An Architecture for Agile Assembly

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Abstract

This short paper outlines new hardware and software technologies and methods being developed for automated assembly of precision high-value products such as magnetic storage devices, palmtop and wearable computers and other high-density equipment. Our Agile Assembly Architecture (AAA) supports the creation of miniature assembly factories (minifactories) built from small modular robotic components. The goals are to substantially reduce design and deployment times and product changeover times, greatly improve quality levels by using sensor-moderated precision motion, and to achieve new levels of manufacturing system portability by shrinking the sizes of typical assembly systems from large room size to tabletop size.

We are developing the key electromechanical elements including novel subproduct couriers, manipulator/feeders, and other modular components. We are implementing a distributed realtime computer architecture, modeling and simulation software, high-level network communication protocol, and graphical programming tools to support this architecture. "Real" minifactories will be programmed by directly interfacing with automatically synchronized "virtual" minifactories.

1 Introduction

Automated assembly is a key part of our manufacturing capability. Current assembly systems have a number of shortcomings such as costly and time-consuming changeover, parts feeding problems, barely adequate inherent precision, lack of programmability and flexibility in horizontal conveyances, limited robot workspaces and large dedicated cleanroom floor space.

In this paper, we outline a new project to develop highly agile automated assembly systems which support geographically distributed design and deployment, and which can be rapidly reconfigured to meet changing market opportunities.

The SCARA assembly robot

A large percentage of today's automated assembly systems are pipelined configurations of SCARA (Selective Compliance Assembly Robot Arm) manipulators and product conveyor belts. The SCARA was developed in the late 1970's by Professor Hiroshi Makino, and has four degrees of freedom (DOF) as shown in Fig. 1.

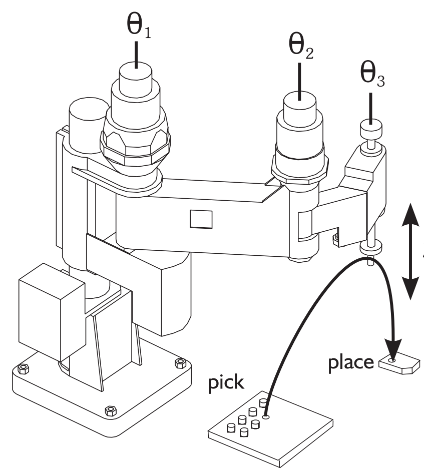

Figure 1: Conventional SCARA assembly robot.

Whereas the SCARA has a proven record and well-known advantages in assembly, it does not lend itself well to the creation of highly integrated systems for precision assembly. A few of the difficulties are:

- large motion range required to access parts feeders
- heavy robot arm must be used to handle very light precision parts
- high accelerations are needed for pick-and-place cycle to sustain high throughput
- serial kinematic linkage with relatively flexible joints can lead to structural oscillation
- dynamic interactions between θ_1 and θ_2 joints must be cancelled by controller
- proximally-located joint encoders for θ_1 and θ_2 limit motion resolution at the last link

Because of these considerations, typical SCARAs used in assembly have motion resolutions and repeatabilities of 50 to 100 μm at best which severely limits their usefulness in high-precision work.

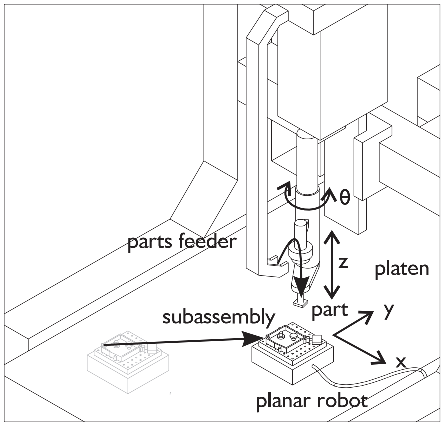

Figure 2: Pair of 2-DOF manipulators used in Minifactory

2 Modular Robotic Elements

We are developing new modular robotic elements which are key to our Agile Assembly Architecture concept.

Cooperating 2-DOF robots

We propose an alternative robot configuration which provides the same four degrees of freedom as the SCARA but greatly ameliorates these problems. The new configuration is shown in Fig. 2, where the four-DOF SCARA is replaced by a pair of simpler 2-DOF robots.

