

# A FLEXIBLE MANUFACTURING WORKSTATION

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The flexible manufacturing facilities for current and future products must meet demanding productivity objectives and still be highly responsive to changeable customer needs. One method used to accomplish the productivity goals in manufacturing is to develop an open hardware and software architecture for production workstations. We describe a flexible workstation that provides specific capabilities in a broad spectrum of manufacturing applications, while conforming to the open architecture standards established within AT&T.

## Background

Increased awareness of the importance of manufacturing to our economic well-being has intensified efforts to understand the manufacturing needs and problems that will be critical to our competitiveness in the future. Broadly speaking, the challenge is to maximize manufacturing productivity. But manufacturing productivity, defined as manufacturing value added divided by manufacturing cost added, turns out to be a complex, highly dynamic function of many variables. Prominent among them are the characteristics of the production facilities used for the fundamental value-adding functions of transforming materials and parts into products.

When evaluating production facilities, one usually focuses on facility cost and on specific capabilities that determine suitability for the particular manufacturing function. While these are important factors, often even more important—for overall effect on manufacturing productivity—may be flexibility, evolvability, ease of use, and compatibility with an overall computer integrated manufacturing architecture (CIMA).

The flexible manufacturing workstation outlined here is a cost-effective production facility for providing specific capabilities that are valuable in a broad spectrum of manufacturing applications. Specifically, it is a high-accuracy, multielement system, where each element may be a robotic manipulator that has three or more degrees of freedom (i.e., the robot's "arm and hand"), an inspection or testing fixture, or a product conveyance tray. The manipulators move on the ceiling or floor of a

Cartesian workspace whose overall size and geometry can be engineered to suit application needs.

These key attributes of the flexible workstation combine to make it an attractive “automation platform”:

- Very high accuracy in performing light assembly operations. The thrust of technology for packaging and interconnecting electronic and photonic devices is toward smallness and denseness. Thus, the capability to do high-precision assembly makes it a valuable tool for manufacturing engineers.
- Flexibility and versatility, not only in the context of “programmability” but also in its intrinsic “multirobot” capability. This allows manufacturing engineers to use cost-effective “helper-doer” strategies for implementing assembly functions in addition to the traditional serial strategies.
- Scalable architecture. This allows the flexible workstation to be applied to many different uses across a diverse set of manufacturing operations (e.g., component packaging and testing, hybrid integrated-circuit assembly, surface-mount assembly, nonstandard parts assembly, equipment and apparatus assembly, component inspection, etc.), while conforming to an overall CIMA.<sup>1</sup> The latter assures easy integration into a manufacturing environment and the ability to assimilate new technology (e.g., new sensing or manipulating elements) as desired.
- A programming language and environment that simplifies the management of multiple, cooperating elements in the workspace (multiple manipulators, cameras, sensors, etc.).

In the rest of this paper, we highlight the aspects of the flexible workstation’s design that are important to realizing these attributes, and describe an initial implementation that is currently in use at an AT&T factory.<sup>2</sup>

### Basic System Structure

A robotic system consists of actuators, such as electric motors, arranged in a way that permits a mechanical structure to move in a well-defined space, referred to as the *robot workspace*. Motions are achieved in a controlled way that allows reproducible actions and flexibility in defining new tasks for the robot.

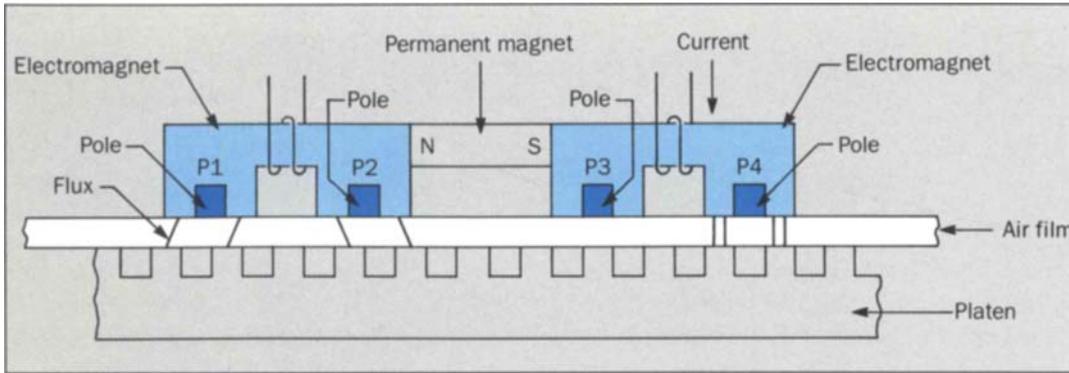
#### Panel 1. Acronyms in This Paper

ANSI	American National Standards Institute
BASIC	beginner’s all-purpose symbolic instruction code
CIMA	computer integrated manufacturing architecture
CPU	central-processing unit
DOS	disk operating system
ECP	equipment control program
I/O	input/output
MRL	multiple robot language
R&D	research and development
SCP	station control program

