Micromanipulation Using A Microassembly Workstation with Vision and Force Sensing

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Abstract. This paper reports our ongoing work on a microassembly workstation developed for efficient and robust 3D automated assembly of microobjects. The workstation consists of multiple view imaging system, two 3-DOF high precision micromanipulators, and a 3-DOF positioning stage with high resolution rotation control, force sensing probe and gripper, and the control software system. A hybrid control scheme using both vision and force sensory information is proposed for precise and dexterous manipulation of microobjects. A micromanipulation experiment that aims to locate the microspheres to the predefined configuration by using an integrated vision and force control scheme is successfully demonstrated to show the validity of the proposed methods.

Key words: microassembly, micromanipulation, visual servoing, force control

1 Introduction

In recent years with the advances in the fields of micro- and nano-technology, handling micro-scale objects and operating in micro and submicron domains have become critical issues. Although many of commercially available micro devices such as inkjet printer heads and optical components are currently produced in monolithic fabrication process with micromachining, other products such as read/write heads for hard disks, fiber optics assemblies and RF switches/filters require more flexible assembly process. In addition, many biological micromanipulations such as invitro-fertilization, cell characterization and treatment are currently performed manually. Requirement of high-precision, repeatable and financially viable operations in these tasks has given rise to the elimination of direct human involvement, and autonomy in micromanipulation and microassembly.

In the literature, several research efforts on autonomous micro-manipulation and assembly tasks can be found in the areas of microelectromechanical (MEMS) assembly systems [1]-[3] and microrobotic cell injection systems [4]-[6]. Kim et al. [1] proposed a hybrid assembly method which combines the vision-based microassembly and the scaled teleoperated microassembly with force feedback.

With these tools, 980 nm pump laser is manufactured by manipulating and assembling opto-electrical components. Dionnet et al [7] designed a system which uses vision and force feedback techniques that allow to achieve accurate and safe autonomous micromanipulation. In the system, microparticles are positioned by pick-up using adhesion forces and release by rolling. Wang et al [4] presents a microrobotic system for fully automated zebrafish embryo injection based on computer vision and motion control. The microrobotic system performs autonomous injection at a high speed, with a successful survival rate. In spite of the numerous works in this area, only a few works [9] and [10] reported fully automatic microassembly tasks in 3D under optical microscopes.

In this work, an open architecture microassembly workstation in which fully automated 3D micromanipulation is executed under vision and force control is proposed. A hybrid control scheme using vision and force is developed to achieve both high precision and dexterity in micromamanipulation. The vision subsystem enables the system to move the end effector to the desired position based on the real-time detection of microobjects and probe tip. The force feedback is used to dexterously manipulate the microparticles without losing contact or applying excessive forces.

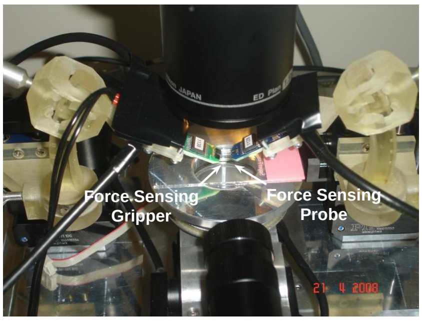
This paper is organized as follows: Section 2 presents the hardware and software components of the workstation. Section 3 explains the system calibration. Section 4 is on micromanipulation using vision and force. A micromanipulation experiment is also provided in this section. Finally, Section 5 concludes the paper.

