5th Int'l Symp. on Microfactories
Besançon, France, October 25-27, 2006.

Vision Guided Pick and Place in a Minifactory Environment

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***Abstract*— We describe new end effector developments incorporating microscope vision and gripping mechanisms for pick and place assembly of small components in a minifactory environment. Instead of performing microassembly under a microscope, in minifactory each assembly agent is equipped with its own microscope. This arrangement facilitates flow-through manufacturing as opposed to work cell approaches. To this end, we have developed a series of new manipulator end effectors, each of which incorporates a long-range objective lens, coaxial illumination, folded optics, and a camera. Modular gripping and other mechanisms are mounted on a universal plate beneath the end effector. A first type uses vacuum and pressure to pick and place components of a lens assembly. A second type incorporates an off-the-shelf tweezer with electromagnetic actuation. The third type incorporates a novel rotation mechanism and MEMS-based gripper which can pick a part from a wafer, rotate it through an angle, and snap the part into a receptacle on a second wafer.**

I. Introduction

Minifactory, which is the physical instantiation of the Carnegie Mellon University Agile Assembly Architecture[1], is a highly modular agent-based system for microassembly. Assembly operations are carried out through cooperative actions between robotic *courier agents* and *manipulator agents*. Courier agents carry products through the minifactory and are based on closed-loop planar motors with speeds of 1.5 m/s and motion resolutions of 200 nm (1σ). Manipulator agents move vertically and in rotation to pick and place parts on products carried by the courier agents under vision and force guidance [1], [2], [3]. Figure 1 shows part of the modular minifactory system under development in our laboratory. The collection of robotic agents in a minifactory is supported by a service infrastructure comprised of a collection of modular base units, platen tiles, and bridges. The system is designed from the outset to enable rapid deployment.

II. Manipulator Agent End effector Design

There are currently four z, θ manipulators in our laboratory minifactory, each with 5 μm vertical resolution, and about 0.0002° (1σ) angular resolution (0.38 μm at the gripper on a 100 mm radius arm) [4]. We have equipped each of these manipulators with microscopes and several different parts gripping facilities (subject of this paper).

[1]Agile Assembly Architecture:
`http://www.msl.ri.cmu.edu/projects/minifactory`.

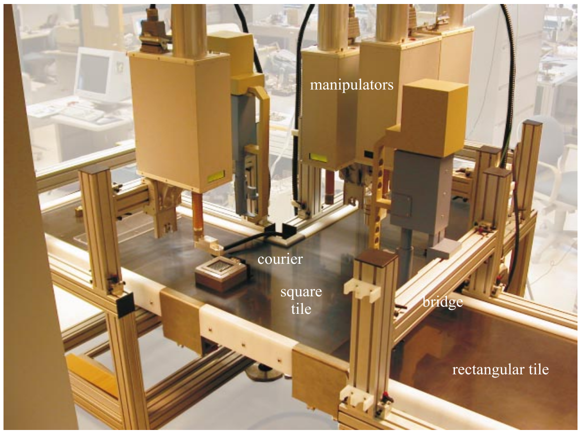
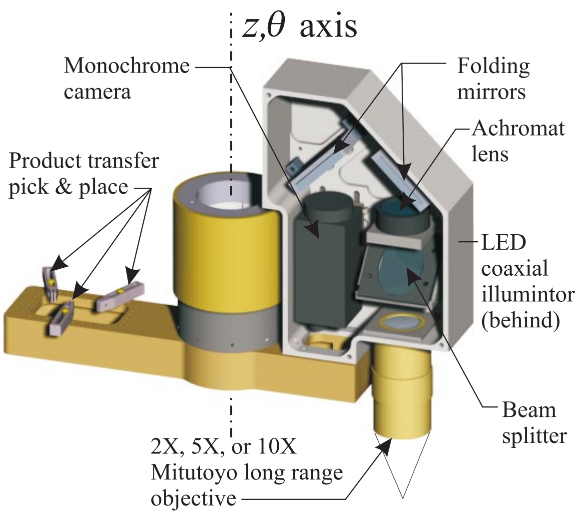


Fig. 1. Photograph of a section of our laboratory minifactory.