Since the beginning of the robot evolution in the early 1950s, many variations of the predominant mechanical structure and actuators have been used in industrial robots. The early systems were used mostly in heavy tasks, such as welding and spray painting. Over the past several years, demand for robotics for electronics assembly has increased, which, in some ways, has redefined the performance requirements for industrial robots. High speed, accuracy, ease of programming, and low cost are key attributes, with different and often more demanding criteria for the electronics industry than for heavy-manufacturing industries.

Most of today’s industrial electronics-assembly robots evolved from the heavy industrial robots of the 1960s and 1970s. Their robotic mechanical structures and actuators have improved significantly, and they offer high performance and relatively low cost. But despite the technological improvements, most of these robots still are heavy and bulky structures, with geometries that do not allow much flexibility in configuring an application environment. Furthermore, if people must interact with this type of machine, extensive protective systems are needed to prevent accidents.

The flexible workstation’s design avoids these drawbacks, while providing a cost-effective capability to assemble and handle electronic devices and other small parts. The basic concept is to use a two-dimensional linear motor to obtain motion on a plane. Additional motions may



**Figure 1. Basic forcer principle. P1 through P4 are poles of the two electromagnets, while N and S are the permanent magnet's North and South poles.**

then be obtained by attaching more actuators to the linear motor, as appropriate, to accomplish desired functions. The linear motor moves on the horizontal plane and another motor is used to provide motion normal to that plane. In this way, one can configure an *X-Y-Z* motion system with up to three more rotational motions for a system with six complete degrees of freedom. Such a system can provide the same motion geometry as conventional robotic systems.

**The Linear Motor.** For the past 15 years, linear motors have been used in positioning applications. Their use eliminates the need for gears or motion converters and provides high accuracy. These motors can accelerate small payloads at relatively high rates and can attain high velocities.

One type of linear motor, developed in the late 1960s, is known as the Sawyer motor. Its principle of operation is based on the interaction of magnetic flux fields to generate a well-controlled propulsive force.<sup>3</sup> A complete single-axis motor consists of an electromagnet assembly, usually referred to as the *forcer*; a toothed ferromagnetic *platen* that the forcer rides on; a *bearing* between the forcer and the platen; and a cable, called the *umbilical*, that brings current to the forcer.

Figure 1 illustrates the basic principle of motor construction and operation. The forcer has a permanent magnet and two electromagnets, each with two toothed poles for a total of four poles, arranged as shown in the diagram. A power supply provides current to the electromagnets.

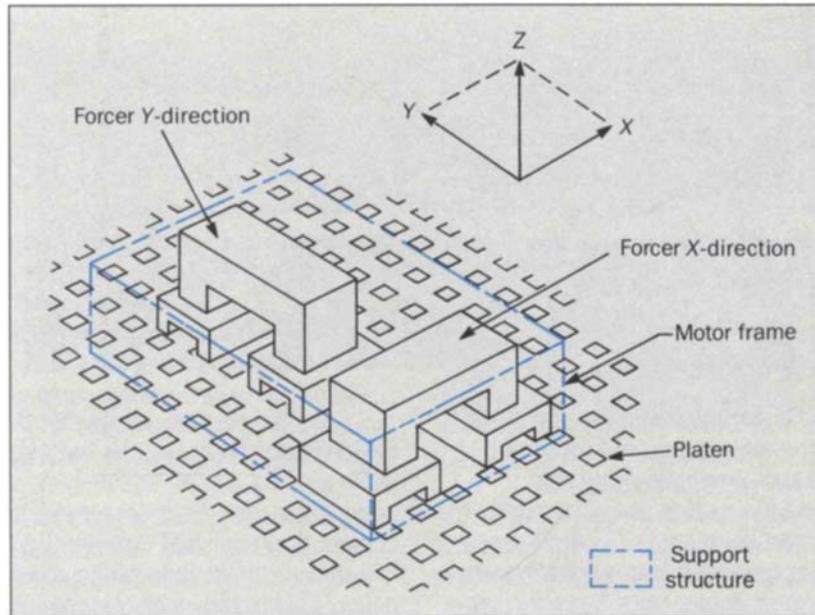
The permanent magnet flux flows through an electromagnet's poles, the bearing, and the platen and, as illustrated on the left in Figure 1, divides in two at both poles if the next electromagnet is not energized. When a current is established through the adjacent electromagnet's coil, the resultant flux can be commutated between its poles. This is shown on the right side in Figure 1, where a current has energized the electromagnet causing all flux to pass through pole P4, and none through P3.

