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Design and Development of a Tabletop Precision Assembly System

R. L. Hollis, J. Gowdy, and A. A. Rizzi
Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania, USA
{rhollis | jayg | arizzi}@cs.cmu.edu

***Abstract*— We describe design elements and their interactions for a tabletop-size precision microassembly system called "minifactory." The system is a proper subset of the Agile Assembly Architecture which includes capabilities for rapidly producing modular virtual factories and configuring their real counterparts. Minifactory is a distributed collection of cooperating intelligent robotic agents that perform microassembly and related operations. For example, we have demonstrated both precision vision-guided and force-guided assembly between cooperating agents. This paper sketches our general approach, focusses on the hardware aspects of minifactory, and discusses the current state of development.**

I. Introduction

Manufacturers are facing increasing pressure to reduce 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.

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-value products are themselves limited to around six months or even less. Additionally, in many cases such volatile products also have very small parts and demanding precision requirements. What is needed are precision assembly systems that are not only flexible, in that they deal with variability in the assembly process, but that are also "agile" in that they can respond rapidly to changing market pressures.

There have been several notable efforts to approaching this problem including design of agile manufacturing work cells [1], modular precision assembly work cells [2], rapidly reconfigurable machining systems [3], over-arching frameworks for manufacturing enterprises [4], and systems viewed as hierarchical collections of manufacturing "holons" [5].

II. Agile Assembly Architecture

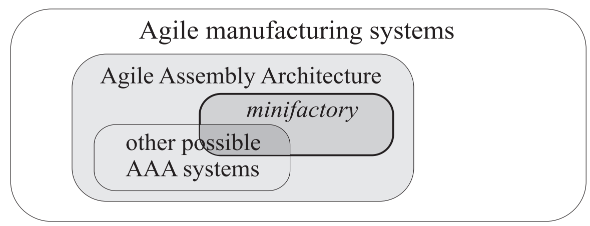


Fig. 1. Venn diagram illustrating the relationship between our Agile Assembly Architecture and minifactory.

The Agile Assembly Architecture (AAA)[1] developed at Carnegie Mellon University is an overarching framework intended to providing manufacturers with the ability to rapidly design, program, and deploy precision automated assembly systems [6], [7]. AAA has two parts: i) a distributed collection of computational/physical robotic agents comprising a "minifactory," and ii) a comprehensive software Interface Tool for shepherding the development of an operating minifactory. The relationship between AAA, minifactory, and other agile manufacturing systems is illustrated in Fig. 1. The minifactory in our laboratory is a proper subset of AAA.

A. AAA Interface Tool

The AAA Interface Tool provides a centralized viewpoint for the design, programming, debugging and monitoring of a virtual or real minifactory [8]. It supports downloading of robotic agent descriptions over the Internet (including 3D model, kinematics and dynamics, programming interface, and protocol descriptions); the physical arrangement of agents and infrastructure elements into multi-agent virtual minifactories through a 3D CAD-like interface; distributed programming of the agents using a scripting language (currently Python)

[1] Web site: `http://www.cs.cmu.edu/~msl`. Select "Projects," then "An Architecture for Agile Assembly."

