TOWARD A SECOND-GENERATION MINIFACTORY FOR PRECISION ASSEMBLY

R. L. Hollis, A. A. Rizzi, H. B. Brown, A. E. Quaid,* and Z. J. Butler†
The Robotics Institute
Carnegie Mellon University
5000 Forbes Avenue
Pittsburgh, Pennsylvania, USA
E-mail: {rhollis, arizzi, hbb}@cs.cmu.edu

Abstract

Manufacturers are facing increasing pressure to decrease development and deployment times for automated assembly systems for a variety of precision mechatronic products. The time and costs of integrating these systems must be significantly reduced to meet new and changing market pressures. We have previously developed an automation framework called an Architecture for Agile Assembly (AAA), and a prototype instantiation in the form of a modular tabletop precision assembly system termed "minifactory." In this paper, we describe components of a new second generation minifactory which embodies many of the principles developed in our research.

1 Background

Many products such as automotive sensor systems, portable computing and communication devices, magnetic and optical disk drives, fiber optic devices, medical devices, and other high-density mechatronic equipment are getting much smaller, with an increasing number of high-precision parts that must occupy ever-shrinking volumes. Simultaneously, this class of products is becoming increasingly volatile. This trend puts increasing pressure on the performance of automated assembly equipment.

Today's approaches to flexible multi-robot assembly lines tend to be what one might refer to as "robot-centric." Everything centers on the robots with ancillary equipment such as conveyances, parts feeders, tooling, sensing, and special function equipment added to the mix in a more or less *ad hoc* fashion. Resulting systems are often very complicated and take a long time to deploy. For example, an assembly line for a new disk drive product may take many months to design, program, and debug. Numerous factors such as incompatible communication protocols, large numbers of cables, fixed conveyances, custom parts feeders, and custom end-of-arm tooling all provide plentiful challenges for manufacturing engineers. If the product is successful in the marketplace, customers will soon want new product variants which, in turn, will demand additional flexibility in the assembly system. Often, the product lifetimes of small high-precision products are themselves limited to around six months or even less. What is needed are assembly systems which are not only flexible, in that they deal with variability in the assembly process, but which are also "agile" in that

*Currently at z-kat, Hollywood, FL, USA.
†Currently at Dartmouth College, Hanover, NH, USA.

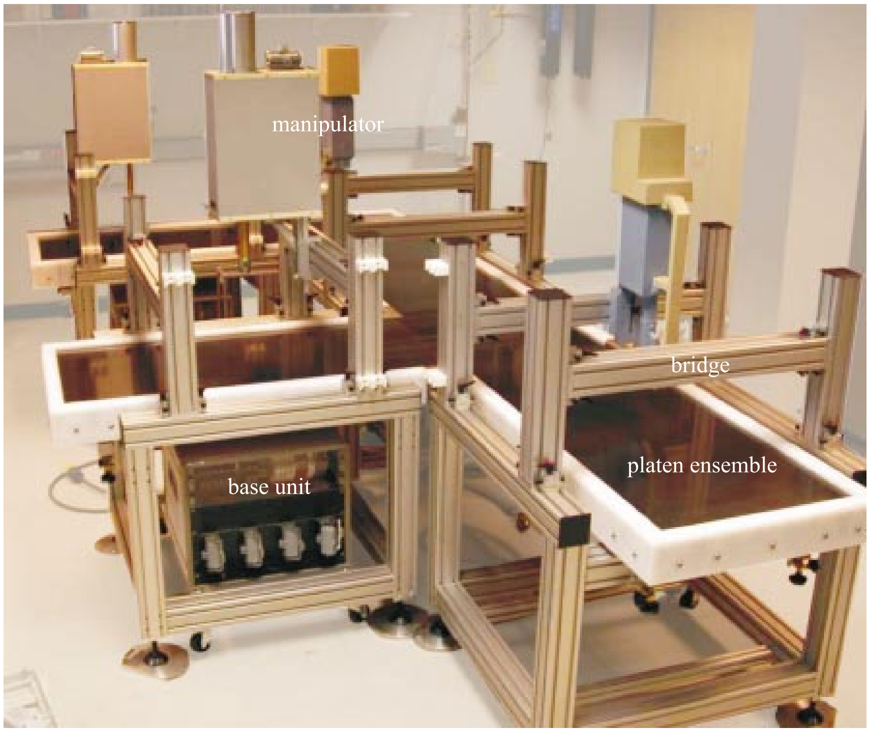


Figure 1: Overall view of minifactory (under construction).

