Miniature Factories: Tabletop Assembly Systems for Mechatronic Products

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Abstract

This paper discusses the need to go beyond individual demonstrations of sensor-based micromanipulation and to look forward to providing flexible automation for microassembly of complete products. For the past several years we have been developing an architecture for tabletop precision assembly systems. The goal of our work is to improve the design, deployment, and reconfiguration of automated assembly systems for small, high-value products requiring high precision. Design and construction of a prototype miniature factory according to our "Agile Assembly Architecture" is underway to validate the research and provide a unique and powerful reconfigurable platform for assembly research and evaluation by industry. We are currently operating our prototype with 1σ motion resolutions of 200 nm. As an application example, a "virtual" minifactory for assembling small electret microphones is presented. We are working toward the goal of providing "real" minifactories for assembling real products in the future. We anticipate that some of the methods currently under development by the micromanipulation community, e.g. MEMS grippers and sensors, can be incorporated into future minifactory systems. The results could allow manufacturers to have the capability for developing distributed microassembly systems with drastically reduced deployment times, higher quality, and a new level of manufacturing system portability.

Introduction

In recent years there has been an explosion of interest in Micro Electro Mechanical Systems (MEMS), because of the new capabilities it offers, and because it embodies batch fabrication methods that include the novel prospect of integrated or self-assembly—not unlike the intricate hand-carved artifacts of gifted craftsmen where complex, beautiful, and interlocking parts are fashioned "all together" out of single chunks of ivory or wood.

As wonderful as this may be, and as important as are its potential economic benefits, the MEMS of today falls short of what is desired, chiefly because (1) it does not embrace assemblies of differing materials, and (2) it lacks effective ways of reaching up into the 3rd dimension. Achieving these goals generally requires some good old-fashioned assembly. We assume that there is (and will be) a need for micro-manipulating individual and/or large groups of very small parts for the purpose of assembling small products.

Loosely speaking, there are two principal problems to be dealt with. First is the problem of precisely aligning parts to be mated, no matter what their size may be. The second is that of picking up and placing parts whose small size presents great difficulties. Our earlier work emphasized flexible sensor-based robotic fine positioning in the high sub-micron regime for assembly and testing [1] and the synthesis of compliances for delicate accommodation tasks [2].

More recently, attention has focussed on the problem of grasping and releasing small parts, where electrostatic forces, surface tension, and Van der Waals forces dominate. For a comprehensive discussion of sticking effects for small parts, see [3]. Arai *et al.* [4], for example, have developed micro end effectors for micromanipulation in which arrays of micro pyramids are employed to reduce adhesive force effects. They have integrated piezoresistive strain elements into the grippers. Very small grippers using piezoelectric and magnetic actuation have been designed [5]. Micro-grippers based on shape memory alloys and guided by computer vision techniques have been recently discussed [6]. Small parts gripping end effectors based on thermally generated pressure and vacuum have been created [7].

Going down in scale, exploration of atomic scale surfaces [8] by teleoperation and telemanipulation of materials at nanometer scales [9] have recently been achieved, but it is difficult to imagine this sort of manipulation competing with automated assembly, if that could somehow be robustly achieved. Scaling issues for micro robots have been discussed by Shimoyama [10].

Recently, more attention has been placed on the overall requirements for the *automation* of micro assembly processes [11]. A product may have one or more interfaces to its environment, such as electrical, optical, fluidic, or mechanical contacts. It may need to be assembled in a hybrid build-up process involving several
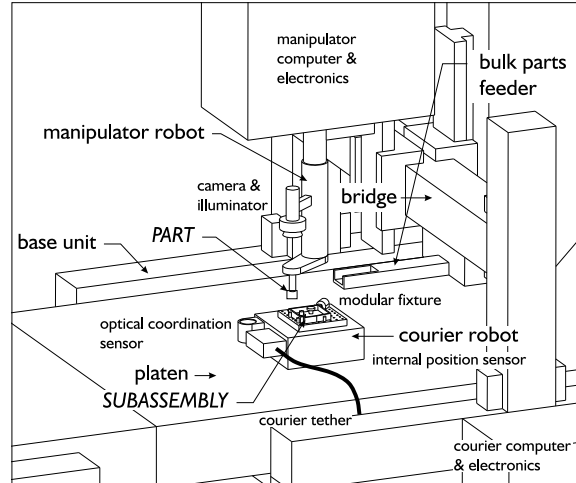
Figure 1: Principal minifactory components.

different materials and several disparate manufacturing processes. There may be many reasons for the assembly of the product to be automated, including component dimensions too small to be effectively handled by people, the need for extremely high alignment accuracies between components, contamination by human operators, and the inability of human operators to focus on the micro-assembly task for long periods due to exhaustion. Finally, there may be clear economic benefits in terms of rapid market response if the automation can be accomplished in a highly flexible way.

