SOME PROBLEMS OF INTELLIGENT CONTROL OF OPEN CNCs AND MANUFACTURING CELLS

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Abstract: Computer integrated manufacturing (CIM) applications are increasingly utilizing artificial intelligent methods. Real-time expert system environments are appropriate tools to develop intelligent controllers. The first part of this paper summarizes some problems of the application of expert systems in the field of CNC and manufacturing cell controllers. Then a new open European CNC architecture (OSACA) is introduced together with knowledge-based, intelligent control application in its environment evaluated by a prototype solution. The next part of the paper deals with simulation based real time control of robotic manufacturing cells to show the way towards holonic manufacturing units. *Copyright @ 2000 IFAC*

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1. INTRODUCTION

Industrial controllers and machine tool controllers have been evolving during the past decades in close harmony with the state-of-the-art of computers. Taking a look at the lists from a decade ago (e.g. Wright and Bourne, 1988) which tried to summarize the commercial needs for the new generation of machine tools it is clear that in many respects great, positive changes have happened. Some important features are proving the evolution:

- the number of scrap parts have reduced following the initial set-up
- the accuracy of manufactured parts has increased
- the set-up time has reduced by designing parts for easy set-up
- the total cost for part fabrication has reduced
- machine throughputs have increased
- machine downtimes have reduced
- the range of possible geometries of parts to be machined has increased
- tooling time has reduced through better operation planning
- the time between part design and manufacturing has reduced

The next list contains some aspects, where the results are not that successful:

- the skill level required for machine set-up and operation did not decrease as expected,
- in spite of the high number of diagnostic features, the controllers are not able to adapt their work to certain recovered situations,
- run-time intelligent error correction is still missing even when the reason of the error is detected,
- the quality of information and the efficiency of information exchange did not increase between the humans and the controllers,
- the diversity of types of information between the controllers and upper level devices is limited (e.g. only, program transfers, status information and start/stop signals).

Comparing the two lists one can say that the machine tool controllers are powerful enough in sensors and in computer capacity. They also have several built-in functions (e.g. online animation-simulation, easier NC program-validation and modification), yet they have not increased their intelligence compared to the expectations given above.

From the point of view of cell controllers - which mean a higher level within a possible hierarchy - some tasks are similar some others are completely different. As a basic requirement cell controllers have to provide independence, or with other words autonomy to the system. And this is typically a task where intelligence may help. This way intelligence led to the idea of the world-wide accepted notion of 'holonic' manufacturing. A holon is something (e.g. a manufacturing cell) that has its own intelligence (able to work independently having the appropriate controller), and that is able to co-operate with its environment (to work together with other cells).

The design of new flexible manufacturing systems (FMS) needs the simulation of different design versions before implementing the 'best' design. Simulation can be used for analyzing the behavior of existing or would-be systems. It is useful for calculating utilization statistics, finding bottlenecks, pointing out scheduling errors, and even for creating manufacturing schedules.

Several expert systems have been developed for manufacturing and other functional organizations to solve a wide variety of problems (Liebowitz, 1990, Smith at al. 1992). There are successfully implemented real-time and industrial solutions which have saved money for the customer, e.g. at Ford Powertrain Operations (Gensym and Ford, 1996) but there are manufacturing companies, that are not using expert systems at all (Wong at al. 1994).

2. INTELLIGENT MACHINE TOOL CONTROLLERS

In an ideal scenario to the intelligent machine tool (Wright and Bourne, 1988) the human mechanist was nearly replaced by the controller: "We must therefore acknowledge that the degree of intelligence can be gauged by the complexity of the input and/or the difficulty of ad hoc in-process problems that get solved during a successful operation. Our unattached, fully matured intelligent machine tool will be able to manufacture accurate aerospace components and get a good part right the first time". They told that an intelligent machine tool having the CAD data, the materials and the set-up plans as inputs could produce correctly machined parts with quality control data as outputs.