they can respond rapidly to changing market pressures. There have been several notable efforts to approaching this problem including design of agile manufacturing workcells [1], rapidly reconfigurable machining systems [2], over-arching frameworks for manufacturing enterprises [3], and systems viewed as hierarchical collections of manufacturing "holons" [4].

At Carnegie Mellon University, we are working on a set of "factory-centric" software and hardware technologies which has the potential to greatly improve the agility of automated assembly systems, while increasing assembly precision to the micrometer level.

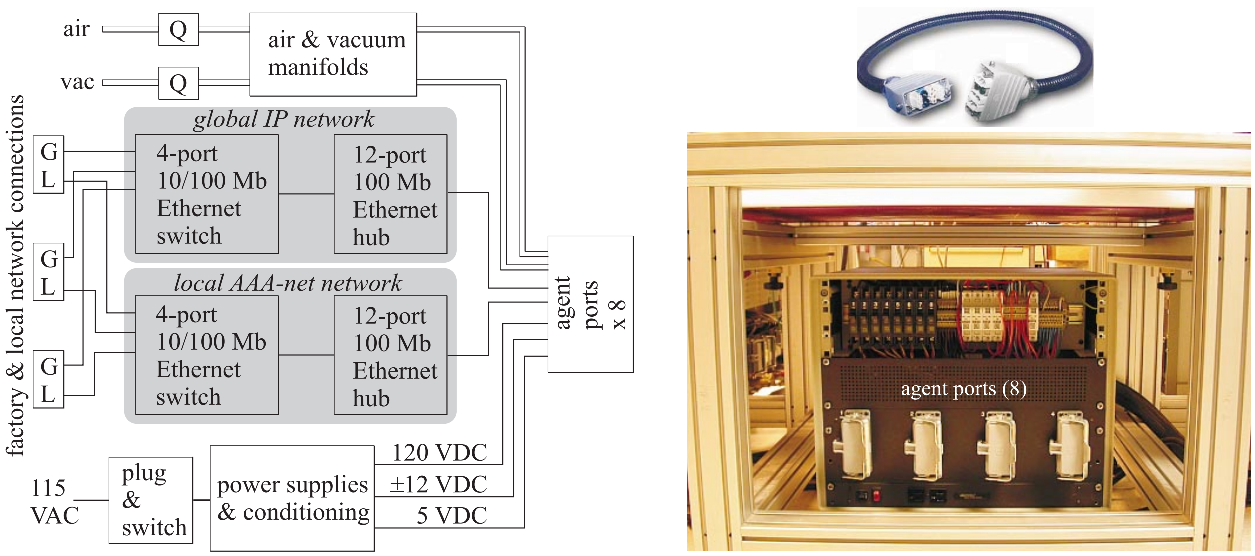
Agile Assembly Architecture

The Agile Assembly Architecture (AAA)* [5] supports the creation of precision assembly systems built from small modular robotic components, which will occupy perhaps one tenth the floor space of today's automated assembly lines. Our goals are to markedly reduce assembly system changeover times, facilitate geographically distributed assembly system design and deployment, and to increase product quality levels.

