A Workstation for Microassembly

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Abstract—In this paper, an open-architecture, reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts is presented. The workstation is designed to be used as a research tool for investigation of the problems in microassembly. The development of such a workstation includes the design of: (i) a manipulation system consisting of motion stages providing necessary travel range and precision for the realization of assembly tasks, (ii) a vision system to visualize the microworld and the determination of the position and orientation of micro components to be assembled, (iii) a robust control system and necessary mounts for the end effectors in such a way that according to the task to be realized, the manipulation tools can be easily changed and the system will be ready for the predefined task. In addition tele-operated and semi-automated assembly concepts are implemented. The design is verified by implementing the range of the tasks in micro-parts manipulation. The versatility of the workstation is demonstrated and high accuracy of positioning is shown.

I. INTRODUCTION

There is a great effort towards miniaturization in the last few decades effects of which can be seen in every aspect of our lives. From laptops to the cellular phones, we always prefer the smallest since the idea of "the smaller the better" has penetrated into our minds and one can be equipped with more gadgets as the miniaturization goes further. However, many problems arise through the miniaturization process because of the scaling effects, manufacturing techniques and, as might be expected, assembly. The incompabilities among the variety of materials and several processing technologies of each individual component as well as the necessity of integration of these components in order to form a functional microstructure require a versatile assembly technology and development of the specific processes, methods and machines.

The production of microsystems integrated with many functionalities, many components made of different materials require flexible, modular, accurate mechanisms, which can finely pick, orientate, move and release different types of objects at the right place. In the presence of microparts, assembly is a key issue in the formation of a product since different functions require different materials within a product.

For achieving high output and quality in microassembly tasks, it is necessary to develop a reliable, open-architecture and reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts. Since the human skills for handling are to be replaced by such an automated machine, micro scale manipulation tools which supersede the human hand in the micro domain, material properties of these tools and

the microcomponents to be assembled gain significant importance. Microassembly, integration of components into complex microsystems is still a primary challenge since some of the fundamental problems originating from the small size of parts to be manipulated, high precision necessity and specific problems of the microworld in that field are still not fully investigated.

Several researches have been conducted to develop microassembly systems. In that context, flexible microrobot-based micro assembly desktop stations (MMS) in which microassembly processes are carried out by automatically controlled microrobots are proposed in [1] [2] [3]. A robotic workstation with the objective of development of a general, not application specific, used for the construction of out-of-plane microcoils is proposed in [4]. A micromanipulation system based on tele-operation techniques and the tele-operation scheme using haptic/visual interface for micro parts handling and control is presented in [5] and a reconfigurable micro-assembly system which can be used to assemble MOEMS and Micro-Fluidic devices is presented in [6].

In this paper, we propose a repetitive and reliable open architecture, reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts. In microassembly, according to the task to be implemented and the parts to be manipulated, a special tool has to be used or developed since the concept of a universal gripper seems impossible. For that reason we propose a platform that allows the realization of different assembly tasks just by changing the manipulation tool in order to overcome the limitations of tools capability of performing only some specific tasks.

On the other hand, since accuracy requirements for microassembly operations are very high; precision and repeatability of such assembly systems must be in the micron to nanometer range for automatic assembly of millimeter and micron structures. Focusing on the high-precision necessity of such a microassembly platform, we achieved motion control with nanometer accuracies.

II. MICROASSEMBLY WORKSTATION

A. Design Requirements

When compared with the assembly in the macro world, necessary requirements for assembly in micro world show significant differences. The main difference between the assembly in the macro and microworld is the positional accuracy required for the assembly machines. Since the size of the parts to be positioned becomes smaller, precision of motion should also become better to assemble the parts accurately. For the robotic manipulators in the macroworld a precision of few microns is typical, however, in the microworld submicron precision is necessary. Positioning at the microscale becomes

considerably more difficult since accurate sensing of the true output is more difficult, and link flexibility can induce residual structural vibrations.