During the last decade many efforts have been made to get closer to this ideal scenario, but the way of information processing within the CNC did not change very much. Knowledge processing and other artificial intelligence methods have not appeared within the controllers. Special heuristic rules, problem-solving strategies, learning capabilities and knowledge communication features are still missing from the controllers.

The new requirements for the integration of manufacturing means the effective use of knowledge through the product life-cycle (from design to production and maintenance (Kim 1995)). In a workshop of the future the control systems should properly process information in a changing environment (e.g. location and position of work-pieces) and it should be able to handle unexpected events (e.g. chipping problems, tool errors) in an intelligent way. That means at least intelligent adaptation capability, but also increasing of the knowledge level, and case-based reasoning and learning from the experiences, too.

As a summary Nam Suh (1995) gives a very good definition to the intelligence in this domain: An intelligent manufacturing process is defined as the process that has the ability to self-regulate and/or self-control to manufacture the product within the design specifications.

Moving towards the reasons of the lack of meeting the requirements in the above definition there is an important distribution comparing the intelligent solutions mapped to the level of the factory. There is an intensive work for intelligent sensors (e.g. Monostori, 1993), and for intelligent cell-controllers with different type of intelligent subsystems (e.g. scheduler, quality assurance, diagnostics, (Mezgár and Kovács, 1994). On the other hand at the controller/workstation level very few applications can be found and it is strange comparing the 10 year old ideal scenario mentioned earlier.

Taking a look at the present controllers an important reason can be found. All the controller vendors offer their products in a nearly black box solution, there are no tools and interfaces to add further user written (intelligent) tasks and subsystems to the basic controller.

The parts manufactured by CNC machines are so wide in range and have so many complicated factors (Raggenbass and Reissner, 1995) that the specifications of the new machine tools are getting extremely different and strongly depend on the applications and on the customers' further needs and habits. This requires more flexibility and openness also for the machine tool control systems. Because of the ever growing adaptation work at every final application, more and more programming of the NC controllers, modifications and enlargements of the functionality should be done by the staff of the application integrator and of the machine tool builder.

3. NEW, OPEN CNC CONTROLLERS

Manufacturing has constantly been a technological domain, in which the industry was driven to apply the current high-tech in the computer and control area. It is no surprise, that the Open Systems concept has also diffused into the manufacturing area, and factory managers are often referring to the *open* manufacturing systems. The terms and definitions are far less exact than the terms applied in the operating systems environment, but by now, the change of the global manufacturing paradigms (Kovács 1996, Saygin and Kilic, 1996) are directing our focus on the key user aspects of openness.

The booming market for industrial automation led to a vendor dominating situation: dozens of controller manufacturers (vendors) are developing, implementing and installing different solutions for automation/manufacturing tasks. The main problem is the large number of incompatible products, when the controllers can not cope with the frequently needed updates, when service, maintenance and repair costs are scoring high, and personnel to be able to work with several different controllers is decreasing in number.

To cope with this situation, some early developments have started in many countries, and also in Hungary. In national reports, the guidelines for compatibility, interoperability and standardized solutions (GYKFT 88) and the requirement specifications for the next generation of CNC controllers had been set in a harmonized way with the GM initiated Manufacturing Automation Protocol (MAP) project. The conclusions from these projects and reports were coinciding with those, being prepared by American, Japanese and other European teams (e.g. the EC sponsored CNMA projects, the MITI-sponsored FAIS project in Japan, OMAC initiative in the USA).

The need for a new and open CNC architecture was emerging at many other places around the world. One of the most important work was done from 1992 within the frame of the European project named OSACA (Open System Architecture for Control Applications) (Pritschow and Sperling, 1994.) The most important results of the project are: an analysis of the state-of-the-art and future requirements of NC controllers, a reference architecture, a general and platform independent API for inner CNC and outside communication and a configuration system supporting the possible machine tool vendors.

