Development of a FMS/FAS System
= The CRI's Pilot Unit =

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Abstract A general overview of the pilot FMS/FAS System installed at the Center for Intelligent Robotics (CRI) of UNINOVA is presented. This System was conceived as a generic infrastructure for a range of products and aimed at supporting three kinds of activities: training, research and demonstration. Main design constraints and adopted solutions are presented. This Pilot Unit is a significative platform to support cooperation activities in various international projects.

1. Introduction

The Flexible Manufacturing and Assembly System -- NOVAFLEX -- installed at the Center for Intelligent Robotics (CRI) of UNINOVA was conceived as a demonstration unit able to handle a set of typical activities of a Computer Integrated Manufacturing (CIM) system.

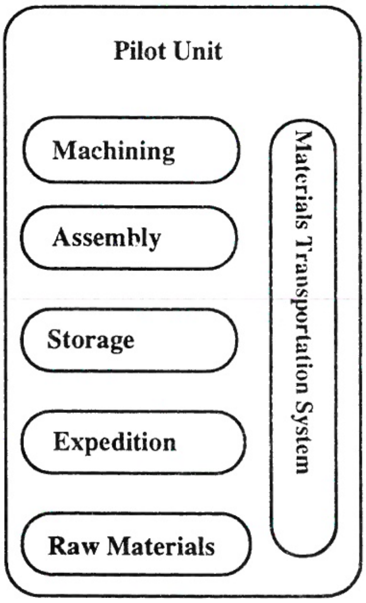

Figure 1 . Main Components of the NOVAFLEX

Beside the machining and assembly subsystems, the Pilot Unit includes a storage component, an input section for raw- materials, a delivery section for finished products and a transportation subsystem that links all the other components.

As one of the basic design goals, the system was required not to be restricted to a particular type of product. The objective was to build a relatively generic infrastructure, that could be adaptable to a range of products with minimal setup effort. The requirement was for a flexible infrastructure, with a representative set of manufacturing resources, and not for a special- purpose system.

This Pilot Unit will support three kinds of activities:

i) training,
ii) demonstration,
iii) research.

The requirements or constraints imposed by these activities have not always been convergent, what imposes some difficult design decisions. As a general rule, flexibility was preferred to efficiency.

Another constraint on the final architecture resulted from the need for integrating some existing equipments, namely the CNC machines.

In fact this was accepted as a challenge typically found in real manufacturing systems. The evolution of an existing manufacturing system has to take into account the existing machinery.

Therefore the various aspects of integration and interoperability between components had to be considered.

As a prerequisite to designing the system's architecture, it was necessary to analyse and understand the main requirements from each class of potential users taking into account the three kinds of intended activities.

Training
In the present framework of transformation of the Portuguese Industry, in which deep changes are

imposed by the need to be competitive in a context of open market, a key factor is the training of technical people that will perform such transformation.

The training needs do not only address engineers but also medium level technicians, who are, in fact, the system operators responsible for its regular operation.

CRI intends to use this Pilot Unit to support training / retraining actions for both levels of technical people. On the other side, taking advantage of the good relationships between CRI and Faculdade de Ciências e Tecnologia -- Universidade Nova de Lisboa, this unit will also support the regular engineering curricula, specially in terms of the final project (5th year). In the same spirit, the system will also provide an important support for the post-graduation students (Master and Ph.D thesis).

Demonstration
A second line of activities intended for thisPilotUnit is the demonstration and analysis of the feasibility of solutions. It is not easy to convince people from industry of new solutions just based on "paper" projects. Simulation-based approaches, although important as a design step, are not sufficient to understand and evaluate all behavior of a planned system. The realization of a physical demonstration system is therefore a very important tool to help in the discussion of the solution and also a catalyzer for gathering precise definitions of requirements and for refining solutions.

This unit can therefore support the joint development of demonstrating solutions by research people and enterprises.

Research
Finally, being CRI a research center, one important goal for the Pilot Unit is naturally the support to the various on-going and planned R&D activities. One important design requirement was therefore, the need for supporting various research areas, such as systems integration, cell control and scheduling, planning, monitoring, diagnosis and error recovery, sensorial perception, etc.

Another very important aspect is the possibility of different groups of being simultaneous users of different subsystems of the Unit for separate experiments. As a matter of fact, this situation is expected to be the most common practice during the systems life time.

