J.G. Aceti | C.B. Carroll

Robotic assembly of the VideoDisc player's arm drive

Electromechanical assembly—an elusive task for robots, and a lucrative area for manufacturing—has begun at RCA.

In April 1982, the VideoDisc Player Manufacturing Technology group at RCA Consumer Electronics and the Electromechanical Systems Group at RCA Laboratories proposed a prototype subassembly as a candidate for robotic assembly. The subassembly was a VideoDisc arm drive to be used in RCA's prototyped J-line player, scheduled to be assembled in the Bloomington plant. This project would become the first large-volume robotic assembly system within RCA. The obstacles to implementation present a double-edged sword, both technological and economic. But, correspondingly, the rewards for meeting the challenge will be a two-pronged solution to lagging U.S. productivity.

Robotic assembly today

Electromechanical assembly presents a formidable task to robotic system designers.

Abstract: *Competitiveness in manufacturing allows only the progressive and flexible companies to survive. Robots will play a role in the factory of the future as the flexible muscle driving the manufacturing process. This is the account of RCA's first introduction of a robot into the production environment of electromechanical assembly. It involves interesting economic and technological issues, and shows cooperation among groups at RCA Consumer Electronics and RCA Laboratories.*

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Programmable mechanical arms have accomplished many industrial tasks—such as spray painting, welding, and part handling—where the task does not require the exacting accuracy of assembly. Assembly requires more of the system—an additional degree of flexibility, adaptability, precision, and in general, sensory feedback mechanisms similar to a human assembler on a production line.

Assembly and inspection of product account for 40 percent of direct labor in the radio and television industry.[1] Many of the "simple" tasks performed by these workers actually require a complex interaction among sight, hearing, and touch that is difficult if not impossible for an electromechanical system to integrate and mimic. Moreover, robotic system designers must pay particular attention to the part-feeding methods that provide the robot with oriented and accurately positioned parts (see box, page 12). And even before that, careful consideration should be given to the design of parts for automatic handling. A more extensive review of this subject is covered in an article by Malcolm Cobb, elsewhere in this issue. Understandably, application of robots for assembly-line work has been minimal—amounting to a little over 5 percent of the robotic systems operating nationwide. A recent survey conducted by *Assembly Engineering* magazine showed that 13.3 percent of the 1,000 assembly plants participating in the study used robots and that 28.3 percent of those robots were part of the assembly line. The other 71.1 percent were used for part handling, electronic component assembly, arc welding, stand-alone operations, inspection, spot welding, fastening, wire harness assembly, and calibration.[2]

Economic and political issues

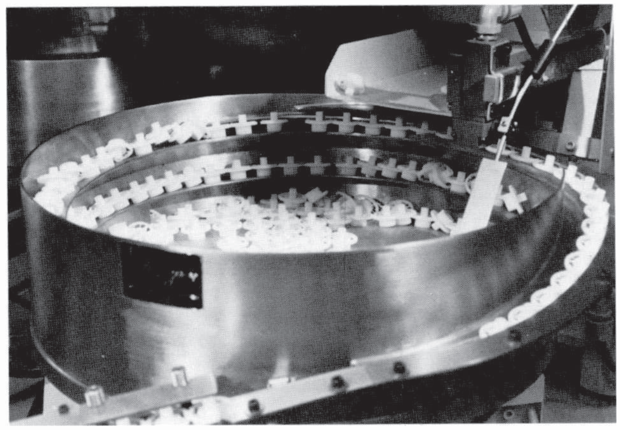
With the impressive array of tasks being performed and the potential economic advantages, why are only 13.3 percent involved in robotics? There are several reasons:

- Risk associated with new machinery
- Labor conflicts
- Inadequate project proposals

Understanding the risk

Those involved with providing, justifying, or using assembly automation equipment have associated the risk of using robotics with that of using uncompromising hard automation—machinery uniquely designed for a specific product, with little possibility for future modification. To a great extent, the difficulties associated with hard automation are appropriate, but the flexibility, reprogrammability, and reduced cost of modern robots have diminished the uncertainty of bringing automation into the factory. Robots can reduce both economic and technological risk—the economic risk of having automated assembly costing more than manual assembly and the technological risk of being inflexible to product improvements. An understanding of the economics when using truly reusable "off the shelf" equipment proves profitable by shortening the payback for each application. When all avenues of savings are consid-

Orienting and feeding parts



Part feeding is a technology that has lagged behind the advanced automation systems it supports. Neither flexible nor sophisticated, part-feeding equipment is usually constructed by artisans working in small specialized shops with welding torch and hammer.