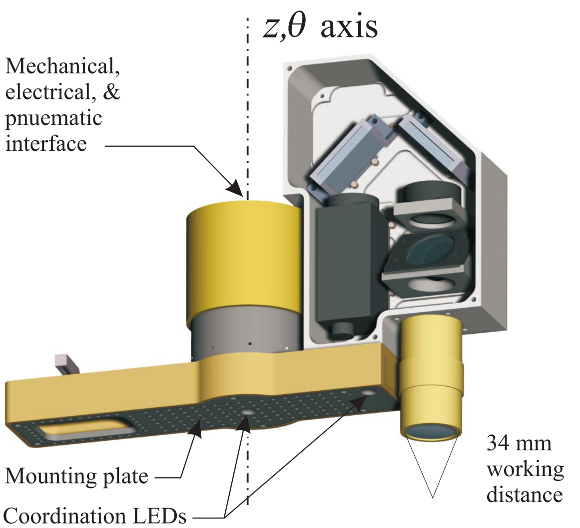
Figures 2(a) and 2(b) show the design, which incorporates a long range objective lens, LED-based coaxial illuminator, achromat focusing lens and folded optics. The end effector mounts on the manipulator vertical axis by a specially designed connector that provides a kinematic mechanical interface, 30 electrical connections, and 6 pneumatic ports. A drilled and tapped mounting plate provides a versatile surface for mounting grippers and other tooling. Several clamps at the rear of the end effector can be used to hold vacuum pickup tubes for picking a product from one courier agent and placing it on another. The entire end effector is supported against gravity by a novel vacuum counterbalance servo in the manipulator [4]. Finally, flashing LEDs in the end effector serve as locating beacons for courier agents which are equipped with *coordination sensors* based on position sensing photodiodes. The coordination sensors have a position resolution of 150 nm (1σ) [5]. This feature enables couriers to precisely locate manipulators to perform 4-degree-of-freedom (DOF) assembly operations.

III. Vacuum/Pressure Pick and Place of Lens Components

One application of the new end effectors is the picking and placing of lens components in a tight-fitting housing. The components include several lenses, spacer rings and screw rings. For each of these components, there is a special "tool" whose bottom side mates with the part and whose top side



(a)



(b)

Fig. 2. CAD model of developed microscope end effectors: (a) upper view showing internal parts, (b) lower view showing electromechanical interface, mounting plate, and coordination LEDs.

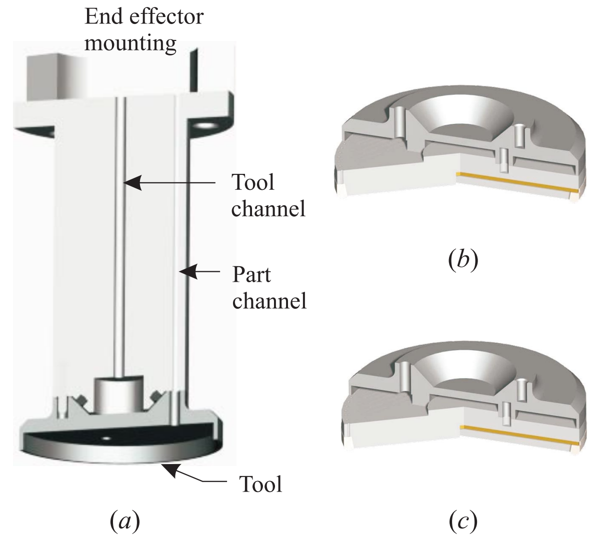


Fig. 3. Vacuum/pressure pick and place: (a) effector design, (b) tool and lens, (c) tool and ring.

