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Design and Simulation Case Studies of Flexible Assembly Cells and Systems

by

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ABSTRACT

The goal of our research project is to design and simulate "generic" robotized assembly and inspection cells, consisting of an industrial robot, part feeding, tool changing and other peripheral devices, designed and/or integrated by us to achieve extremely high flexibility, manufacturing quality and productivity levels.

The core of the concept is to develop an *"intelligent", generic assembly and inspection cell,* capable of changing parts, tools (i.e. robot hands), changing flexible component feeding and orientating devices using a direct access material handling system (e.g. an AGV), as well as capable of communicating with the outside world via standard data communication networks, such as MAP (the Manufacturing Automation Protocol) and/or other LANs (Local Area Networks).

1. Introduction

The major benefit of building a flexible, versus dedicated assembly system is that by developing an *"intelligent and generic"* system built of cells one can save the cost of individual, customized developments which in most cases are redundant and result in rigid systems, which are not capable of reacting to the variation of different batch sizes of different product families, nor to the requirement of producing products in a mixed mode. Such a system represents an advance in the state-of-the-art, and should be regarded as an investment for a future competitive edge.

On the research side, the proposed research work on the ROBCAD/SILICON GRAPHICS solid model simulation system enables us to:

- Provide access to different automatically, semi-automatically and manually generated assembly strategies and more accurate "know how" on how to design for flexible assembly and automation in general,
- Design, simulate and implement robotized assembly equipment fully integrated with a powerful CAD/CAM design, simulation and operation control system,
- Formulate design rules for a knowledge based, expert assembly and inspection system,
- Write and execute task level robot assembly and inspection programs generated off-line, demonstrating a highly integrated, but still modular and flexible system design approach,

- *Design and implement "intelligent" robot tools and grippers,* which have the automatic recoupling facility between the robot tool and the wrist both electronically and pneumatically and provide "on-board" computing power for real-time decision making,
- *Design and implement a Programmable Remote Center Compliance RCC table,* which can accommodate palletized parts, loaded by AGVs - Automated Guided Vehicles - to the assembly/inspection area,
- *Redesign - as necessary - and integrate modular, flexible fixturing systems into the cell, which can be automatically assembled by a robot,*
- *Integrate a variety of different contact and non-contact sensors into the robotized cell in order to calibrate the system in real-time, as well as to increase its* "learning" capability about its positioning and orientation errors in 3D,
- *Enable us to test different (mostly dynamic) operation control rules and production rule based dynamic scheduling strategies.*

To *summarize*, our task is to simulate different strategies, system design concepts and when implemented, demonstrate the way the above outlined design and integration problems can be overcome and rules can be formulated on how to design Flexible Assembly and other manufacturing systems (FAS/FMS). [Ref 1,8].

2. Design Criteria and General Considerations

The goal of designing flexible assembly and inspection systems is to enable the production facilities of the company to accommodate required changes in product design and to react to the market needs without necessitating large and time consuming investment programs. In order to achieve the desired high productivity levels and the shortest throughput time at minimum cost, flexible assembly and inspection systems should be part of an overall CIM (Computer Integrated Manufacturing) concept, integrating the business related (or commercial) systems, CAD, CAM and the flexible production facilities of the "factory of the future".

In general flexible assembly and inspection systems deal with high level distributed data processing and automated material flow using computer controlled robots, material handling, part feeding and part orienting devices, contact and non-contact sensors (e.g. machine vision systems) linked together in a modular way. Through such integrated modularity, such flexible systems can produce small batches and prototypes adaptively and economically, and their control, programming, recovery and integration into larger systems is greatly simplified.

When designing flexible assembly and inspection systems, or other manufacturing systems, one must begin with the analysis and very often with the redesign of the parts to be assembled. Design for assembly, inspection and in general for manufacturing is of crucial importance. In this area CAD/CAM systems need to work with expert systems and should become increasingly "better informed" about *"What is possible?"* and at *"What cost?"* on the shop floor. *The best solution would be to avoid assembly entirely,* but in many cases this is not possible, because of functional constraints, because different materials must be used (e.g. rubber, plastic and steel) in the same subassembly, because of maintenance, because of the required mobility of components, or a combination of the above reasons. If assembly cannot be avoided, the part, or the subassembly should be made suitable for flexible, robotized assembly.