Similar efforts are going on in Japan under the IROFA Consortium, and in the U.S. within the TEAM and ICON projects (ICON 1997).

4. THE OSACA COMMUNICATION

The OSACA project defined and developed a system platform. On the top of the basic components (e.g. hardware, operating system, communication medium) a special OSACA API was defined. All the applications named Architecture Objects (AOs) in OSACA can use and reach all the services of the basic components and each others via the API. This object oriented API fulfils the interoperability, portability, scaleability and interchangeability requirements of an open controller in the sense of communication (Lutz and Sperling, 1995). So this API means full portability and hardware/operating system independence for the applications and presently existing on many different platforms (e.g. WinNT, Solaris, VxWorks, OS2) and communication media (e.g. TCP/IP, shared memory, serial line).

The OSACA API supports data communication between different tasks of an environment and between different environments in the same way. So called shortcuts are used within one single environment to solve time critical data exchange problems.

The API has three layers: a message transport system (MTS), an application services system (ASS) and a communication object manager (COM). The application programmer can reach the API using the COM. Each AO has its own communication objects which can be reached via the COM. Presently three main classes have been implemented: variables, events and processes.

Another result of the OSACA project, the reference architecture for open control system, among others describes which functionality is offered by given AOs by defining attributes and services for each AO. The performance and the functionality of a given AO will easily be scaleable keeping the guidelines of the reference architecture.

The open architecture supports more effective integration of user defined special modules in general, so among others, applications using AI techniques can also be added to the open CNC architecture. This view led us to the examination of the integration of the G2 Real-Time Intelligent Environment (Gensym, 1996) to the OSACA platform.

5. A PROTOTYPE INTELLIGENT MAN-MACHINE INTERFACE

As a prototype of intelligent applications within the OSACA environment, the MMC (man-Machine Communication) task of the WZL (University of Aachen) demo was replaced in our laboratory to a G2 based MMC which applies also rules for its control task. To solve the connection a special interface has been developed which connects the G2 Real-Time Environment to the OSACA using the Gensym System Interface (GSI) over TCP/IP which provides an external task based C interface to the G2. Within this interface task the OSACA C++ based communication API was built together with the GSI.

The OSACA communication presently allows three classes of objects: variables, events and processes. On the other hand GSI supports a wide range of communication solutions with its three types of external communication categories (i.e. setting and getting external variables, calling external procedures and invoking internal procedures from the external system). So all OSACA communication classes and their methods can be solved easily by choosing a solution within the GSI to be able to map the OSACA objects into the G2 inside world. Any OSACA communication variables (e.g. end positions of X, Y, Z and the override of the intelligent MMC demo program) concern a G2 variable and when the G2 user changes the value of any such variable, an automatic mechanism provides its updating through the GSI and the OSACA communication. The following rule shows that as an example:

whenever any axis AX receives a value and
when the gsi-interface-status of g2-osaca-interface = 2
then start set_axis (the string of AX, the value of AX).

It is clear that the suggested, OSACA based open, intelligent CNC solution fulfils most requirements of the 'classical' CNC controllers. Tasks, as trajectory management, path calculations, interpolation for multiple axis, PLC and logical control functions, safety and diagnostic tasks, man-machine communication, DNC systems connections are all easily handled within the same reference control architecture.

Additional features, as user-macros, built-in adaptivity, diagnostics, feed-back for real-time process data , ACO, etc. can only be implemented, when the controller fully offers openness in the wide sense meaning. As other investigations suggest, (as in Rudas A2 and C24), robot controllers fall in to the same category as CNCs of machine tools.

6. THE RELEVANCE OF CELL CONTROLLERS, OR SHOP-FLOOR CONTROLLERS

The typical functions associated with CNCs and robot controllers are classified (by Koren 1997) into the following categories:

- Discrete events,
- Servo and spindle control,
- Interpolation and trajectories,
- Compensations,
- Adaptive control,
- Models and simulators,
- Monitoring,
- Diagnostics,
- HMI and GUI,
- Interpreters and translators,
- Communications with other factory computers.

