The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Hybrid Vision/Force Feedback Control for Pushing Micro-Objects

Shahzad Khan* and Asif Sabanovic†
* Mechatronics System Design, Department of Precision and Microsystems Engineering, Faculty of 3mE
Delft University of Technology, The Netherlands
Email: s.khan@tudelft.nl
†Mechatronics Programme, Faculty of Engineering and Natural Sciences, Sabanci University, Turkey
Email: asif@sabanciuniv.edu

***Abstract*—In 2D microassembly applications, it is inevitable to position and orient polygonal micro-objects lying on a flat surface. Point contact pushing of micro-objects provides a feasible way to achieve the task and it is more flexible and less complex compared to pick and place operation. Due to the fact that in micro-world surface forces are much more dominant than inertial forces, and tend to be unevenly distributed, these dominant forces obstruct the desired motion of the micro-object when using point contact pushing alone. Thus by adopting an hybrid vision/force feedback scheme, it is possible to attain a translation motion of the object as the uncertainties due to varying surface forces and disorientation of the micro-object is compensated by force and vision feedback respectively. In this paper, a hybrid vision/force feedback scheme is proposed to push micro-objects with human assistance using a custom built tele-micromanipulation setup to achieve translational motion. The pushing operation is divided into two concurrent processes: In one human operator acts as an impedance controller alters the velocity of the pusher while in contact with the micro-object through scaled bilateral teleoperation to compensate for varying surface forces. In the other process, the desired line of pushing for the micro-object is determined continuously using visual feedback procedures so that it always compensate for the disorientation. Experimental results are demonstrated to prove nano-Newton range force sensing, scaled bilateral teleoperation with force feedback and pushing micro-objects.**

I. INTRODUCTION

In today's emerging technologies where the sizes of each component/part are decreasing towards micrometer range, the traditional way of macro-assembly process using 6DOF robots is not applicable anymore. This is due to the requirements of high precision motion, high tolerances (usually less than few microns) and the predominance of surface forces on gravity that make assembly process very difficult as the parts tends to stick to the surface [1], [2] and [3]. Furthermore, the parts to be handled are often delicate and fragile, and so an accurate control of the interaction forces (in the range of micro-Newton or even less) are often essential. The first and foremost requirement for the assembly process is to "precisely manipulate" objects. Manipulation includes cutting, pushing, pulling, indenting, or any type of interaction which changes the relative position and relation of entities. This paper concentrates on manipulation by pushing as it is a useful technique for manipulating delicate, small, or slippery parts, parts with uncertain location, or parts that are otherwise difficult to grasp and carry [4], [5] and [6]. The process of manipulation by pushing of micro-objects possesses many challenges due to the requirements of:

- Actuators with high resolution (in nanometer range), high bandwidth (up to several kilo hertz), large force output (up to few newtons) and relatively large travel range (up to a few millimeters) [7].
- Robust and transparent bilateral controllers is needed for human intervention so that high fidelity position/force interaction between the operator and the remote micro environment can be achieved [8], [9].
- Vision based algorithms to estimate the position of the manipulators so that these objects can be pushed along a desired trajectory by overcoming the uncertainties due to surface forces [10], [11].
- Controlled pushing force to generate the desired motion by compensating surface forces arising between the object and the environment [12].

Manipulating objects with high dexterity requires not only precise position control of end-effector but also delicate control of forces involved in the manipulation process which makes it essential to adopt a hybrid approach [13], [14], [15]. In a hybrid approach visual information is required for path planning whereas use of force feedback is utilized to ensure controlled physical interactions. Thus, pushing using only visual feedback is not sufficient but it is also indispensable to sense and control the interaction forces involved in the manipulation process with nano-newton resolution. In this paper, a hybrid vision/force feedback scheme is utilized for pushing micro-objects.

The paper is organized as follows. Section II provides the problem definition and approach and Section III explains the custom built tele-micromanipulation setup. In Section IV, scaled bilateral teleoperation is demonstrated with experimental details concerning force/position tracking between the master and the slave. Finally, Section V provides the procedure for pushing micro-objects along with the experimental results and Section VI concludes the paper and discusses future directions.