In order to be able to design and operate flexible assembly systems built of cells capable of communicating with each other both in terms of material handling and data, one should provide:

- **A suitable modular product design**, preferably using CAD/CAM systems in order to create a solid model data base containing all the design and manufacturing data and production rules related to the particular product.
- **Appropriate dimensional accuracy** of the components to be assembled in order to avoid compliance and jamming problems.
- **Assembly without the need for adjustments** and in-process inspection of certain dimensional values or performance characteristics
- **Full computer supervision**, control and report generation of the assembled components
- **Material quality control and comprehensive, real-time process control**
- **The possibility of individual product and mixed batch assembly** in order to accommodate a variety of different order and assembly sequences as well as dynamic changes in the manufacturing system.

The *individual cell* of a flexible assembly and inspection system, generally consists of:

- **The robot arm** (or arms, with its controller);
- **The necessary grippers and/or robot tools** (preferably in a tool magazine enabling automated robot hand changing);

- **The part feeding mechanism(s);**
- **Palletized part docking** and part locating devices (if required);
- **Part orienting devices** (if required);
- **Other electronic and sensory based** (vision, force, torque sensing, robot calibrating, etc.) devices which are interfaced with it and are used for guidance, safety or generating feedback data regarding the operation of the cell in real-time.

The cell controller should run the *system software,* typically consisting of the *operating system, the manipulator specific modules* and *the programming language interpreter or compiler* and *the communication programs* keeping in touch with the ''outside world''.

3. Cell Programming, System Programming

Cell programming should be done preferably off-line, using robot and/or robot language independent, task oriented, interactive and user friendly languages, or language generators making use of graphics and AI techniques and generating robot dependent code which needs only minor changes if any, when executed on the cell.

When programming the flexible assembly and inspection system one should enable the *dynamic operation scheduling system* (working together with the capacity checking and balancing programs and communicating with the CIM data bases) to select from different alternative assembly and/or inspection sequences. Typically, assuming an ''intelligent system'', inspection operations should be automatically requested and executed as required in real-time by any of the cell controllers, independently of whether or not they have been pre-planned. Similarly, assembly sequences and their possible alternatives should be generated preferably automatically, or with minor human assistance, making good use of the previously mentioned solid model based CAD/CAM data base and the expert design and operation control systems imbedded in the CIM architecture.

4. Cell Tooling and Tool Transportation in the System

As we have emphasized before, automated robot hand changing, or in general *tool changing at cell level is of extreme importance* in order to provide the needed ''tooling flexibility'' and the short tool changing times for the system as a whole. *This problem occurs at the system level too,* but in a different form. Here *there is a need to carry and change entire tool magazine contents, and/or to partly update tool magazines* according to the actual needs, described in each part program (i.e. robot program) and by the current schedule. This task can be economically solved by using the AGV based part transportation system, if the AGV is capable of picking up entire tool (i.e. robot hand) magazines and the cell is capable of docking them. Often the cell robot itself takes care of replacing the contents of the magazine. This might be an economic solution, even if valuable production time is spent on this activity. If the industrial robot could change its end effectors like a human operator when using different tools, then it would become *more versatile* and allow automated assembly of small batch sizes, or individual products arriving in a mix, where dedicated machinery is uneconomic. It would also use few robots, since robots would rather change tools (i.e. hands) than distribute the workload on many different dedicated devices.

To summarize, one must realize that since the robot arm itself is incapable of doing much alone, the peripheral devices, such as the end-effectors and special purpose tooling, part orienting, part storage and part feeding devices, safety and guarding devices and their communication with the robotized cell controller, are of crucial importance and must be considered carefully when designing such cells. In order to cut down setup times and switchover times between different products, parts and components to be assembled and/or inspected should arrive to the cell and be located at the cell in a known orientation and location, enabling the robot to handle them properly. *Furthermore* parts and components involved in the assembly and/or inspection should be able to be loaded and unloaded and transported between cells using preferably direct (or random) access material handling devices (e.g. AGVs), rather than sequential devices, such as the conveyor line.

5. Cell Buffering, Part Transportation and Storage in the System

The materials handling system *links together the different islands of automation* both at cell as well as system level from the transportation point of view. *Serial access, or sequential systems* such as a conveyor line provide low flexibility, and low reliability, since the cells are chained together in a rigid way with a single transportation facility. *On the other hand, random access, or direct material handling systems,* such as AGVs offer the possibility to transport parts, tools, finished components, etc. from any cell to any cell and are more reliable too, because there can be many of them in a system, taking each-other's job as required.