With appropriate geometry of the ferromagnetic surfaces, such as in Figure 1, the commutated flux generates a force with one component normal to the platen and another parallel to the platen. The *normal force* tends to pull the forcer toward the platen. To maintain separation between the forcer and platen, a bearing medium of pressurized air is provided by the umbilical cable and through orifices on the motor surface that face the platen. The *parallel force* is the propulsive force that moves the motor along the platen.

An electronic driver that switches the currents in the electromagnet coils in sequence controls the motor's motion. The frequency of the current determines the speed of motion, and changes in that frequency can control the acceleration.

In conventional motor terms, one can think of the platen as the stator and the forcer as the rotor. The pitch of the platen teeth (0.04 inch in the initial implementation) matches that of each forcer pole, and one complete cycle of current switching through the poles produces motion over one tooth interval. For "microstepping" between the

**Figure 2. A forcer assembly for planar motion.**



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poles, one can appropriately shape the waveforms of the coil currents. (A typical microstep is about 0.0001 inch.)

The nominal motor design that we used can produce a maximum propulsive force of about 10 pounds. Without a payload, it can accelerate at 3g and reach terminal velocities of about 100 inches per second, if enough distance is available.

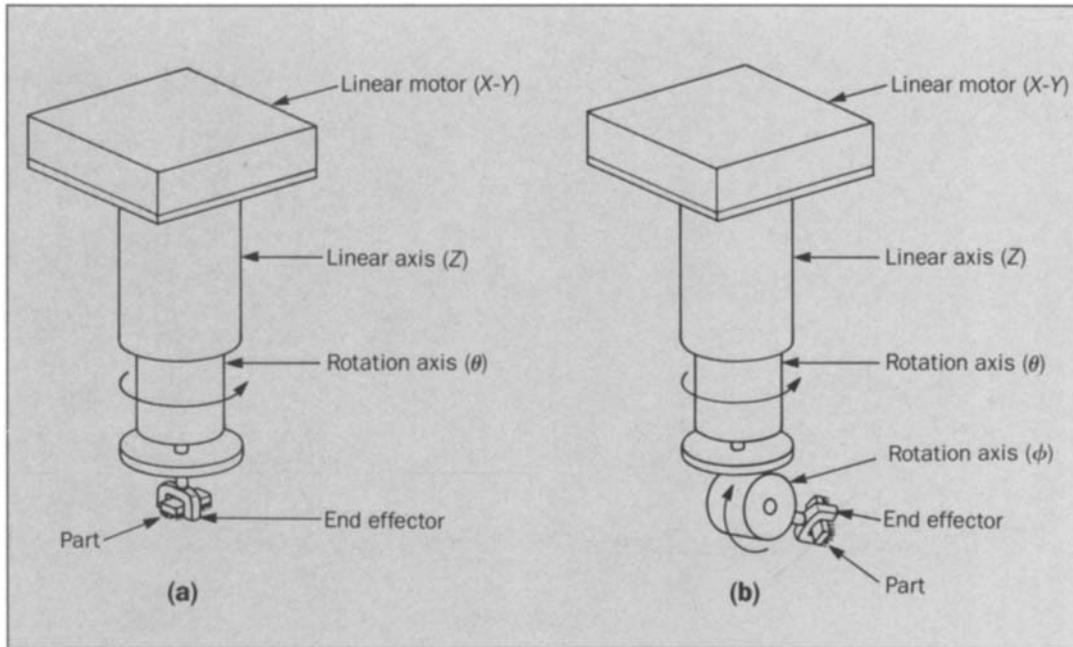
**Using the Linear Motor in a Robotic System.** As Figure 2 shows, the linear motor can be used to achieve planar motion. Two forcers housed in the same frame produce two perpendicular forces. In this way, the motor can move in two orthogonal and independent directions that define its plane of motion. One can achieve any angle of motion through combinations of moves of the appropriate magnitude.

In a two-axis linear motor system, a “waffle” pattern of equidistant square teeth of given pitch form the platen. Because a nonmagnetic material fills the space between the teeth, the motor moves on a two-dimensional smooth surface. The combination of the platen and the air bearing permits exceptionally smooth motion with virtually no friction. Nearly frictionless motion is an important factor for achieving the high speed and accuracy needed in electronics manufacturing.

For motion normal to the platen, one attaches a linear actuator and support structure to the motor body. Another actuator can then be attached at the end of the linear mechanism to provide rotation about the normal axis (Figure 3a). This configuration provides four degrees of freedom ( $X$ ,  $Y$ ,  $Z$ , and  $\theta$ ) in a Cartesian arrangement. Additional degrees of freedom can be obtained in similar ways. Figure 3b, for example, shows a way to design a system with five degrees of freedom—one that can also manipulate objects in a tilt, or angle  $\phi$ .