It would seem that the integration of force and vision feedback in microassembly is of paramount importance. Nelson *et al.* [12] have demonstrated vision and optical beam deflection techniques to provide nanonewton-level force feedback and nanometer-level position feedback. They have successfully manipulated small glass fibers with this technique and project that complex hybrid MEMS devices will require new approaches to the automation of microassembly processes. Feddema *et al.* [13] have investigated the automated assembly of LIGA parts from their CAD drawings under vision control. They have constructed a work cell with a 4-DOF AdeptOne coarse robot, fixed 4-DOF precision motion stage, thermally-actuated micro-tweezers fabricated from high aspect ratio molded polysilicon, and a long distance microscope with computer vision. Small LIGA gears were placed on axle posts using visual servoing.

It seems clear that progress is being made toward automated assembly of fairly complicated MEMS-like devices. The ability to individually assemble these kinds of products is, however, still a long way from achieving viable automation, since a great deal of flexibility and product flow remains to be integrated. It will not be very effective, for example, to have operators load and unload individual parts and assemblies to and from tiny automated assembly stations.

Recently, there have been efforts to integrate parts flow into MEMS-scale assembly. For example, arrays of magnetic actuators have been developed to form tiny bi-directional conveyor belts [14]. Arrays of thermally-activated bimorph structures have been used to translate and rotate small objects [15]. Developments along these lines seem very promising.

Minifactory

It is hoped that the foregoing will suffice as introduction to an ongoing project in the Microdynamic Systems Laboratory* at Carnegie Mellon University. For the past several years, we have been developing an "Agile Assembly Architecture" (AAA) [16, 17, 18] and a modular tabletop precision assembly system "minifactory" [19, 20] for the assembly of small mechatronic products.

The principal components that form a minifactory are shown in Fig. 1. The factory floor, comprised of abutting precision platen tiles supported by base units, forms the stator for multiple planar linear motors gliding above it on air bearings, and also serves as a precision position reference grid. Planar linear motor *courier* robots [21], incorporating a precision 3-DOF ac magnetic position/angle sensor [22], a precision optical coordination sensor, and a modular fixture, are responsible for carrying product subassemblies through the factory, and for cooperative precision assembly operations. Each courier operating in the factory is attached by flexible tethers to its own computer and electronics.

To affect a 4-DOF assembly operation, couriers interact with vertical translation and rotation 2-DOF *overhead manipulators* that pick parts from nearby *parts feeders*. The overhead manipulators have interchangeable modular end effectors, some of which have built-in cameras and illuminators. All end effectors have force/torque sensing capability. The overhead manipulators and other forms of *overhead processors*
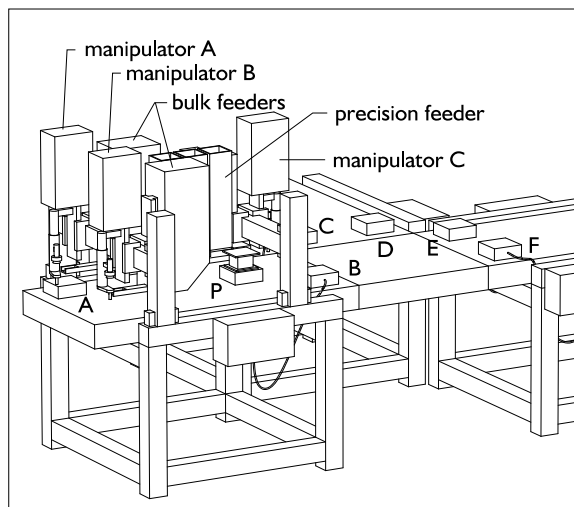
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*http://www.cs.cmu.edu/~msl.