II. PROBLEM DEFINITION AND APPROACH

The problem dealt in this work concerns point contact pushing of polygonal micro-object to achieve translational motion utilizing hybrid vision/force feedback control scheme. Due to dominant and varying surface forces between the micro-object and the planar surface, the motion of the micro-object is unpredictable during point contact pushing. As a result, disorientation of the micro-object occurs which demands the

978-1-4244-3804-4/09/$25.00 ©2009 IEEE

pusher to change the contact point and compensate for the disorientation to achieve pure translational motion as shown in Figure 1.

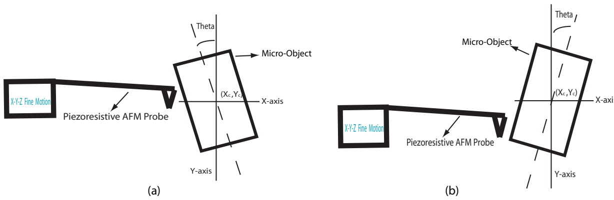

Fig. 1. (a)Pusher contact point for positive error (b) Pusher contact point for negative error

The above mentioned problem is coped up by ensuring that the resultant line of action of the pushing force continuously pass through the desired line by maintaining fixed contact point to compensate for the disorientation of the micro-objects. A method is proposed for pushing polygonal micro-objects using hybrid vision/force control scheme with human assistance. The pushing operation is undertaken by a human operator in X-axis by employing scaled bilateral teleoperation with force feedback to compensate the varying surface forces. Visual control continuously measures the disorientation angle (θ) and generates the necessary control signal in Y-axis such that the resultant line of pushing minimize the error (θ).

Human operator utilizes the scaled bilateral control structure as demonstrated in Section IV. Depending upon the situation human operator which acts an impedance controller can adjust the impedance (effective muscle stiffness) to change from position control to force control to push that micro-object along X-axes with the commanded position/force. Moreover, the operator has the access to the visual information for monitoring the pushing process. Visual control procedures is performed automatically to estimate the correct line of pushing using proportional gain depending upon the error (θ) and finally the velocity of the piezoresistive cantilever is varied in Y-axes at the contact point to ensure that resultant line of pushing passes through the desired line to minimize the error (θ) and achieve translation motion along the X-axes.

III. TELE-MICROMANIPULATION SETUP

The system is composed of three parts, namely a master mechanism operated by the human operator, a slave mechanism interacting with the micro environment and human-machine interface as shown in Figure 2. For the master mechanism a DC motor is utilized, while a piezoresistive microprobe attached on PZT stacks is used for the slave.

XYZ base stages are manually operated PZT which are used for proper alignment of micro object or in other words to bring the micro objects under the workspace. A graphical display is also made available to the operator through the signal processing card where the bilateral control algorithms are implemented. The one degree of freedom master mechanism consists of a brushed DC servo (Maxon motors RE40) and is manually excited with the help of a light rod that is connected to the shaft. The slave mechanism includes different components to ensure reliable and efficient micromanipulation. Capability to control positions with nanometer accuracy and to estimate the forces in nano-Newton scales is required. High magnification microscope is also essential for visual feedback with acceptable resolution.