**Geometry of Motions.** The linear motor assembly, usually called the *manipulator*, in combination with the platen, naturally lends itself to various possibilities for configuring a robotic workstation. The platen can be mounted horizontally, vertically, or at any angle, thus establishing the orientation of the workspace. Using the platen as a horizontal “ceiling” for a workspace is convenient for electronics-assembly applications because it adapts to existing conveyor-driven assembly systems.

The tip of the manipulator can be made to follow any prescribed path in space. Electronics-assembly operations often require only point-to-point positioning capability. In such cases, only speed and accuracy—rather



**Figure 3. Manipulator assemblies. (a) A manipulator assembly with four degrees of freedom (X, Y, Z, and  $\theta$ ). (b) Possible arrangement for a manipulator assembly with five degrees of freedom (X, Y, Z,  $\theta$ , and  $\phi$ ).**

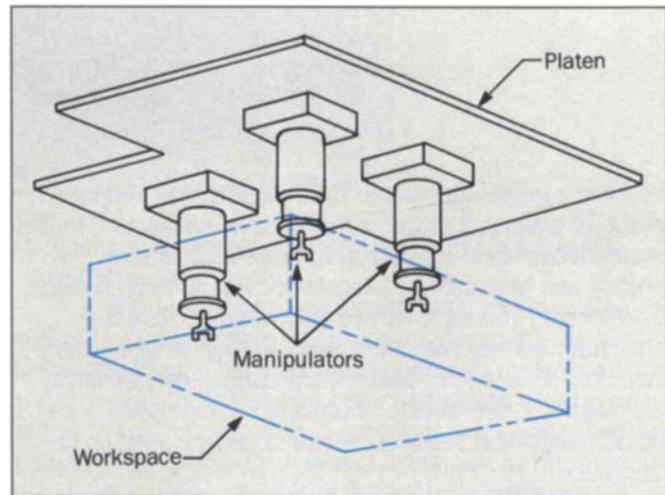
than the path followed—are important.

**Multiple Manipulators.** An important advantage of a system based on a linear motor is that it allows several manipulators to operate on the same platen (Figure 4). However, the size of the platen and the presence of the umbilical cables that somewhat restrict the autonomy of the manipulators limit the number of additional manipulators that can be accommodated easily.

In certain application scenarios, multiple manipulators must follow intersecting paths on the platen. Such an approach requires that we incorporate some strategy for avoiding collisions. In other situations, the paths may not intersect but their end points may coincide. Here, simplified collision-avoidance strategies can be used.

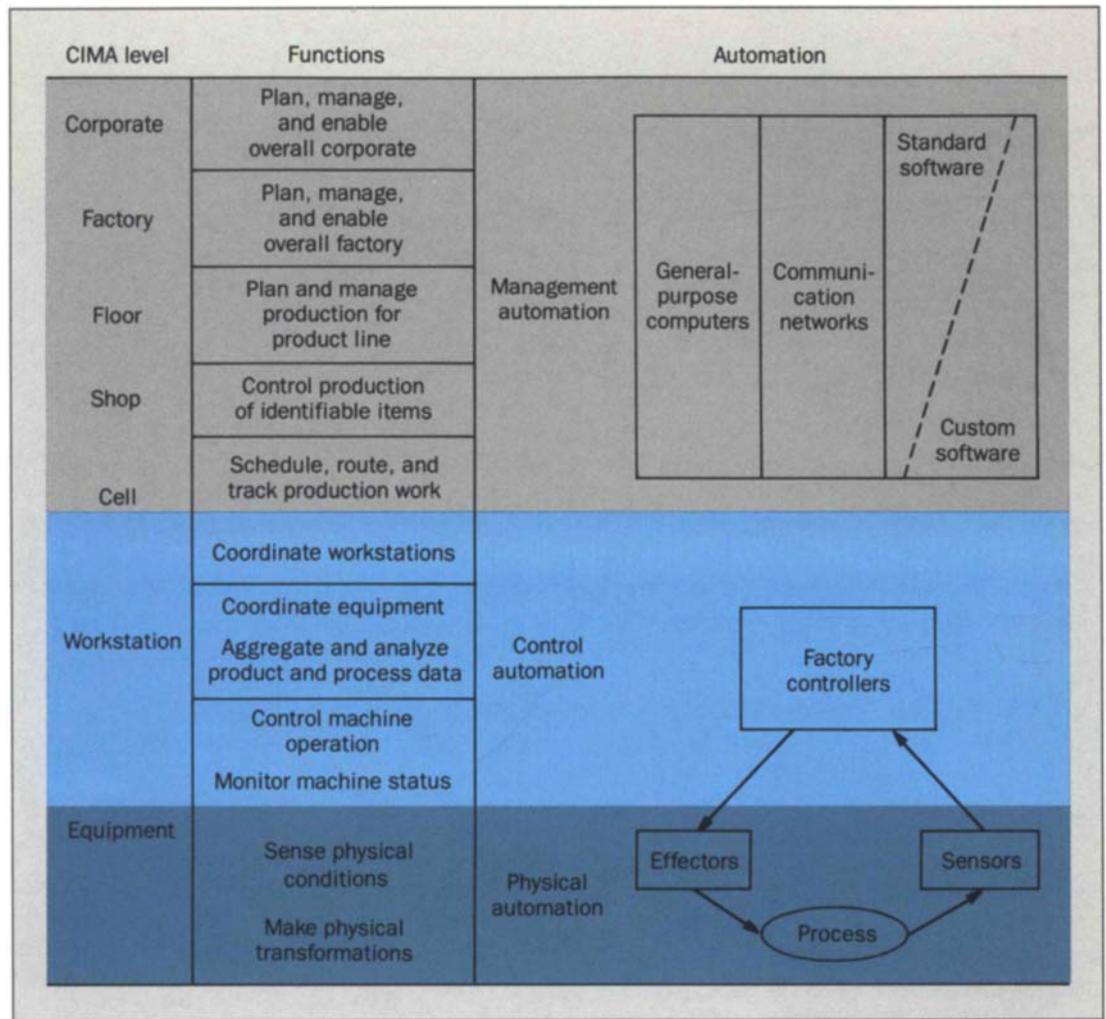
Yet another option for configuring multiple robots for assembly is one where each manipulator is assigned its own workspace, eliminating the need for any collision-avoidance strategy. This is the simplest—and often preferred—implementation, especially for progressive-assembly lines, where it often yields maximum throughput.