6. Dynamic Operation Control

Dynamic operation control in a flexible manufacturing system means that decisions concerning what workpiece is manufactured next on which cell, are made close to the end of the operation currently being performed by the particular cell. In other words the schedule for the flexible assembly and inspection system is not made in advance like on transfer systems, or dedicated lines, because it must be capable of responding to real-time decisions and changes, such as an "urgent order", a "cell break down", a schedule "cell maintenance", etc.

Operation control for robotized assembly and inspection systems can be designed and/or analyzed basically at three different levels, these being:

- **The factory level**, or business level handled by the *business data processing system of CIM*
- **The FMS off-line level**, representing simulation and optimization activities prior to loading a batch or a single component on the FMS/FAS, handled sometimes by the FMS part programming computer, sometimes by the CAM system
- **The real-time controlled level**, taken care of by the FMS operation control system, representing a situation where the parts are physically as well as logically in the process controlled environment.

In order to satisfy the demand generated by the business system modules of CIM (i.e. mainly by MRP and the MPS programs) the first major task is the selection of the appropriate part mix for a defined period of time, which can be as short as a few hours, a shift, a day or a week, but usually no longer than a few weeks. *Note that this period of time will depend very much on how well organized is the part arrival to the system entry point.*

7. Comparison of Dedicated versus Flexible Assembly and Inspection Systems

Conventional or Dedicated Assembly (and Inspection) Systems are designed for *a known part,* or *a family of known parts.* They are optimized both in terms of cycle time, operation distribution between assembly/inspection heads and/or robots as well as for cost. The cycle time in these systems is precalculated, because all parts and all operations to be performed on these parts *are known before the system is designed.* Dedicated systems, even when utilizing robots working along a serial access material handling system, are neither designed for product changes, nor for cycle time alterations. They are *rigid in this sense.*

On the contrary, parts to be assembled and/or inspected on a *truly flexible system* (FAS = Flexible Assembly System) are *not necessarily known (at least not all of them* prior to designing the manufacturing system. Certain limitations in terms of size, weight, material, tolerances, etc. are known, but the FAS is *''open ended from the design point of view, thus a generic approach can be followed''*.

This is an important, often overlooked difference between dedicated systems and the FAS, resulting in

- much higher flexibility,

- reduced development cost of new assembly systems,
- reasonably shorter changeover time,
- the possibility of making goods on order in a mixed mode, rather than economically sized large batches for stock,
- and higher overall system reliability and system efficiency.

If one considers only one factor of the above list, e.g. the reduced development cost of new assembly systems, then one should realize that the development cost of manufacturing systems in general is as high as 50 to 70% of the total cost. Saving most of this cost is substantial when designing the second, third, etc. system.

The other listed factors, e.g. *high reliability and efficiency should not be ignored too, because these are very important issues for the management.*

The proposed design (as shown on Figures 3 and 4) compared to previous systems is flexible and ‘‘generic’’, because:

- It can change tools and parts under a few seconds in random order, resulting in that more operations can be concentrated on each assembly cell (rather than one operation per each dedicated assembly head) and that a large amount of different parts can visit each cell in random order (i.e. as programmed).
- The data communication links provide real time control, maintenance and close to 100% cell efficiency level. (Note that because of reliability problems as well as transportation problems dedicated systems operate usually at only 50 to 70 percent efficiency).

- The FAS is more reliable than any dedicated system, because intelligent cells are linked into a data processing network, and because all parts, part feeding devices, robot tools, etc. arrive and leave each cell (and the system) by means of a random access material handling system.

(Figures 1 to 6 illustrate the above discussed principles).