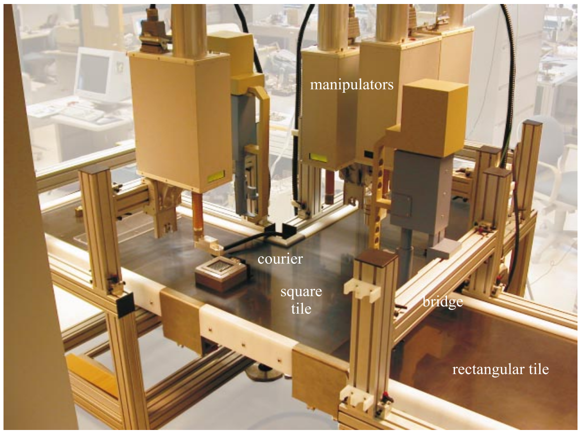
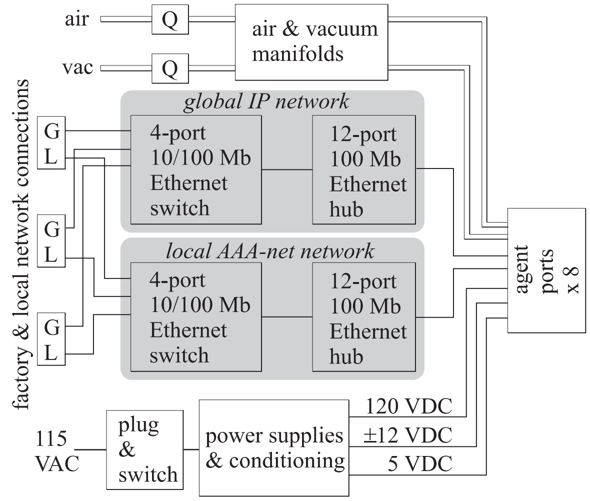
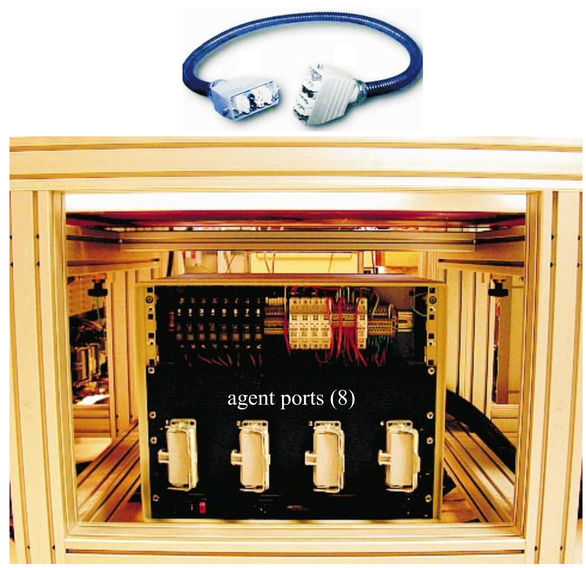


Fig. 2. Photograph of a section of our laboratory minifactory (under development).



(a)



(b)

Fig. 3. Minifactory base unit: (a) block diagram, (b) photograph.

[9]; behavioral simulation of the designed (virtual) minifactory assembling virtual products in real time; a debugging environment to aid in producing correct factory programs; a mechanism for transferring developed programs to a real minifactory; and the ability to monitor the operation of the operating real minifactory. We are continuing to develop the capabilities of the Interface Tool and have recently ported it from SGI/Irix to X86/Linux platforms.

B. *Minifactory Infrastructure*

Figure 2 shows part of the modular minifactory system under development in our laboratory. Active components shown in the figure include *courier agents* (Sec. II-C) responsible for transporting products through the factory and participating in assembly and fastening operations and *manipulator agents* (Sec. II-D) for picking and placing parts.

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 [10].

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 3(a) is a block diagram, and Fig. 3(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 (G) 100 Mb Ethernet network provides each agent with factory-wide connectivity. A second local (L) 100 Mb Ethernet network supporting a custom high-speed AAA-net protocol provides agents with the ability to perform cooperative activity such as distributed sensor-based servoing at rates of several kHz [11]. Power supplies in each base unit supply 120 VDC, ±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: We have developed a system of *modular platen tiles* that can be flexibly arranged in various ways to form *platen ensembles* providing continuous stators (the factory "floor") for multiple closed-loop planar motor courier agents [12], [10]. Platen tiles are either rectangular, 1200×600 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 and position references for courier agents. 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 tiles to form precise and level platen ensembles

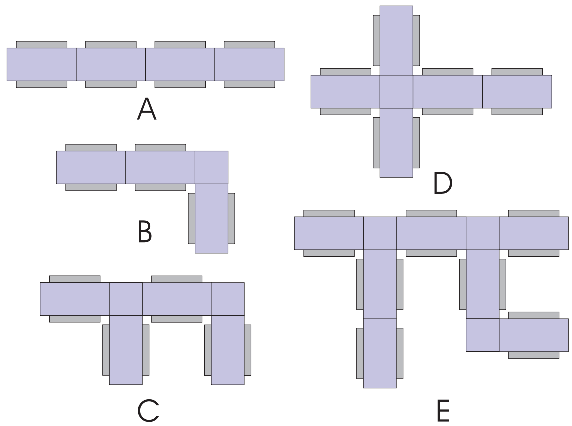


Fig. 4. Several possible minifactory configurations realizable with rectangular and square platen tiles. Each rectangular tile is supported by a base unit.

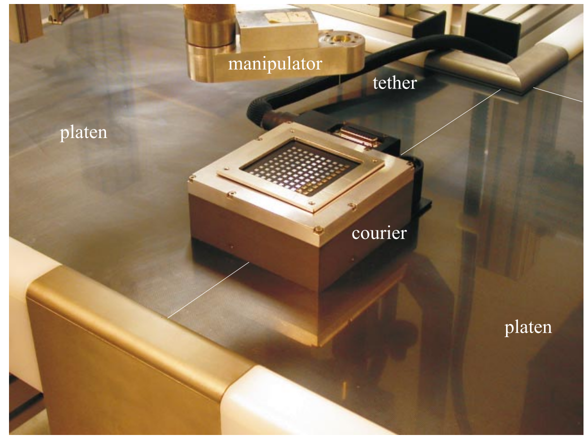


Fig. 6. Courier operating over the interface crack between two tiles (crack emphasized for clarity).

