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Millimeter-Scale Microrobots for Wafer-Level Factories

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Abstract— **Current top down manipulation systems used in micro and nanomanufacturing are many orders of magnitude larger than the parts being handled, leading to difficult tradeoffs between their precision, throughput and cost. This paper presents recent research progress in the manufacturing of millimeter sized robotic positioning technology that allows combining high precision with high throughput along with other application-specific requirements such as strength, dexterity, and work volume. The first robot type is the ARRIpede microcrawler, and we describe recent progress in microrobot packaging and backpack electronics leading to its untethered operation. Precision measurements describing the ARRIpede motion resolution and repeatability are reported. The second microrobot called the Articulated Four Axes Microrobot (AFAM) is a 3D dexterous micromanipulator robot, and we describe nanoindentation experiments using SPM tips mounted on the microrobot. By combining positioning data obtained using laser interferometers and SEM imaging of nanoindentation data, precision metrics such as accuracy, repeatability and resolution of the AFAM robot are determined. Using these two microrobots as basic positioning and manipulation units, we propose a concept for a nanoassembly module, or a so-called wafer-level factory.**

I. INTRODUCTION

Microsystems technology (MST) has brought profound possibilities to the future of science and engineering. Over the past two decades, this technology has found applications within various disciplines like biotechnology, medicine, robotics, optics, automotive engineering, space and propulsion, etc [1-3]. The basic premise of MEMS devices manufactured using MST is that they are small, lightweight and can be manufactured at low cost and in large numbers. Perhaps, one of the most significant roles played by MST or MEMS is that of a portal to exploring the exciting world of nanotechnology. For example, micromachined grippers and probes in conjunction with micromachined piezoelectric actuators are invaluable tools used in nanomaterials characterization, nanoassembly, handling and manipulation of biological cells, etc [4-5].

From a production point of view, micromanufacturing can be defined as the miniaturizing of products, some of which take the form of miniaturized production tools and consequently lead to ultra miniature products. This is illustrated in figure 1. Referring to this figure, the most common route (referred to as routes 1, 2 in the figure) employs macro scale production tools in manufacturing MEMS and NEMS. This is one of the popular approaches, as it adapts already existing technology into building useful microsystems. However, these production tools require space and energy comparable to the production of macro scale products. Ideally, the production of microsystems should spin off miniature production tools represented by manufacturing type 3, such as millimeter scale or micron scale positioning and processing systems that lead to cost efficient micromanufacturing shown in the figure as type 4 and nanomanufacturing (type 5) leading to Nano Electro Mechanical Systems (NEMS). However so far, miniaturization of products has not really led to the miniaturization of production equipment.

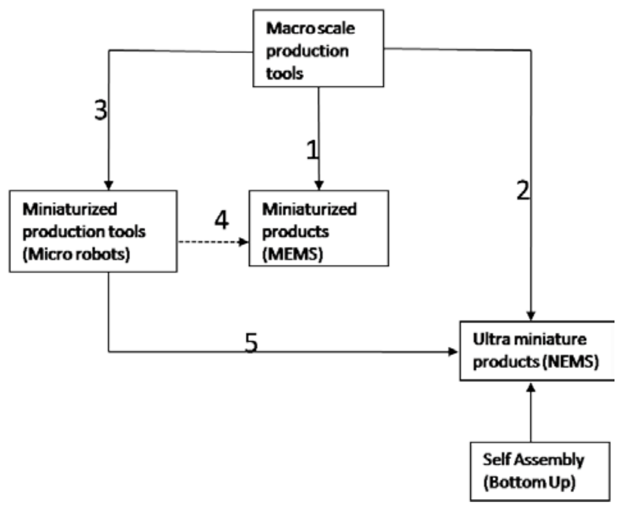

Fig.1. Top Down Micro and Nanomanufacturing; 1,2: Currently used nanomanufacturing technique; 3: Manufacturing microrobots; 4,5: Proposed micro and nanomanufacturing.