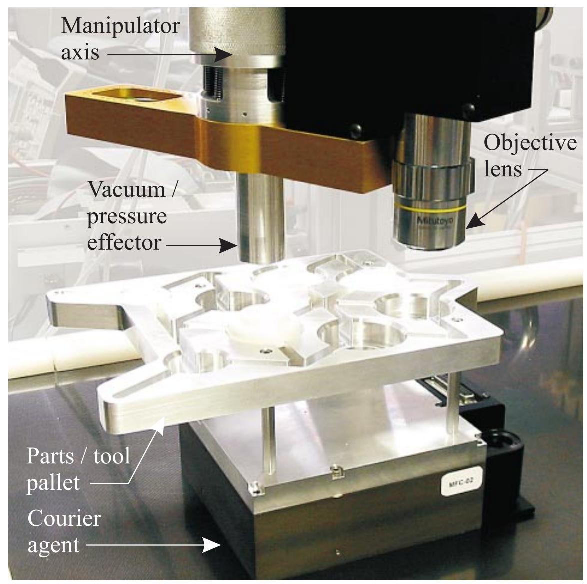


Fig. 4. Parts for an optical assembly, along with associated tools, are carried on a pallet by a courier agent.

mates with a pick/place effector. Figure 3(a) shows the effector design. One pneumatic channel leads to the tool, while a second channel passes through the tool to the part. Using vacuum in both channels, a manipulator can pick up both the tool and the part. Lens and ring parts and mating tools are shown in Figs. 3(b) and 3(c). During part placement, the part channel is switched from vacuum to pressure to release the part. Likewise, after part placement, the tool can also be released at an appropriate location. Tools and parts are stored in nests in a pallet carried by a courier agent as shown in Fig. 4. We chose to place the pick/place effector on the manipulator vertical axis to help facilitate screwing in of threaded ring parts. Thus the microscope field of view is displaced from the effector by about 100 mm, making it necessary to perform blind moves by the courier. Accuracy requirements in this case were relatively modest, making this approach feasible.

IV. Voice-Coil Actuated Tweezers

Small grippers such as MEMS-based microgrippers tend to be fragile and easily damaged. Bailar, Kast and Jones at Sandia National Laboratories have shown that commercially-available non-magnetic tweezers can be used successfully for pick and place of objects such as metal spheres as small as 30 μm in diameter [6]. A big advantage is the fact that a tweezer with bent or misaligned tips can be easily replaced. Their system uses a small model airplane servo and linkage to actuate the tweezers.

We have adopted this approach for the new microscope end effectors. In contrast to the existing approach, we operate the

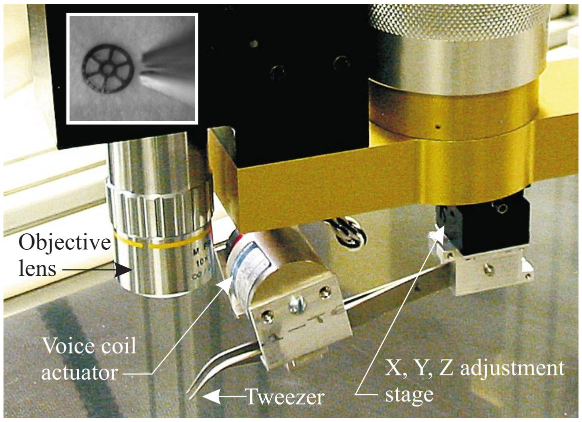


Fig. 5. Minifactory end effector with voice-coil actuated tweezers. Inset: 500 μm LIGA gear and tweezer tips.

tweezers by a small voice coil actuator. The actuator's magnet assembly is attached to one arm of the tweezers and the voice coil is attached to the other. This enables the tweezer arms to move symmetrically at the center of the microscope's field without any friction. Additionally, once the tips are closed on a rigid object, the tweezer gripping force is simply proportional to coil current, making control straightforward.