These requirements led to an architecture in which NOVAFLEX can be operated as either an integrated FMS/FAS system or a set of isolated subsystems (machining, assembly, transportation and storage, etc.). This latter aspect has particular consequences on the design of the control architecture.

Therefore, the need to support these different research areas implied the design of a flexible architecture, from the topology to the control points of view. An easy reconfiguration of its operating mode is an important requirement to support concurrent research activities.

Beside the constraints derived from the mentioned goals there are also constraints imposed by the configuration of the physical space and by the available budget. Space constraints obviously influenced the topological design, specially at the level of materials flow. The system was designed to be installed in two adjacent rooms, with a total area of approximately 60 m^2. In order to facilitate the materials flow, it was necessary to open a connecting "gate" between the two rooms. This gate was not planned in the original building. Budget constraints had, naturally, important consequences, both at the components level, and at the topologic level.

2. General Architecture

2.1. Global Overview

The NOVAFLEX has 5 subsystems:

(1) **FMS subsystem**,

(2) **Multi-Robot FAS subsystem**,

(3) **Automatic Warehouse subsystem**,

(4) **Transportation subsystem** and

(5) **Sensorial subsystem**.

A general view of the system can be found in Figure 2.

Each subsystem can be operated autonomously or as part of an integrated system. Subsystems 4 and 5 are mainly complementary to the first 3 modules. The transportation subsystem itself can work in separate sectors, enablingthe isolated operation of any of the other subsystems.

The transportation medium is a pallet-based conveyor belt. Each pallet can be adapted to transport different kinds of parts and products.