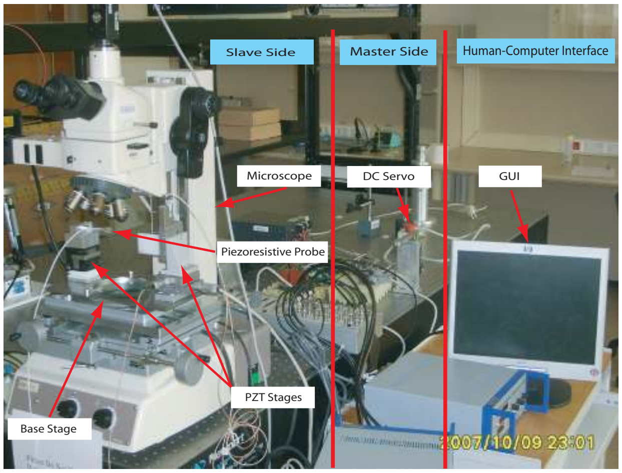

Fig. 2. Experimental setup for micromanipulation

An open architecture micromanipulation system that satisfies the requirements has been developed and used as the slave mechanism. Nano scale positioning of the micro cantilever has been provided using three axes piezo stages (P-611 by Physik Instrumente) which are driven by a power amplifier (E-664) in closed loop external control mode. Potentiometers (strain gauge sensors) integrated in the amplifier, are utilized for position measurement of the closed loop stages which possess a travel range of 100 μm per axis with one nanometer theoretical resolution. Stictionless and frictionless compliant guiding systems exist in the stages. An open loop piezoelectric micrometer drive (PiezoMike PI-854 from Physik Instrumente) has been utilized as the base stage, which is equipped with integrated high resolution piezo linear drives [16]. Manually operable linear drives are capable of 1 μm resolution and the automatic movement range of the micrometer tip with respect to the position can be set 50 μm (25 μm in/out). Nanometer range resolution is achieved for this movement by controlling the piezo voltage using robust control techniques [17]. As for the force feedback, a piezoresistive AFM cantilever (from AppNano) has been utilized along with a inbuilt Wheatstone bridge. A real time capable control card (dSPACE DS1103) is used as control platform and an optical microscope (Nikon MM-40) is used for visual feedback.

IV. SCALED BILATERAL TELEOPERATION

In this section implementation of scaled bilateral control in a custom built tele-micromanipulation setup is presented. Force sensing with nN resolution using piezoresistive AFM (Atomic Force Microscope) micro-cantilever is demonstrated. Force/position tracking and transparency between the master and the slave is presented with varying references after necessary scaling.

A. Force Sensing Using Piezoresistive AFM Microcantilever

In order to achieve force transparency between the master and the slave, it is necessary to sense the force in nano-newton range with high accuracy. Piezoresistive AFM cantilever with inbuilt Wheatstone bridge from AppliedNanostructures is utilized as a force sensor as well as probe for pushing operation as shown in Figure 3. Piezoresistive sensors have been used for many other MEMS applications, including accelerometers, gyroscopes and AFM cantilevers. The primary advantage of piezoresistive microcantilever is that the sensor impedance is relatively low (a few $K\Omega$), and it is possible to extract small signals without interference from noise with off-chip integrated circuits.

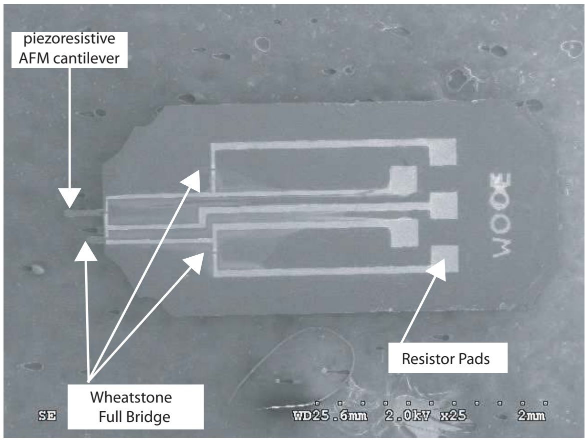

Fig. 3. Piezoresistive AFM Cantilever with inbuilt Wheatstone bridge

The working principle is based on the fact that as the force is applied at the free end of the cantilever using the PZT actuator with the glass slide, the change of resistance takes place depending on deflection of the cantilever. The amount of deflection is measured by the inbuilt Wheatstone bridge providing a voltage output, which is amplified by the custom built amplifier. To match with the initial cantilever resistance value, one of the active resistors in the full bridge is replaced by a potentiometer. The amplified voltage is send to the data acquisition dSpace1103 card for further processing.