2 Microassembly Workstation

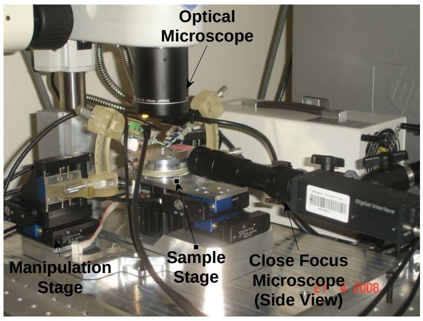
A microassembly workstation is designed for 3D manipulation and assembly of microobjects. The workstation uses two types of end effectors, a force sensing probe and a microgripper which have 0.3 μN resolution at 30Hz, shown in Fig. 1.(a). The force sensing probe and gripper are mounted on two separate 3-DOF fine positioning stages (50 nm closed loop precision). On an x-y-θ positioning stage, (50 nm close loop precision and 4.5×10^{-5} degrees rotation resolution) a glass slide is mounted and is positioned under the force sensing probe and microgripper, depicted in Fig. 1.(b). On the glass slide, the samples, polystyrene balls and biological cells which are used in experiments can be located.

The samples are placed under a stereo optical microscope, Nikon SMZ1500 with 1.5x objective and 0.75 : 11.25 zoom ratio. The optical microscope is coupled with two CCD cameras. While a CCD camera provides coarse view for the sample stage, another one is used for fine and narrower field of view. In addition, a side camera coupled to a 35x close focus microscope with 63 mm working distance and 7.2x7.2 mm^2 field of view is employed to provide a side view to acquire the height information between the sample stage and the end effector. A workstation is employed to acquire the images from the cameras and process the visual information. The resolution of the coarse, fine and side cameras are approximately 4, 1.3 and 2.5 pixels/μm for 2x zoom level respectively.

The positioning stages are controlled by a dSpace ds1005 motion control board. The control software is written in the C programming environment and provides real-time control for moving and positioning the stages precisely. The computer vision software is written in C++ language by using OpenCV libraries.



(a)



(b)

Fig. 1. Microassembly Workstation, (a) Microgripper and Probe, (b) Sample and Manipulator Stages

The optical microscope can provide only 2D visual information of the x-y plane due to small depth of field. Although exploiting defocus can yield a coarse information along the z axes, it results in poor accuracy for micron precision applications and it is computationally expensive. Therefore, a close focus microscope is used to monitor the image information in x-z plane and interaction between the sample stage and the end effector. Since it has a relatively large working distance, the samples and the probe/gripper can be well focused for an adequate range along y axes.

3 System Calibration

Visual information is the crucial feedback to enable the micro-manipulation and -assembly tasks. Processing visual data determines the path of the end effector in the image frame; however, the input of manipulator is given in its own frame. Thus the mapping between the manipulator frame and the image frame forms a critical component for servoing the probe and the gripper. In order to compute the mapping, a calibration method is developed and implemented.

Several calibration methods exist in the literature that are mostly used in macro scale vision applications [11], [12]. However, these methods cannot directly be employed to calibrate an optical microscope coupled with a CCD camera due to the unique characteristics of the optical system. Large numerical apertures, high optical magnifications and very small depth-of-field property of optical microscopes restricts the calibration to a single parallel plane. Although some methods [13],[14] were proposed to calibrate the optical microscope, they are computationally complex and cannot propose a solution for the close focus microscope, side view, since it does not have the same image forming components with a typical microscope. Therefore a simple modification to Tsai's algorithm [11] is done via weak perspective camera model assumption.

The algorithm used is as follows:

1. The end effector is detected using a template matching method and is started to be tracked.
2. The controller generates number of points for the end effector which corresponds to the corners of a virtual calibration grid.
3. The pixel coordinate of the probe/gripper is computed using the Normalized Cross Correlation (NCC) technique for each given position.
4. Once the positions of the end effector in camera and manipulator space are recorded, the Radial Alignment Constraint (RAC) [11] is employed to compute the rotation and translation from the manipulator coordinate frame to the image coordinate frame.
5. The total magnification (M) of the system and the radial distortion coefficient (κ_1) can be obtained by a least square solution which minimizes the following error:

$$error = \frac{\Sigma^N[(x_i - \tilde{x}_i)^2 + (y_i - \tilde{y}_i)^2]^{1/2}}{N} \ . \tag{1}$$

where N is the total number of points, (x_i, y_i) are image coordinates of a point and $(\tilde{x}_i,\tilde{y}_i)$ are the projected world coordinates for the computed rotation and translation. The average error ranges from 0.01 to 0.08 pixel for the coarse, fine and side views. Since the magnifications of the lenses and cell sizes of cameras can differ, the average error in metric coordinates varies from ten nanometers to less than a micron.