An additional benefit of the linear-motor-based manipulator is the ease of adding or removing new manipu-



**Figure 4. If a system is based on a linear motor, multiple manipulators can operate on the same platen.**

**Figure 5. The computer integrated manufacturing architecture (CIMA) provides a functional framework for organizing manufacturing operations. The flexible workstation's control architecture meets this standard's workstation and equipment levels.**



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lators in a given workspace. Each manipulator weighs about 10 pounds, and the umbilical cable connects it to the system controller. Traditional robots weigh hundreds of pounds and have moving weights of from 50 to 80 pounds. These heavy robots must be rigidly attached to some structure, making rearrangements in the workspace difficult. The linear-motor-based manipulator floats on an air bearing in the presence of a small force that opposes its motion, making it relatively safe and easy to position on the platen.

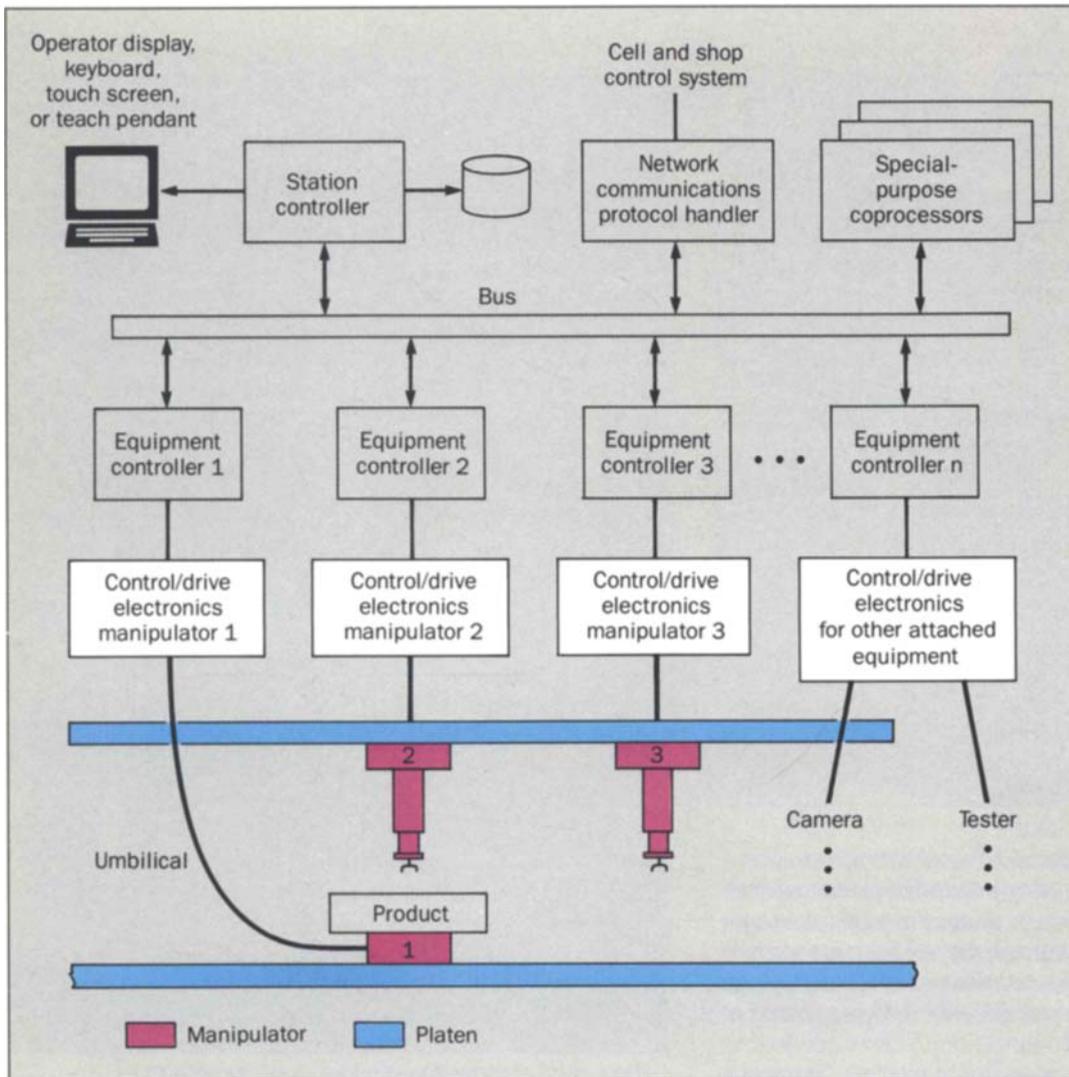
#### Control Architecture

Standardizing on an appropriate control architecture for automation results in many important benefits. As has been reported,<sup>1,4</sup> AT&T has adopted a seven-level com-

puter integrated manufacturing architecture, or CIMA (Figure 5). The flexible workstation's control architecture conforms to the CIMA standard's workstation and equipment levels and can also be used as an R&D vehicle for further refinement of the CIMA.

**Hardware.** A bus-based system is well-suited to control the flexible workstation. Such systems can be readily scaled, using multiple processors, to provide great computing power when needed, and can be easily reconfigured by changing plug-compatible hardware.

Figure 6 shows such a system for the flexible workstation. The system always includes a "station control" central-processing unit (CPU) and may also include CPUs to operate pieces of equipment, such as manipulators, parts feeders, vision systems, etc. The diagram also