1) Experimental Results for Force Sensing:

Figure 4 [18], [17] represents the push/pull forces between the tip and glass slide. As the distance between the tip and glass slide decreases the attractive forces increases and vice-versa. The result clearly indicates that force sensing with the resolution of nN range is achieved.

B. Scaled Bilateral Control Structure

In the micromanipulation applications, scaled bilateral control is used for teleoperation where master/human is not able to access the micro environment on the slave side. Since the master and the slave are working on macro and micro scales respectively, thus its indispensable to use general bilateral controller to scale the position and forces between two sides for extensive capability [19]. In other words, position information from the master is scaled down to slave and force information from the slave side in scaled up to master as shown in Figure 5. Piezo-stage on the slave side is required to track master's position as dictated by the human operator. The $1D$ force of interaction with environment, generated by piezoresistive cantilever, on the slave side is transferred to the master as a force opposing its motion, therefore causing a "feeling" of the environment by the operator. The conformity of this feeling with the real forces is called the "transparency". Transparency is crucial for micro/nanomanipulation application for stability of the overall system. Furthermore, for micro system applications, position and forces should be scaled in order to adjust to operator requirements. Position of the master manipulator, scaled by a factor α, is used as a position reference for the slave manipulator, while the calculated force due to contact with environment, scaled by a factor β, is fed-back to the operator through the master manipulator.

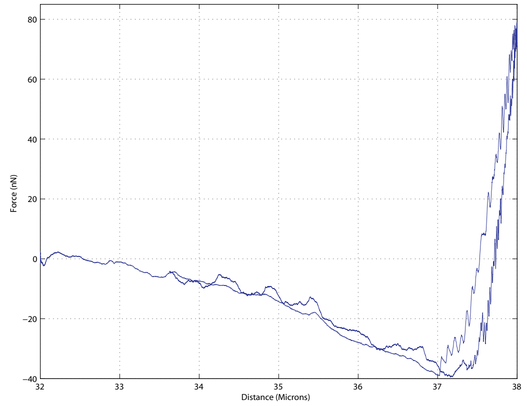

Fig. 4. Force for smooth step position reference.

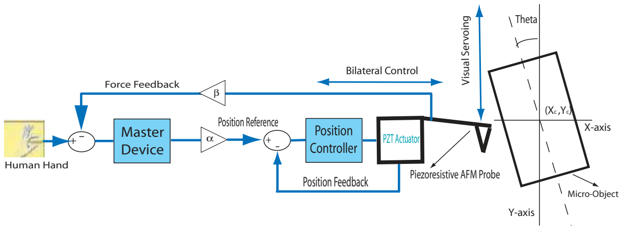

Fig. 5. Hybrid control structure for pushing micro-object

Low pass filter have been implemented to eliminate oscillations both on master side because of oscillatory human hand and also on the slave side due to piezoresistive cantilever dynamics. Position of master manipulator and force of slave manipulator are filtered by a first order low pass filter implemented in digital form using back difference method with a cutoff frequency of 100 Hz.

1) Scaling of the Position and Force Information: Since the master and slave side resides on macro and micro scales respectively, thus its very vital to appropriately choose the scaling factor in order to attain the optimum performance. In the ideal condition, the steady state condition of the bilateral controller should be Eqn.(1).

$$\begin{aligned} x_s &= \alpha x_m \\ F_m &= \beta F_s \end{aligned} \tag{1}$$

Where α and β represents the position and force scaling respectively. x_m and x_s denotes the master and slave position respectively, and F_m and F_s denotes the master and slave force respectively. To be able to meaningfully interact with the micro environment, positions and forces are scaled to match the operator requirements and to maintain stability by satisfying the condition $\alpha\beta < 1$ [20].

In the first and second experiments, scaling factors of $\alpha = 0.027\frac{\mu m}{deg}$ and $\beta = 0.00366\frac{N}{nN}$ are used, implying an angular displacement of $1deg$ on the master side corresponds to a linear displacement of $1\mu m$ on the slave side and a force of $1\,nN$ on the slave side corresponds to a force of $0.0036N$ on the master side.

