Image based Online Tracking and Control of Nano-Manipulator for Collision Avoidance in Micro/Nano Assembly

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***Abstract*—Authors present development of online tracking and control of nanomanipulator (MM3A®) tip to assist automation of micro/nano assembly procedure. The development presented here captures online images of the moving nanaomanipulator's tip, and then with a predefined application specific safety margin it generates a visual attention region on the screen for tip-tracking. Any micro/nano object, featuring as low as one pixel size, if comes within threshold region, it detects possibility of collision and a visual event is generated to take hold of the user attention. Its detection capability is limited only by vision system's resolution. Besides keeping track of safety margin, linear speed of the tip is also computed online. Online information of collision possibility and tip speed allows user to modify necessary controls to bring more safety in manipulation of costly and very delicate parts of the system. It also saves time and cost by avoiding unnecessary attention and collisions. It has been practically demonstrated in an experimental set up of Nano-manipulator (MM3A) working in sub-micron accuracy, equipped with a force measurement tip (FMT®), interacting with a micro-cantilever spring under a light microscope.**

I. Introduction

Automated microassembly has been identified to be a critical technology in emerging micro and nano systems technology (MST & NST) by members of the private sector and government funding agencies. No commercial success of either of these technologies is possible without reliable and cost-effective assembly and packaging technologies for the finished products at micro and nano scales.[1]

Packaging and assembly cost is a major portion which can range between 20% to 95% of the overall cost of the products, averaging around 30-50%, thus packaging and assembly of microsystems is a crucial part of in product development. Hence cost effective packaging and assembly is the key factor to the success micro scale system in market [2,3]. In these directions Nanorobotic manipulators [4,5] with 6-DOF nanomanipulation capability, multi-endeffector etc. have been reported. For three dimensional and nano robotic manipulation inside SEM for development of carbon nano-tube based and other devices have been found much attention [6, 7, 8, 9, 10, 11]. Application based design and development of a fused vision force feedback robust controller for a nanomanipulator in nano fiber based fabric production has been shown [12].

With the increase in demand of productivity and consistency in micro and nano scale, manufacturing assembly and packaging automation with robots needs to be employed in every production line;partially or fully to the extent it is possible. Collision avoidance has been of major importance in automated robotic operations. With much attention in micro and nano scale manufacturing and device making it has now to be viewed as one of the most demanding challenge. Handling of these micro and nano components in very small working cell, sometimes within a SEM chamber with very costly nano/micro scale robots, needs to be addressed in terms of avoiding collision as well as controlling end-effectors when even a small vibration or skid can damage a costly part of a product or assembly system. The utility of collision avoidance and online speed tracking in multiple nano robot environment becomes even more important for safety and control in automation when vision aid is limited to 2D or 2.5D, as we cannot get actual 3D vision as a user looking at PC monitor.

The paper is organized as follows: section-II describes the system setup, section-III develops model and kinematics for speed and position of MM3A end-effector, section-IV algorithms for tip tacking and speed computation, section-V results & discussion and section-VI discussion and finally conclusion.

II. Description of experimental setup

The Nanomanipulator system's complete block diagram and setup photograph is shown in figure1 and figure 2, respectively. It consists of nano robots with nanoelectronic controls which can operate under a light microscope or a SEM (Scanning Electron Microscope). These manipulators have joint configuration as RRP (revolute-revolute-prismatic), these utilize two rotational joints with 0.1 micro radian resolutions and one prismatic joint with 0.25 nm resolution. This Nanomanipulator is equipped with well-behaved kinematic and backlash-free characteristics besides having nano scale precision to achieve accurate manipulation. The manipulator's tip can be controlled under a light microscope is in fraction of micrometers whereas under a SEM, it is in nanometers. A Microcantilever based force measurement tip has been attached to the MM3A Manipulator at its end-effectors position. To demonstrate experimental viability of tip-detection algorithm a micro spring placed next to it. Using MM3A controls the manipulator can interact