Microrobots offer unique advantages while blending into the current top-down nanomanipulation techniques. Some of them can be listed as:

- Enabling simultaneous sensing and manipulation.
- Enable massively parallel nanoprobing, nanoindentation and manipulation.
- Multi-point surface characterization to compensate uncertainties.

The idea of enhancing nanomanipulation capability using multiple robotic systems is being pursued by other research teams [6-8]. In [6,7], the authors present a nanomanipulation system with a large work volume, with 16 DOF's 3-D positioning and orientation control of the end effectors, and which can carry multiple end effectors for complex operations. The authors also present nano device assembly and characterization of CNT's using this system. The focus of the research presented in this paper is to further miniaturize such multiple DOF nanomanipulation systems to range between few hundred microns to a few millimeters, thus enhancing the parallelism and cost efficiency.

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A wafer-level factory is defined as a combination of tools and processes configured to manufacture nanosystems by addressing tradeoffs between throughput, cost, precision and energy consumption. Central to such a factory infrastructure is nanotooling, which creates cooperative interaction between available nanomanufacturing technologies related to processing, manipulation, and sensing while still addressing product specific requirements. This is illustrated in figure 2.

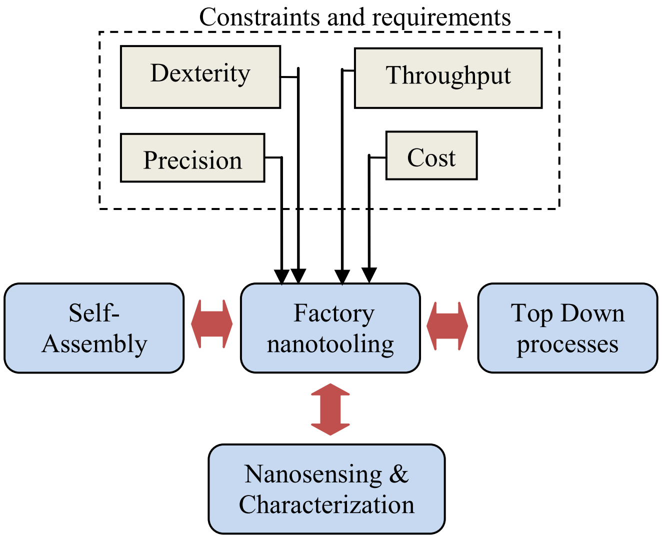

Fig.2. Planning for Hybrid Nanoassembly in the Wafer-level Factory.

Key nanotools in the wafer-level factory are positioning systems and end-effectors that provide the ability of nano objects to be pushed or pulled, bent, twisted, cut, picked and placed, positioned, oriented, and assembled to form the desired nano patterns, structures, devices and systems. A survey of current state-of-the-art in nanomanufacturing shows various tool configurations use Scanning Probe Microscopy (SPM) tools, such as the Atomic Force Microscope (AFM) to accomplish these tasks. These tools can also be used as sensors to determine the state of the parts after manipulation. However the drawback of using these as nanorobots is that they can be cost ineffective and highly serial. At any given time, an AFM tip is either used as a sensor, or as an actuator, thus slowing down the process and introducing switching uncertainties.

The motivation behind our work is to create MEMS based microrobots, and use them in high-throughput wafer-level factories. In this context, we present research progress in the manufacturing of two classes of microrobots- the ARRIpede microcrawler used for mobile part positioning, and the dexterous nanomanipulator called AFAM (Articulated Four Axes Microrobot). We envision that multiple instances of these robots will collaborate inside a nanofactory like scenario to carry out coordinated tasks.

This paper is organized as follows: section II describes the ARRIpede concept and details progress in its packaging required for untethered operation. Section III presents the AFAM concept, and nanoindentation experiments to measure its precision. Section IV discusses a parallel nanoassembly module using the two robots. Finally, section V concludes the paper and discusses future work.