Figure 2: Typical minifactory layout.

such as screw drivers, lasers, orbital head formers, welders, gluers and the like are clamped anywhere along the structural bridges. Each overhead device can be manually adjusted in height. The horizontal bridge beam can also be adjusted in height, and can be manually positioned anywhere along the base unit. Like the couriers, each overhead manipulator or overhead processor has its own computer and electronics.

Each active piece of manufacturing equipment in a minifactory is referred to as an *agent*. Agents are mechanically, electrically, and algorithmically modular, and are interconnected by modular service buses which provide power, air, vacuum, and network connections.

The design of truly flexible parts feeding agents remains a difficult research topic. We are considering two main types of feeders. The first is *bulk parts feeding*, suitable for low-cost parts that can be jumbled together in bins. The second is *precision parts feeding*, suitable for more delicate and costly parts. A precision parts feeder consists of a courier which services a set of parts magazines. Each part magazine is a column containing a stack of trays, with each tray containing oriented and located parts. The parts-feeding courier drives under a column which it believes contains parts and raises its elevator to get a tray. If there are no parts in the column the courier moves on to another. Once the courier gets a tray, it brings the parts to an overhead manipulator which can transfer the parts from the tray to product subassemblies held by other couriers.

At present, our prototype minifactory has one platen, one courier, and one overhead robot. The courier is operating in closed-loop mode with a 1σ motion resolution of 200 nm [21]. The overhead manipulator currently operates with about 4 μm motion resolution. The optical coordination sensor, used to automatically measure the spatial relationships between couriers and overhead devices, is currently operating at a 1σ resolution of 150 nm. We have demonstrated very simple coordinated pick and place operations with small electronic parts. Our next set of hardware, currently under construction, will have six platen tiles, four couriers, and four overhead manipulators. It is expected that this collection will be sufficient to demonstrate many aspects of minifactory operation.

Application Example: Microphone Assembly

As an application example, we will look at using minifactory to automate the assembly of small electret microphones. The current assembly of these products, which are no more than a few millimeters across (see Fig. 3), is done by hundreds of workers using stereo microscopes and tweezers. The work is highly precise, highly skilled, and highly repetitive. The present process is adequate, but the long lead time for training assembly workers means that it is difficult to increase production capacity in response to market demand. In addition, as technological advances allow theoretically smaller and smaller microphones, the difficulties of using human labor in their mass assembly will only increase. To meet these demands for this product, there is an obvious need for high precision, yet very flexible, automation.

Minifactory and AAA provide a platform which will support and integrate the various precision manufacturing processes that need to be developed to assemble the tiny microphones. Figure 4 shows a virtual (simulated) factory which performs most of the assembly of one type of microphone. It was rapidly developed in cooperation with the microphone manufacturer using the *interface tool* component of the AAA software. Minifactory's flexibility and pervasive modularity allowed us to develop this factory incrementally, *i.e.*, starting with factories that build sub-components, and subsequently building up to the larger factory depicted in the figure.

In the first factory, which consisted mainly of platen tiles A and B in Fig. 4, only the assembly of
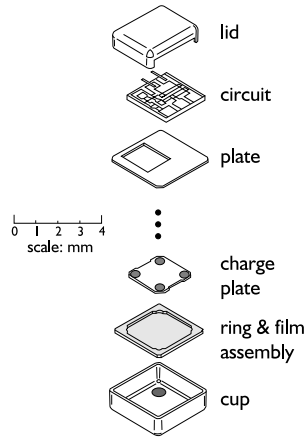
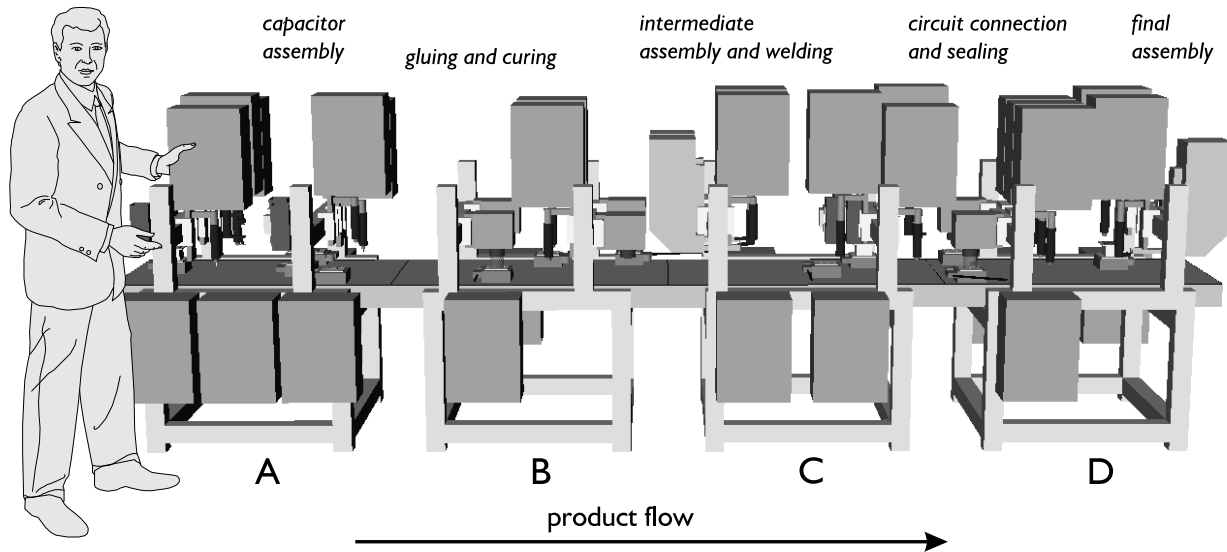Figure 3: Simplified exploded view of microphone assembly.

