}{\partial \theta_5} \end{bmatrix} \quad (3)$$

3.4. Torque

The master arm can apply the force to the user at the end-effector. The force is a result of the torque generated by the motors at joint 1 and joint 2. In addition, the force at P_3 is used to create the virtual wall which helps the user by guiding the movement in particular lines. The torque for each joint can be obtained by using equations (4) and (5).

$$\tau = J^T F \quad (4)$$

$$\tau = K_t i \quad (5)$$

The torque can be controlled by the motor driver circuit as it is proportional to the input current. The relationship between voltage and current was obtained by fitting the data shown in figure 14. The relation is in equation (6). (Here, i is current and v is voltage.)

$$i = 0.0444v \quad (6)$$

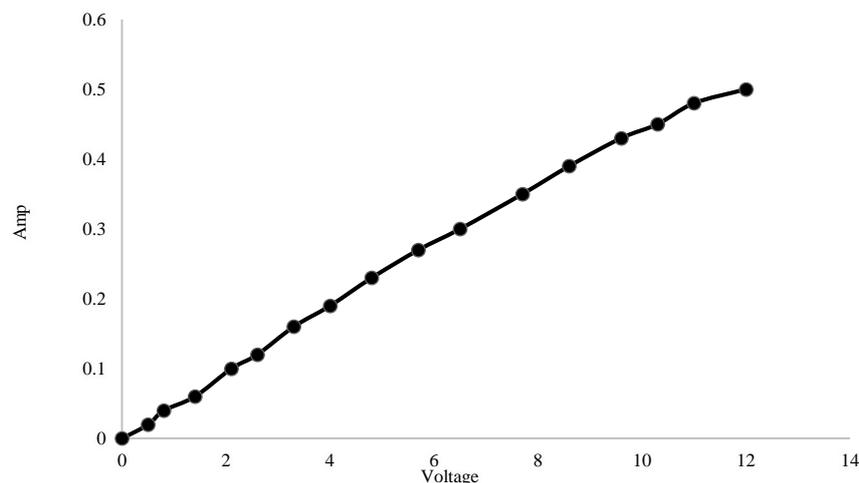


Figure 14. Current and voltage in motor

3.5. Virtual Fixture

According to the movement in micro environment, the user cannot sense the reaction force between an oocyte and the microneedle during the ICSI operation. Visual fixture [3] is one way to model virtual force by using the virtual wall concept that can be modelled the system with spring and damper in equation (7).

$$F = k\delta x + b\delta \dot{x} \quad (7)$$

Figure 15 shows the model of the force feedback. The set point is a target of the end of the microneedle. If the microneedle's end is at the distance from the target, the virtual force will be created according to equation (7) and sent to the master arm. This can help the user to move a microneedle's end along the desired path to the target. The variable δx is distance between position of microneedle and position of the set point.

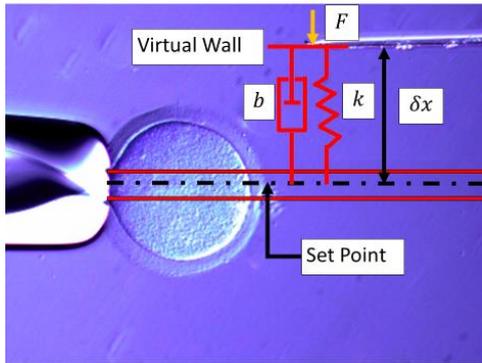


Figure 15. Model of force feedback in virtual fixture

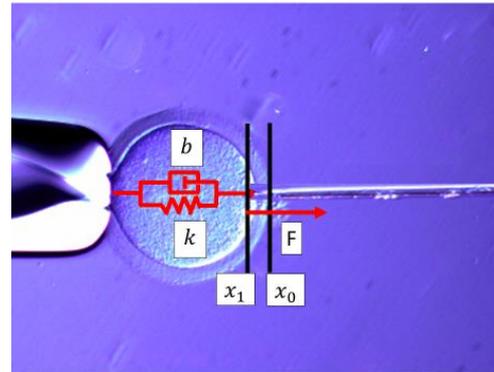


Figure 16 Model of force between microneedle and oocyte

Virtual fixture is used to create the virtual force to enable the tactile perception between the oocyte and the microneedle. In figure 16, the model of virtual force is equation (7) where δx is distance between x_0 and x_1 .

4. Implementation

The final prototype is shown in figure 17. The system consists of a controller STM32F746, a motor drive VNH5019, and motor Faulhaber series 3257 to create a master arm prototype. The flowchart is shown in figure 18.