Visualization becomes a more significant issue in the micro world as there are limitations such as orientation of the microscopes, magnification and depth of field. Microscopes limit the ability of directly seeing the objects of interest. High magnification, necessary for imaging the microworld, restricts the field of view to a very small area causing the lack of global information about the object. At high magnification rates, depth of field becomes a problem as the limited depth of field obstructs the clear view of non-planar objects and the moving structures. Another problem is that the working distance limits manipulation operations. The number of degrees of freedom may also become a drawback since there may be occlusions as a result of the complicated end-effector structure.

Another issue that has great significance in micromanipulation is the effect of force scaling. While the size of the objects become smaller, inertial forces scale down faster than adhesive forces since inertial forces depend on the volume of the object and adhesive forces depend on the surface of the object. As a result of the effect of adhesive forces, releasing the object after gripping becomes a great problem. Therefore, the effect of adhesive forces should be carefully considered for a robust micromanipulation as it brings limitations to manipulation capabilities such as preventing the motion of the object.

Differences between the assembly in macro and micro world form the basic requirements for the design of a microassembly workstation. We are proposing an open architecture and reconfigurable system – both hardware and software – so that the system should be designed in such a way that it can adapt easily to different applications which brings out flexibility as another design requirement for the workstation.

B. Design and Implementation

For targeting a precise, flexible and robust microassembly workstation, the system should be configured in such a way that the final system will be as simple as possible and highly efficient. The overall system structure of the workstation is presented in Fig. 1. The system consists of the following subsystems:

Manipulation system consists of a tool manipulator and a sample stage which provides the necessary motion for micromanipulation operations. Tool manipulator consists of coarse and fine positioning stages providing necessary travel range and the accuracy for the manipulation so that positioning errors from the coarse positioning can be compensated by fine positioning stages. Sample stage provides the usage of the substrate surface more effectively by moving the different regions of the substrate into field of view.

Control system is the main control unit of the system consisting of a PC and an embedded controller board. The control system should have the capacity for the real-time control of all axes simultaneously. Implementing a centralized structure, a main control computer, giving reference values and not possessing any direct sensor or actuator connections and a module control computer implementing a fast control loop by taking the reference

values from the main control computer is necessary. A high performance personal computer (PC) is configured as the main control computer and the system configuration is shown in Fig. 2.
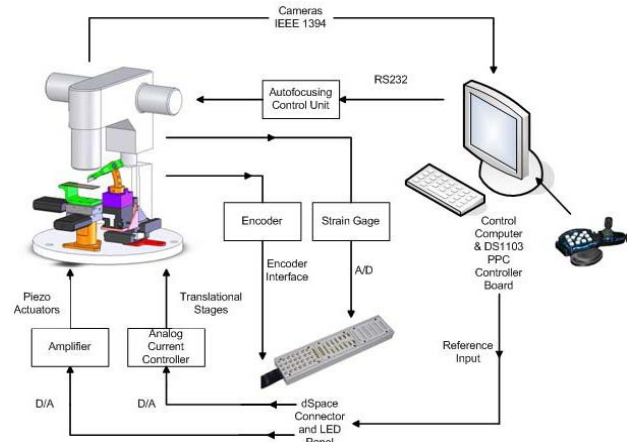

Figure 1. Whole system configuration

Vision system consists of the optical system; a stereoscopic optical microscope, CCD cameras and an autofocusing control unit, and the illumination system which is configured to provide backlighting by means of a mirror system using a fiber illuminator as the light source. Vision system configuration is shown in Fig. 3.

