Design of Microassembly Through Process Modeling in Virtual Reality

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ABSTRACT

In this paper we present a virtual reality simulator for the entire construction process of microsystems via microassembly. The simulator can check the feasibility and estimate the yield prior to actual execution. The simulator uses custom developed robotic algorithms to quantitatively identify and track uncertainty propagation in a microassembly process. Planning, control and event handling schemes such as calibration, visual servoing, fault detection etc. are implemented in a realistic manner and can be visualized in virtual 3D in real-time. Furthermore, the scaling effects in sub-millimeter scale that generally causes misalignments due to dominant surface forces are uniquely taken into account in the proposed simulator. The software application, entirely developed in-house, can expedite micromanufacturing by cutting down on the production cycle iterations while ensuring a lower capital investment and guaranteed high yield.

Keywords: automated microassembly, virtual reality simulation, micromanufacturing

1 INTRODUCTION

Microassembly is a relatively new and unexplored field of study in manufacturing of low cost, heterogeneous microsystems which lacks standard frameworks for designing of parts and manipulation cells as well as formalizing control parameters. Considering the huge cost overhead in machining of the microparts, it is not only useful but also imperative that a modular approach with reconfigurable assembly cells be followed in order to put together the complex, heterogeneous microsystems. However, a disadvantage with reconfigurable assembly systems is the issues with low attainable precision. In micro domain, where the precision requirements are very high due to stringent tolerance budgets, selecting the correct configuration of the assembly work cell becomes a key factor in success. In view of the complex nature of a microassembly work cell, where the small volume is often constrained by large number of sensors and robotic stages, reconfiguration iterations employing actual hardware with fairly limited knowledge on the projection of success factor can be very cumbersome and time consuming.

Therefore, in this paper, we propose a simulation environment called *"Microsim"* (figure 1) that can estimate, with high probability, the success rate of a typical microassembly operation for a specific design of the device and configuration of robotic assembler along with planning and control schemes for automation. Unlike standard numerical simulation tools, the proposed application takes microassembly into virtual reality where random events such as lighting conditions, vibration noise and so on impact the assembly in a similar fashion as they would do during actual assembly.

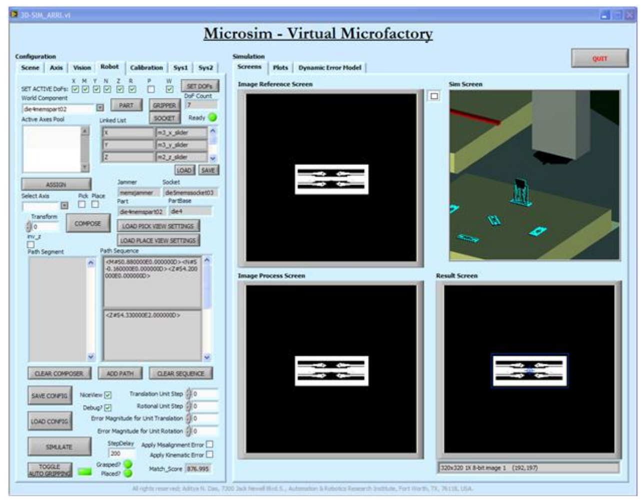

Figure 1: *Microsim* virtual reality simulation interface.

2 VIRTUAL ROBOTICS DEVELOPMENT

The *"Microsim"* simulator implements robotic schemes such as calibration, servoing etc. in virtual 3D as discussed below.

2.1 Virtual Parts, Robot System and Sensors

The virtual components in the simulator such as the microparts, robotic assemblers and feedback sensors are modeled in VRML (virtual reality markup language) format for easy portability among standard 3D modeling software and the *"Microsim"* application. A few of the 3D models are shown in figure 2. The *"Microsim"* application extracts information regarding the robot kinematic chain including the name of the links, hierarchy of the joints, constraints, sensor specifications etc. from the 3D model. System calibration and process automation are carried out with the aid of machine vision executed on the virtual parts. For this a set targeted cameras are attached to the microscope models in the 3D space. Random ambient conditions such as lighting, vibration etc. are modeled in real-time within user specified limits.