II. ARRIPEDE CONCEPT & IMPLEMENTATION

The ARRIpede consists of an array of prismatic joints on a Silicon substrate. It is capable of planar motions within three degrees of freedom *(XYθ)*, occupies a total volume of 1.5 cm^3, weighs 4.5 g, including its MEMS micromechanical joints and backpack electronics. The micromechanical components are constructed using a combination of conventional lithographical fabrication processes and automated microassembly. The robot exhibits excellent steering ability with 1 DOF designs. The prismatic joints consist of chevron electro-thermal actuators with a microsnap fastener. Silicon legs assembled to these microsnap fasteners move back and forth to create a stick and slip crawling motion. Figure 3 shows the ARRIpede concept. In our recent papers [9, 10], we described the principle of operation, assembly, preliminary power consumption, payload carrying capacity, and control simulations with the microcrawler.

In this paper, we present recent progress in microrobot packaging allowing its untethered operation, and precision measurements of its operation. Packaging was accomplished by designing the backpack electronics to take the form of a PCB stack on top of the MEMS substrate, using custom die and wire bonding operations to form interconnects between PCB and MEMS substrate, and sequencing the micro robot manufacturing operations to overcome some practical limitations imposed by clearance between components.

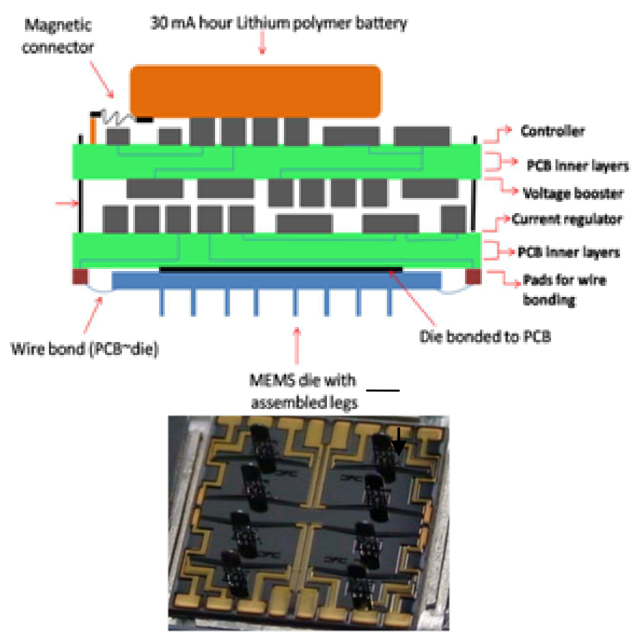

Fig.3. ARRIpede: Top-Microrobot package cross-section; Bottom: MEMS substrate with assembled legs.

The target application of the ARRIpede is mobile part transfer on a wafer level factory, and requires untethered operation with an on-board power source. The power supply module consists of a battery and amplification/regulation circuitry required to drive the actuators. This module is carried in the form of a back-pack. Thus, ARRIpede packaging includes the integration of the micro mechanical module with the electronics module and the battery. This is depicted in figure 3.

The packaging requirements for the ARRIpede include:

- Design of the backpack module to minimize its weight and restrict its volume relative to that of the micro mechanical assembly (substrate and legs).
- Design of electrical interconnects between various electronics modules and between the power module and the MEMS substrate.
- Bonding the MEMS substrate to the backpack electronics.
- Sequencing the packaging process and its integration with microassembly.

A. Backpack Electronics

The power electronic boards described in our previous work [9] consist of a voltage booster circuit, current regulator and the controller circuits as three separate two layered PCB designs. We redesigned these PCB's using four layered PCBs, and the three circuits were placed are now on two stacked dies connected through electrical standoffs. These standoffs act as structural supports, electrical interconnects, as well as thermal sinks for some of the SMD components. The new design forms a backpack that weighs approximately 4g including the battery.