We are developing AAA as a distributed system of tightly integrated mechanical and computational robotic modules containing information about their own capabilities and with the ability to represent themselves to other factory entities and negotiate with their peers in order to participate in flexible factory-level cooperation [6]. A unified interface tool [7] will allow users to select and order these mechanisms over the Internet and to assemble, program, [8] and monitor them in both a simulated factory environment and the real factory environment. AAA relies on factory-wide standard procedures and protocols, and well-structured autonomy to simplify the process of designing and programming high-precision distributed assembly systems. The architecture makes use of modules' self knowledge and ability to explore their environments to make the transition between simulation and reality as painless and seamless as possible.

Our instantiation of these ideas is a modular tabletop factory that we refer to as *minifactory*.

* `http://www.cs.cmu.edu/~msl`. Select "Projects," then "An Architecture for Agile Assembly."



(a) (b)

Figure 2: Minifactory base unit: (a) block diagram, (b) photograph.

The key technical ideas include the use of distributed low-DOF robotic modules or *agents*, and integrated product transport and manipulation. By agent, we explicitly mean a mechanically, computational, and algorithmically modular manufacturing entity capable of both communication and physical interaction with its peers. The entire system is composed of compact elements with standardized mechanical and electrical interconnects allowing for the rapid setup and adjustment of a factory system.

Minifactory

Most precision assembly today is done with SCARA robots having repeatability in the range of 50 μm at best. Vision can provide increased precision, but placement accuracy is still limited by the motion resolution of the robot. Thus true micrometer-level assembly operations usually require the addition of costly precision motion stages, relegating the robot to mere load/unload tasks. There are fundamental limitations to the precision of the ubiquitous SCARA robot design. The problem lies with the shoulder and elbow joints where actuators and encoders are located far from the end effector. One tick of the shoulder encoder, for example, results in a fairly large displacement of the end effector. Intervening joint friction and flexibility, and arm dynamic effects reduce precision even more. Additionally, the SCARA's precision depends greatly on the arm configuration. We have developed a viable alternative to the SCARA which can robustly perform micron-level assembly.

Minifactory employs closed-loop planar motor robots, or "courier" agents which carry product sub-assemblies. The couriers interact with fixed overhead agents such as 2-DOF pick-and-place manipulators to accomplish 4-DOF assembly operations. In our prototype system, based in part on modified commercial hardware, we previously demonstrated courier speeds of 1.5 m/s and motion resolution of 200 nm (1σ) [9]. Manipulators are equipped with detachable modular end effectors which can incorporate, *e.g.*, vision and force sensing. We have demonstrated cooperative precision vision- [10] and force-guided [11] assembly operations between couriers and manipulators.

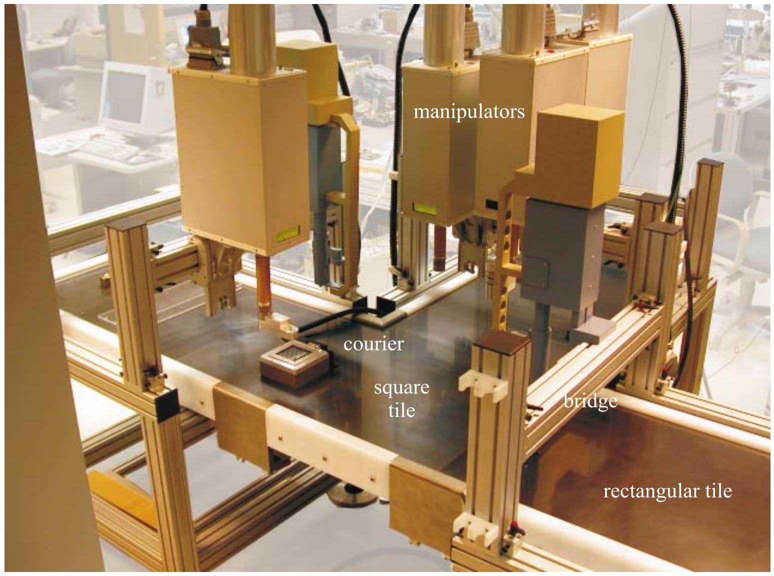


Figure 3: View showing T-junction, with three rectangular tiles and one square tile.