End effectors and necessary fixtures are used interchangeably in the system. Microgrippers, probes and other manipulation tools can be the matter of choice and necessary fixtures are designed to be easily integrated to the system. The whole system is placed onto an actively controlled damping table in order to get rid of environmental vibrations. Actual system is shown in Fig. 4.
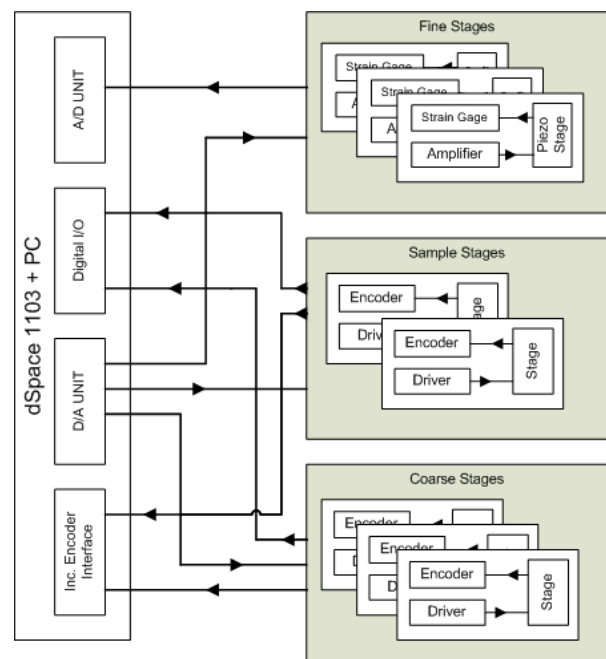
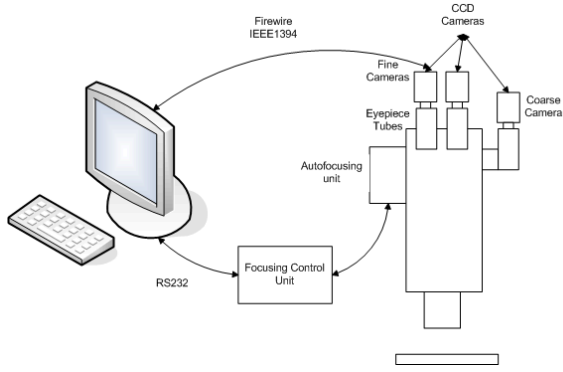

Figure 2. Control system architecture
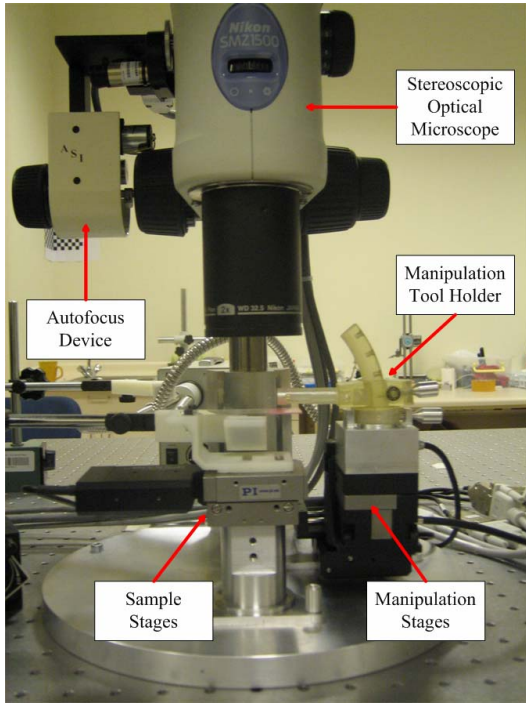
Figure 3. Vision system

Figure 4. Microassembly workstation

C. System Supervision and Control

Motion control is the basis for the microassembly workstation since the precision and accuracy of the assembly tasks mostly depend on the control performance. Main considerations of the system supervision and control are related to the motion control and image processing. In order to achieve high accuracies for the motion, control method needs to be considered carefully. Vision system along with local feedbacks from other sensors supplies the external sensory feedback for the motion control unit. By using some image processing techniques, position of parts to be manipulated and the manipulation tools with respect to each other, which are necessary for the implementation of automated assembly tasks, are extracted. As the motion units operate according to the feedback supplied by visual information, vision system must be very precise for the sake of realization of the assembly tasks. In tele-operated tasks, only the mapping has great significance since the user defines the motion. However, for the automated tasks vision system gains significant importance as it gives the reference for motion according to the extracted position information.

1) Motion Control

For the systems where high precision motion control is required, robustness of the control algorithm is the most crucial factor. Moreover, if the plant has high nonlinearities such as hysteresis in piezoactuators or friction, using a robust controller designed according to the nominal plant parameters and which rejects parameter uncertainties would be advantageous.