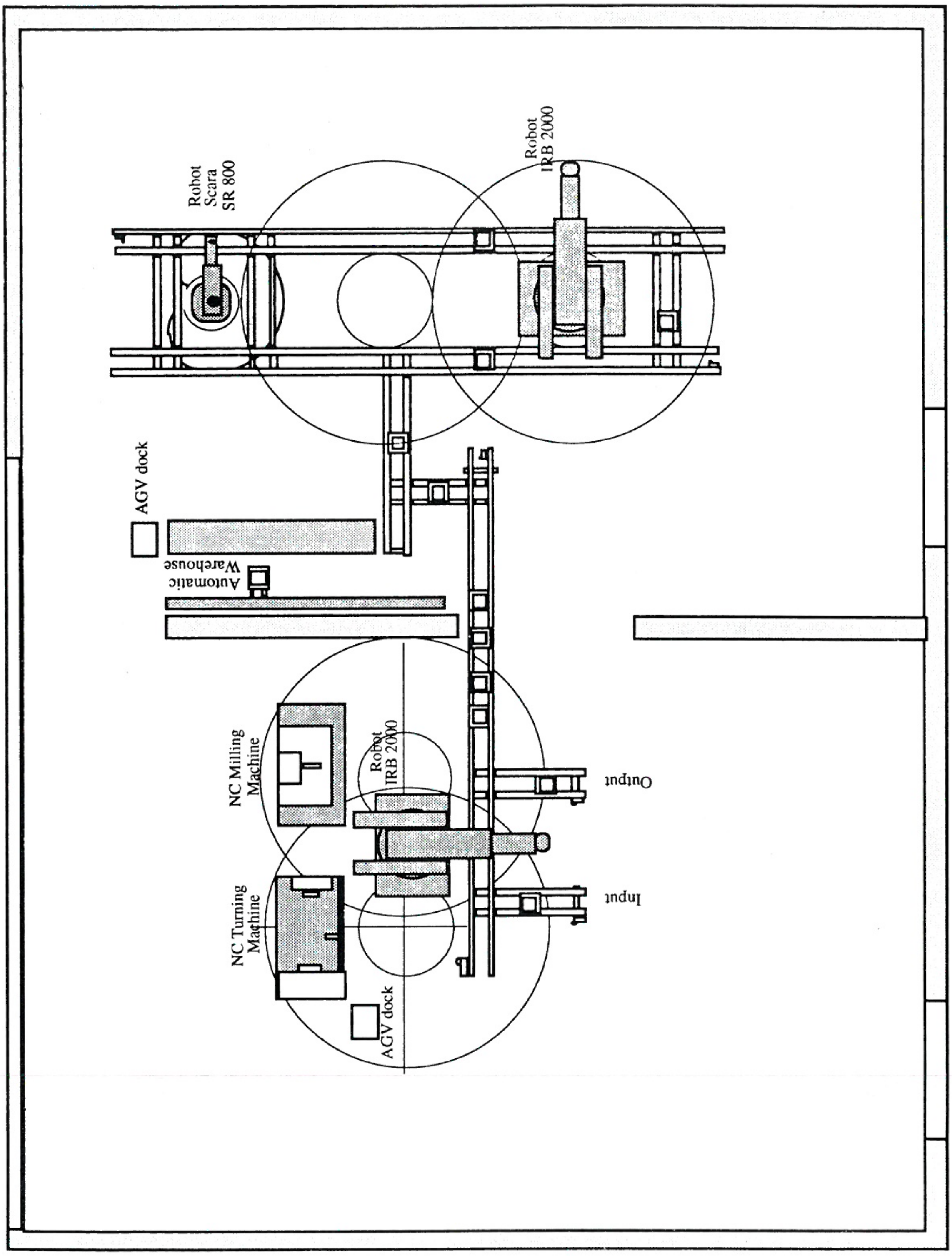

Figure 2 - NOVAFLEX System Overview

2.2. FMS Subsystem

The FMS subsystem includes a small scale milling machine (DENFORD StarMill) and a turn (DENFORD StarTurn). A 6 DOF Robot (ABB IRB2000) serves these machines, ensuring the "link" between them and the conveyor system.

The NC equipment existed before the design of this system and was integrated with the robot to form a flexible machining cell. The robot is installed on top of a controllable axis, allowing two different operating positions in order to serve the two machines (Figure 3).

The materials to be machined are transported to the robot working area by conveyor-belts. These materials can come from either the automatic warehouse or the entry point for raw- materials. After processing, parts are sent to the shipping point, to the automatic warehouse or to the assembly system.

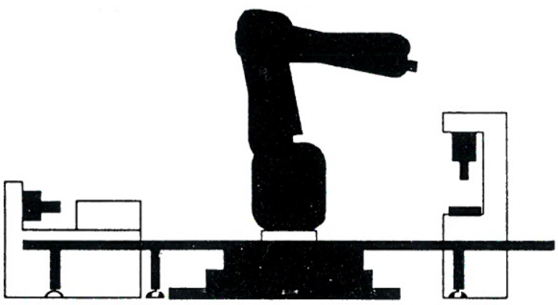

Figure 3 . Machining Subsystem

2.3. Multi-Robot FAS Subsystem

The main characteristic of the assembly subsystem is the possibility of performing:

- Assembly operations in an autonomous way
- Sequential operations (line) for assemblies involving 2 robots
- Cooperation work (parallel) between two robots
- Assembly operations performed by a moving robot. For this, one robot is mounted on a moving chariot that can be synchronized with the conveyor.

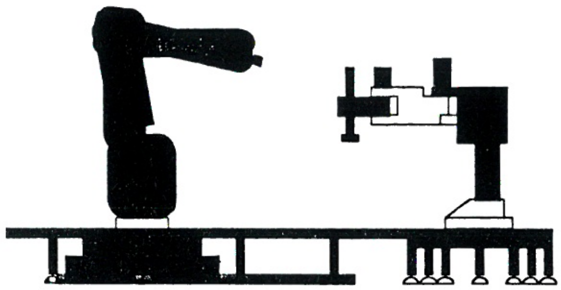

Figure 4 . Multirobot Assembly Subsystem

The assembly subsystem is therefore composed of two robotized cells. They can be operated in an isolated or in an integrated way.

The available robots are:

- [1] Robot BOSCH TURBO SCARA 840
- [2] Robot ABB IRB 2000

2.3.1. Assembly Cell 1

This cell is centred on the SCARA robot (BOSCH SR840) which includes an automatic tool exchange mechanism.

Some of the most important features of this robot are presented below:

- Degrees of freedom - 4
- Loading capacity - 10 Kg
- Repeatability - ± 0.05 mm
- Reach length - 800 mm
- Operating area
  - Axis 1 - ±90°
  - Axis 2 - ±130°
  - Axis 3 - 0..160 mm
  - Axis 4 - ±360°
- Speeds
  - Axis 1 - max. 160°/sec
  - Axis 2 - max. 200°/sec
  - Axis 3 - max. 450mm/sec
  - Axis 4 - max. 400°/sec
- Drive - DC servomotor
- Pressure range - 4 .. 8 bar
- Outputs - 40 (0.1A;24VDC)
- Inputs - 64 (24VDC)

The control system for the SR 840 is a CNC control with several ranges of programming possibilities.