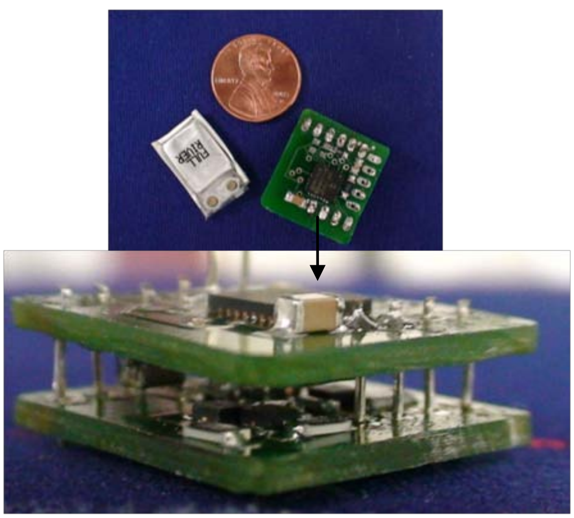

Fig.4. Backpack electronics version 2: Top-PCB stack and Li-Poly battery; Bottom: Power electronics stacked to form a backpack.

B. Manufacturing sequence

The process of assembling and packaging the microrobot involves multiple steps and the steps involved need to be carefully sequenced to incorporate conflicting process requirements. For example, the solder used to attach SMD (surface mount device) components onto PCB reflow at 300^{o}C while the epoxy used for die attach and wire bonding reflow at 150^{o}C. This implies that the backpack power electronics module has to completed and tested before die attach. As a result, microassembly of legs to substrate has to precede attachment of die to the PCB since the components on the top side of the backpack will lead to large tilt of the substrate during microassembly. Thus the micromanufacturing sequence we followed is depicted in Figure 5, and includes: 1. Parallel execution of microassembly and population of PCB's to form the backpack; 2. MEMS die to PCB attach using the packaging station; 3. Forming electrical interconnects between the MEMS actuators and current regulator circuits; 4. Connecting the Li-Polymer battery to the voltage booster and controller circuits.

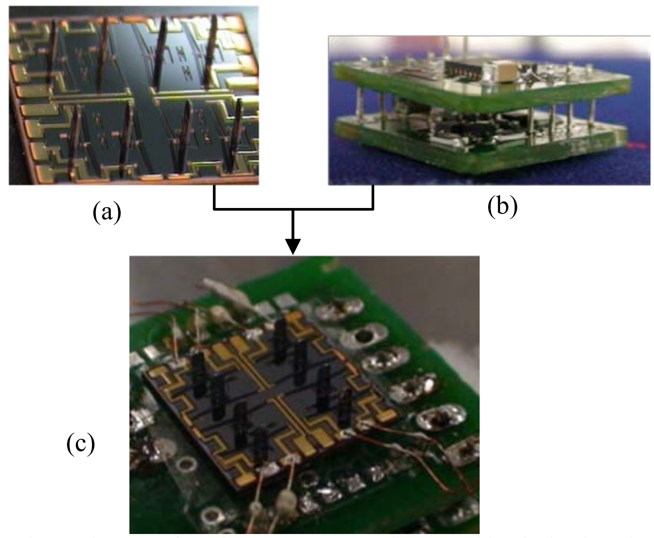

Fig.5. Micromanufacturing sequence: (a) Microassembly of robot legs (b) Power electronics backpack assembly; (c) Wire bonding.

C. Precision Measurements

Following successful manufacturing, the microrobot precision was determined using an interferometer setup shown in figure 6.The precision metrics to be determined included the positioning repeatability of the microcrawler and the actuation resolution of the electrothermal actuators. As shown in figure 6, the precision measurement setup included interferometers measuring the displacement along X and Y. The sensors chosen were Keyence LK-G10 series with a measurement resolution of 10nm and a range of 2mm. The sensors were aligned to reflect light off the ARRIpede legs and thus measured the robot displacement in XYθ as well as the displacement resolution of individual legs. As shown in figure 6, the measured parameters include incremental motion ΔX and ΔY.