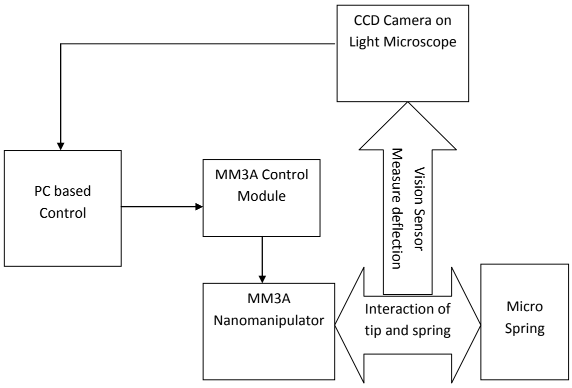
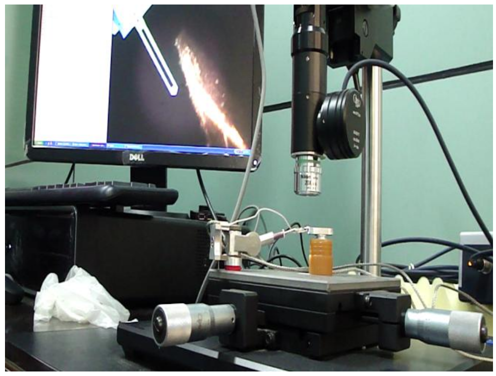
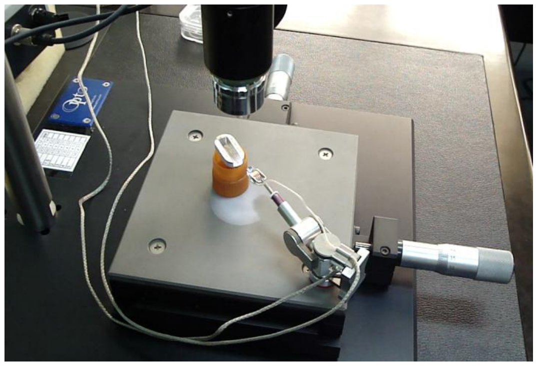


Fig. 1. Micromanipulator MM3A Set up, Block Diagram



(a) Micromanipulator MM3A Set up



(b) Cantilever

Fig. 2. Nano-Manipulator experimental setup

with objects in its work space at micro and nano scale. Using image processing technique in MATLAB, the tip is marked with a circle and once the tip comes in vicinity with object, color of the circle gets changed. The CCD camera system sends images to PC where these are captured in MATLAB program and analyzed for tracking tip position, speed and presence of objects within safety range.

III. Modeling and Kinematics of Nanomanipulator

The MM3A Nanomanipulator has three degrees of freedom as shown in figure 3(a). It has been represented as an equivalent RRP manipulator in figure 3(b), and its kinematic equation has been derived using Denavit-Hartenberg convention, taking actual physical dimensions into consideration.

Using D-H convention the coordinate transformation matrices for the successive links can be written as shown below.

$$^0T_1 = \begin{vmatrix} cos\theta_1 & 0 & sin\theta_1 & l_2cos\theta_2 \\ sin\theta_1 & 0 & -cos\theta_1 & l_2sin\theta_1 \\ 0 & 1 & 0 & l_2 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$^1T_2 = \begin{vmatrix} cos\theta_2 & 0 & sin\theta_2 & 0 \\ sin\theta_2 & 0 & -cos\theta_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

$$^2T_3 = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

After multiplication the composite homogeneous transformation matrix becomes, ${}^0T_3$=

$$\begin{matrix} cos\theta_1cos\theta_2 & sin\theta_1 & cos\theta_1sin\theta_2 & dcos\theta_1sin\theta_2 + l_2cos\theta_1 \\ sin\theta_1cos\theta_2 & -cos\theta_1 & sin\theta_1sin\theta_2 & dsin\theta_1sin\theta_2 + l_2sin\theta_1 \\ sin\theta_2 & 0 & cos\theta_2 & -dsin\theta_2 + l_1 \\ 0 & 0 & 0 & 1 \end{matrix}$$