This robot allows movement on straight lines with optional location in space, and with programmable path velocity, through linear interpolation; it also allows movement in an orbit with optional location in space, and with programmable path velocity through circular interpolation; PTP movements are also possible.

The robot can be programmed using a PASCAL like language - BAPS. With this language, the user can have guarded movements, which seems to be an important feature of this robot.

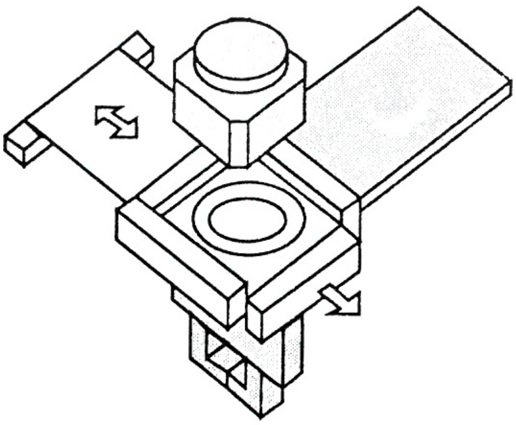

Figure 5 . Tool Exchange System

A magazine of tools, with various grippers, is available to the robot through its tool exchange system. This system is the BOSCH Exchange System GWS 20.

The magazine holds the grippers currently not in use. A proximity switch is integrated with the magazine for presence checks and code interrogation.

Available grippers are:

(1) SCHUNK Pneumatic parallel-gripper

Model - PGN 64
Gripping force - 220 N
Workpiece weight - 1.2 Kg
Mass - 270 g
Air consumption per stroke - 10 cm^3
Stroke - 6 mm

(2) SCHUNK Pneumatic centric-gripper

Model - PZN 64
Gripping force - 580 N
Workpiece weight - 3 Kg
Mass - 400 g
Air consumption per stroke - 25 cm^3
Stroke - 6 mm

(3) SCHUNK Pneumatic parallel-gripper

Model - RH 918
Gripping force - 100 N
Mass - 480 g
Stroke - 60 mm

(4) SCHUNK Pneumatic parallel-gripper

Model - PUG 100
Gripping force - 1550 N
Workpiece weight - 7.5 Kg
Mass - 2.3 Kg
Air consumption per stroke - 140 cm^3
Stroke - 31 mm

Mounted on the robot wrist, there is a force/torque sensor (SCHUNK FTS 30). The controller of this sensor provides the Fx, Fy and Fz force components and the Mx, My and Mz momentous; it also ensures the interface to the computational architecture.

Assembly operations can be performed on top of fixtures installed in selected pallets. Pallets can be stopped within the robot working area resorting to a positioning device with a precision of 0.1 mm.

Parts feeding is also achieved by pallets, whose stop locations are controllable by the computational system.

The implemented architecture supports a "dynamic" buffer of up to ten pallets.

Finished products and subassemblies processed in this cell may be sent to the warehouse, to another cell or to the delivery section.

2.3.2. Assembly Cell 2

This cell is based on a ABB IRB 2000 robot.

Some of the most important features of this robot are presented below:

- Degree of freedom - 6
- Loading capacity - 10 Kg
- Repeatability - ± 0.1 mm
- Reach length - 800 mm
- Operating area
  - Axis 1 - ±179°
  - Axis 2 - +100° to - 110°
  - Axis 3 - ± 60°
  - Axis 4 - ±200°
  - Axis 5 - ±120°
  - Axis 6 - ±200°
- Speeds
  - Axis 1 - max. 115°/sec
  - Axis 2 - max. 115°/sec
  - Axis 3 - max. 115°/sec
  - Axis 4 - max. 280°/sec
  - Axis 5 - max. 300°/sec
  - Axis 6 - max. 300°/sec
- Drive - DC servomotor
- Pressure range - 4 .. 8 bar

• Digital Outputs - 16 (0.2A;24VDC)
• Digital Inputs - 16 (24VDC)

A very interesting feature is the possibility to have power and air supply available at the grippers, because user wiring and pressurized air supply is routed inside the robot arm.

The robot is controlled through soft keys, joystick and the robot-language ARLA.

This robot allows the same type of movements as the robot described in Assembly Cell 1, but with more spatial flexibility due to its 6th dof.

The robot is installed on top a movable chariot along an axis that can be controlled incrementally.