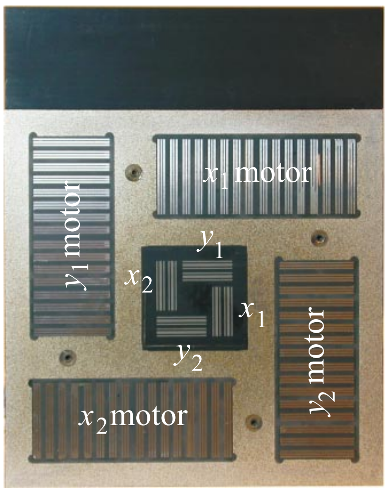


Fig. 5. Courier agent: Bottom view of courier showing motor sections and 3-DOF ac-magnetic position/orientation sensor.

with L-junctions, X-junctions and T-junctions to support a variety of minifactory layouts. Figure 4 illustrates several minifactory configurations supporting branching operations. Figure 2 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: 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 Fig. 2.

C. Courier Agents

Courier agents travel on air bearings over the platen ensemble at altitudes of 10-15 μm, transporting product subassemblies 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 [13]. In our prototype first-generation minifactories, the couriers were based on commercial planar motors retrofitted with novel 3-DOF ac magnetic position sensors [14], [15] permitting their operation as closed-loop servos. These couriers achieved 1.5 m/s speeds with 200 nm (1σ) motion resolution [16]. 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.

Figure 5 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 ac-magnetic 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. 6]. Couriers use intrinsic force sensing to find the boundaries of their platen tiles by bumping into the curbs, and can also detect 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.

D. Manipulation and Processing Agents

A manipulator agent, shown in Fig. 7, 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

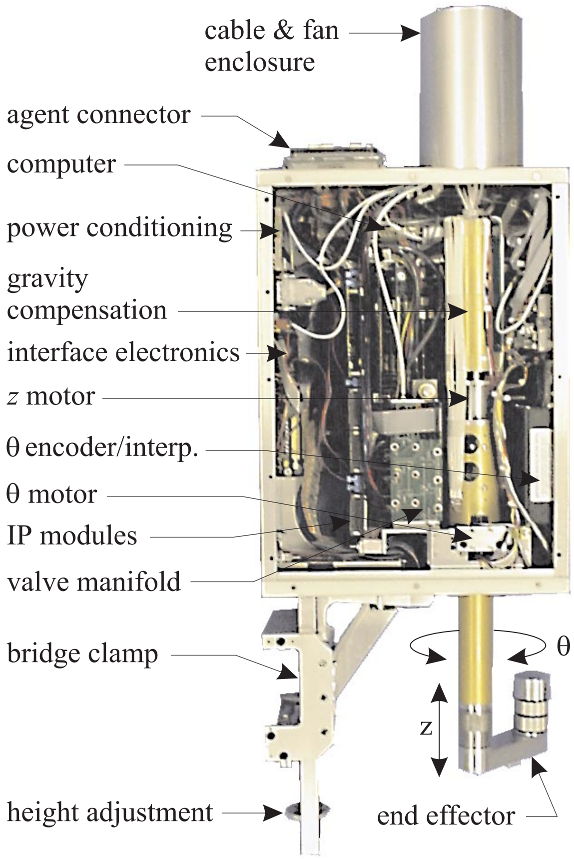


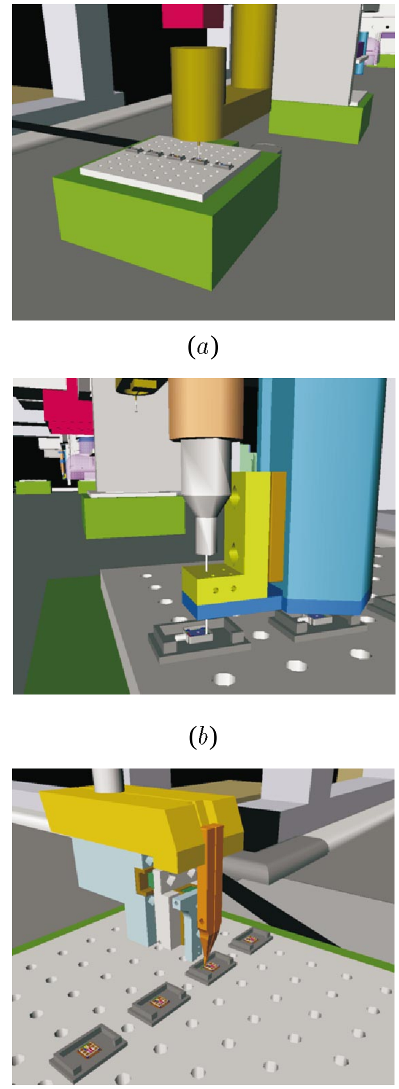
Fig. 7. Two-degree-of-freedom ($z - \theta$) manipulator agent (cover removed)