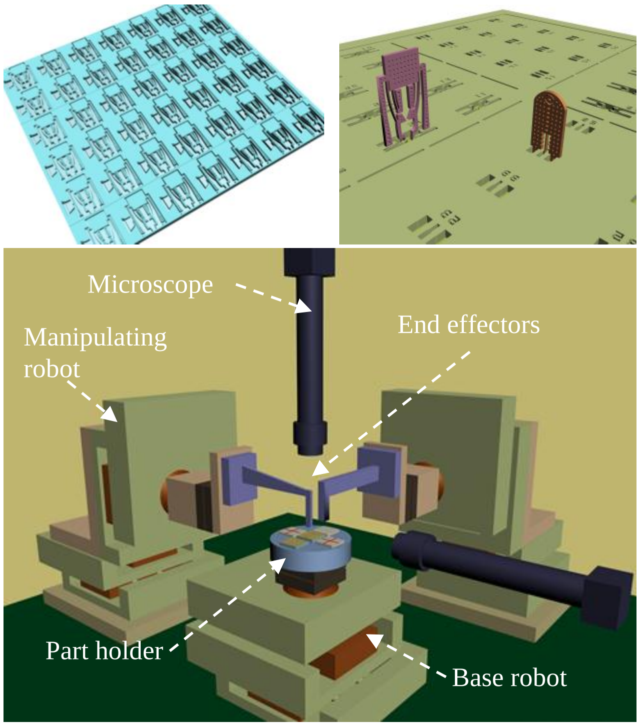

Figure 2: Virtual components: an array of virtual parts (top left); two virtual assemblies (top right); a virtual manipulation system with three robots and two microscopes for feedback (bottom).

2.2 Calibration in virtual 3D

Calibration (or Kinematics Identification) refers to a set of procedures for locating the robot end-effectors in a global coordinate frame. In the simulator we incorporate a simple, but very effective calibration scheme based on linear interpolation of a set of taught fiducials. We consider the un-scaled coordinate frames attached to manipulators, as shown in Figure 2, for calibration.

In this calibration scheme, a unique feature is selected on the part holder (see figure 2). Next the joints of the base robot are moved to multiple values in order to place the feature at several random locations in the field of view. The feature is detected through machine vision pattern matching technique to give the location, in pixels, in the two dimensional image space. From the data, a *Jacobian* matrix between the robot joint space and the microscope image space is calculated using least square linear fit method. This *Jacobian* matrix is later used for active servoing.

The calibration scheme and transformation matrix identification in virtual 3D is shown in figure 3. A typical transformation matrix for the three degrees of freedom base robot (see figure 2) corresponding to x, y shift and rotation β of the feature in the image coordinate system, in pixels, is shown in table 1.

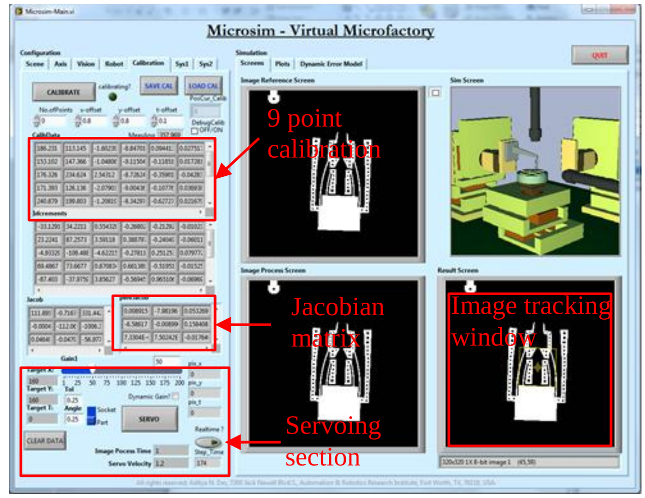

Figure 3: Calibration in virtual 3D

Jacobian	Robot x	Robot y	Robot θ
Image x	112.882	-2.21848	322.636
Image y	0.327998	-112.33	-1008.99
Image β	0.120375	-0.107332	-57.0379

Table 1: Transformation matrix relating 3 degrees of freedom robot space to two dimensional image space.

2.3 Active Servoing in Virtual 3D

Another important aspect of robotic automation for assembly i.e. feedback sensor based active servoing method has been implemented in the *"Microsim"* virtual 3D simulator.