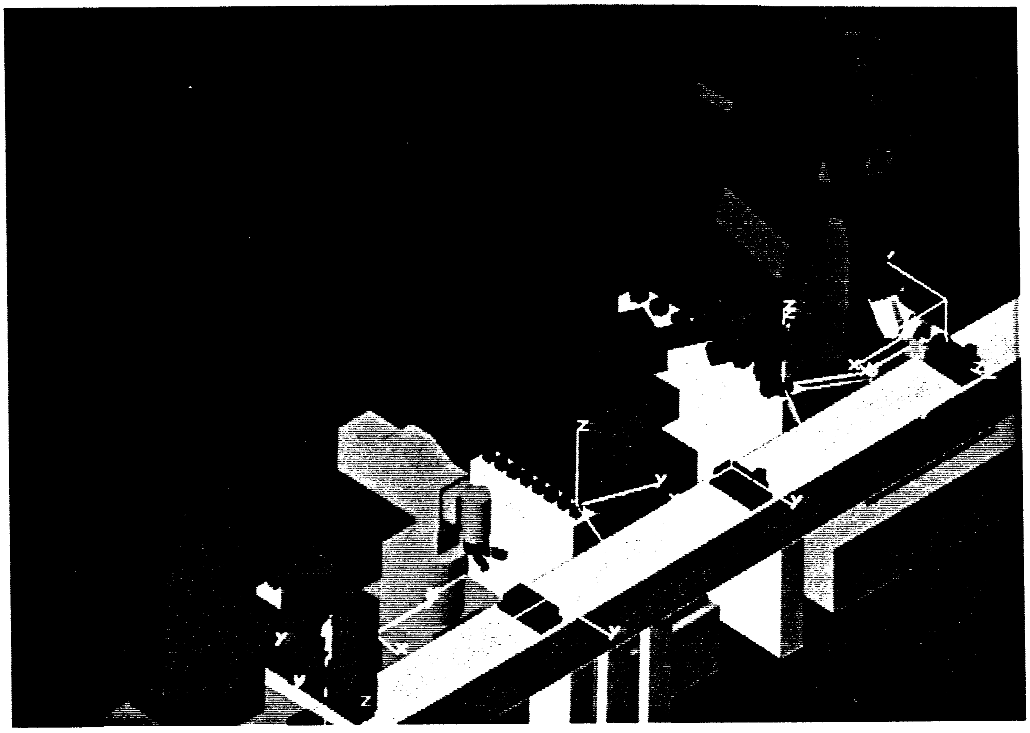


Figure 1 Solid model animation of the conventional assembly line, utilizing industrial