2) Experimental Validation for Force/Position Tracking: In order to validate the position tracking between the master and the slave, the commanded position from the master is transferred after necessary scaling to be tracked by the slave side. Figure 6 illustrates the experimental results for position tracking along with the tracking error of the bilateral controller. It can be clearly seen that the slave tracks the master position with high accuracy. This position tracking performance is acceptable for precisely positioning the micro cantilever.

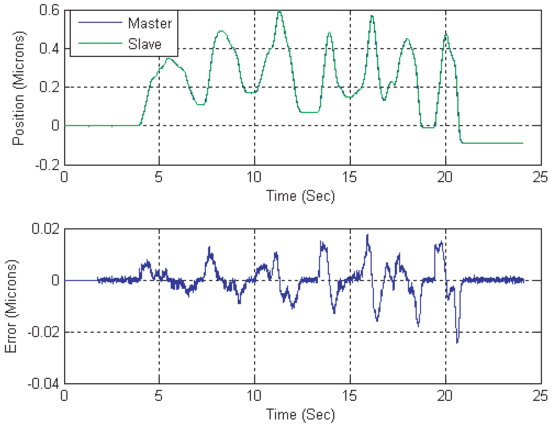

Fig. 6. Position Tracking between the master and the slave

In order to validate the force tracking, the slave forces encountered from the environment is being transferred to the master side after necessary scaling. Figure 7 demonstrates the force tracking between the master and slave along with the tracking error plotted in nN unit for better comparison. It can be clearly observed that the master tracks the slave force precisely and large variation in master forces allows the human operator to switch between position/force control.

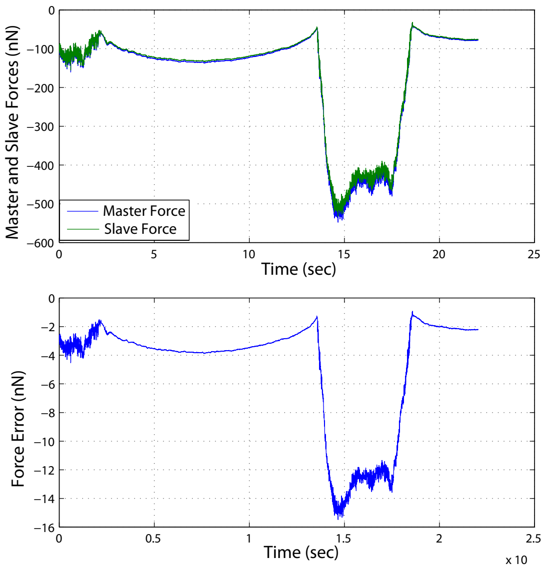

Fig. 7. Force tracking between the master and the slave

V. POINT CONTACT PUSHING SCHEME

Precise positioning of micro-objects lying on a substrate using a point contact pushing to track a desired trajectory posses lot of challenges. The pusher or probe needs to controlled in such a way to reorient and transport the micro-object to its final location using a stable pushing[1] operation. Using only a point contact with a limited number of freedom the task of pushing on a horizontal plane can be realized.

A. Hybrid Vision/Force Control

Figure 8 represents the scenario of pushing rectangular object using a point contact pushing to achieve translation motion. The rectangular micro-object has two points, namely COM (center of mass) and origin (0,0). The contact point of the pusher is taken as the origin of the reference frame. The X-axis and Y-axis of the micro-object frame rotates with respect to the reference frame and the orientation angle error (θ_e) is continuously measured using visual processing. The velocity of the probe along x-axis ($\vec{V}_x$) and y-axis ($\vec{V}_y$) are controlled by visual feedback and human operator, respectively. The desired velocity vector $\vec{V}_{des}$, resultant of $\vec{V}_x$ and $\vec{V}_y$ which passes through the desired angle (θ_d) to counteract the orientation angle error (θ_e) caused by irregular surface forces and allow the micro-object to obtain translational motion. The desired angle (θ_d) is calculated as Eqn.(2), which depends upon the orientation angle error (θ_d) of the micro-object.

$$\begin{aligned} if\theta_e < 0, then\, \theta_d &= \theta_e + \pi/2 \\ else\, \theta_d &= \theta_e - \pi/2 \end{aligned} \tag{2}$$

---

[1] The probe or pusher is always in contact with the micro-object during the pushing operation.