Cell controllers, that are typically applied to manage flexible manufacturing cells and systems, can be discussed in a very similar fashion. The above listed functions apply to these Cell controllers as well, but priorities and weights of the functions can significantly be different from those.

- Discrete events of direct control are less in number , and required response times are longer,
- Servo and spindle control are usually not handled directly at this level, but through DNC functions performed by connected CNCs, RoCs,
- Interpolation and trajectories are embedded into part programs,
- Compensations are managed on a higher level.
- Adaptive control functions can be applied partially also at the cell level but not completely,
- Modeling and simulation is very important at cell level,
- Monitoring is essential for all cell elements and the complete manufacturing environment,
- Diagnostics run for full environment, cell and cell-element levels.
- Human-machine interface must be versatile for cell level, and also for cell-element level, so it must be a virtually universal interface for all.
- Interpreters and translators apply for cell level too,
- Communication is the primary aspect of a cell controller, since its task is to fully manage in a harmonized way the information flow, responsible for the control, and observation, monitoring of the environment.

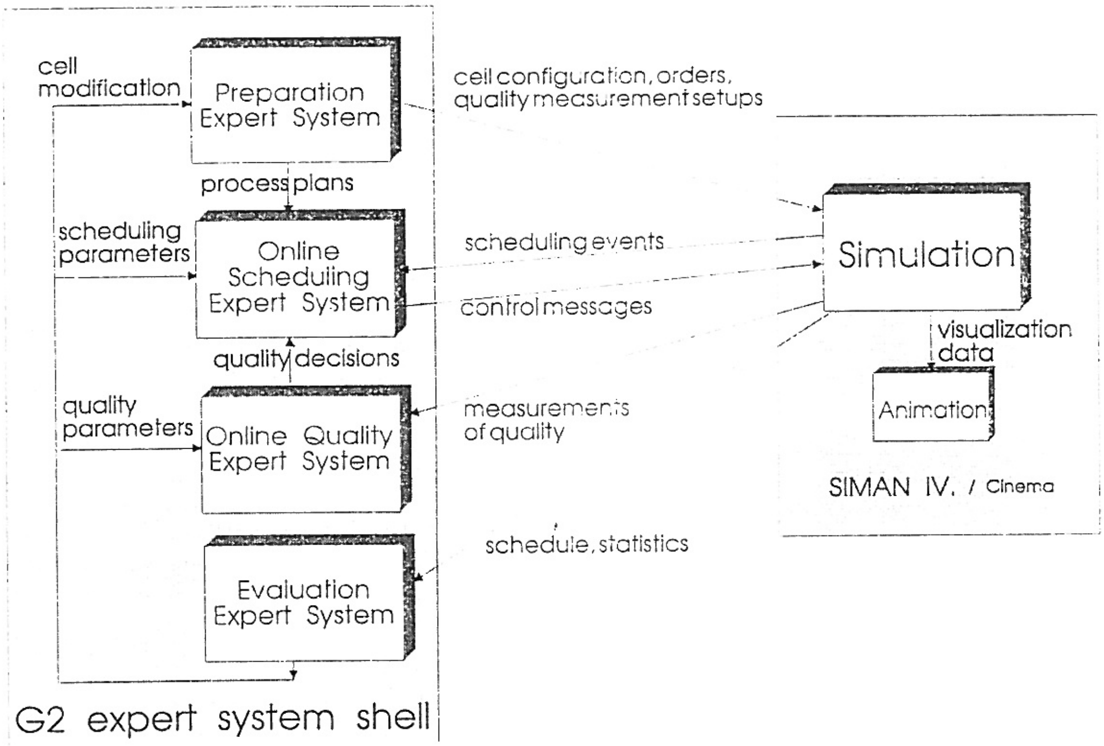
As additional cell-controller functions, scheduling and rescheduling should be implemented, which tasks are almost always missing at the CNC level controls. The way, how a cell-controller manages errors, and exploits the resources within a cell, determines the real value and benefit of flexible manufacturing. When scheduling is not an off-line function, when diagnostics and error-handling are implemented, the continuous valuable work of a cell can be maintained. Intelligent tools and methods are of high priority at these functions.