2 Minifactory Infrastructure

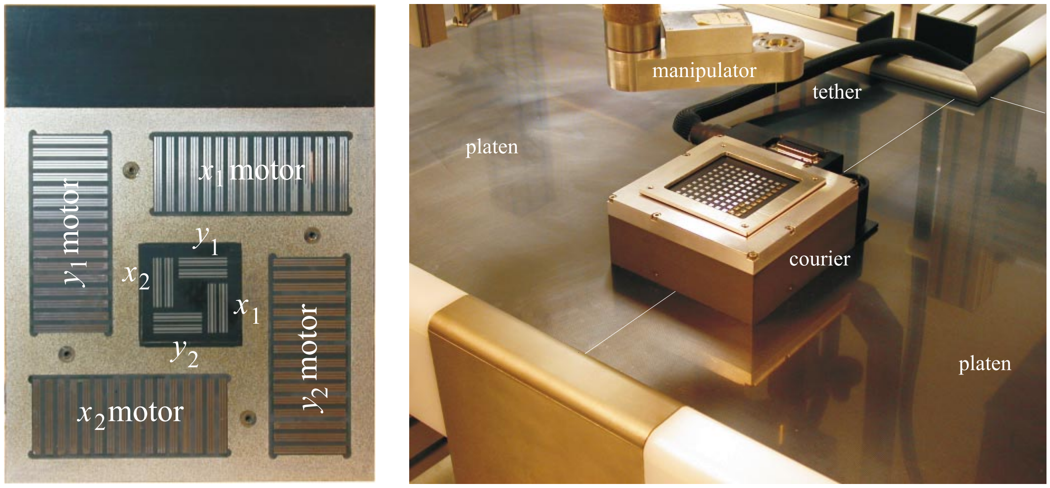
The infrastructure of our second-generation minifactory is comprised of a collection of modular base units, platen tiles, and bridges. The system is designed from the outset to enable rapid deployment.

Base Units

Minifactory base units supply air, vacuum, power, and network services to the various modular agents comprising the minifactory as well as providing structural support for the rectangular platens and the bridges. Figure 2(a) is a block diagram, and Fig. 2(b) is a photograph, also showing an agent cable. Air and vacuum are daisy-chained between base units by quick-connect fittings Q and distributed via manifolds to each of the 8 agent ports. A Global IP 100 Mb Ethernet hub and switch provide each agent with factory-wide connectivity. A second local 100 Mb Ethernet hub and switch supporting a custom high-speed AAA-net protocol provides agents connected to the same base unit to perform cooperative activity such as servoing at rates of several kHz [12]. Power supplies in each base unit supply 120 VDC, $\pm$12 VDC, and 5 VDC to each of the agent ports. Four agent ports are provided on each side of each base unit. Any given agent in the minifactory can plug into any agent port by means of a single modular plug and cable. Our current laboratory minifactory has four base units, supplying services to a potential collection of 32 agents, sufficient for micrometer-level assembly of a moderately complex precision product.

Platen tiles

A key difference between our second-generation minifactory and the prototype, is the use of *modular platen tiles* which can be flexibly arranged in various ways to form *platen ensembles* providing continuous stators for multiple closed-loop planar motor courier agents [13]. Platen tiles are either rectangular, 1200$\times$600 mm or 600 mm square. Rectangular tiles have a mass of 77 kg and feature a planarized array of 720,000 ferromagnetic posts on a 1 mm pitch. The post array provides electromagnetic reaction forces for the courier motors, and position references. The tiles are light enough to be handled by two persons, and are supported on the base units by a series of precision leveling screws and locating fixtures. Square tiles are used in conjunction with the rectangular



(*a*) (*b*)

Figure 4: Courier agent: (*a*) bottom of courier, (*b*) courier operating over the interface crack between two tiles (crack emphasized for clarity).

tiles to form precise and level platen ensembles with L-junctions, X-junctions and T-junctions to support a variety of minifactory layouts. Figure 3 is a photograph of a section of our minifactory taken at a T-junction formed by three rectangular tiles and one square tile. The tiles are joined and unjoined using specially-developed mechanisms. Square tiles need no support. Tiles are fitted with modular UHMW polyethylene curbs providing boundaries for courier operation.