The most common feeding method, bowl feeding, provides the builder with versatility to handle many different parts, and provides the user with many years of reliable service. Being the lowest-cost feeding method, designers should prepare for automating the assembly with bowl feeders by following some guidelines for part design.

Not all parts can be bowl fed. Delicate, sticky, light, tangled, or abrasive parts are generally not bowl fed. For most parts the overriding concern is geometry, and in particular, symmetry. If a part is either symmetric or grossly asymmetric, then feeding will be easier and more efficient.

Dr. Geoffrey Boothroyd, of the University of Massachusetts in Amherst, has researched this subject quite thoroughly and has produced a handbook called "Feeding and Orienting Techniques for Small Parts." Although the text is all-encompassing, three rules can be stated to cover most design problems:

1. Avoid projections, holes, or slots that will cause tangling with identical parts when placed in bulk in the feeder. This may be achieved by arranging that the holes or slots are smaller than the projections.
2. Attempt to make the parts symmetrical to avoid the need for extra orienting devices and the corresponding loss in feeder efficiency.
3. If symmetry cannot be achieved, exaggerate asymmetrical features to facilitate orienting or, alternatively, provide corresponding asymmetrical features that can be used to orient the parts.[6]

Providing the bowl builder with well-designed parts simplifies the bowl design and supplies the factory with a more reliable and efficient system.

ered, a window appears on the production volume scale (typically between 0.25 million and 2 million parts per annum) where robots compete favorably with manual labor and hard automation.

In addition to the typical costs associated with getting a robot up and running, an economic analysis includes the varying costs associated with auxiliary equipment (that is, fixtures, part-feeding mechanisms, vision systems, automatic tools) essential to support the assembly robot. For assembly applications, these costs can amount to three times that of the robot itself. With knowledgeable foresight, robotic assembly can still be had with minimal risk. Considering the robot by itself:

> "Robot manufacturers estimate that it will cost (average) about $6 per hour to operate a robot, based on a two shift operation and a useful equipment life of 8 years. If direct labor costs are around $16 per hour in a five-day, two shift operation, then justification is no problem . . . . This will give a payback period of less than two years for most robots . . . ."[3]

Labor conflicts

Due to insignificant unemployment relating directly to robots, few real conflicts have erupted between labor and management. Many robotic applications, especially in the metal-working industry, have replaced hazardous or tedious jobs without much complaint. But eventually, as large numbers of robots begin working on the plant floors, serious problems could erupt. Proper training programs can benefit the workers and the factory by channeling personnel into new and more appropriate jobs as system operators, programmers, and maintenance experts.

Inadequate proposals

When proposing the use of robots, it is essential that manufacturing engineers outline the potential risks and savings for management. Increased use of robots will occur not by the justification methods of the past but by outlining the additional savings beyond reduction of labor and increased quality. The value of robots as reusable tools must be considered, as must the value of increased flexibility gained by manufacturers who must constantly deal with consumer demand, part quality, and seasonal production variations.

In addition, the proposal should adequately define the need for maintenance personnel capable of supporting robotic systems, and show an increased awareness of the safety issues involved.

Robotic assembly within RCA

To dispel some of the reservations and to consider the possibilities, groups at RCA Laboratories are investigating various phases of flexible manufacturing. Flexible manufacturing, in a practical sense, is the means to vary the manufacturing process to accommodate changing market demands, product changes (within a family of products), without additional capital expenditure or labor. In particular, the area of robotic assembly is being studied for application in RCA's manufacturing facilities. What better way is there to learn and apply new-found knowledge than by doing a "real" job?

Designing the product for automation assembly

The initial task was to consider the feasibility of robotically assembling a 24-piece subassembly, the VideoDisc arm drive. After consideration, our first response was that the product could indeed be robotically assembled, but not economically. Several small external retaining rings, set screws, and a 3/8″ long extension spring presented formidable assembly tasks for the mechanical arm. Thus, we attempted to modify the design to one that is easier to assemble.

Applying a disciplined set of guidelines (Fig. 1), we designed a simplified product. The principal improvements were:

- Fifty percent reduction in part count
- Layered assembly
- Elimination of set screws and retaining rings
- Elimination of extension spring

Of course, there was no reduction in the capability or quality of the product (Fig. 2).