In the following sessions the intelligent control of flexible manufacturing cells and systems (FMC and FMS) will be discussed. In our experiments, first we used intelligent tools for the modeling and simulation of such systems.

7. MODELING AND SIMULATION IN FMS DESIGN AND CONTROL

Simulation activities essentially assist in designing FMS and in designing FMS control. The basic purpose of the simulation of a modeled FMS in our hybrid simulation and scheduling system (SSS) is to find the best schedule by comparing the results of different scheduling strategies implemented in the G2 knowledge base using the same model. The other goal of the simulation system is to simulate different production tasks on a given FMS and finally to facilitate the evaluation and comparison of different FMS designs for the same tasks. This last target requires to build up several, new simulation models.

The hybrid SSS package (see Kovács, 1994) has four basic parts, where the three expert system modules (Preparation Expert System, Advisor Expert System and Evaluation Expert System) implemented in G2 are connected to the simulation engine. The Preparation Expert System creates the simulation model based on the user's instructions. The Advisor Expert System gives advises to the Simulation Module in scheduling and quality assurance decision points, and the Evaluation Expert System evaluates the results of the simulation and gives suggestions for modifications. The simulation engine implemented in SIMAN/Cinema package performs the task of simulation and animation.



8. APPLICATION OF REAL-TIME CONTROL

If the 'best' or an appropriate FMS model was chosen for implementation based on the simulation results, and the implementation is done the next task is operating the system.

Recent discrete manufacturing and/or assembly systems (FMS/FMA) are more and more often using MAP/MMS (Manufacturing Automation Protocol/ Manufacturing Message Specification) (Brill and Gramm, 1991). MMS technology is widely available from many vendors and really gives a safe and open solution according to the demands of OSI (Open System Interconnection). Many users do not exactly know that they have such interconnections, they just enjoy the useful features of MAP. On the other hand the so called intelligent control is getting to be a general demand. There is a vivid discussion in literature and in private communications among control engineers about the existence and need of intelligent control (Franklin et al.,1994).

Some experts claim that there is nothing that really could be called intelligent control. Most of them are speaking only about process control, and not about discrete manufacturing or robot control, however the control tasks and problems of manufacturing systems are basically similar to those of batch-like process control. Now, without going into discussions in this issue we accept the need and necessity of intelligent control which we intend to solve by means of knowledge based (KB) expert systems. We also say that some commercial expert systems provide good problem description and software development tools where the programming is closer to the problem to be solved and to the user to have to support with limited Real-time facilities (Laffey et al. 1988).