Figure 4: Virtual minifactory for microphone assembly.

the capacitors, which are the heart of the microphone, is performed. The factory takes sheets containing 16 electret "charge plates," which are the fixed, charged part of the capacitor, cuts each charge plate off, precisely forms it and places it on a ring/diaphragm—which is the element that will vibrate in response to sound. The resulting assembly is then glued and cured.

The initial factory used one courier on platen A for fabrication of the charge plate and one on platen B for the assembly, gluing, and curing of the capacitor. The factory on average produced a capacitor every 25 seconds, but the agents in the factory spent much of their time waiting for other agents, since each courier was involved in at least one time consuming process. For example, it takes about a minute to cut out all of the charge plates from the carrier and each of the glued subassemblies must be cured for six seconds. The obvious way to improve factory throughput is to add parallelism: instead of having one courier on platen A, there are two so that the charge plate feeder will never have to wait for a charge plate once the factory gets up to speed. Similarly, instead of having one courier on platen B, there are two so that while one courier is curing its product the other is getting its product assembled and glued. The resulting factory segment has an average throughput of one assembled capacitor every 9 seconds.

The agent coordination primitives which are part of AAA make the addition of such parallelism fairly straightforward. It was unnecessary to make significant changes to the programs for the overhead manipulators, and the programs for the couriers needed to be made only slightly more complex, *i.e.* by designating some "parking areas" for couriers to sit in while they are waiting for safe passage to and through other manipulators.

This simple initial factory does show many of the major components of our minifactories. For example, the first step in any assembly process must be parts feeding. In this initial factory, all parts are fed into the

system on trays via precision parts feeders.

Most of the processes in the initial factory do not represent a high level of cooperation between agents: a courier drives up to a precise spot underneath a manipulator which then performs an action. One example of a high precision, highly cooperative operation is gluing. The courier arrives under the gluing agent carrying an assembled capacitor, and then it must perform a coordinated "dance" under the gluing agent which will result in tiny, precise stripes of glue being laid down on the assembly. In this case, the couriers are not simply high precision delivery vehicles, but they must perform a continuous cooperative operation with the gluing agent to make sure that the proper amount of glue is put in the proper location.

The final 37-agent factory pictured in Fig. 4 was built up incrementally, one platen at a time. The processes that take the assembled capacitor, glue it to the bottom metal outer cup of the microphone, weld on a ground plate, attach the circuitry, and attach the top outer cup of the microphone were added and debugged in sequence. It is expected that this incremental approach will be typical, both in simulation and in constructing real minifactory systems. As assembly processes are developed and debugged, the factory can be reconfigured to use that assembly process. In this manner, the development of an "all or nothing" style of automation is specifically avoided.

In developing this factory, an additional kind of parts feeding was used. For example, the bottom cup of the microphones in this factory will be fed by a bulk feeder. Operators will fill a "bin" with bottom cups which the bulk feeder will then singulate and orient appropriately for pick-up and transfer by the bottom cup manipulator. The technology used in this bulk feeder has not been determined yet, but could use vibration processes coupled with simple sensors.