One of the top positions of this axis is planned as the normal operating area for cell 2. The other top position "inserts" the robot in the working area of cell 1, allowing for multi-robot co-operation tasks.

The movement of the robot chariot may be synchronized with the conveyor belt in order to allow assembly operations while a pallet is moving. There are, obviously, some limitations regarding the operations that are possible in this mode. One main limitation is the low precision given by the uncertainty about the position of the pallet, which is subject to sliding and vibration factors. Another potential problem can arise from the different speeds of the robot and the conveyor. This latter aspect may be attenuated by synchronizing the conveyor driving motors and the robot chariot motor.

A magazine of tools, with various grippers, is available to the robot. The tool exchange system is the SCHUNK Pneumatic Exchange System GWS.

The magazine held the grippers currently not in use.

Available grippers are: PGN64, PZN64 and RH918 from SCHUNK.

The tool's magazine moves with the robot along the axis.

Due to the large working area of the IRB 2000 robot, no special requirements were made on the materials' feeding conditions.

As in cell 1, the assembly operations are planned to be performed with the support of fixtures installed in pallets and of a positioning system (precision of 0.1 mm).

In a future stage, other feeding devices, as well as additional fixturing tables may be installed.

2.4. Transportation Subsystem

The transportation subsystem is, perhaps, the most "visible" part of the entire unit. It is a conveyor-based pallet transportation network that links the various subsystems.

Each pallet is designed to support parts/products up to 10 Kg, and with a volume of up to 200x200x200 mm.

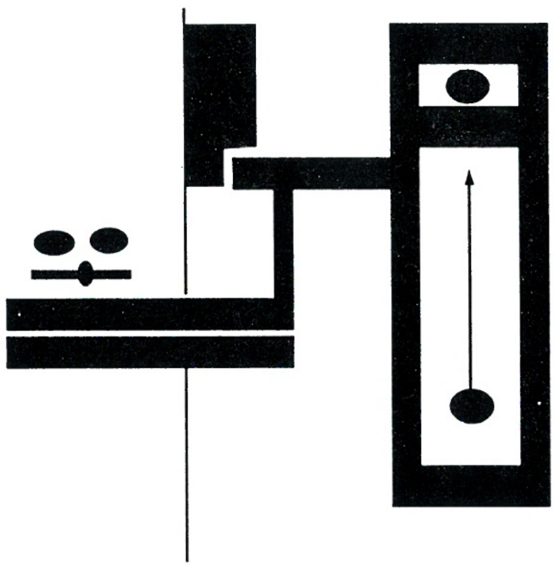

Figure 6 . Main Pallet Flows in NOVAFLEX

As a pallet can be used for different purposes - for carrying raw- materials, machined parts, subassemblies or finished products - different pallet flows have to be supported. In order to have a dynamic system, it is necessary to have a pallet identification system. With such a system, it is possible to dynamically re-route pallets according to a global control strategy.
The selected identification system is based on a read/write memory device, attached to each pallet. The information stored in a pallet's memory will "drive" the actions applying to that pallet: activate a positioning device (stopper), actuate an elevator, etc. (Figure 7).
The installed pallet identification system is the BOSCH ID80/E composed of Mobil Data Tag (MDT), attached to each pallet and Read/Write Units (SLS).
The communication between a SLS and a MDT may occur when the pallet is within a range of 15 mm. The data transfer can be done with the stopped or moving pallet .
The SLS components, controlled by a host unit, are distributed along the transportation subsystem and located in all strategic points where decisions can be made about the next route to be followed by the pallet.

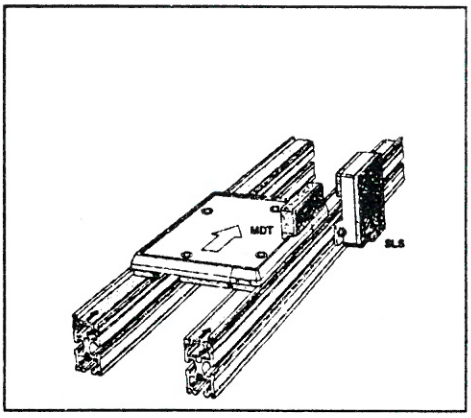

Figure 7 . Pallet and its Identification Device

Examples of information to be stored in a MDT:

- part identifiers
- assembly data
- machining data
- information on product status
- etc.

The SLS module includes a program memory, a data memory, I/O ports and a communications interface.