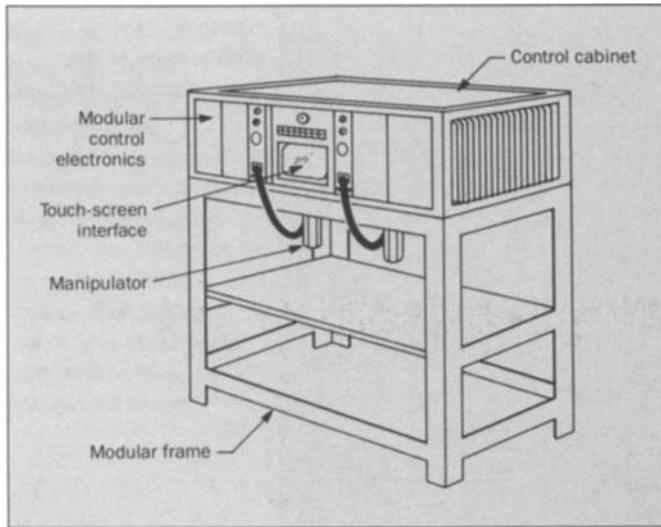
**Figure 6. Control architecture of the flexible workstation.**

shows drive electronics for equipment that operates manipulator axes of motion. The manipulator configuration can be modified to meet application needs without extensive redesign. Also, vision and testing capabilities can be integrated easily with this architecture.

**Software.** Separate equipment control programs (ECP) control each item of equipment in the workstation and are coordinated by a station control program (SCP). The SCP and ECPs run in the flexible-workstation support environment that provides needed database managers, robot drivers, other low-level I/O (input/output) functions, and interface functions to communicate with the cell controller. The ECPs run concurrently with the SCP in the

station control processor or independently in the equipment control processors.

We developed a new, interpretive language (the multiple robot language, MRL) for programming the flexible workstation. This language supports procedure calls and includes a multitasking kernel that allows user programs to run concurrently under a single-tasking operating system (e.g., DOS). (The kernel is the part of the software that allocates resources and controls processes.) MRL includes a relevant subset of the ANSI BASIC commands, plus commands for robot movement, sensor I/O, touch-screen control, and coordinate-transformation operators. It is written in C language and is portable to a wide



**Figure 7. An implementation of the flexible workstation.**

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range of computing environments.