In order to record positioning data, the robot actuators were driven to operate between 15 to 1005Hz in steps of 15Hz, and at each step actuated 10 times for 10 seconds. The variance in the actual positions reached indicates the repeatability. Figure 7 shows the variation of the robot repeatability along the X plane of motion. As seen from this repeatability plot, the robot is repeatable within a range of 5μm at 75Hz to around 15μm at 900Hz. We have shown in our past work [9] that a single robot leg step at this frequency is close to 15 microns, while crawling over a Silicon substrate. Thus, while operating close to its thermal bandwidth, the robot is repeatable to within a single step. This finding is very encouraging particularly with the goal to manufacture this robot for nanopositioning applications. Furthermore, the motion resolution of the robot is around 20 nm, close to the measurement resolution of the interferometer setup.

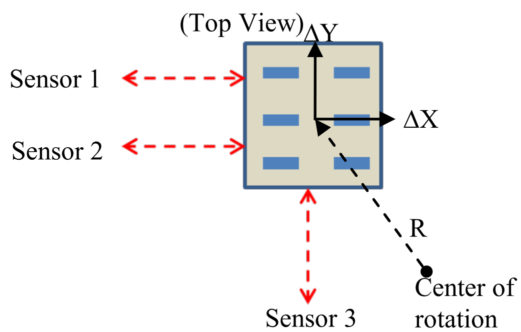

Fig.6. Diagram of the ARRIpede precision measurement setup.

III. AFAM Concept & Implementation

While the ARRIpede is a mobile microrobot, the Articulated Four Axes Microrobot (AFAM), is a fixed base nanomanipulator consisting of an operating work volume of 50μm x 50μm x 75μm with a 2P2R (Prismatic Prismatic Revolute Revolute) kinematic configuration - X, Y, Pitch and Yaw. It occupies 6mm^3 in total volume with room for further down scaling. This design goes beyond other MEMS positioners in categories such as such as range of motion vs. exerted force, and range of motion vs. precision. It is constructed using a combination of hybrid microassembly and high aspect ratio micromachining. Structurally, the first version of the microrobot consists of Silicon 2$^1/_2$D parts and a 30μm diameter Cu wire. The robot joints and attachment of the end effector are accomplished by microassembly using compliant snap-fasteners, monolithic flexure joints, and epoxy glue. Actuation is carried out by two banks of in-plane electrothermal actuators, one coupled through an out of plane compliant socket, and the other one coupled remotely using a 30 μm diameter Cu wire.

In our previous work [11], we have presented details on the microrobot design, fabrication, assembly and preliminary precision measurement using a Veeco® surface profiler. In this paper we characterize its precision metrics including resolution, repeatability and accuracy and application of the microrobot for nano indentation on polymer thin films.

A. AFM Tip Mounting

In order to investigate and demonstrate possible applications of the microrobot in a nanomanipulation scenario, we mounted a Veeco ® DP-10 AFM (Atomic Force Microscope) probe onto the Tool Center Point, as shown in figure 9. The probe is attached to a custom designed micro-fixture designed with a triangular groove that fits the thin arms of the AFM cantilever. Following this, epoxy is dispensed along the groove to bond the probe. The robot TCP ~ fixture assembly is accomplished using a compliant snap fastener.

Using this setup, the AFAM is driven to create nano indents on a 2μm thick Parylene layer. The robot Jacobian described in [11] was used to derive the actuation required for the tip to reach the target locations shown in figure 10. Finally, the indent locations reached by the robot is used to determine the robot accuracy and repeatability.