Due to its programming capability, an SLS can actuate as local controller (through its I/O ports). But it can also be linked to a host system through an interface DIN 66019. Therefore, centralized or distributed controlled strategies can be implemented and evaluated on the installed architecture.

The topology of the transportation subsystem was constrained by the need to allow co-operation between the two robots of the two assembly cells. As a consequence, the robots had to be installed inside the rectangle defined by conveyors 5,6,7 and 9 (see Figure 6).

One aspect to be noted is the adopted solution to link the machining cell and the assembly / warehouse zone (conveyors 1 and 2). Due to the restricted gate between the two rooms, a two-layered solution, served by two elevator devices, was adopted.

Conveyor 3 is reversible, allowing transportation of pallets from the assembly/warehouse room to the machining cell and vice versa.

Conveyor 4 is linked to the warehouse subsystem, becoming one of the key points of the system, leading to potential bottlenecks.

This conveyor is used in the following flows:

- FAS to Warehouse and vice versa
- FMS to Warehouse and vice versa
- FMS to FAS and vice versa

To bring pallets into the 2 assembly cells, conveyors 5, 6 and 7 will be used. Conveyor 7 also includes a positioning device (stopper) to be used during assembly operations in cell 2, which is a constraint to the flow of pallets towards cell 1. During assembly operations using robot 2, no pallet can be moved to cell 1. This situation can easily be found in the Petri net model (Figure 8).

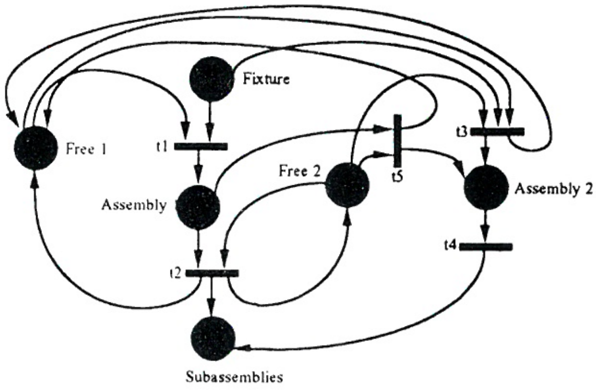

Figure 8 . Petri Net Model of the FAS

The control algorithm must take these constraints into account. In order to operate cell 1, the required pallets have to be transferred to the corresponding working area, before the start of the assembly operations in cell 2. This constraint also justifies the dynamic buffering of 10 pallets associated with cell 1, as mentioned before. This buffer is implemented by conveyor 9 and part of 5 and 7.

2.5. Automatic Warehouse Subsystem

This subsystem consists of an array of 50 storage slots, served by a 3 axis manipulator. Each slot can store a pallet and the parts/products it is carrying on.

There is a conveyor link between the warehouse and the transportation subsystem.

There is an SLS attached to the automatic warehouse arm. This SLS can perform read/write operations from/to the MDTs installed in the pallets. The warehouse controller has the possibility of checking whether a pallet is present or not, through an SLS operation. More than detecting the presence or absence of pallets in slots, the system can even determine which pallet type the slot contains. This is an important feature during initialization and is also a safety feature preventing picking a wrong pallet type.

As the warehouse is an important component of the system, several material flows from/to it can be identified:

Machined parts

From/To FAS1 or FAS2

Subassemblies

From/To FAS1 or FAS2

Finished products

To delivery zone

Raw -materials

To FMS

To FAS1 or FAS2

From Input Zone

Pallet-installed Gabarits

To FAS1 or FAS2

Empty pallets

From FAS1, FAS2 or FMS

2.6. Sensorial Subsystem

Beside the pallet identification systems, a multi-sensorial perception system is also being planned.

Due to the specificities of this area, the design and installation of such a system were organized as a separate sub -project, not described in this paper.

2.7. Safety Requirements

The safety aspects are very important in these types of systems. In a country where there is no long tradition regarding safety conditions and procedures, it seems very important to consider them seriously in a system that is going to be used in training activities.

Therefore the analysis and installation of safety "devices" is being planned according to the ISO standard 11161 - Industrial Automation Systems - Safety of Integrated Manufacturing Systems - Basic Requirements.

This standard was developed to provide safety requirements and guidelines for the design, construction and installation, programming, operation, use and maintenance of integrated manufacturing systems. It describes the potential danger situations associated with such systems and provides a set of recommendations to avoid risks.