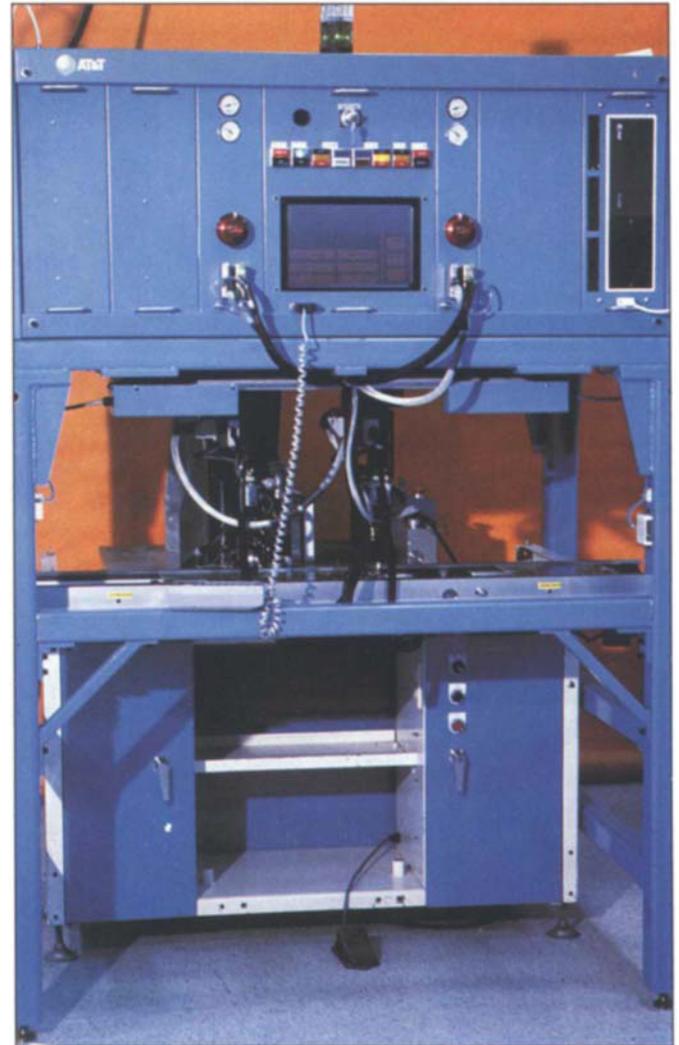
MRL has been designed to allow the user to arrange the application according to the AT&T standardization strategy for controllers.<sup>1</sup> As specified in this strategy, each item of equipment is controlled by an associated ECP that executes as an autonomous task; an SCP that also executes as an autonomous task does the coordination. MRL includes intertask communication to allow needed coordination, and provides the ability to execute “immediate” commands from the console.

In combination, these features of MRL make it easy for an application programmer to create and debug programs that:

- Control and coordinate the activities of the flexible workstation’s equipment (individual robots, parts feeders, other peripheral devices).
- Set up the workstation’s routine application so that an operator at a touch-sensitive display screen can completely control it.