The θ_3 and z axes of the SCARA are retained and fixed in the workspace. These degrees of freedom can be made highly precise by co-location of sensors and actuators that can be rigidly referenced to mechanical ground. The θ actuator can be carried by the z actuator (or vice versa), or a two-dimensional cylindrical motor design with a single moving part can be used, e.g. [1]. We refer to this robot and its associated feeder as a "manipulator/feeder."

The problematic θ_1 and θ_2 axes of the SCARA are discarded in favor of an x, y stage "courier" robot which carries the subassembly. Moreover, this robot is implemented as a two-axis linear motor capable of traveling above a flat platen surface over a large workspace. This robot is also tightly referenced to mechanical ground. Planar motor robotic systems exist commercially, e.g. [2], but these systems essentially imitate the SCARA configuration.

As indicated in Fig. 2, the two robots must execute coordinated motions in order to replace the functionality of the SCARA. Since the θ, z robot manipulator picks a part which might be only loosely oriented in the feeder, it must perform a rotation in order to correctly align the part in the subassembly, while the x, y courier robot must move the subassembly to the correct position in the workspace. Thus the SCARA uses all of its degrees of freedom for both the pick and the place operation, whereas the new configuration uses two degrees of freedom for dealing with the part, and two separate degrees of freedom for dealing with the subassembly to accomplish the same purpose. This means that the motion required to position the subassembly can be overlapped in time with the motion required to pick the part (as indicated by the two motion arrows in Fig. 2)—something the SCARA cannot do. Another important feature is that each of the 2-DOF robots can be approximately an order of magnitude smaller in size than the typical SCARA for assembling the same-size product. This leads to a large increase in achievable precision. It also allows the shrinking of conventional automated assembly systems from large room size to tabletop size.

Planar motor sensing and control

Whereas high-performance servo-controlled rotary and linear actuators exist in well-developed forms, unfortunately the planar linear motor is available today only in the form of moderate-performance open-loop microsteppers, which prevents the achievement of maximum potential performance. To help ensure against loss of synchrony (missing steps), only two-thirds to three-fourths of the available force margin is typically used, reducing the potential maximum acceleration and velocity. Even so, susceptibility to loss of synchrony remains if large enough unanticipated external forces are acting. Additionally, settling times after moves are longer than desirable and there is no way to reject low-frequency external disturbances. There is only moderate stiffness requiring high power dissipation when holding a position.

These problems can be alleviated by incorporating a position sensor to accurately measure the relative displacements of the planar linear motor robot and its platen at a bandwidth that is high enough to be used for servo control.

The motor sections have fine teeth (typically 0.5 mm wide on a 1.0 mm pitch) and the platen has a two-dimensional array of square teeth of corresponding width and pitch. After chemical machining, the platen surface is planarized using epoxy to form the air-bearing surface. We are investigating ac magnetic, and optical fluorescence sensing techniques [3]. The magnetic sensor has achieved 1 μm position resolution and is compact and easy to fabricate. The optical fluorescence sensor has the advantage of complete insensitivity to nearby motor fields.

We are currently working to integrate these sensing techniques into the planar linear motors and plan to use variable structure control methods for greatly enhanced performance.

3 Miniature factories

We are developing prototype miniature factories (minifactories) for precision assembly that are based on the modular robotic elements presented in the previous sections. Platens for the closed-loop planar motors will be in the form of field-joinable tiles, enabling many different assembly line topologies to be realized. Each platen tile is supported by a modular base unit supplying power, air, vacuum, and network services. Modular structural bridges attached to the base units and spanning the platens will support the manipulator/feeders. Additional overhead equipment such as glue-dispensers, lasers, screw driving heads, and metal forming (spinning, swaging, etc.) tools can be incorporated.

Each active modular robotic element has its own powerful local computing resource and is represented by a software agent. Each agent implements servo control algorithms, maintains state information, communicates with any or all other agents, and contains internal functional and geometric descriptions of itself for use during minifactory modeling, simulation, and programming.