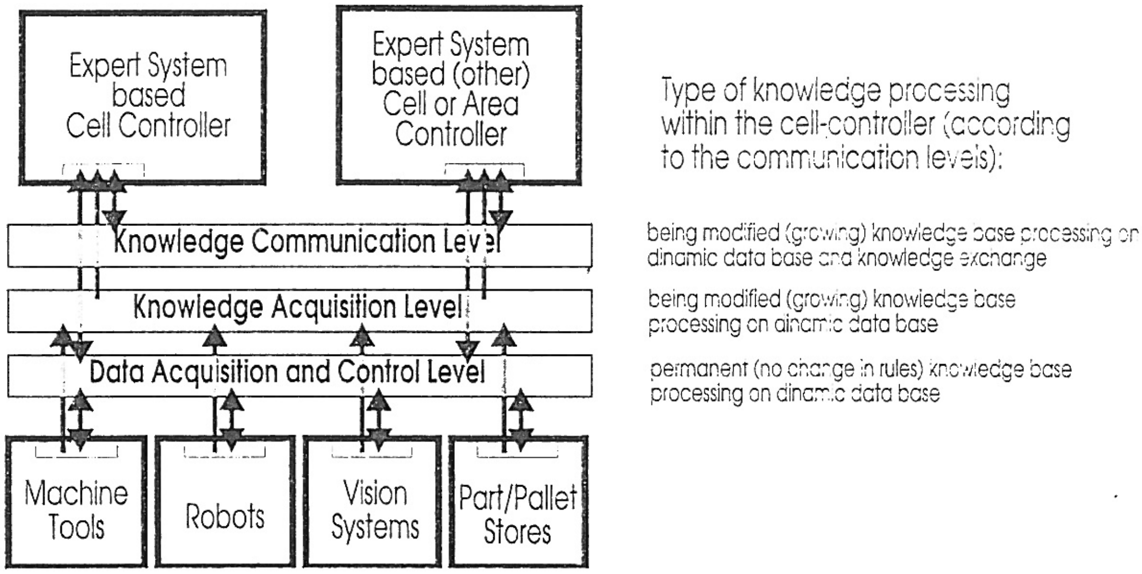
To speak about real-time control we need all scheduling data, as the starting and finishing date of all operations of all equipment (machine-tools, robots, transfer units, as, AGV, etc.) together with the possibilities of downloading control programs (RC, CNC, PLC) to all equipment, and to accept and evaluate different signals from them, etc.

The structure and the functionality of the SSS system were designed and developed in a way that later the simulation might be changed to a real FMS environment, and the expert system (ES), in our case our programs in the G2 environment would be the real-time controller. The prototype applications of SSS were developed with the real data (layout, capacities, process plans, machine parameters, etc.) of some academic and industrial FMS. The application specific and independent parts were separated in the expert systems.

9. REAL-TIME COMMUNICATION WITH EXPERT SYSTEMS

The practical problems of the communication of expert systems in CIM applications can be divided into two parts. One is the hardware-software connection (physical) and the other is the logical one between the controller(s) and controlled devices (Kovács and Nacsa, 1997). If this decomposition is not so sharp many problems may occur during the development and specially in maintenance of the software later on..

There are relatively easy programming interfaces (etc. C/C++) in most available ES shells. These interfaces provide data transfer and communication possibilities with external tasks, stations, etc. They support clear and easy programming to reach objects, to call procedures, to set and get variables, etc.. The interfaces are dedicated to specific software tools of the ES and they are general towards the external world without being able to take into account the requirements of the given application. So nearly each CIM implementation requires special software development to cover this gap between the external world and the ES.



The communication functions depend on the capabilities of the expert system. The way of learning and knowledge management determines the logical levels of the communication. Three different types of working mode and different levels of the communication of an intelligent cell-controller in a CIM environment are shown in figure (Nacsa and Kovács, 1994). These levels are implemented - of course - within the same protocol. This picture just explains the different possible meanings of given messages. The lowest level has the basic control and data acquisition type messages. The other two levels have messages if and only if the 'intelligence of the cell controller is not hidden'. Hidden intelligence means in this term that the knowledge based technology is applied only inside the cell controller and it has no specific actions via the communication channel. A typical example of the hidden case if a KB system is built up on the top of a traditional control system using its original communication. The knowledge acquisition and the so-called knowledge communications were separated. The first one contains specific data for modifying or verifying the knowledge of the given controller. When a KB system shares its knowledge (new or modified) it belongs to the knowledge communication level (Buta and Springer, 1992). The communication messages of the most real and pilot KB applications belong to the lowest, possibly to the middle logical level.

10. THE OBJECT-ORIENTED VIEW OF MMS

Going back to the so-called physical connection there are many alternatives. Most controller and controlled device vendors offer good (proprietary) solutions to communicate and also vendor independent standards are available.