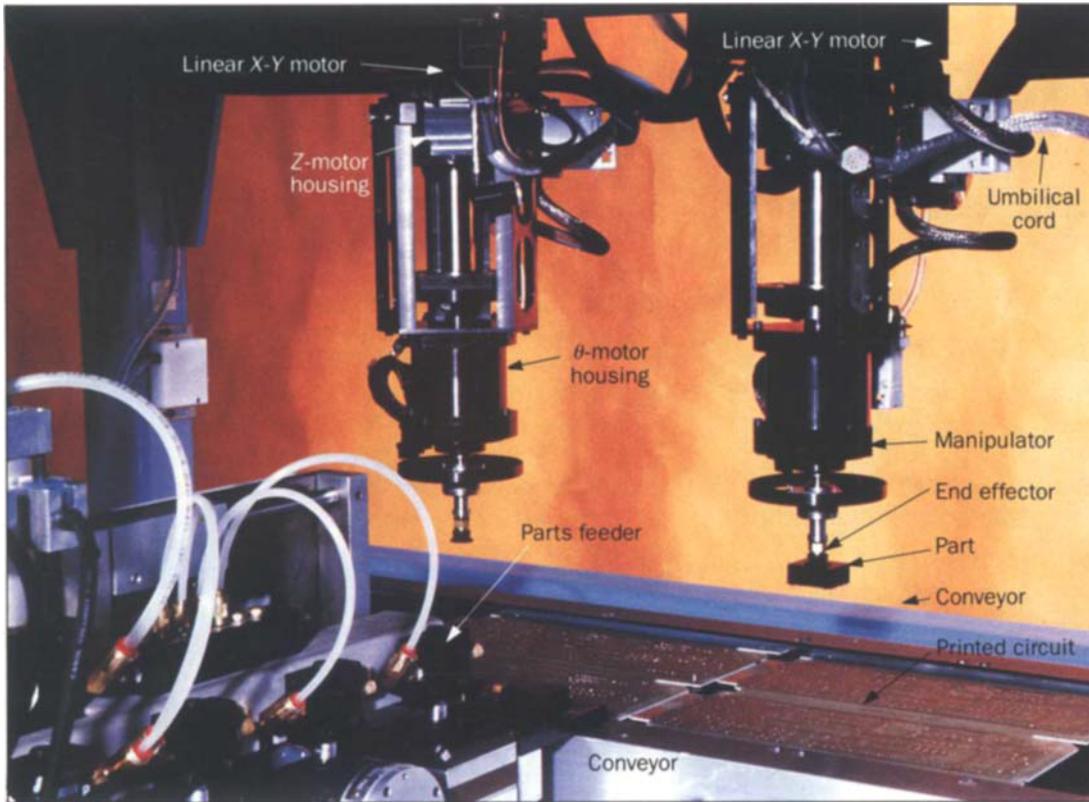
#### **Implementation**

Figure 7 shows the first implementation of the flexible workstation.<sup>2</sup> In this two-manipulator system, an



X-Y-Z frame that supports the manipulators, platen, control electronics, and computer establishes the overall workspace. The physical design—with drive electronics, motion control, computer, and operator I/O elements packaged in separate pull-out drawers—provides for a high degree of modularity.

The manipulators have been designed for small assembly operations and include motion in the Z axis and a  $\theta$  rotation about the Z axis. They have provision for air, signal, and power sources through the linear motor’s umbilical cord. Application-dependent end effectors are attached to the manipulator, and can include vacuum and servo grippers with sensors. The manipulator assembly can be changed to meet specific application needs.



**Figure 8.** This integrated flexible workstation installs non-standard parts into printed circuit boards. (Facing page) The workstation's control cabinet with a touch-screen display for the operator occupies the top portion of the modular frame. The workspace is below the cabinet. Two manipulators move on the "ceiling" of the workspace, above a conveyor that

transports printed circuits. Umbilical cable (the white tubing) provides pressurized air, signals, and power. An external-equipment control cabinet sits at the bottom between the frame's legs. (Above) Each manipulator has its own workspace. The  $\theta$  rotation and the Z axis enable the manipulator to lift and position each part correctly.

To minimize floor-space requirements, the workstation's electronics are located above the workspace. Conveyors can be integrated with the workstation beneath the platen, and parts-presentation equipment can be located on the four sides of the structure that surrounds the platen area.

The first flexible workstation was installed at an AT&T manufacturing location,<sup>2</sup> where it is being used to insert nonstandard components into printed circuit boards. In this application, each manipulator is assigned its own workspace beneath the platen. The assembly functions are partitioned so that the two manipulators (Figure 8) can operate autonomously, thus providing up to twice the throughput of a single-manipulator system at a fractional incremental cost.

#### Summary

The current version of the flexible workstation has proved to be reliable, accurate, easy to use, and cost-effective. Consequently, plans are underway to use it in a variety of applications, including nonstandard component assembly, electronic testing, progressive assembly, and device packaging.

The flexible workstation is also proving to be a valuable platform for proving-in controller architecture and standardization strategies. The inherent parallelism that this multiple-element system provides is potentially of great benefit, but can also be a source of complexity. We desire that our controller architecture and standardization strategy allow management of parallel systems, while deriving full benefit of their capabilities. We are testing and

refining the standardization approach as we pursue full realization of the benefits of parallelism in the flexible workstation.

#### Acknowledgments

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#### References

1. R. L. Campbell, "An Architecture for Factory Control Automation," *AT&T Technical Journal*, Vol. 66, No. 5, September/October 1987, pp. 77-85.
2. L. S. Decelle, "Design of a Robotic Workstation for Component Insertion," *AT&T Technical Journal*, Vol. 67, No. 2, March/April 1988, pp. 15-22.
3. J. Dunfield et al., "Sawyer-Principle Linear Motor Positions Without Feedback," *Power Transmission Design*, Vol. 16, No. 6, June 1974, pp. 72-76.
4. L. B. Boza et al., "CIMA—An Integrated Architecture For Product Realization," *AT&T Technical Journal*, July/August 1986, Vol. 66, No. 4, pp. 17-24.

#### Biographies (continued)

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