Today we would have taken the new design and quantitatively analyzed the improvements. Using a software package called *Design for Automatic and Manual Assembly,*[4] an assembly efficiency would be derived for comparison among any suggested improvements. Design-for-assembly cannot be overemphasized as a critical point in the design-for-manufacturing process. Not only is there a savings in part cost but also a drastic reduction in assembly time.

> "Experience shows that it is difficult to make large savings in cost by the introduction of automatic assembly in the manufacture of an existing product. In those cases where large savings are claimed, examination will show that often the savings are really due to changes in the design of the product necessitated by the introduction of the new process. It can probably be stated that, in most of these instances, even greater savings would be made if the new product were to be assembled manually. Undoubtedly, the greatest cost savings are to be made by careful consideration of the design of the product and its individual component parts."[5]

Less inventory, increased reliability, and higher quality are also realized without any additional capital investment if assembly is considered during the design phase. In addition, it is appropriate to design for automatic assembly by specifically allowing for automatic feeding/handling of components. Simple modifications may be made at this point for the purpose of robotically or automatically handling the part.

Modeling the assembly

Having a workable model, a strategy for assembly must be considered within the limits imposed by manufacturing. For the gearbox, the production rate was naturally a critical issue. One system working one shift had to produce 1,400 assemblies—one about every 20 seconds.

Knowing approximate execution times for various robot maneuvers, a machine-time schedule can be readily constructed. The user must creatively determine the sequence of events and must discover if any auxiliary equipment (that is, fixtures, vision, tactile feedback, etc.) will be employed. For maximum flexibility, a minimum amount of tooling should be considered. On the other hand, additional tooling can be used effectively to "buy time" by assisting the robot. Typically, dedicated hardware is required to feed parts to the robot (that is, bowl feeders, magazines, pallets). Unlike the robot, dedicated hardware is not easily reusable, and therefore, is less economical for medium-volume applications.

After many attempts, a scenario, or sequence of events, for assembling the gearbox was produced that called for an assembly time of under 20 seconds, and required a minimum amount of dedicated hardware (Fig. 3). In this case, hardware was used only to apply grease, accurately position parts, pre-mesh the three gears, and automatically apply screws. The scenario also required that:

- The potentiometer, lever, and gear be manually assembled—the design did not allow efficient use of the robot for this assembly.
- The three reduction gears be premeshed and a palnut accurately located below the cluster (a palnut is a formed sheet metal nut that is pushed rather than turned on a shaft).

1. Strive to minimize number of parts.
2. Select a base to which other parts will mate, that is, design the product in layers to allow each part to be assembled from above.
3. Ensure that the base part has features that facilitate locating and securing of mating parts.
4. Use liberal chamfers, tolerances, tapers, and rounded edges where possible.
5. Avoid expensive and time-consuming fastening operations, such as screwing, soldering, and so on.
6. Assure that parts remain in an oriented form from vendor to factory floor, or be certain that parts can be easily fed by conventional means.

Fig. 1. *General rules for designing a mechanical product for manual and automated assembly.*