Bridges

The second-generation minifactory features modular structural bridges which are manually clamped at arbitrary locations on the base units, featuring a horizontal beam which can be manually adjusted in height to accommodate various agents. These bridges are evident in Figs. 1, 3, and 5.

3 Courier Agents

Courier agents travel on air bearings over the platen ensemble at altitudes of 10-15 μm, transporting product sub-assemblies through the minifactory, and cooperating with manipulator and processor agents to perform precision 4-DOF assembly operations. The courier motors use the Sawyer principle developed in the late 1960s [14]. In our prototype first-generation minifactories, the couriers were based on commercial planar motors retrofitted with novel 3-DOF ac magnetic position sensors [15, 16]. These couriers achieved 1.5 m/s speeds with 200 nm (1σ) motion resolution [9]. Our new couriers are designed from the "ground up" to operate on new metric platen tiles, with smaller footprints, about 30% increased force densities, increased sensor area and signal output, improved air bearing, improved "brain boxes" and tethers, and flexible services permitting auxiliary actuation mechanisms and modular vices, etc. to be mounted on their top surfaces. We have currently completed one of these second-generation couriers, and are in the process of manufacturing an additional set of 9 more couriers.

Figure 4(a) is a photograph of the active bottom surface of a courier agent, showing a pair of x motors and pair of y motors, each providing up to 30 N force and up to about 5 Nm of torque using all 4 motors. The 3-DOF position/orientation sensor is centrally located and operates on principles similar to an LVDT [17]. Owing to the precise horizontal and vertical registration of mating platen tiles, couriers are able to fly over the interface cracks [Fig. 4(b)]. Couriers use intrinsic force sensing to find the boundaries of their platen tiles by bumping into the curbs, and can also detect