robots along a conveyor line in a dedicated way.

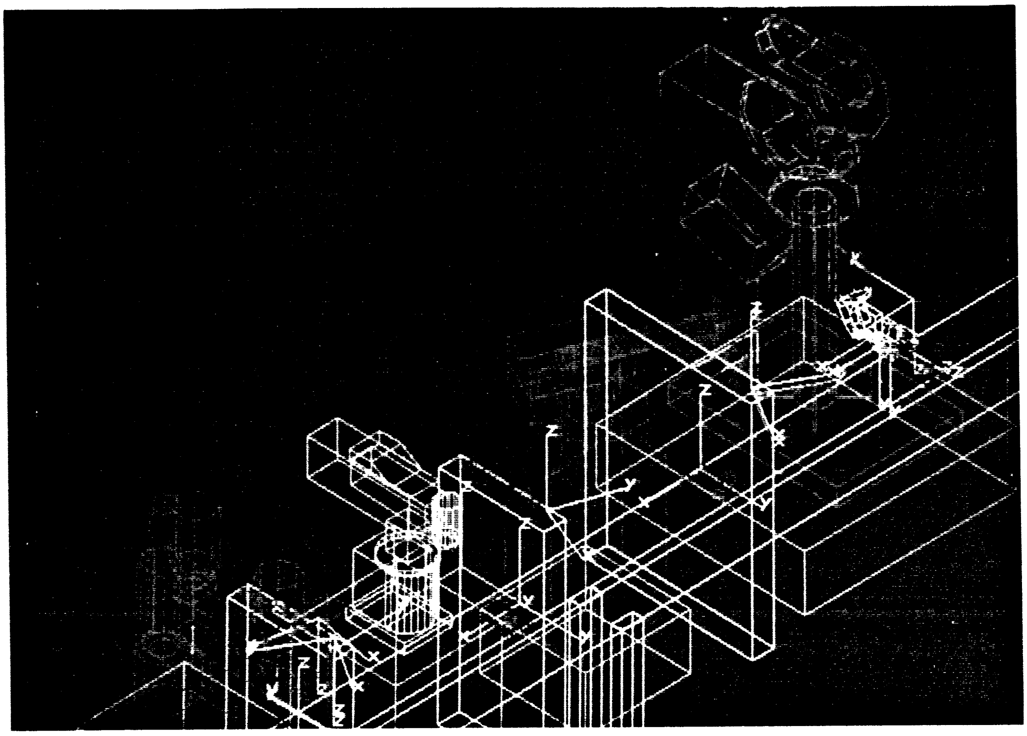
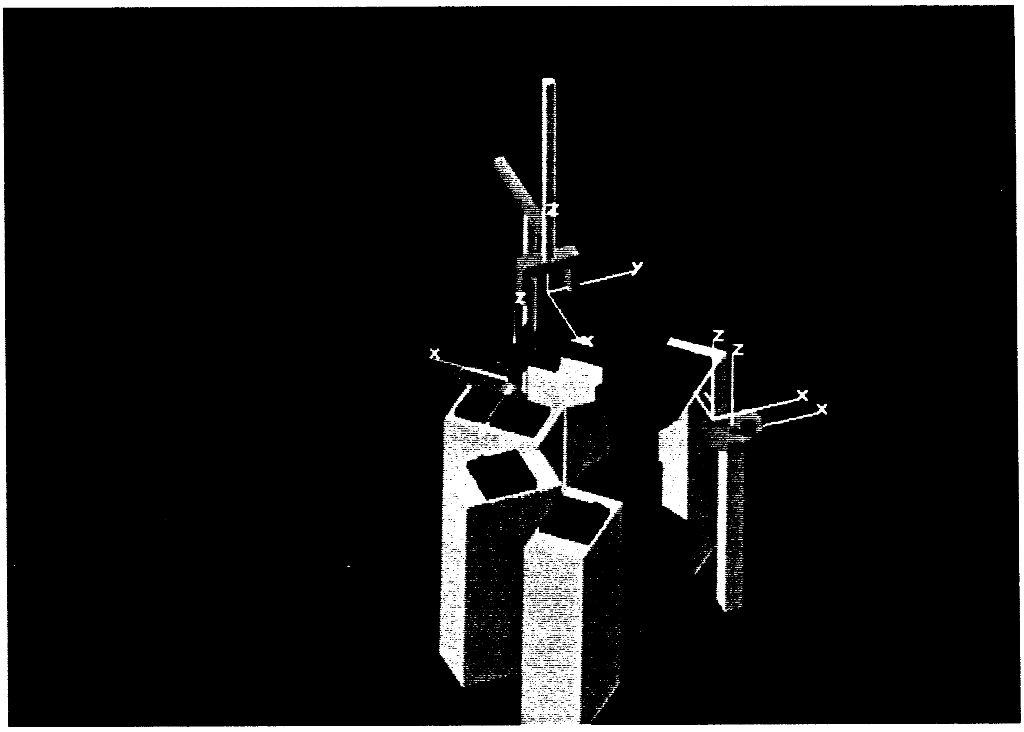