In closed loop control, the micro components are aligned to the desired position in the reference frame by using a Jacobian dynamic visual servoing scheme. The Image Jacobian *'J'* (see table 1) maps the change in 2D image coordinates x, y and orientation β to robot joint angles θ_1, θ_1..., θ_α where *'α'* is the number of robot joints:

$$[\Delta\tilde{x} \quad \Delta\tilde{y} \quad \Delta\tilde{\beta}]^T \cong J\left[\Delta\tilde{\theta}_1 \quad \Delta\tilde{\theta}_2 \quad \cdot \quad \cdot \quad \Delta\tilde{\theta}_\alpha\right]^T . \qquad (1)$$

Using the pseudo-inverse of the *Jacobian* matrix, the *"Microsim"* simulator can servo the virtual robots to desired alignment position in the sensor image coordinate frame through servoing command:

$$\left[\dot{\theta}_1 \quad \dot{\theta}_2 \quad \cdot \quad \cdot \quad \dot{\theta}_\alpha\right]^T = -cJ^+[\tilde{x} \quad \tilde{y} \quad \tilde{\beta}]^T , \qquad (2)$$

where *'c'* is a positive constant which acts as the gain for servoing. $\left[\tilde{x} \quad \tilde{y} \quad \tilde{\beta}\right]^T$ gives the separation vector for the tracked feature in current sensed image data and desired image data. A PD controller is then used for the feedback control to stabilize this separation vector to zero:

$$u(t) = K_P e(t) + K_D \frac{d}{dt} e(t), \qquad (3)$$

where *'e(t)'* is the tracking error given by:

$$e(t) = J^+ [\tilde{x} \quad \tilde{y} \quad \tilde{\beta}]^T . \qquad (4)$$

More details on how the visual servoing control is implemented can be found in [5]. Figure 4 shows the result from an active servoing operation where the virtual micropart has been servoed using equation (2), from a random offset to a target location in the image coordinate system.

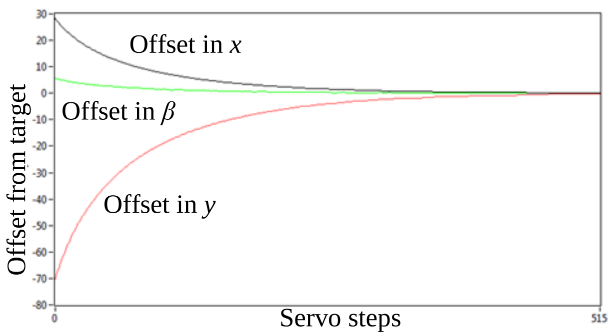

Figure 4: Active servoing results from virtual 3D simulator.

In the virtual 3D, using realistic values for robot speed, this task has been completed in approximately 2 minutes that also includes the time for machine vision.

2.4 Event handling in Virtual 3D

As there are no direct way available in virtual reality to detect physical events such part gripping, snap locking, breaking of part due to misalignment in positioning, slipping of part from the end-effector an so on; the *"Microsim"* simulator depends on vision based detection of events. An additional virtual camera from the side, angled 15^o to the horizontal, enables a near perspective view to part contact. The captured image during process simulation is compared with a ideal case image (see figure 5) and based on a pre-defined tolerance limit, the success or failure in assembly is simulated.

The assembly sequence is automated through a task list of manipulator move steps. Optionally, a debug mode can be activated to look into the sub-steps with more detail.

2.5 Software Development Platform

The *"Microsim"* virtual reality simulation software has been developed using National Instruments® LabVIEW® platform. We also use LabVIEW® for automation of our actual microassembly hardware as shown in figure 6. The simulation application has been written in such as a way that the algorithms for major functionalities can remain same in the actual and virtual assembly automation applications. This enables direct implementation of the simulated microassembly process steps on the real microassembly system.

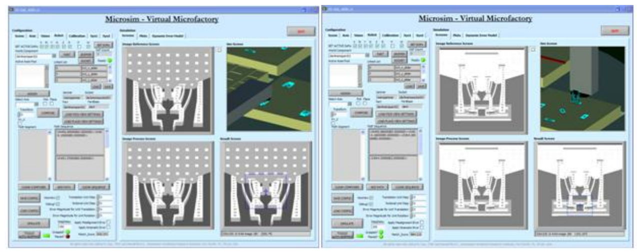

Figure 5: Simulating part gripping (left) and release after snap locking (right).