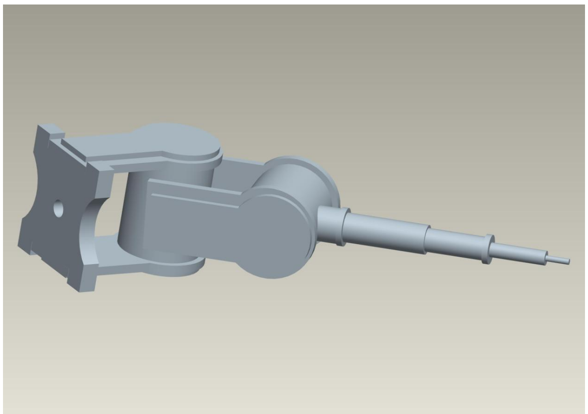
Using the above result forward and inverse kinematic relationships is determined, given below. Using the forward kinematic relations' first derivative approach, manipulator tip's linear speed relation has also been determined. So, the tip positions can be evaluated as,

X=d cos θ_1 sin θ_2 +l_2 cos θ_1

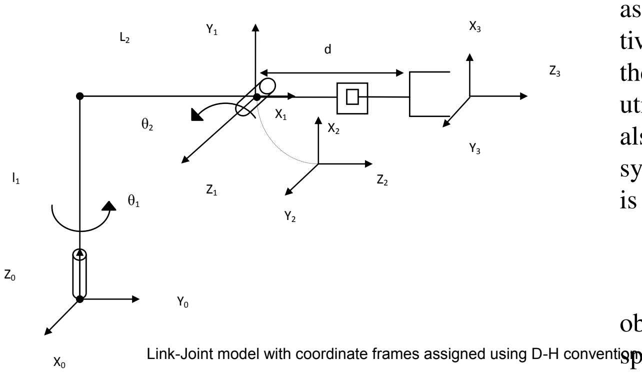
Y=dsin θ_1 sin θ_2+l_2 sin θ_1

Z=-dsin θ_2 + l_1

And corresponding speed can be written as,



(a) Simulation Model of MM3A



(b) Link-Joint model of MM3A

Fig. 3. Modeling of MM3A

$$\dot{X} = \dot{d}cos\theta_1 sin\theta_2 - d\dot{\theta}_1 sin\theta_1 sin\theta_2 + d\dot{\theta}_2 cos\theta_1 cos\theta_2 - l_2\dot{\theta}_1 sin\theta_1$$
$$\dot{Y} = \dot{d}sin\theta_1 sin\theta_2 + d\dot{\theta}_1 cos\theta_1 sin\theta_2 + d\dot{\theta}_2 sin\theta_1 cos\theta_2 + l_2\dot{\theta}_1 cos\theta_1$$
$$\dot{Z} = -\dot{d}sin\theta_2 - d\dot{\theta}_2 cos\theta_2$$

Using the Inverse kinematic relationship the joint variable can be determined as,

$\theta_1 = atan2(Y, X)$
$\theta_2 = atan2((\sqrt{(X^2 + Y^2)} - l_2), (l_1 - Z))$
$d = (l_1 - Z)/cos\theta_2$

IV. Algorithm for End-Effector Position and Speed Tracking

Tracking of the nano-manipulator's tip requires knowledge of the tip coordinate in space. In the present case, image has been captured using a CCD camera mounted on an optical microscope, through MATLAB program. This gives information of a plane only and hence this is essentially a 2 DOF tip tracking. Figure 4 shows the flow chart of the procedure programmed for collision avoidance. Similarly, the image captured has been processed to get manipulator's end effector's speed in X and Y direction respectively. The manipulator tip is planned to remain in a circular region of a predefined threshold radius so as to keep safe distance from object to avoid collision, as long as this condition remains true user can navigate safely. At some moment if other object features in the circular region safety condition is found broken and circle color changes immediately to mark the event and user is accordingly warned to control. In the MATLAB program the average run time of the code is analyzed and time interval between successive frames of images is computed as average time, which is utilized to generate time derivatives. Here under the advantage of structured environment, the shape information and background information has been utilized to achieve customized results for the system. This also is necessary to improve real-time response of the overall system, any generalization of the image processing elements is therefore avoided to reduce computational load.