resolution of 5 micrometers [20].

Modular end effectors attach to the distal end of manipulators through a quick-change bayonet-style interface with 30 electrical connections and 6 pneumatic connections. 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. End effectors have one or more LED beacons for automatic calibration with courier agents [19]. We currently use vacuum grippers for picking and placing small parts and plan to use MEMS-based grippers for very small parts. 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, although it is not yet certified.

We plan to augment our four existing manipulator agents with additional types of interchangeable end effectors. Simpler, smaller, and lower cost manipulators are also under consideration.

Besides precision pick-and-place operations, a number of fastening operations are needed for viable microassembly. We have modeled several different types of processing agents and simulated their operation using the AAA Interface Tool. Figure 8 shows several virtual agents operating in a 29-agent virtual minifactory which assembles small microphone devices.



(a)

(b)

(c)

Fig. 8. Virtual factory views of small microphone assembly processes from the AAA Interface Tool: (a) manipulator agent placing micropart on a product held by courier agent, (b) dispensing agent, (c) microwelding (gap welding) agent.

For example, Fig. 8(a) shows a vision-guided precision pick and place operation, Fig. 8(b) shows a dispensing agent placing small drops of uv-curable adhesive, and Fig. 8(c) shows a microwelding agent performing a wire bonding operation. We have not yet developed real processing agents for dispensing and welding operations, but it is expected that they can be implemented by providing appropriate hardware/software "wrappers" around existing industry products. For example, we have started work toward converting a leading edge automatic screwdriver into a screwdriving agent for our system.

III. Discussion and Status

The AAA/minifactory project, outlined in this short paper, has been in progress over the course of nearly 10 years. We continue to develop and refine both the hardware and software. The architecture emphasizes a degree of modularity and performance which we believe is unique. Novel characteristics of this approach include:

- Agents that are self-representing and self-describing [21].
- Groups of simple 2-DOF agents cooperate to perform 4-DOF assembly operations [22].
- Product transport is integrated with precision product positioning, eliminating the need for belt-like conveyances and fixturing.
- The system operates in a distributed manner without centralized control.
- Design, programming, and operations monitoring is done through a comprehensive centralized viewpoint (Interface Tool) [8].

In our first-generation minifactory (now retired) we demonstrated cooperative visual servoing between manipulator agents and courier agents and vision-guided parts placement. In these experiments, a manipulator agent rotated while viewing a small part held by a courier agent. The courier agent's actuators were slaved to the manipulator agent via the AAA-net, transiently forming a 4-DOF system with approximately 15 μm tracking error while moving at 5 mm/s [23].

We also demonstrated cooperative force servoing between a manipulator agent and courier agent at several-mN force levels. In a series of experiments, a test plate was mounted on the courier agent and a vacuum pickup using hypodermic tubing was attached to a custom-developed piezoresistive force sensor integrated with a manipulator agent modular end effector. Vertical contact, lateral edge following and peg-in-hole insertion trials were performed. As before, the courier agent's actuators were slaved to the manipulator. Robust results were achieved at speeds of 10-50 mm/s [24].

For the past several years our effort has focused on completion of the second-generation minifactory shown in Fig. 2. The new minifactory incorporates numerous enhancements over the prototype but is not yet fully operational. All of our work on the project to date has been of a fundamental and generic nature which has served us well. We are now beginning to explore relationships with industry to select strategic areas of application to real product microassembly.

Acknowledgments

The ongoing work on AAA/minifactory has so far involved more than 30 persons. The authors especially thank Arthur Quaid, Zack Butler, Wing-Choi Ma, Michael Chen, Rich DeLuca, Shinji Kume, Greg Fries, and Rob Schlender for their intellectual contributions and hard work. We thank Michael Ehrenstrasser and Mark Endress for their efforts in creating virtual factory implementations, and Andreas Best for his work in porting the Interface Tool. This work was supported in part by National Science Foundation grants CDA9503992, DMI9523156, and DMI9527190.

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