V. 5TH AXIS ROTATION MECHANISM FOR ASSEMBLING 3D MEMS

Microassembly of MEMS devices has been traditionally done using microgrippers or passive end effectors. Microgrippers typically consist of two opposing arms that either open or close upon actuation, and have been fabricated using techniques such as micro-electro-discharge machining [7], surface [8], and bulk [9] micromachining. The structural fragility, increased packaging complexity, and uncertainties due to variations in actuator displacements tend to limit the practical usefulness of these microgrippers in MEMS assembly. In contrast, Zyvex Corporation has pioneered the use of passive "jammers" to facilitate assembly of MEMS parts with specially designed connectors into mating sockets to create 3D assemblies [10]. The passive jammer design has an in-plane stiffness that is 3 orders of magnitude higher than microgrippers fabricated in the same technology, while out-of-plane stiffness is increased by 2 orders of magnitude. Our most recent implementation makes use of a jammer fabricated using the CMOS-MEMS process [11], incorporating piezoresistors for force feedback.

A library of connectors, sockets and jammers has been developed. A typical assembly procedure is illustrated in Fig. 6. Parts are fabricated and undercut, leaving support from fragile tethers. The jammer is inserted into the compliant handle of the part and pushed towards the tether until it fractures, completely releasing the part from the wafer. The part can then be lifted vertically from the wafer, rotated through 90°, and inserted into the receptacle opening of a socket until its feet snap into the locking notch. A typical microassembled system produced in the Zyvex Membler system is shown in Fig. 7. The Membler

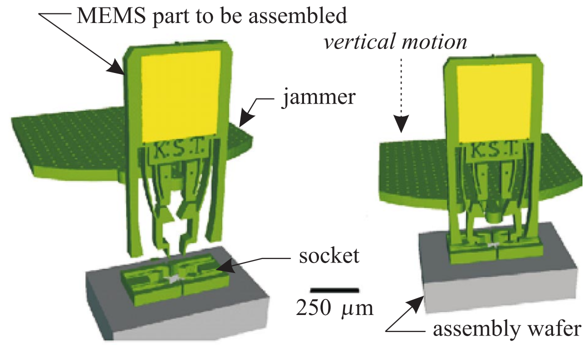


Fig. 6. MEMS jammer and socket configuration during assembly.

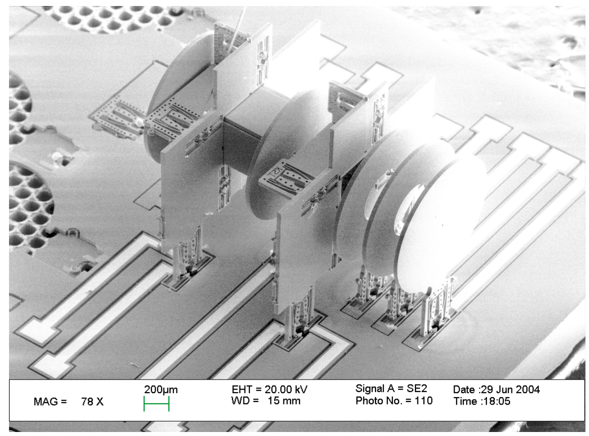


Fig. 7. 3D MEMS assembly produced in the Zyvex Membler system.

is a configuration of highly accurate commercial motion stages [10].

Wheras the Membler works well for prototyping, it is much less suitable for production. Accordingly, at Carnegie Mellon University we are (1) developing CMOS-MEMS jammers with integrated force sensors, and (2) augmenting our 4-DOF minifactory system with an optional 5th DOF, to enable MEMS parts to be detached from a "parts" wafer carried by a courier agent, rotated 90° out of the wafer planes and assembled into a "product" wafer carried by a second courier agent. This arrangement facilitates the flow-through manufacturing approach of minifactory, as opposed to the more traditional work cell methods for microassembly. The assembly operations will be carried out under vision and force guidance rather than depending on absolute motion accuracy as in the Membler.