4 Agile Assembly Architecture

Figure 3 illustrates the main features of our proposed AAA. In Fig. 3(a), a manufacturing engineer (minifactory *designer*) is shown interacting with a comprehensive modeling and simulation environment. Functional models of the minifactory components are distributed—they reside within each minifactory module at the geographic location of the module vendor company. When a minifactory model is generated in, *e.g.*, Pittsburgh, the various robotic modules which make up the model might be physically located in Akron, or Detroit, etc. Thus the modeler/simulator in Pittsburgh needs no prior knowledge of the components. Further, by accessing and incorporating data from each on-line module remotely (by Internet), the modeler/simulator has only up to date and reliable information—instead of catalog or faxed data sheet information which might not reflect the currently available module product. During the creation of the minifactory design (model), the designer is free to select and try out (simulate) a wide variety of configurations using modules from many different sources to arrive at a final design (virtual minifactory) shown in Fig. 3(b). The designer may also make use of various tools such as automated assembly sequence planners, schedulers, and layout tools.

From the perspective of the minifactory module supplier or *vendor*, manufacturing modules complying with the minifactory paradigm are designed, built, and programmed by traditional means. Modules offered for use are placed "on the shelf" and plugged into the Internet, thereby becoming available to any minifactory designer. Synchronizing and lockout means are provided to mediate simultaneous engagement by multiple designers. Modules selected by (geographically distant) designers for use in real minifactories are leased according to usage schedules or other criteria and air-shipped to their destinations [Fig. 3(c)] ready for set up and work within hours of their arrival.

From the perspective of the minifactory *builder*, who may be geographically separated from both the designer and module vendors, the minifactory is rapidly set up manually by "snapping together" modules and hooking them up to four bused services (power, air, vacuum, network) as illustrated in Fig. 3(d). This is done by following a plan generated as a by-product of the minifactory design process. It is neither necessary to configure the minifactory exactly according to the model, nor to precisely place each of the modular robotic elements. One or more high-performance general-purpose workstations are connected for modeling, simulation, programming, debugging, and operation monitoring.

Once the (real) minifactory is physically configured and set up, an automated process is begun whereby the subproduct courier modules "explore" their local domains to determine the precise locations and identities of all other modular elements as well as the topology and boundaries of the available workspace. This information is broadcast by each courier module and collected by the workstation modeler. Combined with geometric and functional information from each of the other modules, a complete minifactory model is automatically generated by the minifactory itself [Fig. 3(e)]. This model resembles the original design model, except the new model accurately reflects the actual "as built" minifactory.

From the perspective of the minifactory *programmer*, once the automatically-generated model is complete, it is programmed manually from an attached workstation using mostly graphical methods as illustrated in Fig. 3(f). Each active minifactory module embodies an agent representing it which presents multiple views to the programming environment. For example, the functional controls of a module are accessed and manipulated through its *dashboard* view. A module's public input and output ports are available through its *interface* view, etc. The minifactory is programmed by graphically connecting outputs to inputs and specifying actions to be performed from internal repertoires. For example, a part handled by a manipulator/feeder module can be aligned with and placed on a subassembly carried by a courier module (as in Fig. 2) by specifying a set of coordinating actions which must occur between modules to carry out this task.

From the perspective of the minifactory *operator*, once the minifactory is programmed, execution takes place in an event-driven, asynchronous manner, without supervisory control at any level [Fig. 3(g)]. Attached workstations perform monitoring and debugging functions (in event of non-recoverable failures). Supplying the minifactory with parts on demand is done manually, and removal of finished products is done by other automated or semi-automated means.

At any later time, the minifactory can be reconfigured to respond to changing market requirements [Fig. 3(h)]. Modules can be added or removed, and new minifactory models can be automatically re-generated. At any time, modules no longer needed can be returned to the on-line pool for use by other manufacturers [Fig. 3(i)].

5 Project Status

We began working on several aspects of the AAA in early 1994.

Solid models of minifactory elements and various minifactory layouts have been developed, allowing us to generate animated sequences which include parts placement on subassemblies carried by couriers.

We have invented two position sensing technologies for the planar linear motors that comprise the minifactory couriers [3]. Critical electromechanical