In addition, plausible simulated processes such as resistive welding had to be developed for this product. In a proposed minifactory resistive welder, the effector has two prongs: one which serves a double purpose as a gripper and an electrical conductor while another serves purely as a conductor. The fixture on the courier which holds the bottom cup has been specially designed to have a conducting plate on the bottom which remains in contact with the bottom cup once it has been fixtured. The effector can pick up an intermediate plate from a bulk feeder and place it on the bottom cup in the fixture. As the plate is placed, one prong of the effector comes in contact with the conducting plate of the fixture, and current can be run through it to weld the intermediate plate to the bottom cup. Such a resistive welding process is actually extremely well suited to the minifactory paradigm, since it allows precise positioning and fastening to happen simultaneously. An alternative process such as laser welding would require fixing the intermediate plate to the bottom cup at one agent, and then somehow holding that position while the assembly moves on to a laser welding agent.

With minifactory, there are many different choices to be made for how products flow from place to place. For example, we have deliberately complicated our final factory to make some points: There is a glue station on platen B which is used for two completely different gluing operations, *e.g.* the gluing of the charge plate into the diaphragm and the gluing of the subassembly into the bottom cup. Thus, in this factory, products do not just flow from left to right as would be predicated by a normal automated factory with a line of work cells connected by a conveyor belt. The bottom cup gets bulk fed onto a courier on platen C, moves "backwards" to platen B for gluing and then gets transported back to platen C after gluing for curing, welding, and unloading. Minifactory's flexibility enables a developer to easily adjust the product flow in response to the delicate balance between maximizing throughput and minimizing the number of agents involved in the factory. In this case, because of the lengthy curing times, having only one gluing agent shared by four couriers performing two different processes did not prove to be a bottleneck. The throughput of the final simulated factory was still the same as the throughput of the original simple simulated factory segment, *i.e.* one assembled microphone was fed into the output precision parts feeder on platen D every nine seconds.

Future Research

In the application example just illustrated, the electret microphone product (Fig. 3), while quite small relative to human assembly considerations, is well within the range of sizes that can be easily handled in a minifactory using "conventionally" produced micro-grippers, and 2D gray-scale computer vision techniques. In the future, we will be looking for ways to robustly integrate MEMS grippers and sensors into the minifactory system to deal with even smaller products. This integration will not be easy. One of the most difficult challenges will be dealing with environmental vibration levels. It is anticipated that active feedback compensation will be necessary for precisions below 100 or 200 nm.

A major obstacle to precision assembly of large numbers of MEMS-like products is that the assembly process itself remains essentially a serial one. We believe there may be significant opportunities within the AAA/minifactory paradigm for implementing wafer-scale parallel assembly methods using arrays of passive and active MEMS gripper devices.

Summary and Conclusions

Sensing, gripping, and positioning of small parts to high precision for microassembly is becoming an increasingly active area of research. The assembly process itself, regardless of scale, has been a very active area for robotics for many years. These considerations have been referred to as "assembly in the small" by Whitney [23]. He refers to the larger functional, logistical, and economical problem of assembling viable products as "assembly in the large," which has also been extensively studied.

In this paper we have briefly discussed how "assembly in the small" might meet "assembly in the large" through the AAA/minifactory paradigm. We have briefly presented the example virtual assembly of a small electret microphone whose size, though small, does not yet provide severe challenges in terms of parts picking and alignment precisions. It must be emphasized that building virtual minifactories is the easy part of producing minifactories to assemble microphones or other small products. Many of the actual assembly and joining processes would require considerable efforts to make into reality. In addition, the initial "real" factory would inevitably produce products that are inferior in quality to the products produced by hand: the design and hand assembly of these microphones have been fine tuned for decades, and any change in the assembly process will, at first, lead to performance degradation.

We believe that minifactory's pervasive modularity provides a mechanism for incrementally producing assembly systems which can approach, and eventually surpass, the quality of the by-hand assembly system, without having to be a single all or nothing automation effort. Additionally, the ability to perform robust sub-μm assembly operations anywhere throughout the factory will help ensure high quality. As process quality improves, advantage can be taken of minifactory's modular transport mechanisms to increase throughput and reliability without having to rework the processes themselves.

Finally, we have hinted at a future path where the results of current research in MEMS-like devices for microassembly can be integrated within the AAA/minifactory paradigm.

Acknowledgements

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