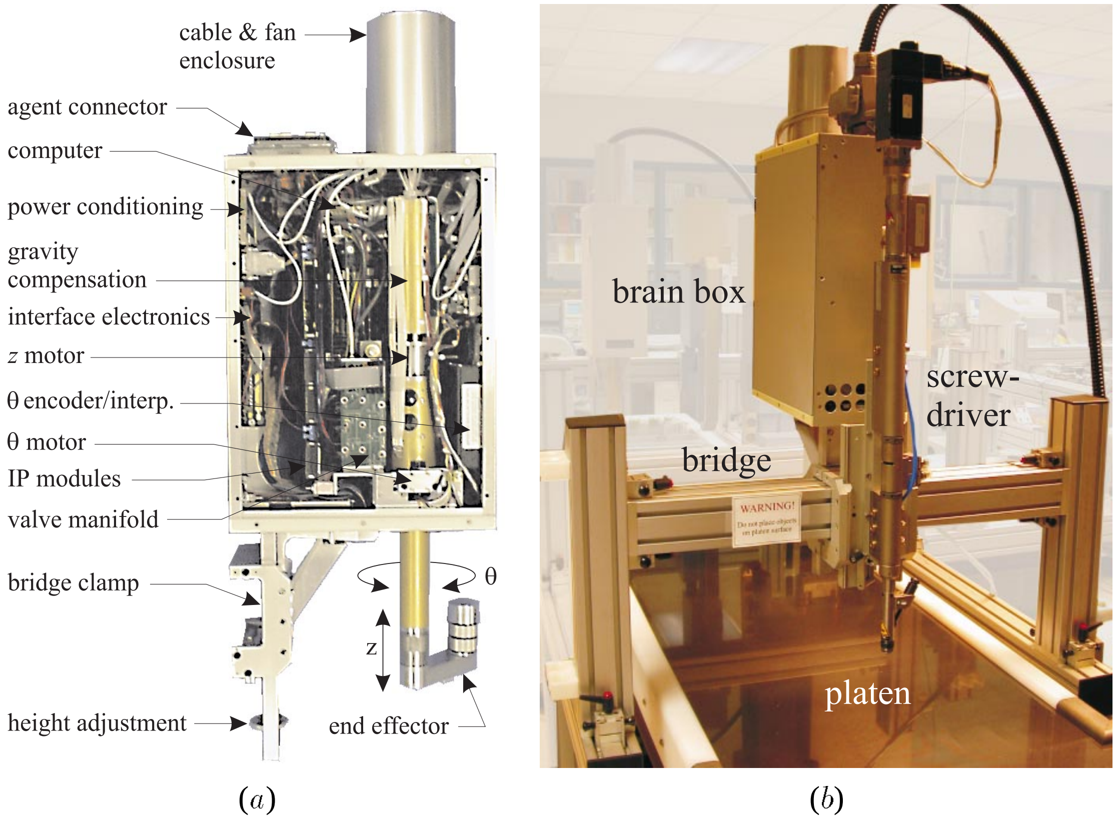


Figure 5: (a) Two-degree-of-freedom $(z-\theta)$ manipulator agent (cover removed), (b) Weber Screwdriving Systems automatic screwdriver agent (under development).

the interface cracks between tiles. This enables a collection of couriers to accurately map the factory "floor" comprised of the platen ensemble [18].

In addition to their ac-magnetic position sensor, couriers carry an upward-looking optical *coordination sensor* based on a lateral-effect position sensing photodiode [19]. This sensor enables couriers to precisely locate LED beacons incorporated into overhead agents such as manipulators. The sensor has a resolution of 150 nm (1σ) in a bandwidth of 100 Hz.

4 Manipulation and Processing Agents

A manipulator agent, shown in Fig. 5(a), has a rotational (θ) DOF greater than $360°$ and a vertical (z) translation of about 150 mm. Our manipulators have an angular slew rate of 500 deg/s, angular resolution of 0.0002 deg (1σ) and vertical resolution of 5 micrometers [20]. A typical modular end effector has a camera, illuminator and force sensor mounted on the end of a 100-mm radius arm to facilitate parts picking. The manipulator and associated electronics are packaged in an enclosure or *brainbox* that can be handled easily by one person and mounted with an adjustable clamp to a minifactory bridge structure without tools. It is designed to be clean-room compatible.

A typical operating scenario is as follows. The end effector swings and moves downward to retrieve a part presented by a local parts feeder. The gripper moves down to a specified height, or until the integral force sensor detects the part. Vacuum is turned on to lift and hold the part. The part is lifted and the end effector swung to the nominal assembly location. Meanwhile, a courier agent positions a sub-assembly below, taking into account the measured, lateral position and orientation of the part with respect to the manipulator camera. As the manipulator carries the part downward for insertion, the courier moves to the correct lateral position using information from the manipulator. The component is pressed into position on the sub-assembly by the final z

motion, based on position and/or force signals. A puff of air releases the part, and the manipulator returns to the start position to begin the next cycle. The entire cycle takes less than a second.

Figure 5(b) shows an automatic screwdriver, really a special kind of manipulator/feeder agent. It interfaces in exactly the same way as a manipulator agent, or any other agent in the minifactory, and is capable of feeding and driving small screws into products carried by couriers. Speed and torque profiles are programmable.

5 Discussion

In this paper we have briefly presented principal components of our new second-generation minifactory. We are working to complete the system in preparation for demonstrating precision assembly of several different products.

Future work will include research on flexible methods for feeding small bulk parts, tray feeding for precision high-value parts, micro fastening techniques such as adhesive dispensing and welding, and additional work on visual- and force-servoing.

We have recently become aware of other notable work with the same objective using a similar approach. These include recent work at the Fraunhoffer Institute in Stuttgart [21] and at the Singapore Institute of Manufacturing Technologies [22].

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