Variable structure control with sliding modes, frequently named as sliding mode control, is characterized by a discontinuous control action which changes structure upon reaching a set of predetermined switching surfaces. This control may result in a very robust system with its built-in disturbance rejection, which in turn implicitly compensates for the unmodeled dynamics, and thus provides a possibility for achieving high precision and fast response.

Discrete time implementation of sliding mode control for the system is as follows;

Considering the system:

$$\dot{x} = F(x,t) + B(x,t)u . \qquad (1)$$

where $x \in \Re^n$ is the state vector of the system. $F(x,t) : \Re^n \times \Re^+ \to \Re^n$ is a continuous and bounded linear or nonlinear function which defines the uncontrolled dynamics of the system. $B(x,t) : \Re^n \times \Re^+ \to \Re^{n \times m}$ is a continuous and bounded matrix with $rank(B) = m$ for every x,t couple, yielding the system to be linear according to the control input. $t \in \Re^+$ is the independent time variable. Derivation of the control law starts with the selection of positive definite Lyapunov function candidate, $v(\sigma)$ satisfying the Lyapunov stability criterion;

$$\dot{v}(\sigma)v(\sigma){<}0 \qquad (2)$$

For a Lyapunov function of the form

$$v(\sigma) = \frac{\sigma^T \sigma}{2} \qquad (3)$$

derivative of the function

$$\dot{v}(\sigma) = \sigma^T \dot{\sigma} \qquad (4)$$

Designing the control function such that

$$\dot{\sigma} + D\sigma = 0 \qquad (5)$$

derivative of Lyapunov function becomes a negative definite function as

$$\dot{v}(\sigma) = -\sigma^T D\sigma \qquad (6)$$

satisfying the Lyapunov stability criterion, where $D \in \Re^{m \times m}$ is a positive definite symmetric matrix defining the slope of the sliding manifold at each dimension. Lyapunov function and its derivative having opposite signs with the aid of control enforce the system to move to $\dot{v}(\sigma) = v(\sigma) = 0$ ensuring stability.

For the discrete time sliding mode development, continuous motion equation should be replaced by its discrete time equivalent

$$x_{k+1} = F_k(x_k) + B_k(x_k)u_k \qquad (7)$$

for $\;x_i = x(i\Delta t)\quad x \in \Re^n,\quad F_i = \Delta t F(x_i, i\Delta t) + x_i$
$F : \Re^n \to \Re^n$, $B_i = \Delta t B_i(x_i, i\Delta t)\;\; B_i : \Re^n \to \Re^{n\times m}$
$u_i = u_i(\Delta t)\;\; u_i \in \Re^m$, $i \in Z^+$ and Δt is the sampling time.

For a tracking error $e_x = x^{ref} - x$, σ is selected as $\sigma(x) = Ge_x$ for $G \in \Re^{m\times n}$ such that $\det(GB_k) \neq 0$ to satisfy control objectives on the sliding manifold $\sigma(x) = 0$.

$$\dot{\sigma} = GB(u - u_{eq}) \qquad (8)$$

solving for u_{eq}

$$u_{eq} = u - [GB]^{-1}\dot{\sigma} \qquad (9)$$

Since u_{eq} is a continuous function, approximation of the current value of u_{eq} yields to

$$\widehat{u}_{eqk} \approx u_{eqk-1} = u_{k-1} + [GB_k]^{-1}\dot{\sigma}_{k-1} \qquad (10)$$

writing $\dot{\sigma}$ in discrete form using Euler's approximation

$$\dot{\sigma}_{k-1} = \frac{\sigma_k - \sigma_{k-1}}{\Delta t} \qquad (11)$$

putting (8) in (5) and solving for u_k

$$u_k = u_{eqk} - [GB_k]^{-1}D\sigma_k. \qquad (12)$$

using the approximation

$$u_k \cong u_{eqk-1} - [GB_k]^{-1}D\sigma_k \qquad (13)$$

solving (10) and (11) together

$$u_{eqk-1} = u_{k-1} - [GB_k]^{-1}\frac{\sigma_k - \sigma_{k-1}}{\Delta t} \qquad (14)$$

putting (14) into (13)

$$u_k = u_{k-1} - [GB_k]^{-1}\left((D + \frac{1}{\Delta t})\sigma_k - \frac{\sigma_{k-1}}{\Delta t}\right). (15)$$

simplifications yield to

$$u_k = u_{k-1} - [GB_k\Delta t]^{-1}\left((1 + DT)\sigma_k - \sigma_{k-1}\right). (16)$$

The control structure (16) is suitable for implementation, since it requires measurement of the sliding mode function and the value of the control applied in the preceding step. Thus (16) is used as control structure as discrete sliding mode for translational stages and piezo actuation.