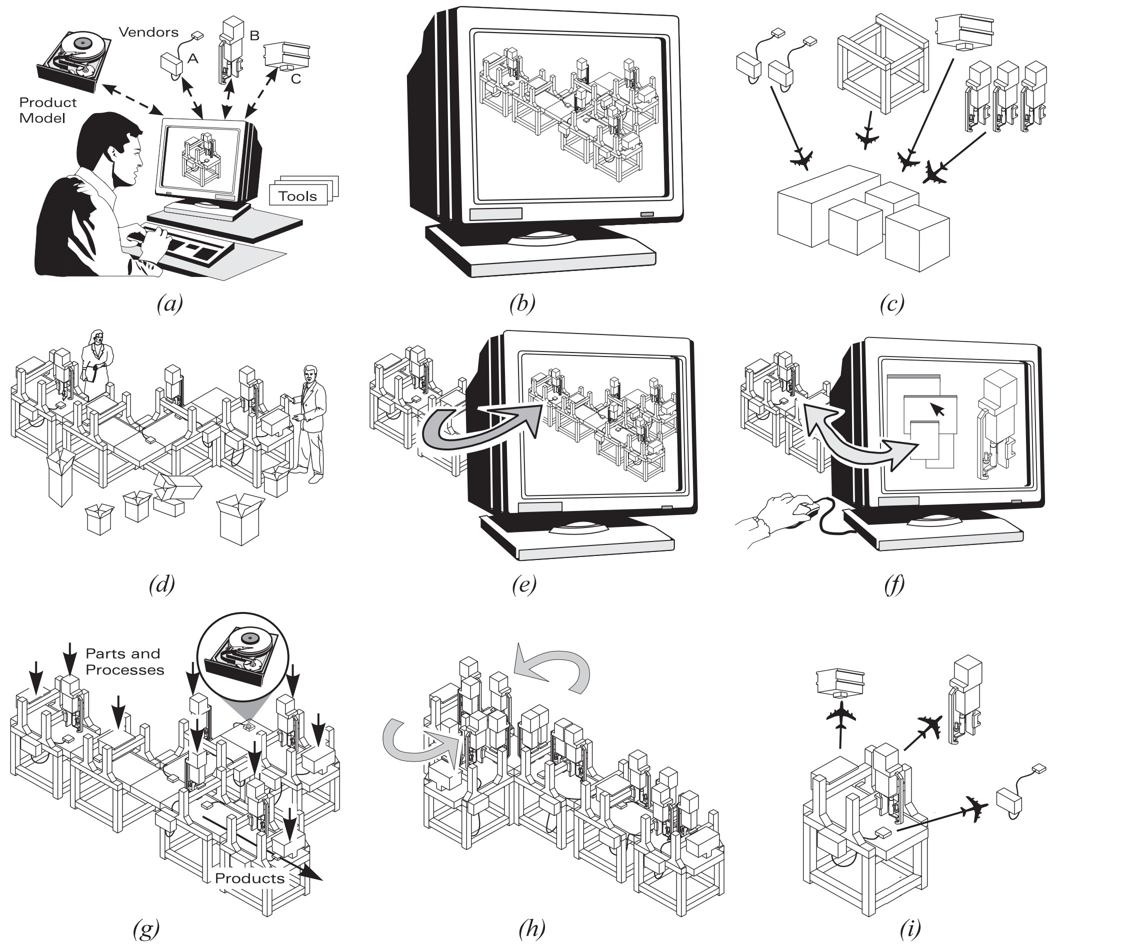

Figure 3: Proposed Agile Assembly Architecture Scenario. (a) Design with access of remote modules via Internet, (b) completed geometric and functional model, (c) ordering and shipment of modules to manufacturing site, (d) rapid assembly of minifactory, (e) automatic generation of updated model from real minifactory, (f) interactive graphical programming, (g) operation, (h) rapid re-configuration to meet changing requirements, (i) re-use of components no longer needed.

properties requiring modeling for the planar linear motors have been identified and we have begun to characterize the key properties. A simulation using a simple motor model demonstrated the dramatic performance improvements possible by adding sensors and closed-loop control.

We have studied the problem of flexible bulk parts feeding in the minifactory context, and have invented a novel singulation mechanism using flexible belts to extract parts from the storage bin, deliver them to the orientation subsystem, and return unselected parts to the bin.

A "Version 0" minifactory based on commercial parts is under construction and partially operating.

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References

[1] R. Hammer, "Combined linear-rotary direct drive step motor." U.S. Patent 5,093,596, March 1992.

[2] V. Scheinman, "RobotWorld: a multiple robot vision guided assembly system," in *Robotics Research, the Fourth International Symposium* (R. Bolles and B. Roth, eds.), (Santa Cruz, CA), pp. 23–27, MIT Press, 1987.

[3] A. E. Brennemann and R. L. Hollis, "Magnetic and optical-fluorescence position sensing for planar linear motors," in *Proc. Int'l Conf. on Intelligent Robots and Systems*, vol. 3, (Pittsburgh), pp. 101–107, August 1995.