V. Results and Discussion

Different experiments have been performed to determine object in the vicinity of the tip with planar motion. Due to space constraint only two major results are shown (Figure-5 and 6), where figure 5(a) and 6(a) demonstrate sufficient distance from the cantilever and the tip is marked with a black circle while figure 5(b) and 6(b) depict sufficient vicinity and marked with red circle. All circles are created on the actual picture using MATLAB with two predefined threshold value, one with large margin of collision and other with smaller margin. As the event happens the circle colour changes to catch the visual attention of the user. Accompanying video is available at laboratory's homepage(http://mnaclab.yolasite.com) and can be demonstrated whenever necessary.

Figure 7 describes the trajectory of the tip, which is a part of a large circle. Complete circle cannot be captured using the optical microscope as field of view is limited here.

A. Determination of speed experimentally

In this case the time interval between successive frames has been evaluated in MATLAB, using average time taken information in acquiring successive image frames (10 ms) linear speed of the tip has been found. The shift in x-y coordinates of the tip has been evaluated in images and its time derivative gives speed information. Rotational speed of the joint can be evaluated from the linear speed. Figure 8 and 9 show displacement and speed component in X and Y direction of the tip. During one experiment instance the

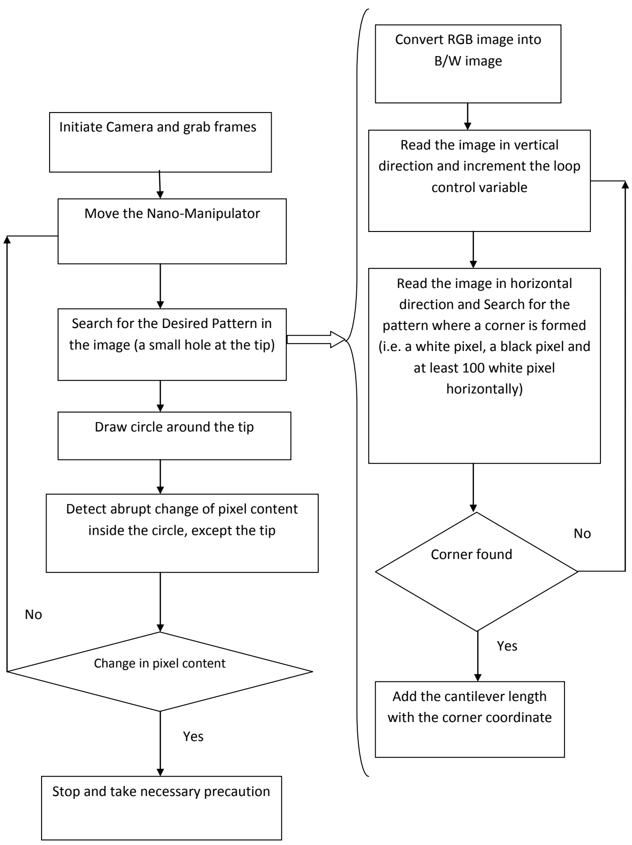
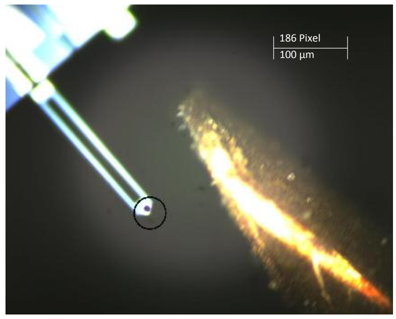
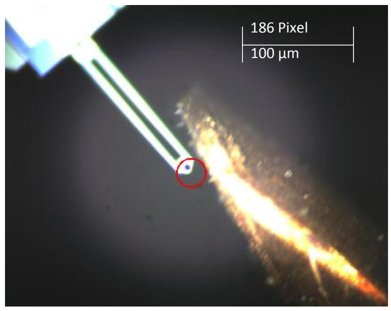


Fig. 4. Flow Chart for Collision Avoidance



(a) Safe operation zone



(b) Collision possibility detected(Marked by color change)

Fig. 5. Operation with small threshold

average speed calculated as X axis = 0.3531 pixel/s, Y axis = 0.3052 pixel/s using the relation 186 pixel = 100 μm, we get velocity components, X axis velocity = 0.18 μm/s and Y axis velocity = 0.16 μm/s