Step responses of the translational stages are shown in the following figures for 10 and 1 microns respectively.
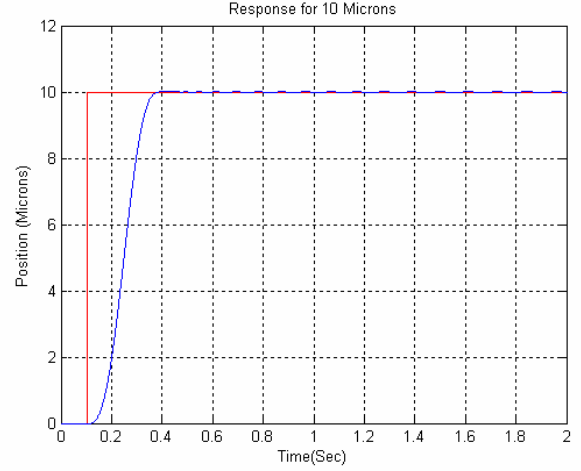

Figure 5.   Step response of translational stages for 10 μm
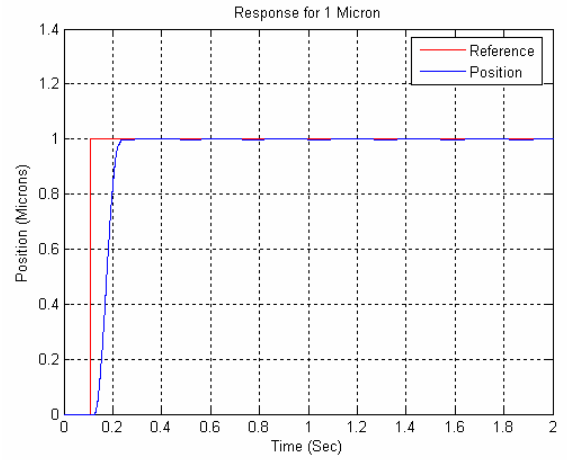

Figure 6.   Step response of translational stages for 1 μm

As it can be seen from the figures that for the given position references, performance of the translational stages is satisfying since the responses are good but only suffering from a 0.007 microns oscillation representing the resolution of the encoder. That amount of error can be neglected in our case since it can be compensated by the fine translational stages.

Disturbance observer implementation (Fig. 7) for the piezo actuation in this workstation is explained in [7] and directly used in the system.

The resulting step responses of the piezo stages for different references are shown in Fig. 8 and Fig. 9.

As seen in the figures, system is able to achieve the desired position with a fast rise time. However the system suffers from the noises belonging to high
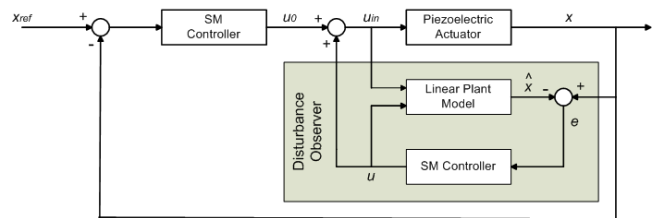