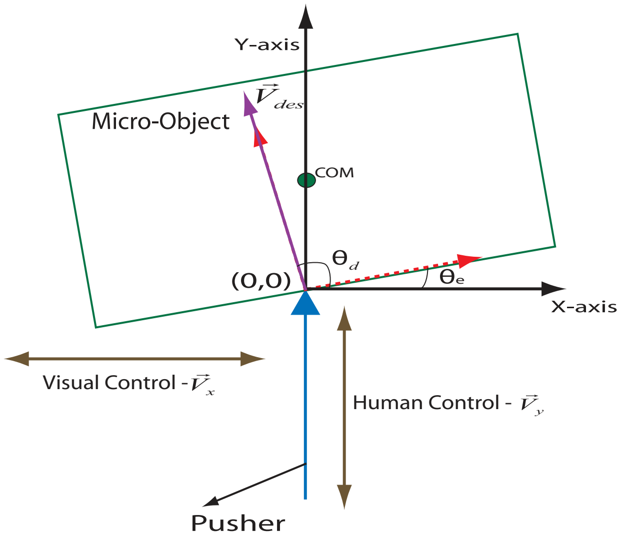

Fig. 8. Pushing approach using hybrid vision/force feedback

The resultant velocity vector $\vec{V}_{des}$ needs to make the desired angle to compensate for the disorientation error to achieve translational motion. The value of $\vec{V}_y$ cannot be controlled to achieve the desired velocity vector as it is administered by the human operator, rather it is only a measurable quantity. The variable $\vec{V}_x$ can be calculated by taking into consideration the value of $\vec{V}_y$ to achieve the desired velocity vector $\vec{V}_{des}$ making an angle θ_d as in the following equations.
The relationship between the $\vec{V}_x$ and $\vec{V}_{des}$ can be written as Eqn.(3) by analyzing Figure 8 and solving for $\vec{V}_{des}$ yields Eqn.(3).

$$\vec{V}_{des} \cos \theta_d = \vec{V}_x \tag{3}$$

Similarly, the relationship between the $\vec{V}_y$ and $\vec{V}_{des}$ can be written as Eqn.(4) and inserting the Eqn.(3) into Eqn.(4) will yield Eqn.(5)

$$\vec{V}_{des} \sin \theta_d = \vec{V}_y \tag{4}$$

$$\vec{V}_y = \vec{V}_x \tan \theta_d \tag{5}$$

The Eqn.(5) indicates that it is possible to only control $\vec{V}_x$ to achieve the resultant velocity vector $\vec{V}_{des}$ to pass through desired angle.

B. Experimental Validation of Pushing Operation

In order to validate the above mentioned pushing algorithm, several intermediate experiments were conducted by pushing a rectangular micro-object of size 200 μm at the mid-point of the length of rectangle and the line of action is made to pass through the center of mass. The pushing operation is performed by the human operator with force feedback along with visual feedback operation to compensate for any disorientation error. Figure 9 demonstrates the snapshot of the pushing operation and it can be clearly observed that after several steps the micro-object starts to rotate. Thus, it is unmanageable to translate a micro-object by only pushing through force feedback but visual feedback is necessary to compensate the disorientation error.