VI. Conclusion

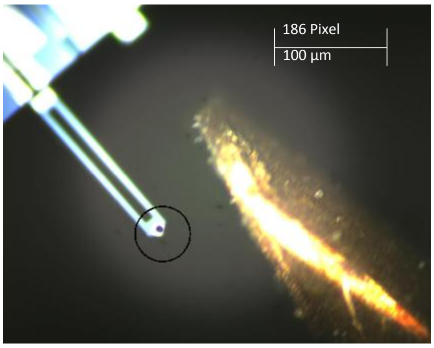
Tip tracking and collision avoidance algorithms are described here and practically implemented on MM3A based nanomanipulator system. It has been shown that it assists user to exercise proper control at right moments. Otherwise, in absence of such aid, one has to keep extraordinary high attention and move with slow speeds even when there is less risk, and one loses attention sometimes when it is very much necessary. In such micro/nano experiments, to judiciously apply sufficient attention, higher speeds and lower speeds of movement the threshold marker and its event notification along with speed information is of very significant help. It improves overall time performance and system safety.

The system's capability in detecting end-effector collision with an object feature in varying image environment is enhanced to great extent; it can be sub-micron or nanometer depending on vision system's capability. This is due to the fact that it reports an event even when one pixel equivalent feature of an object enters in safety marked region.

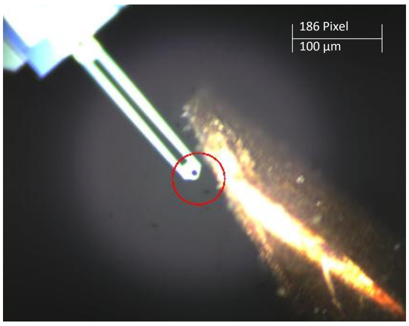
The development presented here would be central and key part in automated controls of micro/ nano manipulating system in micro/nano assembly because controls are required to take image feedback only. The possibility of mounting other sensor on micro/nano part being assembled is remote, at the same time loading manipulator with different sensor, similar to big industrial robots, is also not practical.

Acknowledgment

Authors would like to thank CSIR for funding the research program under Network Project, NWP-30 and CEERI Pilani for creating supporting facilities for the project. Authors also wish to thank Dr. P. Bhanu Prasad, Mr. Suman Barman, Mr. Talebar Singh and Mr. Govind Ram for their valuable discussion and support towards this project.



(a) Safe operation zone



(b) Collision possibility detected(Marked by color change)

Fig. 6. Operation with large threshold

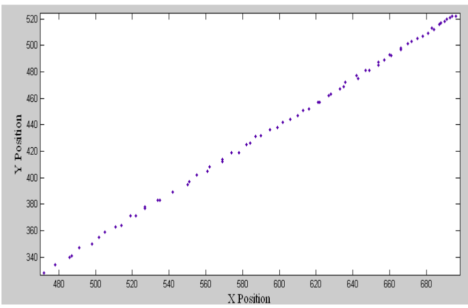


Fig. 7. Tip Trajectory

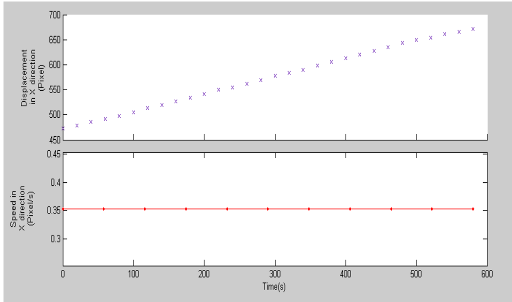


Fig. 8. Displacement and Speed graph of the Tip in X direction

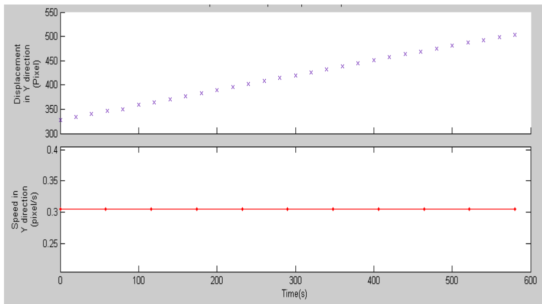


Fig. 9. Displacement and Speed graph of the Tip in Y direction

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