Figure 2 The above shown simulation can also be displayed using wire frame modeling.



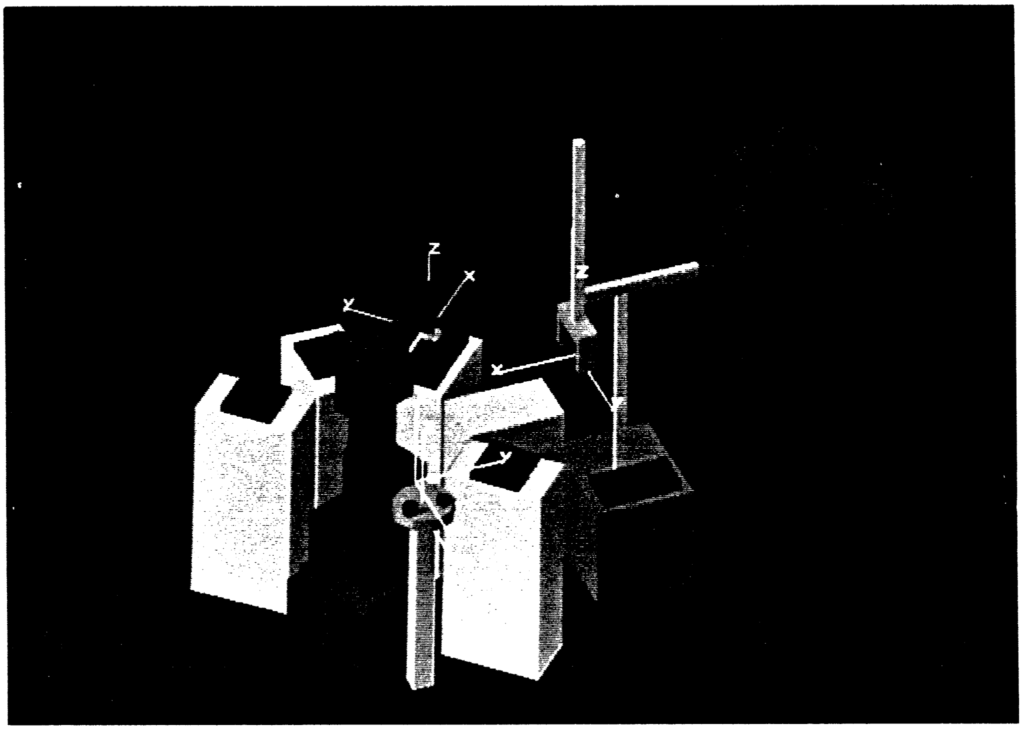
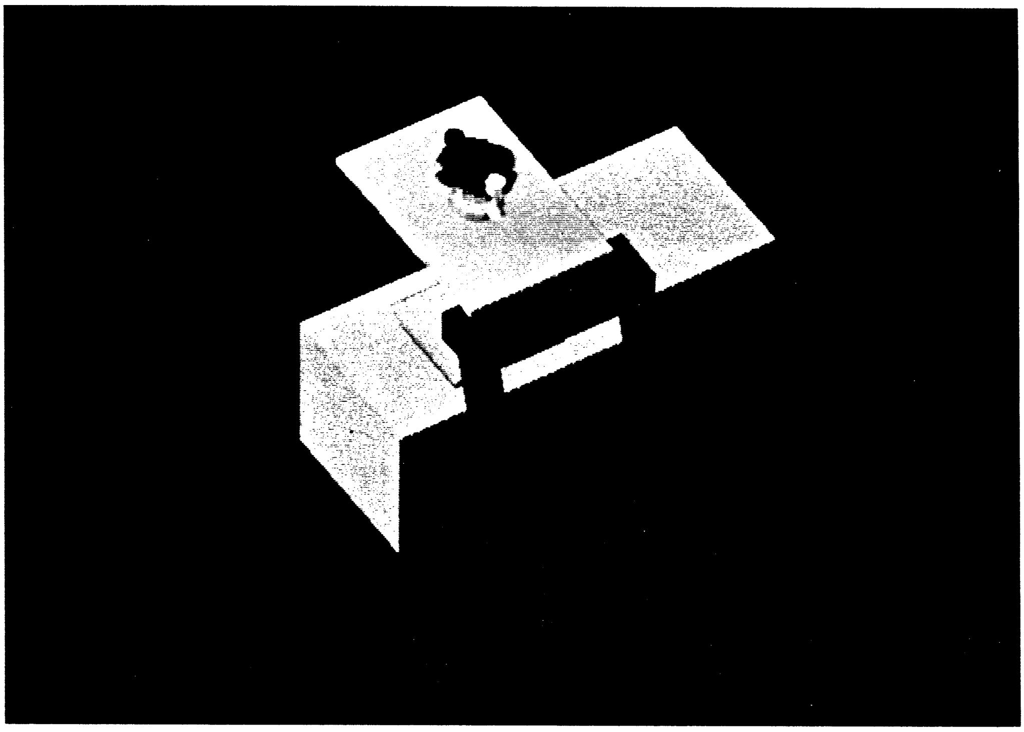
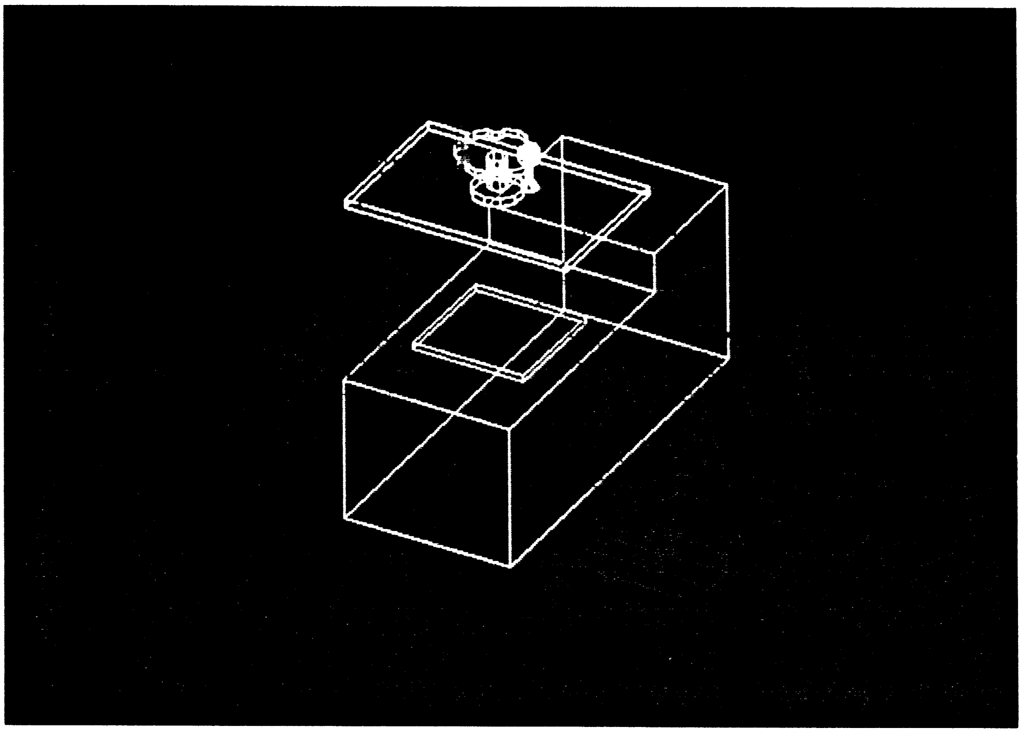