Figure 8 is a photograph of the developed minifactory end effector mechanism for picking and placing Zyvex-style MEMS parts. The (virtual) horizontal rotation axis of the device is located approximately 12.5 mm above the wafer planes, allowing a courier agent carrying a wafer sufficient clearance to position itself arbitrarily under the mechanism. Controlled rotation of $\pm 47.5°$ is achieved by a friction capstan rolling on a precision arc-shaped guideway, driven by a small gear motor with incremental encoder. Rotational resolution

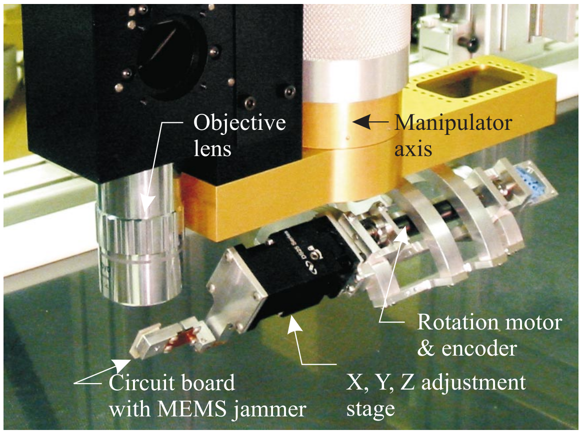


Fig. 8. Minifactory 5th axis mechanism for 3D MEMS assembly.

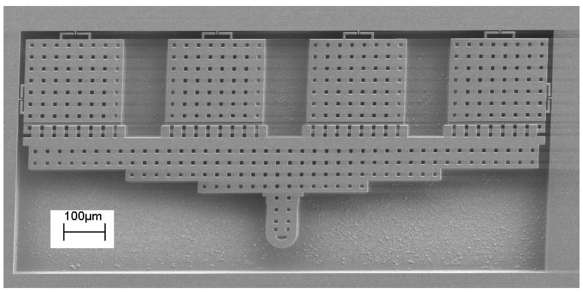


Fig. 9. CMOS-MEMS jammer with integrated piezoresistive force sensing.

is approximately 0.09° and speed is approximately 15°/s. A small manual 3-axis translation stage and small angular adjustment features attached to the rotating member give the ability to fix the MEMS jammer near the center of the microscope's field of view in focus approximately 34 mm below the objective lens.

The single crystal silicon jammers used previously have no force sensing. In the new CMOS-MEMS implementation shown in Fig. 9, a piezoresistive half-bridge is integrated in areas of high stress and low stress concentrations to detect out-of-plane forces. FEM analysis was used to determine the stress distribution with an applied load at the tip of the jammer. An off-board balanced modulation-demodulation scheme outputs voltages of approximately 0.1 V per micron of deflection with a noise level corresponding to less than 100 nm.

VI. Discussion

To date, four of the new end effectors with microscope optics and cameras have been designed, built, and tested. All three of the pick and place gripping mechanisms have been designed, built, and are currently being tested . These are i) vacuum/pressure gripping of precision optical components, ii) electrodynamic actuation of off-the-shelf tweezers for gripping of small metal parts, and iii) a 5th-axis rotation mechanism and CMOS-MEMS jammers with integrated force sensing for 3D MEMS assembly. We are now beginning a series of experiments with detailed measurements to evaluate their efficacy. For example, future work will include development and evaluation of a number of real time vision algorithms and visual servoing techniques. Future work will also explore force-servoing techniques with the new MEMS jammers. We believe the end effector and gripping mechanisms described in this paper will greatly expand the range of applications accessible to minifactory and other approaches to flow-through precision manufacturing.

Acknowledgment

The authors gratefully acknowledge the efforts of Cornelius Niemeyer, Mark Dzmura, Mike Cozza, Christoph Bergler, Zoran Jandric, and Kenneth Tsui. This work was supported in part by research contracts from Sandia National Laboratories, Zyvex Corporation NIST/ATP, and the Pennsylvania State University Electro-optics Center.

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