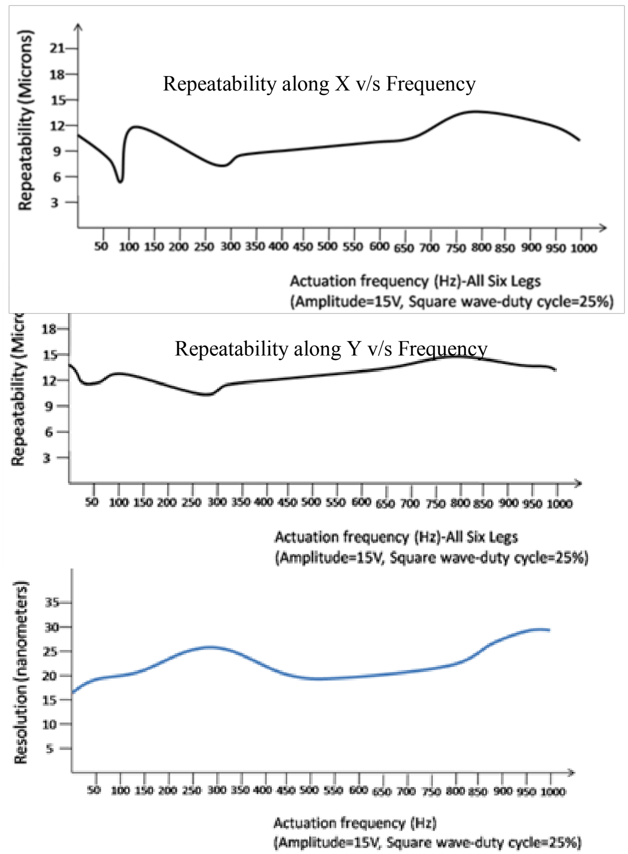

Fig.7. Top- ARRIpede repeatability along X, Middle Y; Bottom- Electrothermal actuator resolution.

B. Accuracy and repeatability

In order to estimate the robot accuracy, the letters "ARRI" are indented and before every indent, the AFM tip is brought back to the same initial condition. Following the indentation operation, the error in the indent location compared to the target locations desired is used to determine the accuracy. In the example shown on figure 10, a total of 27 points are reached. Using this technique, the average accuracy of the microrobot is measured to be around 500nm.

In order to measure the microrobot repeatability, the pattern indented is repeated and the actual positions reached are measured by analyzing the polymer surface inside of a Scanning Electron Microscope. The repeatability is defined as the variance in the actual positions reached. This is a function of the operating point in the robot's workspace. Figure 10 shows the repeatability obtained using the Jacobian along the XY plane of the Polymer.

Referring to figure 10, the measured repeatability indices $\sigma_{cal\_x,,y,z}$ vary as follows:

$$\begin{aligned} 205nm &\geq \sigma_{cal\_x} \geq 100nm, \; 0 \leq x \leq 50\mu m \\ 220nm &\geq \sigma_{cal\_y} \geq 100nm, \; 0 \leq y \leq 50\mu m \quad (3) \\ 210nm &\geq \sigma_{cal\_z} \geq 100nm, \; 0 \leq z \leq 75\mu m \end{aligned}$$

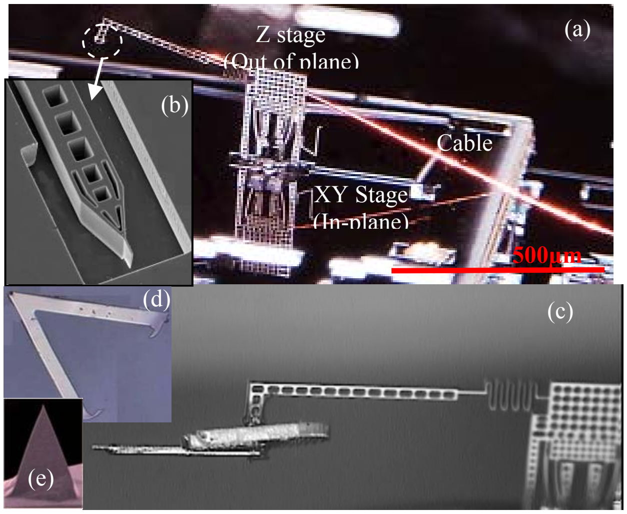

Fig.8. AFM probe mounted onto microrobot using a micro fixture (a) AFAM robot with cable attached; (b) Tool center Point; (c) AFAM with AFM tip mounted; (d) AFM cantilever; (e) 2μm AFM tip