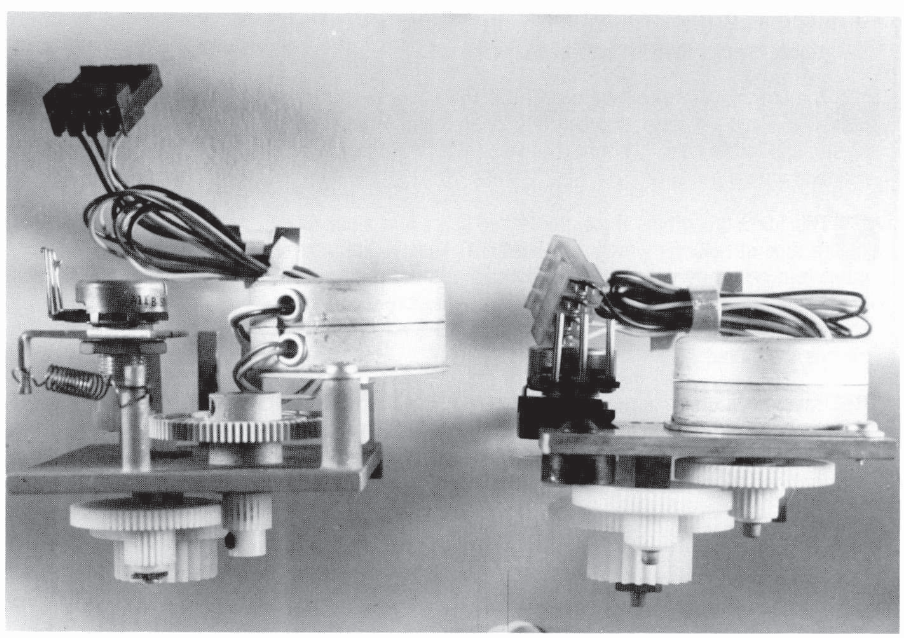
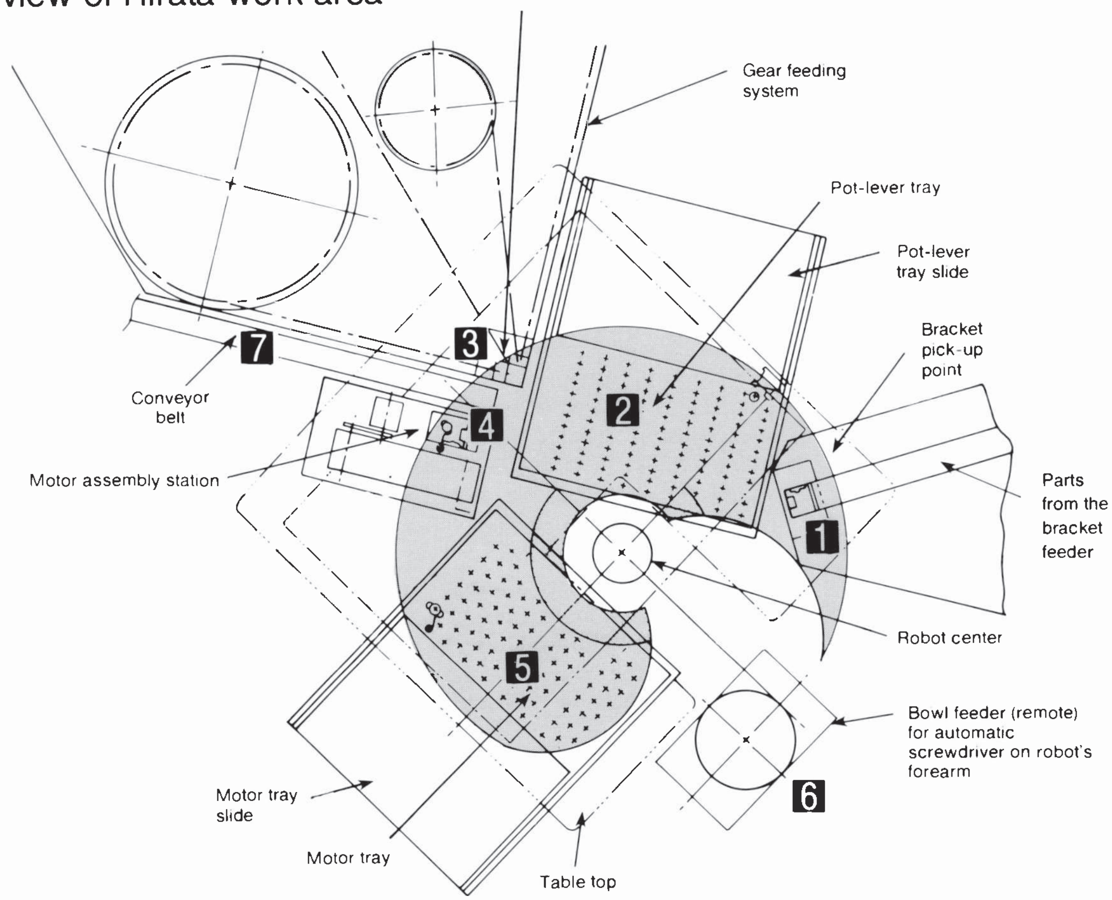


Fig. 2. *Following the design guidelines for assembly, the prototype design (left) was simplified, thereby making automated assembly feasible and manual assembly much faster.*

Overview of Hirata work area



1 The robot picks up a bracket from the bowl feeder's nest. The nest is instrumented to detect the part and test the bracket's three gear shafts for straightness. Failed parts are removed by the robot and rejected. A small amount of grease is also applied to each shaft for lubrication between the rotating gear and metal shaft. The gripper raises the part from the nest and a sensor on the gripper checks that the part is properly held.