Figure 3 & 4 The flexible assembly cell simulation shown on both of the above photographs represents a truly flexible approach to assembly and inspection, because not only the robots, but the routing of the parts, the part changing as well as the robot hand changing is under program control and can be done in any programmed order.





Figures 5 & 6 The docking stations can be accessed by the AGVs, thus any docking station can be used as a work area, as well as a feeding station, or a place for another tool (i.e. robot hand) magazine, etc. as required by the real-time production control system.

8. Comparison List of Unique Features - Dedicated versus Flexible Systems

CHANGEOVER TIME and cost

- In the case of dedicated, or conventional systems, changeover time typically takes several hours to several days and is often impossible.
- It can be as short as a few seconds to a few minutes in the case of flexible systems as long as the "new" product(s) fall into some size, weight, tolerance, etc. limitations as discussed in Section 2.

PRODUCT MIX

- In the case of dedicated systems the product mix (if there is any) must be preplanned and predesigned, prior to implementing the assembly/inspection system.
- New parts can be added, mixed in random mode into the flexible system as long as the appropriate robot tools (i.e. robot hands) are available and certain limitations of the parts, such as weight, size, material, tolerances, etc. are not violated.

PART PRESENTATION

- Typically parts must be kitted and/or fed using a variety of incompatible, special purpose feeding, loading, orienting etc. devices in the case of dedicated systems. In such systems part orientation errors can cause major breakdowns, because misfed parts intend to jam. If such an error occurs, the entire dedicated system must be stopped and production is at halt until the jammed part is removed.

- Flexible systems do not need, but can accept kitting, but known (i.e. oriented) part presentation must be provided, preferably using standard, interchangeable pallets.

CYCLE TIME

- Dedicated systems have a fixed cycle time and cycle time alterations are resolved by providing relatively high work-in-progress values.
- Flexible systems are not sensitive for cycle time changes. One could say that in the case of flexible systems the cycle times can and/or are different for each product and that the cycle times can be changed dynamically during production without causing any interruptions to the system. Work-in-progress in flexible systems can be reduced virtually to zero, in practice typically to one.

SENSITIVITY TOWARDS DYNAMIC CHANGES

- Dedicated systems are very sensitive for any changes.
- Flexible systems are not sensitive for changes, thus are ideal for extreme requests like prototype assembly/inspection during regular production time, testing new product assemblies and learning from the results using "closed loop" CAD/CAM/FAS system.

EXPANDABILITY

- Dedicated systems are hard or often impossible to expand. The high cost factors should not be overlooked too, when changing virtually *anything* on dedicated systems.

- Flexible systems consisting of "well designed" cells are easy to expand. They are designed for dynamic changes both in terms of product mixes, as well as product quantities.

ASSEMBLY HEAD, ASSEMBLY SYSTEM UTILIZATION

- Dedicated systems cannot achieve 100 percent utilization. Their utilization level is typically 50-75 percent at system level, consisting of 25-30 assembly/inspection heads minimum.
- Flexible systems can achieve almost 100 percent efficiency, since they are more reliable and are not sensitive for changes.