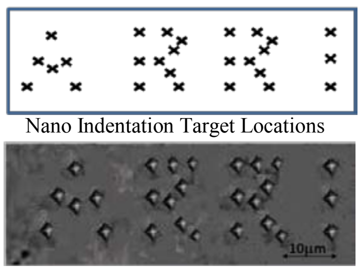

Fig.9. Nanoindentation using AFAM

C. Resolution

The AFAM resolution is determined using a laser interferometer setup similar to that described in section III and as shown in figure 11. In this particular case, figure 11 described pitch measurement. Using the Jacobian described in [11], the electrothermal actuators associated with causing pitch motion are actuated until the Keyence LK-G10 laser interferometers detect minimum motion. This voltage varied nonlinearly with pitch actuation and varied between 0.01V at the center of the work volume to 0.03V upon reaching extreme points in the 3D envelope. Using this setup, the measured resolution is summarized as follows:

$$110nm \geq \sigma_{res\_x} \geq 50nm,\ 0 \leq x \leq 50\mu m$$
$$105nm \geq \sigma_{res\_y} \geq 52nm,\ 0 \leq y \leq 50\mu m \qquad (4)$$
$$0.035^o \geq \sigma_{res\_\phi,\psi} \geq 0.018^o,\ 0 \leq \phi,\psi \leq 9^o$$

These measurements represent conservative estimates of the microrobot resolution limited by the Keyence sensor resolution (10nm + noise). In fact, the motion resolution of the AFAM is expected to be below 10nm, which corresponds to the reported resolution of thermal MEMS devices.

The electrothermal actuators used in the AFAM can be represented by a first order transfer function [13] with a typical thermal bandwidth of 50Hz. This leads to expected displacements of about 14.6μm of pitch/yaw motion at 500Hz (taking into account displacement amplification at the Z stage), and ignoring the harmonic response of the mechanical structure Future work will investigate the dynamic response of the AFAM.

IV. Parallel Nanoassembly Module Using Multiple AFAM and ARRIPDEDE Microrobots

The wafer-level factory concept proposed in this paper consists of multiple nanomanipulation modules connected via parts transfer using ARRIpede microcrawlers.