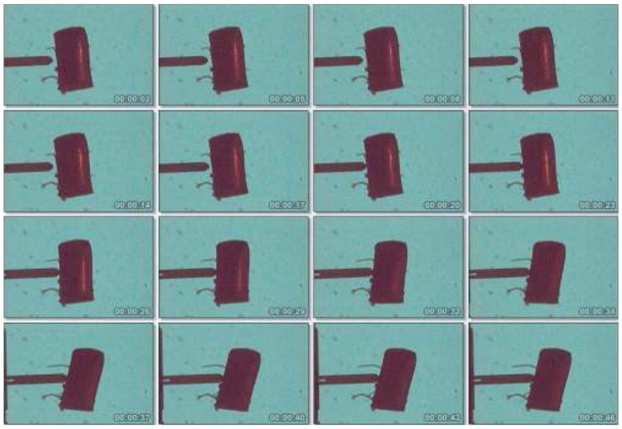

Fig. 9. Snapshot of pushing rectangular object at the mid-point of the rectangle and line of action passes through center of mass of the object.

Figure 10 demonstrates the snapshot of pushing rectangular micro-object such that the line of action is continuously made to pass through desired angle using hybrid vision/force feedback. Visual processing continuously tracks the objects, calculates the desired angle and generate the necessary velocities in X-axes so that resultant line of action passes through the desired angle. In this way the orientation angle error is compensated to attain translational motion. Figure 11 shows the position of Y-axes and forces during pushing operation.

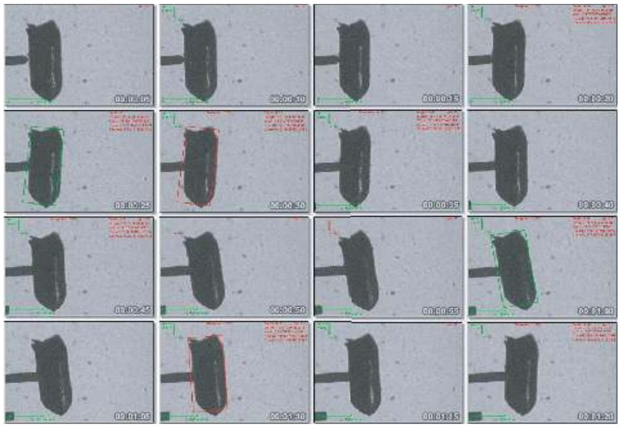

Fig. 10. Snapshot of pushing rectangular object using hybrid vision/force control

VI. CONCLUSIONS

In this paper, a method for pushing polygonal micro-object using hybrid vision/force feedback scheme by utilizing custom built tele-micromanipulation to attain translational motion is proposed. The pushing operation is undertaken by the human operator using visual display which acts an impedance controller and can switch between velocity control to force control by adjusting the stiffness (muscle stiffness) depending upon

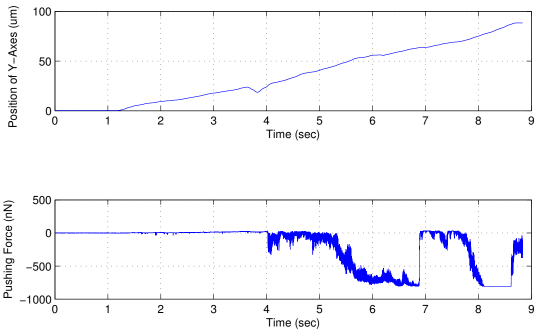

Fig. 11. Top represents the position of Y-axes and bottom figure shows the pushing force.

the behavior of the motion of the micro-object. Visual module provides the information about the position and orientation of the micro-object to calculate the line of action such that it passes through the desired angle to compensate the orientation angle error. Experimental results concerning nN resolution force sensing, force/position tracking between the master and the slave is presented along with the pushing operation. In future, the work would be focussed on extending from 1DOF master slave system to multiple DOF system to enable the human operator to perform dextrous task.

VII. ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial contributions by TUBITAK, Ankara, Yousef Jameel Scholarship, Berlin and Delft University of Technology, The Netherlands.

