

Miniature Factories for Precision Assembly

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Abstract

In spite of many recent advances in MEMS technologies for integrated planar devices, most products of the future will continue to require assembly from separate parts because of differing material property requirements, the need to have a three-dimensional extent, or because of many different end user functional needs. Because many products will be very small and complex, or larger products will incorporate smaller complex subproducts, there will be an increasing need to provide technologies and systems for sensor-based micromanipulation and automated precision assembly. For the past several years we have been developing an architecture for tabletop precision assembly systems. Our goal is to improve the design, deployment, and reconfiguration of automated assembly systems for small mechatronic products requiring high precision. Design and construction of a prototype miniature factory according to our "Agile Assembly Architecture" (AAA) 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 one sigma motion resolutions of 200 nm. Central to the AAA concept is that of a "virtual" factory which is automatically registered and synchronized with the actual factory. As an application example, a virtual minifactory for assembling small electret microphones is presented. These microphones are currently assembled under stereo microscopes by hand with tweezers and other tools. We are working to provide "real" minifactories for assembling real products. Methods currently under development by the micromanipulation community, *e.g.* MEMS grippers and sensors, can be incorporated into future minifactory systems. 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.

Keywords: minifactory, agile manufacturing, precision assembly

1. Introduction

For a wide range of different products, 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. 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.

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 example, Arai *et al.* [1], have developed micro end effectors for micromanipulation in which arrays of micro pyramids are employed to reduce adhesive force effects.

Recently, more attention has been placed on the overall requirements for the *automation* of micro assembly processes [2]. 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 different materials and several disparate manufacturing processes. There may be many reasons for the assembly of the product to be automated, including

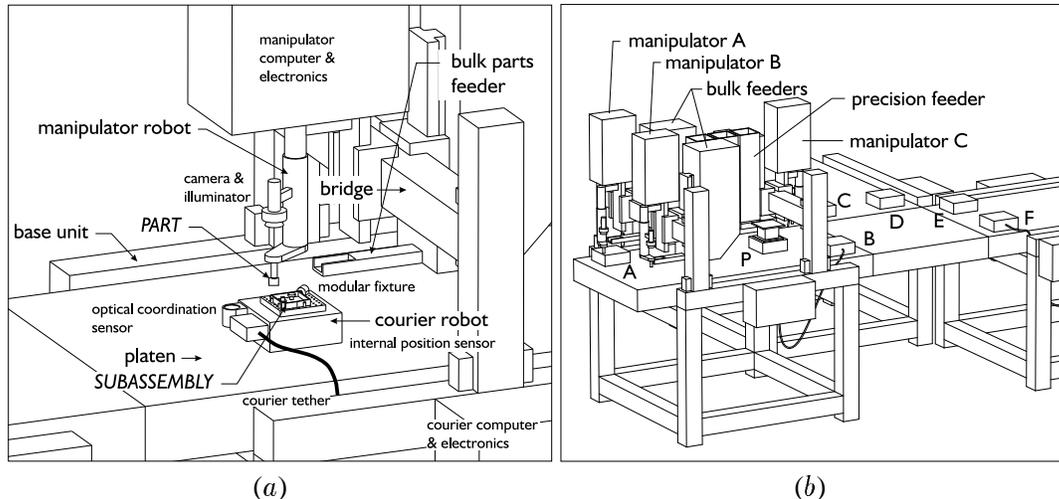


Figure 1: Minifactory: (a) principal components, (b) typical layout.

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.* [3] have demonstrated vision and optical beam deflection techniques to provide nanonewton-level force feedback and nanometer-level position feedback.

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.

2. Minifactory

An ongoing project for rapidly reconfigurable automated assembly is being conducted in the Microdynamic Systems Laboratory* at Carnegie Mellon University. For the past several years, we have been developing an “Agile Assembly Architecture” (AAA) [4, 5] and a modular tabletop precision assembly system “minifactory” [6] for the assembly of small mechatronic products.

The principal components that form a minifactory are shown in Fig. 1(a). 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 [7], incorporating a precision 3-DOF ac magnetic position/angle sensor [8], 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* such as screw drivers, lasers, orbital head formers, welders, gluers and the

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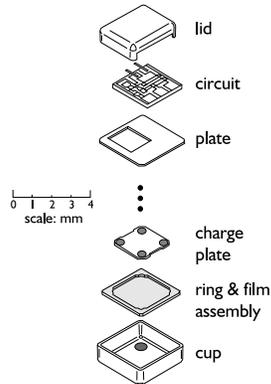


Figure 2: Simplified exploded view of microphone assembly.

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.

Figure 1(b) shows a typical minifactory layout. 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.

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 [7]. The overhead manipulator currently operates with about $4\ \mu\text{m}$ 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.

3. 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. 2), 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 3 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*

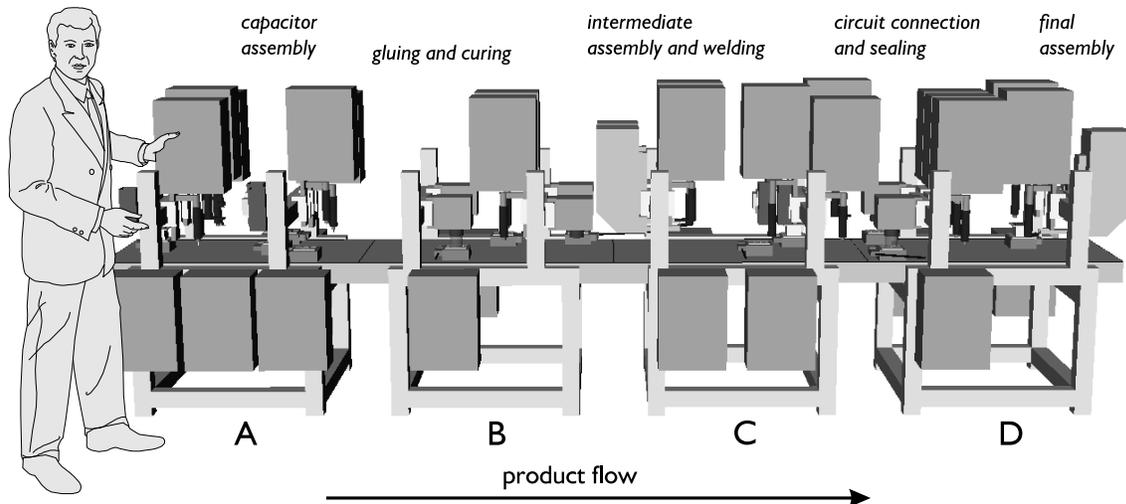


Figure 3: Virtual minifactory for microphone assembly.

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. 3, only the assembly of 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. 3 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.

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.

4. Future Research

In the application example just illustrated, the electret microphone product (Fig. 2), 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.

5. 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 [9]. 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.

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