In the CIM area there are more accepted models or modeling tools to describe the objects of an FMS. In the communication point of view the most promising one is the object oriented view of the so-called MMS (Manufacturing Message Specification), which is originally an application layer protocol in the MAP

OSI networks. MMS gives a so-called VMD (Virtual Manufacturing Device) view about each resource of the FMS. In a VMD it is possible to create, read and write different types of variables, to up- and download domains that can be programs or machine data, to start and stop different tasks (with program invocations) and to handle events.

The object-oriented view of MMS allows the design the VMD model of a certain device. It is immediately possible to use this model as a specification of the communication where the services (what one can do with a given object of the VMD) are defined and they are working in the MAP networks.

As the goal of this work is to provide Real-time, intelligent control of FMS the next step was to apply all development results given in the previous sections and to integrate the independently working and tested software-hardware modules.

11. A PRACTICAL EXAMPLE TO AN OSI CONTROL SYSTEM

As a first experimental set-up a simple configuration was chosen. From earlier projects a Mitsubishi robot was available with serial DNC connection to a PC that had a MAP interface. The trivial TIC-TAC-TOE game was played against the robot according to the following manner: a user could play against the G2 system. Of course it is not a problem for that such a system needed. But this well-known game is able to demonstrate very clear the 'intelligent' features of the control. On the other hand the full capability of the MAP networking was used.

A special gateway was developed between the ES and the robot. It couples the G2 system interface (called GSI) to the MMS standard communication. In this case it was the 'gap software' mentioned earlier. This special gateway of the G2 allows to develop any discrete manufacturing applications to develop in G2 using MMS standard interface without the need of modification of the interface. In the demo version the gateway supports the context management and some program invocation management services.

For this solution a special object hierarchy MLGO (MMS like G2 objects) and procedure set were needed within the G2 to let the other part of the knowledge base to handle the MMS interface.

In a work of a student (Tömösy, 1994) it was examined how the complete MMS object structure can be built up within the G2. It took a lot of efforts and gave a relatively complicated and not too useful structure. Because of the different services and their parameters many external procedure calls were defined. All implemented MMS services have their own GSI procedures and all MMS object types have their internal G2 object description. The complexity of the inner structure was the same as the MMS itself. The previous solution reduced the necessary objects and procedures to some general terms. It uses limited number of external GSI procedure calls also, but give a rather general (few limitations) interface towards MMS.

12. CONCLUSIONS, FUTURE PLANS

A basic problem of using artificial intelligence means, as e.g. expert systems to be built into the CNC is to solve the interfacing of the AI tool and the other parts of the CNC. The new generation of OPEN CNCs, which provide open APIs permits the integration of intelligent subsystems into the controller. An early example with intelligent man-machine interface of an OSACA based CNC illustrates the suggested solution. The development of more sophisticated applications are being under consideration.

The last part of this paper deals with intelligent real-time control of FMS. As an example the simulation of a real FMS and then a robotics cell (where the robot is defined as a virtual manufacturing device (VMD)) controlled by a real-time computer system is presented. The control software is implemented using the same real-time intelligent environment (G2), which is used for the SSS software.

We made some research and development in the CNC/MAP/MMS/VMD problems, and the application possibilities of expert systems was studied in the OSI communication point of view. An interfacing problem was solved when the G2 system and the MAP/MMS network were connected to reach Real-time intelligent control.

These results are useful and interesting for the future when they will be applied fore more complex and sophisticated large scale manufacturing and assembly systems which hardly can be designed and controlled without using simulation and expert systems.

The 'intelligent ' cell controller will allow us to build 'holonic' type of manufacturing entities, fulfilling all basic tasks of cell controllers, as :

- Optimal scheduling (task distribution within the cell),
- Job processing (management of work-pieces, tools and technologies) to assist scheduling,
- Diagnostics of all equipment within the cell,
- Event management (alarm-alert management in case of troubles),
- Journalizing (logbook) service of all events,
- Configuration and reconfiguration of the cell,
- etc.

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