2.8. Pneumatic Installation

A pneumatic network was installed in order to be used by various devices, namely the robot grippers and tool exchanging mechanisms.

3. Computational Architecture

In order to define the computational architecture to be used in this system, it is necessary to consider the diversity and heterogeneity of existing controllers.

In this system, several local controllers must co-exist: ABB robot controllers, BOSCH robot controller, Transportation subsystem controller (BOSCH PLC CL 300), warehouse controller, platform controller, CNC Milling and Turning machines controller.

Each controller has its own facilities. It is, therefore, necessary to define an architecture able to integrate all these controllers, ensuring a coherent and effective interoperability between them.

This part of the project has not been finished yet. It is our intention to design a distributed control architecture based on autonomous agents. An infrastructure to support negotiation and other forms of co-operation between agents is being investigated.

The client-server paradigm in a network of UNIX machines, resorting to Remote Procedure Calls, is being used.

4. Conclusion and Further Developments

The installed FMS/FAS system described above is not a finished or closed project.

The purpose was to build an open infrastructure to which new functionality can be added and evaluated.

NOVAFLEX is intended to be a dynamic system, able to adapt to the research challenges in Intelligent Manufacturing Systems.

A set of internal research projects are now being started to explore, evaluate and extend the installed system, namely in the areas of supervision architecture, perception systems and dynamic scheduling.

Another area that can benefit from the existence of this unit is the field of Systems Modelling. Experiments with OOP languages, generalized Petri Nets and EXPRESS/STEP are being developed.

As a benchmark, a toy clock - NovaCLOCK - was designed and is being used as our first test case (Figure 9).

This benchmark illustrates various kinds of operations, requiring different robots:

- stack like pin-into-hole -> SCARA robot
- horizontal (X direction) pin-into-hole) -> 6 DOF robot
- assembly of clock hands -> parallel co-operation of two robots

The insertion of pin P by one robot requires the second robot to hold the hand H (Figure 10).

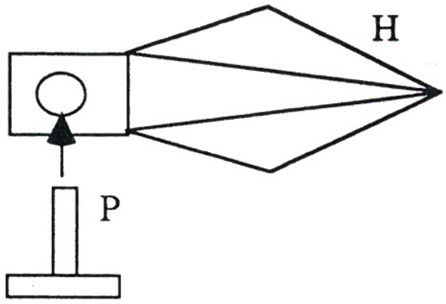

Figure 10 . Detail of Clock Hand Assembly

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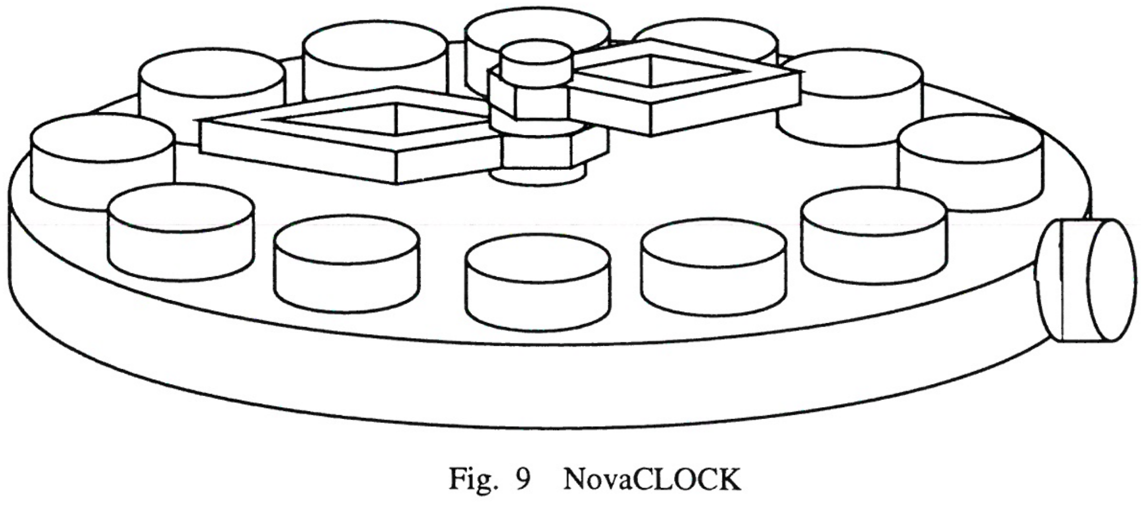

Fig. 9 NovaCLOCK