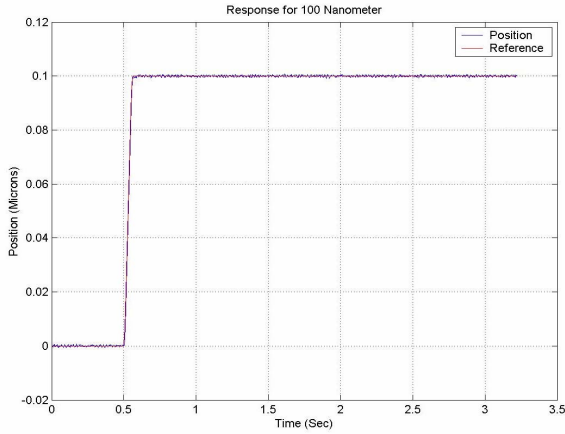
Figure 7.   Observer Implementation

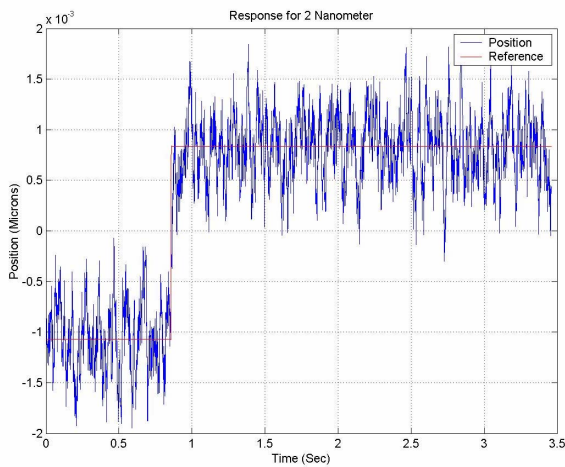Figure 8.   Step response of piezo stages for 100 nm

Figure 9.   Step response of piezo stages for 2 nm

frequency range resulting from the measurement devices which affect the steady state of the system and forces an oscillatory behavior with maximum amplitude of 1-1.5 nanometer.

2)   Vision System

The main functionality of the vision system is guiding the user for manipulation tasks and the extraction of positions from the images which are necessary for the implementation of automated assembly tasks. Typical tasks of position extraction for the microassembly process are; determining the positions of the parts to be manipulated and the manipulation tool, pushing or gripping locations, etc.

The position determination process involves the following steps; segmentation of the captured images by thresholding, extraction of sharp contrast changes indicating the corners or edges of object boundaries existing in the image, identifying the objects and extracting necessary information.

Additional to the position determination, there are some pre-processing issues related to the vision system. These pre-processing issues include procedures which are necessary to be completed before the implementation of the assembly tasks, necessary for the acquirement and determination of system parameters and the knowledge about the models of the objects to be identified. These procedures are autofocusing for the acquirement of a clear

image necessary for the implementation of image processing algorithms, depth information and the camera calibration for mapping the image space to real world coordinates.

In that context, the vision structure is as follows; first autofocusing is enabled to get the clear image for further processing, determination of the positions of necessary components is realized in image space and finally, according to the parameters determined by mapping from image space to real world, necessary information is fed to the motion system in order to realize the assembly tasks.

D.   Experiments and Results

For the testing of the reliability of the system several experiments are implemented in two modes of operation; tele-operated and semi-automated. Experiments which will be defined in this paper are realized using polystyrene microspheres with diameters of approximately 70 μm and a sharp tungsten probe as the manipulation tool. Tele-operated micro assembly is realized in two different ways; by giving commands on the screen with mouse clicks or by means of a joystick. Semi-automated micro assembly involves the intervention of the operator to some extent. The operator only chooses the particle to be manipulated and the destination point where the particle is to be moved, the rest is executed automatically.

In tele-operated systems, hand motions of a human operator are transferred to the motion system by means of a man machine interface (MMI). Our system is configured to be used by a joystick enabled to give commands to the X and Y axes of the manipulation stages. The operator can also give commands from the graphical user interface (GUI) by simply using the mouse and clicking on the screen to choose the home and destination points.

Fig. 10 shows a predefined line template formed in tele-operated mode. Target positions of the particles are indicated with circles on the screen and the target position of each particle is determined according to the distance between the particle and the target position. Each particle is intended to be moved to the closest target point. In order to guide the operator, pushing points of each particle and the trajectory denoted by a line between the center of the micro particle and the target point are displayed on the screen. The operator, by simply clicking on the screen, moves the probe tip to the pushing point and then pushes the particle through the line to its target point. This process is repeated at each step.