REFERENCES

[1] R. S. Fearing, “Survey of sticking effects for microhandling,” in *IEEE/RSJ Intelligent Robots System*, pp. 212–217, 1995.
[2] D. O. Popa and H. E. Stephanou, “Micro and meso scale robotic assembly,” in *WTEC Workshop: Review of U.S. Research in Robotics*, 2004.
[3] K. Furuta, “Experimental processing and assembling system (microfactory),” in *International Micromachine Symposium*, pp. 173–177, 1999.
[4] K. M. Lynch and M. T. Mason, “Stable pushing: Mechanics, controllability, and planning,” *The International Journal of Robotics Research*, vol. 15, no. 6, pp. 533–556, 1996.
[5] K. M. Lynch, “Locally controllable manipulation by stable pushing,” *IEEE Transactions on Robotics and Automation*, vol. 15, no. 2, pp. 318–327, 1999.
[6] M. Sitti, “Atomic force microscope probe based controlled pushing for nano-tribological characterization,” *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 3, 2003.
[7] S. Khan, M. Elitas, E. D. Kunt, and A. Sabanovic, “Discrete sliding mode control of piezo actuator in nano-scale range,” in *IIEEE/ICIT International Conference on Industrial Technology*, 2006.
[8] M. Sitti and H. Hashimoto, “Teleoperated touch feedback from the surfaces at the nanoscale: Modeling and experiments,” in *IEEE/ASME Transactions on Mechatronics*, vol. 8 of *1*, pp. 287–298, 2003.
[9] T. Tsuji, K. Natori, and K. Ohnishi, “A controller design method of bilateral control system,” in *European Power Electronics Power Electronics and Motion Control Conference*, vol. 4, pp. 123–128, 2004.
[10] S.Khan and A.Sabanovic, “Semi-autonomous scheme for pushing micro-objects,” in *IEEE ICIT (International Conference on Industrial Technology)-2009*, 2009.
[11] S.Fatikow, T.Wich, H.Hulsen, T.Sievers, and M.Jahnisch, “Microrobot system for automatic nanohandling inside a scanning electron microscope,” in *IEEE/ASME Transactions on Mechatronics*, vol. 2 of *3*, pp. 244 – 252, June 2007.
[12] S. Khan, A. O. Nergiz, M. Elitas, V. Patoglu, and A. Sabanovic, “A hybrid force-position controller based man-machine interface for manipulation of micro objects,” in *IEEE/MHS International Conference on Micro-Nano Mechatronics*, 2007.
[13] W. Zesch and R. Fearing, “Alignment of microparts using force controlled pushing,” in *In SPIE Conf. on Micro robotics and Micromanipulation*, 1998.
[14] Y. Zhou, B. J. Nelson, and B. Vikramaditya, “Fusing force and vision feedback for micromanipulation,” in *IEEE International Conference on Robotics and Automation*, 1998.
[15] H. Xie, L. Chen, L. Sun, and W. Rong, “Hybrid vision-force control for automatic assembly of miniaturized gear system,” in *IEEE International Conference on Robotics and Automation*, 2005.
[16] C. Pawashe and M. Sitti, “Two-dimensional vision based autonomous microparticle manipulation using a nanoprobe,” *Journal of Micromechatronics*, vol. 3, no. 3–5, pp. 285–306, 2006.
[17] S.Khan, A.Sabanovic, and A.O.Nergiz, “Scaled bilateral teleoperation using discrete-time sliding mode controller,” in *IEEE Transaction in Industrial Electronics*, p. In Press, 2009.
[18] S. Khan, A. O. Nergiz, A. Sabanovic, and V. Patoglu, “Development of a micromanipulation system with force sensing,” in *IEEE/IROS International Conference on Intelligent Robots and Systems*, 2007.
[19] M.Elitas, S.Khan, A.Sabanovic, and A.O.Nergiz, “Function based control of constrained motion systems for microsystems applications,” in *IEEE Transaction in Industrial Electronics*, 2008 (In Review).
[20] K. Fite, J. E. Speich, and M. Goldfarb, “Transparency and stability robustness in two-channel bilateral telemanipulation,” in *ASME Journal of Dynamic Systems, Measurement and Control*, 2001.