4 Micromanipulation Using Vision and Force

In the literature, several micromanipulation works are presented with no sensor [15], only visual feedback [8],[9] and both vision and force information [1],[7],[6]. Since manipulating an object needs the ability to observe, position, and physically transform the object, both vision and force are essential feedback types for our versatile micro-assembly system. Because the workstation is designed for various microscale applications including biological manipulation, both vision and force control are strongly demanded to ensure successful operation and prevent damage to the objects.

4.1 Visual Feedback

Visual servo control relies on techniques from image processing, estimation and control theory. In our system, several image processing algorithms are developed to detect and track the micro-objects, probe and gripper. Since micro polystyrene balls are used in the experiments, detection of the microspheres at video rate from all the top and side cameras becomes crucial. Having a priori knowledge on the size and shape of the microparticles, the generalized Hough transform which is robust under noise is implemented to detect the spheres, after the connected components are extracted in the entire frame. Using the procedure, the positions of microballs can be detected in the full frame (640x480 pixel) on the sample glass at a rate of 30 Hz.

It is also crucial to detect and update position of the end effector from the top and side cameras during the experiments. Since the end effector is moved in the 3D, two algorithms are required to detect the position of the probe in the x-z and x-y plane. For the images acquired from the side camera, the probe is detected by using template matching with the NCC comparison method. Because determining the contact point of the probe in the x-y plane is vital in order to locate microspheres precisely, the detection of probe tip is computed in subpixel accuracy by exploiting the known CAD of the probe.

Real-time measurement of the features on the image plane must be done in an efficient, accurate and robust manner. In order to satisfy those criteria, the Kalman filter is employed to estimate the positions of image features given the measurements from the feature extraction module. During the micromanipulation experiments, the locations of two image features, position of the probe tip and the particle which is being pushed are tracked by the tracking module at a frame rate of 30 Hz.

A simple proportional control [16] to ensure an exponential decoupled decrease of the error ($\dot{e} = -\lambda e$) is designed:

$$v = -\lambda {L_s}^{\dagger} e = -\lambda {L_s}^{\dagger} (s - s^*) \ . \tag{2}$$

where and ${L_s}^{\dagger} \epsilon R^{6\times k}$ is the pseudo inverse of interaction matrix L_s, s and s^* are visual features being tracked and desired features respectively, and λ is a positive scalar. It is also possible to design control laws that optimize various system performance measures. An optimal visual control design that aims to minimize the tracking error and the control signal energy can be found in [17].

4.2 Force Feedback

Visual information without force feedback is not adequate for sophisticated micromanipulation tasks which require a high degree of dexterity. Using only visual data can model and control positioning of an object. However, pure position control for delicate or fragile objects such as biological material cannot ensure safe and successful manipulation strategies. Furthermore, force feedback in the micromanipulation tasks can also be used to detect the interaction forces between the end effector and the object [4],[5]. In our system, force from the probe sensor is monitored to continuously push the objects without losing the contact between the probe and the objects during the manipulation tasks. An example plot which demonstrates the interaction force between the microsphere and the force sensing probe for a pulse positioning input is given in Fig.2.

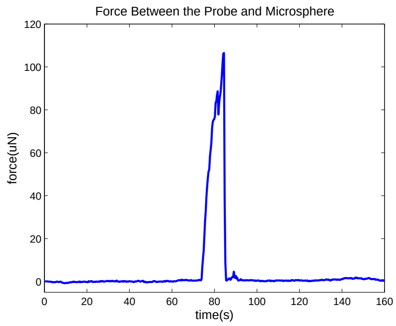
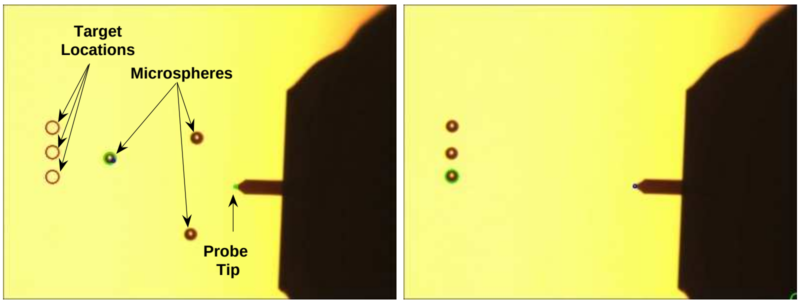