In semi-automated microassembly, the operator intervention to the assembly operation is limited. By this way, the tasks of the assembly procedure are commanded to the manipulation system one by one by the operator. The tasks are pre-programmed and the operator simply defines some of the parameters necessary for the assembly. The operator selects the particle to be manipulated and the destination point by simply clicking on the particle on the screen. The rest of the operation is managed automatically. After the handling of the initial steps by the operator, relative distance data calculated by the vision system is fed to the motion system while sensory feedback (position data) from the motion stages is sent back.

Throughout the experiments carried out in both tele-operated and semi-automated modes of the workstation, it

is observed that the pushing operation should be realized gradually by pushing, retracting back and then pushing again. The reason for such an operation is that pushing for long distances causes the particle to roll around itself and the probe tip resulting in the failure of the pushing operation. Also there is the possibility of the particle stick to the probe as a result of that rolling. When the particles roll to the side of the probe the contact surface increases causing the particle stick to the probe which will fail the assembly process. As a result of that the semi-automated tasks are implemented in a step-wise manner. The probe is moved to the defined pushing position and then along the line trajectory determined the particle is pushed for a small amount and then the probe is retracted back.
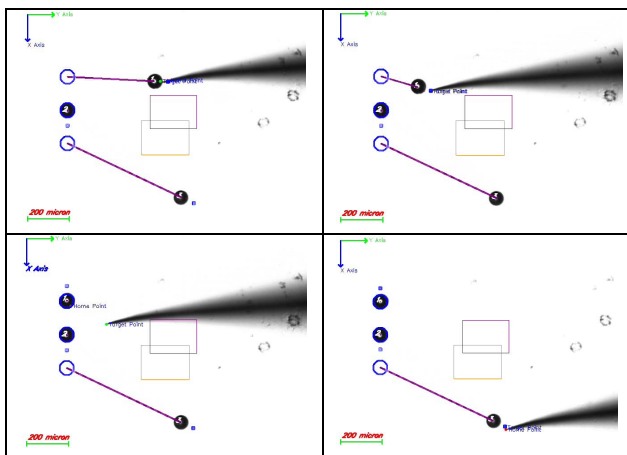

Figure 10. Line template formation

A line formation experiment steps are shown in Fig. 11. In that experiment, operator selects the particle and the destination point to where the particle will be moved at the end of the operation. This selection is made by the operator for each particle. After the manipulation of each particle to its destination, the probe returns back to the initial position and the new task is generated by the operator. The rest of each operation is executed automatically.

III.   CONCLUSION

In this paper, design and realization of an open-architecture and reconfigurable microassembly workstation for efficient and reliable assembly of micromachined parts is presented. Design necessities for an automated microassembly workstation are explained in detail and the realization of the system considering these necessities is demonstrated.

Realized microassembly workstation represents an important step towards the automatic, autonomous assembly of micrometer-sized parts by means of sensory feedback. We demonstrated the functionality of the system on several experiments in different modes of operation, tele-operated and semi-automated. The results of the experiments are promising in the sense of precision, accuracy, reliability and repeatability. With the integration of motion planning algorithms, the system will have the ability to function in fully automated mode where there is no human intervention.
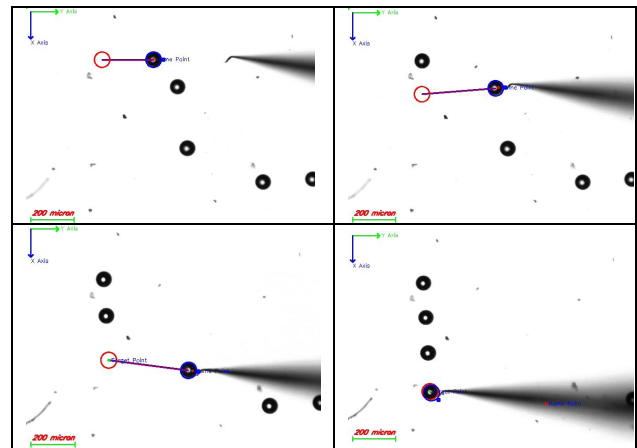

Figure 11. Line formation – semi-automated

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