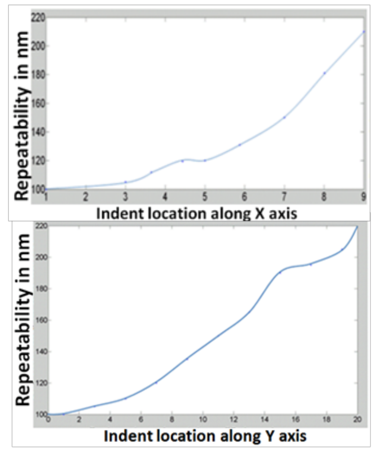

Fig. 10. AFAM repeatability along polymer XY plane

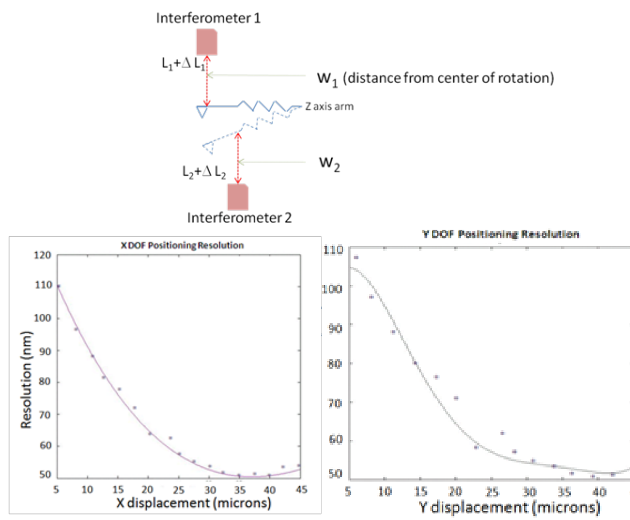

Fig.11. AFAM resolution measurements

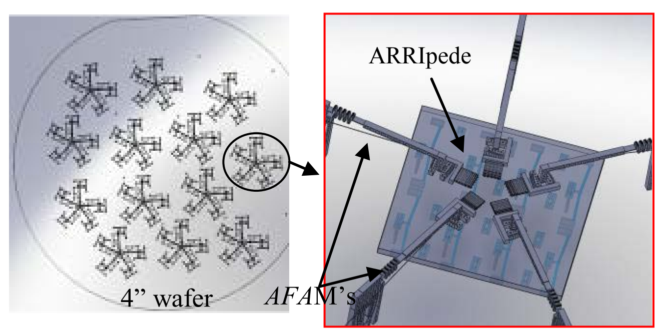

Fig.12. Left: Nanofactory on a 4" wafer; Right: Nanoassembly module

Each manipulation module consists of multiple AFAM micro robots with AFM probe tips attached as end-effectors, illustrated in figure 12. Each nanomanipulation module consists of scanning and manipulation sub modules, as detailed in table 1, overcoming inefficiencies due to the current use of a single AFM probe for both sensing and manipulation.

A given task can be distributed amongst all modules available or within a sub group. We envision that most of the time, the nanomanipulation modules will operate in calibrated open loop mode. The microrobot Jacobians will be used to repeatedly drive the probes through a pre-detetermined trajectory. The elimination of closed loop control decreases cycle time and results in increased throughput. This trajectory varies from between robots belonging to the same module and between different modules. The trajectories are product specific and include the inter play between manipulation and processing. For example, one module could be assigned the task of nanotube bending, which requires fixturing the nanotubes using probes and impinging a suitable gas (such as Oxygen) at the specific bend location.

Table 1: Nano factory scanning and manipulation attributes

Operation	Scanning	Manipulation
Technique	SPM, SEM	Probing using MEMS robots + SPM
Control	Closed loop (SPM)	Hybrid (open+closed) Open loop using micro robot repeatability or closed loop using SPM tip)
Bandwidth	High	Low
Frequency of tool usage	Intermittent between manipulation steps	Continuous
Sensory	Laser, Electron Beam/ Tunneling current for TEM	Force sensor (designed with microrobot for in-situ sensing)

The operation of the nanomanipulation module is modeled as a stochastic process. Scanning modules which consist of high resolution scanning using SPM or imaging using SEM, monitor the state of the nano parts/assemblies before transfer between consecutive modules. Thus, the factory is housed within a typical SPM/SEM station. Due to the fact that the nano manipulation modules are not actively controlled, the scanning task also gives information on the yield of the preceding process. The availability of closed loop manipulation using the scanning module is employed as a secondary manipulation process when necessary.

Based on the precision data outlined in the previous sections, a typical nanoassembly module occupying a volume of $30mm^3$ can be specified to consist of an almost cylindrical work volume with cylinder diameter given by 100 microns and a height of 75 microns. The module can be configured to consist of 5 AFAM's and 1 ARRIpede with a total of 23 degrees of freedom.

V. Conclusions and Future Work

Based on precision experiments presented in this paper, we can conclude that the ARRIpede and AFAM micro robots can be used as nanopositioning modules in a Wafer-Level Factory. The AFAM has a measured repeatability (in open loop operation) ranging between 100nm~200nm, and a positioning resolution smaller than 50nm, and therefore, can be used for 4DOF dexterous manipulation and assembly at the nano scale. These specifications are conservative estimates limited by the measurement technique adopted.

Future work includes using higher resolution interferometers and the SEM to characterize the actual robot precision metrics. Due to its force output capacity of 100mN at the end-effector (TCP), it can also be configured to carry various types of nano grippers or sensors. Future work also includes a complete frequency analysis of the microrobots to determine optimal frequencies of operation.

The ARRIpede microcrawler, has an untethered motion repeatability of 6~12μm, and a resolution of 20nm along the direction of motion, complements the use of the AFAM as a nano-mobile stage. The micromanufacturing plan presented in section III is important to realizing untethered operation of the crawler, and can be modified and extended to accomplish other MEMS based microrobot.

We envision that in the future, multiple instances of such robots can be housed within a common "Wafer-level Factory". Future work includes further refining the microrobot designs, demonstration of cooperative manipulation of nano parts and synchronized operation of these robots within a SEM/AFM system.

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