2 The arm moves to remove one of the 108 pot-lever assemblies. Each pot-lever is accurately located and retained by a plastic clip in the tray. The arm is lowered until the bracket is snapped onto a pot-lever.

3 This station contains three premeshed gears and a palnut (a type of fastener which is pushed on). The system interrogates four proximity sensors for positive location of each part before the arm lowers the bracket into the assembly. Each shaft on the bracket moves into its mating gear until the longest shaft pierces the palnut.

4 Having captured the gears and the palnut, the robot positions the partial assembly in the motor assembly station. This station is equipped to sense that the pot-lever was properly installed and that one of the two screws is applied in the next sequence.

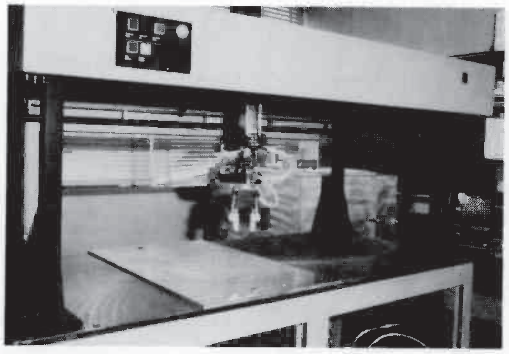
5 The gripper is moved over and selects one of 108 motors from a tray similar to the pot-lever tray and moves back to the motor assembly station. The motor is moved in a way that meshes the pinion smoothly. While placing the part on the bracket, the system actuates a clamp that will hold the motor in place while the robot positions the screwdriver and applies two screws.

6 A Weber automatic screwdriver mounted on the forearm of the robot is fed screws from a remote bowl feeder via a pneumatic feed tube.The system controller positions the arm and actuates the driver. After fastening a motor to the bracket, the robot swings around to the bracket station to begin the sequence again.

7 Simultaneously, the motor assembly station flips the completed assembly onto a belt conveyor, which moves the part away from the robot. If the robot has successfully completed the assembly, it will travel down the conveyor to an operator for visual and electromechanical inspection. Incomplete assemblies are directed to a rework bin. Incomplete assemblies are caused by parts missing in trays or nests or the robot failing to pick up a part. If a missing part causes a jam, the system will stop and notify the operator via a red rotating beacon. Inconsequential misses are ignored by the robot and sorted on the conveyor, thus minimizing downtime. At the completion of 108 assemblies, the system automatically stops and turns on the rotating beacon. The operator simply replaces the empty trays with filled ones and presses a resume button.

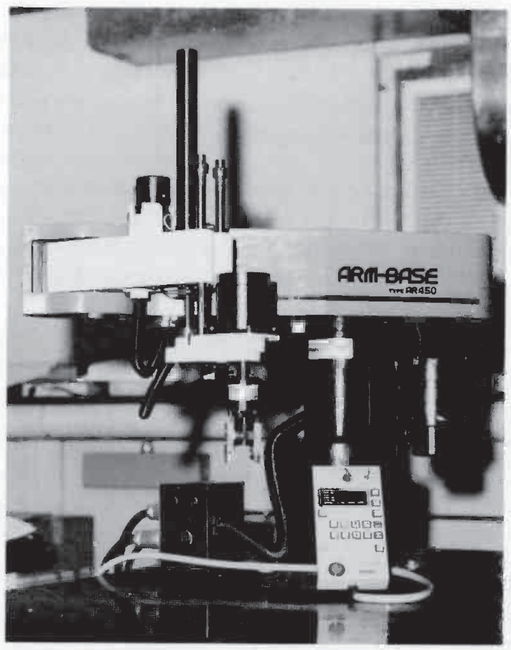
Fig. 3. *Assembly sequence and overview of Hirata work area and ancillary part-handling equipment. The nautilus-shaped area encloses the work area of the robot. The actual robot, the robot controller, and the Weber screwdriver are not shown. Several bowls, for example, the 40" diameter bowl for bracket feeding, are not shown.*

- The motor and its pinion be pre-assembled—the motor manufacturer provided this service.