Figure 17. The prototype of master arm

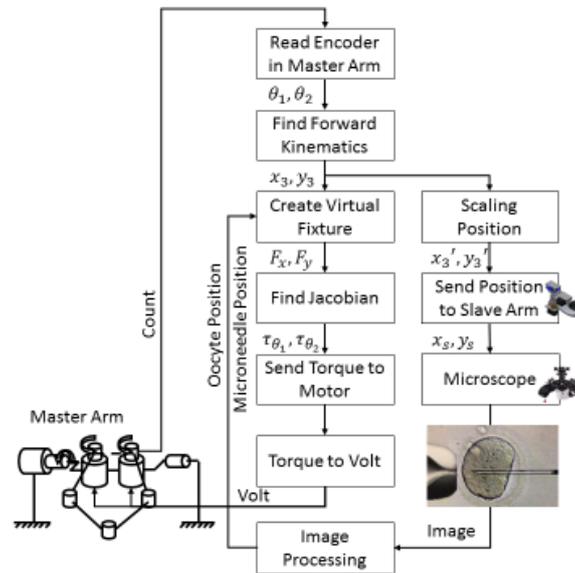


Figure 18. Flow chart diagram of master arm

5. Experiment

The experiment is designed for testing the concept of tactile perception of the user while using the master arm. The experiment was done on the master-slave system shown in figure 19.



Figure 19. System components in research

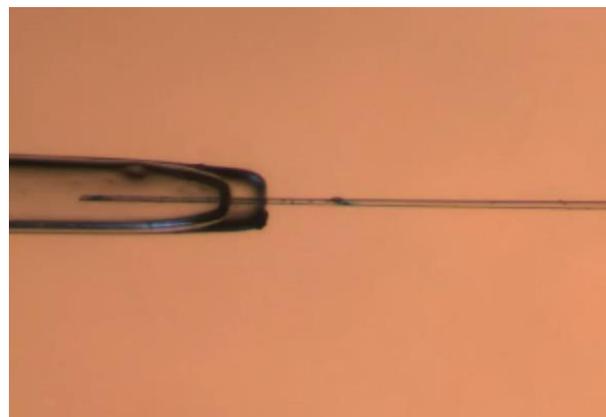


Figure 20. Microneedle is insert into micro pipette.

The goal of the experiment is to test the accuracy and precision of the system while it is controlled by the user. In the experiment, the user needed to control the semi-micromanipulator by using the master arm to move the microneedle in a straight line and insert it into the micropipette. The virtual fixture is used to create a virtual wall with spring and damper to constrain the movement along y-axis. The parameter in experiments are virtual spring constant 0.01 N/m and damping constant 0.01 Ns/m . The procedures in the experiment are:

- 1.) User control master arm in straight line.
- 2.) Create virtual fixture to create virtual force with spring and damper to constrain x axis.
- 3.) Send force generated from virtual fixture to user through master arm.
- 4.) Use image processing to track the micro needle.

The result of the experiment is presented in figure 20. Where the microneedle was in the micro-pipette. Figure 21 shows that real micro needle position. For the result, the microneedle can be moved along the straight line with the error within ± 10 microns in y-axis.

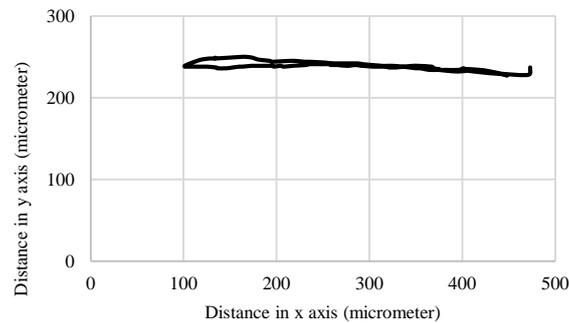


Figure 21. Result in experiment insert microneedle into micropipette.

6. Discussion

From the experiment of tactile perception in figure 19, the user was able to use the master arm control microneedle to move in a straight line; however, certain position error was occurred caused by a mechanism created with 3D printer. The precision of the printed parts is quite low (0.1 m), which leads to the backlash that affects the precision of the joint control in the mechanism. When the master arm has the backlash, it affects the slave arm so that the control of microneedle movement will be less precise. However, this backlash can be eliminated by using the parts manufactured with higher precision. As a result, the accuracy and precision of the system will be improved.

7. Conclusion

In this research, the master arm for using in In-Vitro Fertilization process has been developed. The master arm was able to help embryologists to work more intuitively by creating the virtual force that enables tactile perception. The concept has been proved from the experiment result that the user can control the microneedle in the way that precision and accuracy are needed. However, they can be improved if the precision of the mechanism is improved. For the future work, we focus on bilateral control for IVF and design a new micromanipulator.

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