3 VALIDATION VIA REAL MICROASSEMBLY EXECUTION

In order to validate the *"Microsim"* virtual reality simulation tool, we have used a multiscale assembly and packaging system [1] and a complex heterogeneous micro-optical sensor as case study. The microassembly experimental platform comprises of 20 degrees of freedom which can be arranged in multiple configurations extending up to four individual robotic manipulators (figure 6). The microsystem under evaluation is a wide range spectrum analyzer called microspectrometer [2] (figure 7).

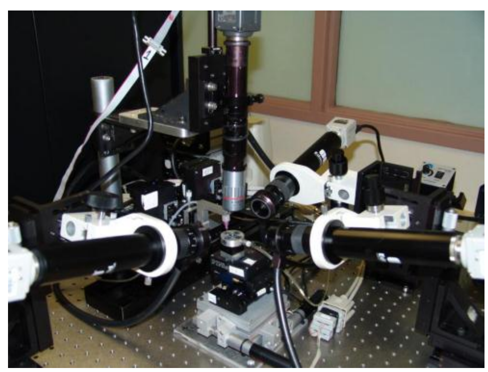

Figure 6: Reconfigurable microassembly work cell.

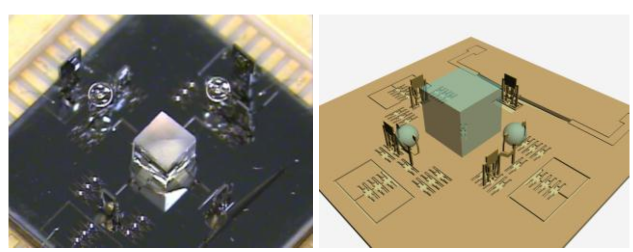

Figure 7: Actual assembled microspectrometer on a 1sqcm die (left); virtual assembled microspectrometer (right).

Based on the mechanical assembly and the optical alignment precision required for each component of the microspectrometer, multiple assembly sequences and assembler motion paths with different control schemes have been tested for 1200 iteration using *"Microsim"* and the results are shown in table 2.

Parameters	**Case 1: Open Loop**	**Case 2: Closed Loop**	**Case 3: Hybrid Control**
Overall yield	10%	99.9%	92.5%
Average time	10 min	80 min	35 min
Sensor count	0	4	2

Table 2: Comparison for 1200 simulated microspectrometer assemblies using different control schemes in virtual 3D.

In order to validate the simulation predictions, actual experimental implementation was carried out using 10 assemblies for each of the three control schemes for the microspectrometer on the microassembly setup shown in figure 6. The results are shown in table 3. As seen in table 3, the results are similar to the simulated microassembly results in the virtual 3D.

Parameters	**Case 1: Open Loop**	**Case 2: Closed Loop**	**Case 3: Hybrid Control**
Overall yield	<1%	90%	85%
Average time	6 min	90 min	40 min
Sensor count	0	4	2

Table 3: Comparison for 30 actual microspectrometer assemblies with 10 each using open loop, closed loop and a hybrid control scheme.

The results had aided in selecting an appropriate assembler configuration and an optimized microassembly process to provide the necessary manufacturing metrics as well as the expected device performance (figure 8). Once high yield assembly plans are successfully simulated using *"Microsim"*, they are ported and executed on the actual assembly cell via custom built automation software. The assembly of the microspectrometer has been carried out using a hybrid control scheme [3] and a precise path search algorithm [4].

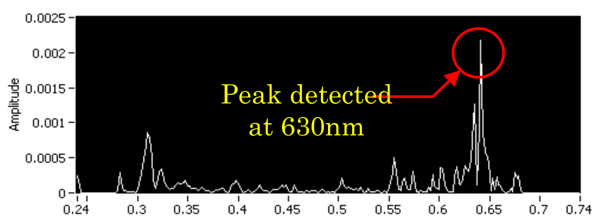

Figure 8: Spectrum detection with microspectrometer for a 635nm source.

4 CONCLUSION

In summary, we exercise a holistic approach towards microscale manufacturing where different aspects of microassembly are evaluated concurrently in custom designed virtual reality simulation software in order to achieve low cost, complex and heterogeneous micromanufacturing. This approach is envisaged towards reducing the time and cost to market a microsystem.

In future, we plan to integrate the *"Microsim"* virtual reality simulator with another uniquely developed software application called *"Design for Micromanufacturability or DfM^2"*, in order to offer a quantitative prediction tool to estimate standard manufacturing metrics such as process yield, cycle time, production cost and device performance.

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