IBM 7565 (RS-1 shown)
Coordinate system: Cartesian
Repeatability: ±0.005
Actuators: All hydraulic
Maximum velocity: 40 in/sec
Payload: 5 lbs
Controller: IBM Series 1 computer
Cost: $120,000 typical

Fig. 4. *The IBM 7565/RS-1 robot (Series 1 computer and operator terminal not shown) is one of the most advanced systems available today. Using the system's advanced optical/tactile sensors, the robot is capable of executing complex tasks that require iterative part positioning for precision assembly.*



Hirata AR-300 (AR-450 shown)
Coordinate system: SCARA type
Repeatability: ±0.002
Actuators: dc servo motors
Maximum velocity: 55 in/sec
Payload: 4.5 lbs
Controller: Hirata program controller
Cost: $18,000

Fig. 5. *Hirata AR300/AR450 robot was first manufactured for Hirata's own customized automation equipment. Noted for its low cost and repeatability, it has become favored for small electromechanical assembly tasks.*

Prototype testing

Prototype fixtures and software were then developed for the IBM RS-1 robot (Fig. 4), which is an advanced assembly robot. Concepts, cycle times, reliability, and robot performance were all evaluated for the selected scenario. The sophistication of the RS-l provides the flexibility to modify programs quickly and to experiment with different techniques (See also, J. Baldo's description of Astro-Electronics' IBM robot application elsewhere in this issue). At this point we tried, as an exercise in "devil's advocacy," to identify and work with imperfect parts that statistically are hard to find but, when present, cause an outstanding percentage of problems. Also we looked for handling problems. In this case, we discovered a particular way of wrapping the motor's leads in small bundles to prevent the possibility of their getting caught on a fixture during assembly.

From this stage, with the initial boundary conditions satisfied, a proposal was developed for management that outlined:

- Which robot was required?
- What hard tooling was required?
- How much money was required?

For this case, the IBM RS-l would have been excessively sophisticated in terms of both the robotic skills required and the cost.

A Hirata AR-300 robot was proposed due to its repeatability and low cost (Fig. 5). Also, the Hirata robot is found in several RCA facilities including Lancaster, Indianapolis (Sherman Drive), Princeton, and now Bloomington. This type of robot is called 'SCARA' (selective compliance assembly robotic arm) and is less costly and more suited for certain assembly tasks than the rectilinear-type RS-l. While spherical or cylindrical coordinate robots such as the Puma 600 have roughly isotropic rigidity, the SCARA-type robot is designed to move anisotropically. The SCARA-type robot, therefore, is designed to respond selectively to loads applied at the gripper. The kinematics of the Hirata, which moves in a nautilus-shaped work area (Fig. 3), allows compliance in the X-Y (horizontal) plane, which permits compensation that is helpful when the robot is locating a part in a fixture or hole having a tolerance smaller than the repeatability of the robot, as when pressing a peg into a chamfered hole. But the robot is rigid in the Z (vertical) axis, for pressing, as required for screw driving or press fitting.

Programming the Hirata

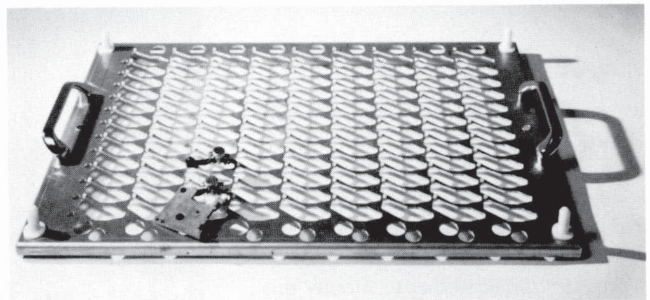
The Hirata AR-300 system consists of the robot, controller, and a pendant. The pendant is the user's interface to the system providing teach, programming, and two run modes (step and continuous). The user basically inputs all position points (up to 1,000) and then writes his program in sequential steps (up to 256). For this system a control panel with four control pushbuttons, a counter, and eight status lights was added to simplify the operator-robot interface. The panel also eliminates the ability and need for the factory operator to use the pendant, thus preventing accidental changes in the program.

Position points can either be taught or programmed in, but our experience was that taught points were more accurate and quicker to input than those programmed. Most robots have this peculiarity in that their accuracy is dependent on a buildup of mechanical tolerances, but that once a point is taught the robot can repeatedly move to that same position.

Feeding parts

Hard tooling, as identified in the prototype stage, became the greatest expense in developing this system. The handling, orienting, and feeding of parts as they come from the vendor is a formidable job. The design

The robot-CAD/CAM connection



Feeding an assembly robot accurately positioned parts is a major concern for robotic system designers. Parts sometimes cannot be fed/oriented automatically due to some delicacy of the part. You must then rely on tray feeding, which provides a queue of manually placed and accurately secured parts accessible by the robot. Two such trays were required for the arm-drive assembly system.