Fig. 2. The Contact Force Between the Probe and the Microsphere

4.3 Path Planning for Collision-Free Transportation of Microobjects

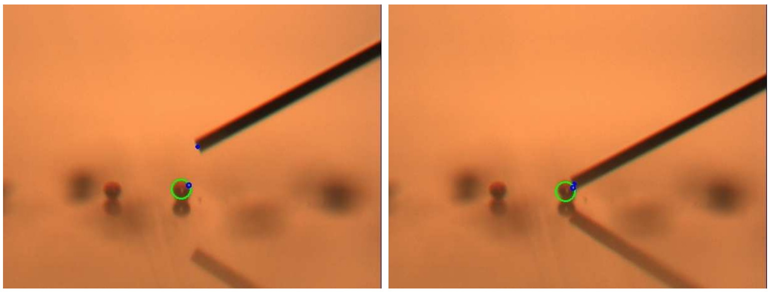
In the previous sections, the required modules to dexterously manipulate the microparticles were presented. Using the feature extraction, tracking, visual and force control modules, we are able to move several microparticles serially along the computed path and generate a pattern by locating them accurately. An illustrative scene for the pattern generation task is given in Fig. 3.



(a) (b)

Fig. 3. Automatic Micromanipulation of Microspheres, (a) Initial Configuration of Workspace, (b) Constructed Line Pattern

The serial micromanipulation process includes five stages: z movement, explore, obstacle avoidance, pushing and home modes. In the z movement mode, the probe tip is positioned along the z axes by processing the workspace image acquired from the side camera, depicted in Fig. 4. In the explore mode, probe is positioned such that all the workspace is visible and no occlusion occurs due to the probe position. Thus the global particle map can be extracted and used in the path planning. As the probe approaches to the determined particle, there may be an obstacle on the way to the destination. To avoid collision, a rectangular region twice of the size of the obstacle is generated, and the rectangular path is followed by the probe as long as no obstacle exists on the way to the particle. An illustrative figure is shown in Fig. 5. In the home mode, the probe



(a) (b)

Fig. 4. Visual Servoing in the x-z Plane

is moved to its initial position with the obstacle avoidance support so that the particle map in the workspace can be updated with no occlusion of the probe.

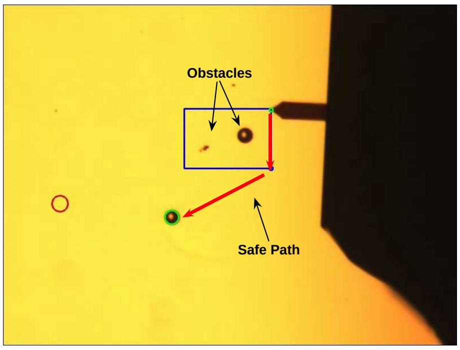


Fig. 5. Obstacle Avoidance

As a result, a micromanipulation experiment in the developed system with suitable hardware and software modules is successfully demonstrated. In the experiment, three microspheres are transported to the desired locations in 45 seconds with 0.7 micron accuracy which is the resolution of the optical microscope.

5 Conclusion

A microassembly workstation which is capable of manipulating the microobjects dexterously by using vision and force is presented. In the vision subsystem, an optical microscope and a lateral view close focus microscope are employed to servo the end effector in 3D by tracking the end effector and microobjects during the manipulation tasks. A force sensing sensor is used to monitor the interaction forces between the probe and the microparticles to keep the pushing force in the optimal range.

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