9. Simulation Results Using "The FMS Software Library" and Solid Model Simulation Techniques Using ROBCAD

In order to demonstrate the concept outlined above three wire frame and three solid model based animation and simulation programs have been developed. These programs running on the Silicon Graphics Workstation and ROBCAD represent important steps in our cell design and simulation efforts. (Figure 1-7)

The ROBCAD solid modelling and workcell design system provides software support in the following fields:

- **Design of workcell components**, using solid models of objects, such as robots, feeding devices, AGV docking stations, etc. designed by the user

- **Workcell layout design** allowing to call up the workcell components of a library and positioning them on the screen in order to achieve the optimum workcell layout
- **Task definition and task programming within the cell.** Each component in the workcell must be controlled. This can be done by describing their function using a Pascal like Task Description Language (TDL). Different kinematically operated components then can communicate with each other via signals and pulses issued to each other by the task level procedures.
- **Simulation of the operation of the cell.** These set of programs allow the execution of the task control programs. The results are shown in terms of animated solid or wire frame models, but attributes such as collision check, cycle time display, the active co-ordinate frames and tcp frames are displayed and limit checks (that can be programmed too) are performed for each axis of every animated object, etc. are also available. Other features, like speed and acceleration control (linear only) for each axis, viewpoint changes, zoom, pan, translation, rotation of the graphics images and other usefule features can be programmed.

```
task of robl ;

#define         GO_ROC          go_robl
#define         READY           robl_ready
#define         PIN             pinl
#define         LOC0            locl0
#define         LOC1            locl1
#define         LOC2            locl2
#define         DIST            30
#define         HOME            joints(0,0,0,0)
                var             PIN,part:compmodel;

                when GO_        ROB==on do
                                approach DIST from LOC1;
                                move LOC1;
                                take PIN;
                                depart DIST;
                                approach DIST from LOC2;
                                generate PIN at LOC0;
                                move LOC2;
                                leave PIN onto part;
                                move HOME;
                                signal READY;
                end when;
end task;
```

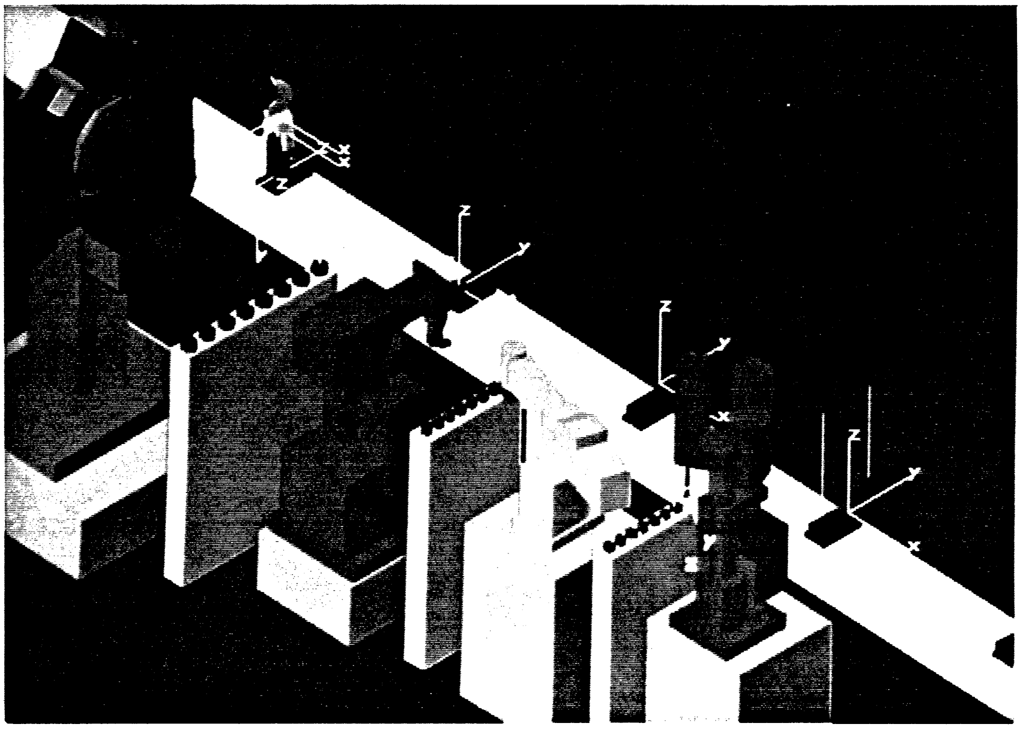


Figure 7 Task Description of the rightmost Robot (IBM 7545) in The Simulated Line

The simulation programs shown in Figures 1 to 7 compare the outlined ''conventional/dedicated'' and the truly ''flexible'' systems and demonstrate the drawbacks of the dedicated versus flexible system design. They also show the unique features of the proposed flexible and generic assembly and inspection system.

10. Acknowledgements

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