Both the motor, with its 16-inch-long wires, and the potentiometer-lever assembly were considered too delicate and too difficult to feed automatically. With the assistance of CAD/CAM facilities available at the RCA Laboratories, trays were developed for the components mentioned. The designer had to both determine and avoid interference problems and "dense-pack" as many parts onto a 16- by 24-inch tray as possible. On the Computervision system, a design was produced, verified, and then downloaded to a Spindle Wizard (computerized numerically controlled milling machine) where two stacks of six trays were machined. A pot-lever tray consists of 108 positions that secure the part and allow clearance for the extended shafts on the bracket (not visible). The same number of plastic spring clips, which retain the pot-lever, were designed on the same system and downloaded to a Graziano NC Lathe for production.

Software is now available for some CAD systems that not only allows modeling of parts and fixtures but also shows the robot's kinematics. An entire workcell can be animated for analysis before any hardware is purchased. In the future, robot software will be developed in this manner and fed directly to the workcell, eliminating robot downtime for programming. The CAD/CAM-robot system will be a valuable tool in the factory of the future.

of a reliable feeding mechanism is usually best left to those companies who are skilled in the art. If the parts are relatively small and are not delicate, a vibratory bowl feeder is commonly used. This type of feeder has a helical track that passes around the wall of a bowl. When a driving vibration is applied to leaf springs mounted under the bowl, the effect is to cause parts in the bottom of the bowl to climb up the track to an outlet at the top of the bowl. Various devices are welded into the bowl that allow only properly oriented parts to reach the outlet. Delicate parts or parts that tangle, such as motors, are better fed either by magazine or tray.

In summary, the proposal presented for this system included a Hirata AR-300 robot and the following feeding systems:

- Vibratory bowl for feeding brackets
- Vibratory bowl for feeding 3rd-reduction gears
- Vibratory bowl for feeding 2nd-reduction gears
- Vibratory bowl for feeding lst-reduction gears
- Vibratory bowl for feeding palnuts
- Tray for holding 108 motors (with spares for reloading)
- Tray for holding 108 pot-lever assemblies (with spares for reloading)

In addition, a Weber automatic screwdriver, a nest for meshing the three gears, and a motor assembly fixture had to be built/purchased.

An overview in Fig. 3 shows the placement of feeding mechanisms into the robot's work area. Starting at the bracket feeder and then working counterclockwise the robot follows the scenario presented in the figure.

Safety

Safety of the operator is paramount in the system's design. For this application, the robot's work area was totally enclosed in removable plexiglass sheets. These lightweight shields are easily removable but, if removed, cause all power to be dropped from the arm. Feeding equipment is outside the enclosure and can be replenished without interrupting the system. Additionally, the motor and pot-lever trays automatically move out from the work area on a slide for replacement.

ADAM

To ensure a safe, efficient transfer of the system from Princeton to Bloomington, the engineers and the technicians from the plant visited the Laboratories before shipment. Seeing and working with the equipment in the lab allowed the present users to become familiar with the equipment as well as with programming the robot. They nicknamed their first robot ADAM (arm-drive assembly machine).

After almost two years of development and six months of actual construction, the Hirata system was dismantled and shipped to Bloomington in early November to begin production on the factory floor (Fig. 6).

What we have learned

As of this writing, the arm-drive assembly system has only been operating for a short time. We intend to keep track of the system's performance, and in particular, the reliability of the Hirata robot. Our future work in robotics and design for robotic assembly will be based on our present experiences with this system. In a nutshell, we found our greatest effort and cost was in part feeding, not in programming or using the robot itself.

Part feeding curtails flexibility, increases costs, greatly increases floor space required (as compared with the robot itself), and lengthens the concept to delivery time. Bowl feeding requires that parts remain exactly

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Since 1977, Mr. Aceti has worked for RCA Laboratories, Princeton, N.J., as a Member of the Technical Staff in the Electromechanical Systems group. His work as a Project Leader includes a solar-energy concentrator, computer-based automatic parts-inspection devices for VideoDisc caddies, and flexible manufacturing systems. In 1983, he received an RCA Laboratories Outstanding Achievement Award for his designs of automatic inspection systems for delicate plastic parts. He also holds a U.S. patent for this work.

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In 1973, Mr. Carroll transferred to the RCA Palm Beach Division, Palm Beach Gardens, Florida, and worked on products using mini- and microcomputers for hotel/motel management. He rejoined RCA Labs in 1975, and he received an RCA Laboratories Outstanding Achievement Award for work on equipment for optical scanning and readout of the RCA VideoDisc. He then led the mechanical design effort that succeeded in producing early prototypes of a flat-panel television system. Mr. Carroll holds seven U.S. patents.

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the same, thus making modifications to the product impossible—modifications for which the robot could easily be reprogrammed. Part feeding accounted for almost 70 percent of the purchased part costs for the system, leaving only about 20 percent (the robot) reusable, thus decreasing the savings. Bowl feeding requires two to four months for construction while a robot can be programmed in a day or two. However, with all the drawbacks, bowl feeding remains the most cost-effective method for orienting and feeding bulk parts.

In the future, the use of robots for assembly will depend on an improvement in the methods to deliver oriented parts to the robot workcell. Vision and tactile feedback systems are presently too expensive and slow for most applications. In the near future, these systems should be available at reasonable costs and will be fast enough to assist the robot in handling unoriented parts. Still, most applications will require ingenuity on the part of designers, manufacturing engineers, and purchasing department personnel. Parts should be delivered already oriented, such as in egg crates or pallets. Disciplined methods such as the *Design for Assembly* software, previously mentioned, will assist engineers in making parts

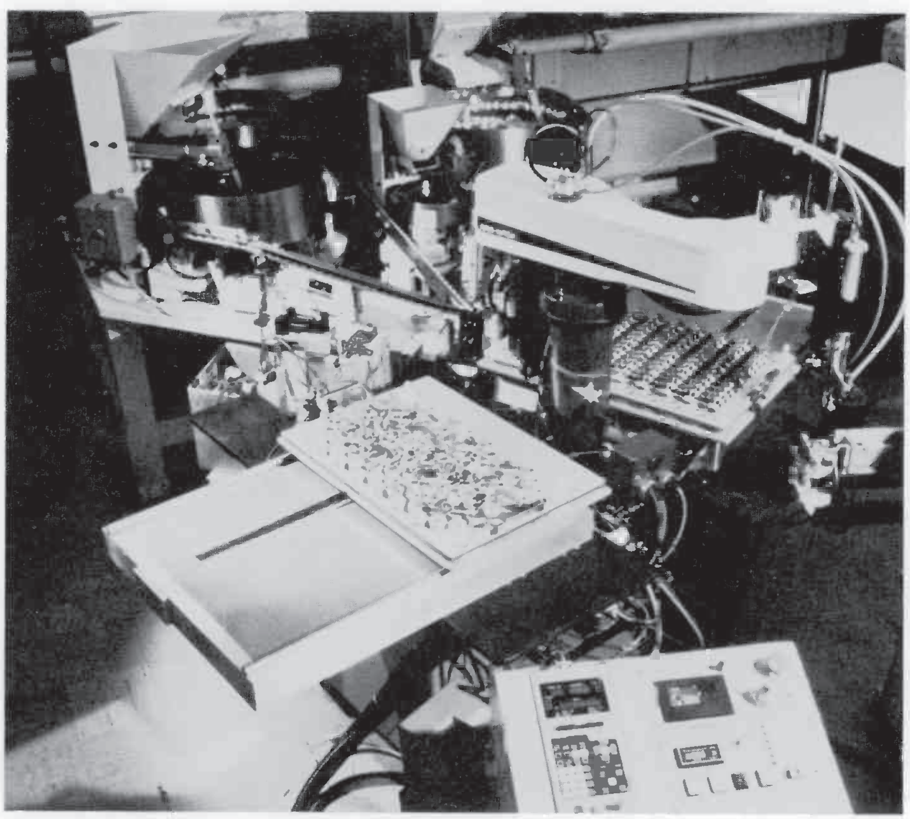

Fig. 6. *The Hirata gearbox assembly system, without its protective Plexiglas envelope, is shown in the Laboratories environment.*

that can be efficiently fed by ordinary means.

Conclusion

From television receivers to VideoDisc players, electromechanical assembly is a vital factor in RCA's future. Competition in this arena is fierce and the winner will provide the consumer with what he wants when he wants it. As flexible manufacturing becomes more of a reality, and robots play a vital part, the competition will become only more aggressive. We must continue to plan and implement effective modern techniques in our engineering and manufacturing.

Acknowledgments

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