Integration of Autonomous Mobile Robots into the Industrial Production Environment

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Abstract: The raising automation of flexible manufacturing systems (FMS) demands flexible automated material handling and transport systems. Furtheron new concepts of information processing of FMS are necessary in order to reach optimal economic results with complex production systems. The realisation of a flexible transport system using a mobile robot will be shown. The further development, also presented in this paper, leads to an autonomous mobile robot, which improves the flexibility for material handling processes and supports distributed control processing for a whole FMS.

1 Overview

The presented research project shows the development of information technologies for autonomous mobile robots in an industrial production environment. There are several projects aiming at the development of autonomous robots. Each of these projects has a well defined system environment where the tasks to be performed autonomously are described (see Rembold /1/, Rajan /2/). For the use of autonomous mobile robots in industrial production processes environment analysis and the resulting requirements are most important for future economic applications. The shown autonomous mobile robot is designed for

- transport tasks between depots and machines with tools and workpieces,
- change and discharging of manufacturing and assembly units.

The second chapter shows the state of mobile robots in flexible manufacturing systems (FMS) and the possible advantages. The second part of the chapter shows possible developments in the future and analysis demands for usable autonomous mobile robots deduced by the economic targets given by management.

The third chapter shows the structure of the whole project, in which several institutes of the Technical University of Munich are working on it. The structure of the project reflects the structure of the information processing system being divided in (figure 1):

- locomotion and navigation
- manipulation
- general control and information processing technologies.

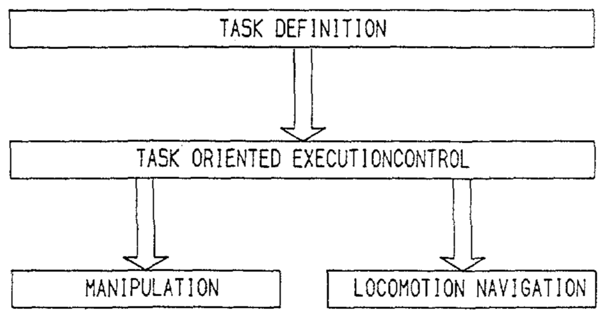

Figure 1: Structure of Subprojects of AMR- development

This last item is divided into two subitems:

- system control
- manipulation and sensoric.

These are the subprojects researched by the "Institut für Werkzeugmaschinen und Betriebswissenschaften" (iwb) .

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2 Mobile Robots in the Production Enviroment

The increasing flexible automation demands the integration of flexible automated material flow systems. The handling, exchange and transport of workpieces, tools and chucks become an important step towards highly automated FMS. Futhermore, the increasing complexitity of automated systems requires new solutions to reach a satisfying avalability for a whole FMS and optimized control strategies to improve the return of investment.

Already in 1983 the iwb started to construct a mobile robot for FMS (see Milberg /3/, /4/). The mobile robot is used in a computer directed FMS consisting of an automated saw center, two turning machines and one machining center (figure 2).

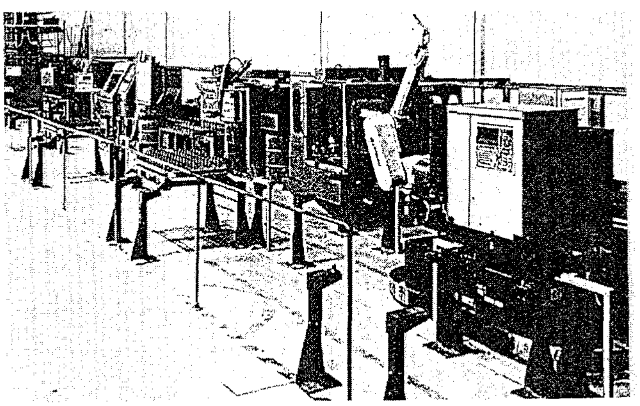

Figure 2: Flexible Manufacturing System of iwb

An inductive guided vehicle transports paletts with workpieces. The mobile robot charges and discharges the machinetools. Because of the mobility of the robot, the machine tools could be set up in accordance to the material flow. The machine tools need not to be positioned around a stationary robot with its restricted working area.

The mobile robot of iwb is fixed on a palette which can be moved by an inductive guided vehicle (figure 3).

For operation, the robot is put on supports. On the supports the position of the robot is adjusted with an accurancy of 0.2 mm. At its places of operation the robot is connected to an electric circuit and to the shoopfloor control system. During transportation a battery backup supplies the robot for a

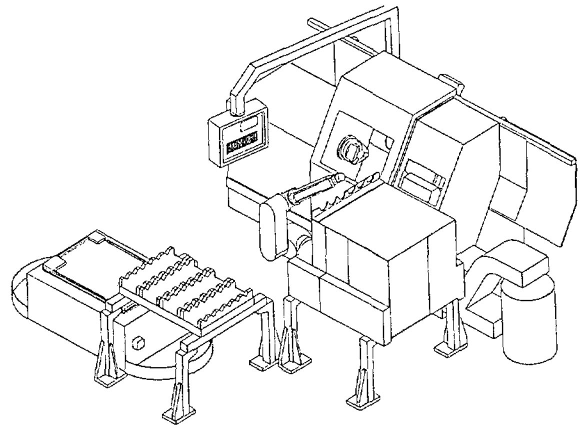

Figure 3: Mobile Robot on a Support

maximum time of 20 minutes. In order to reach higher flexibility the robot is equipped with several gripping devices. During operation time the vehicle can perform other work such as transportation of paletts loaded with workpieces. The advantages achieved by the concept of mobile robot are:

- layout design can be adapted to the needs of materialflow
- during machine operation the robot can be used to serve other machine tools
- during robot operation the vehicle can be used for transport tasks
- the robot can be easily replaced in case of errors or for maintance purposes.

The concept of dataprocessing for the FMS is based on the principles of distributed systems (figure 4). Each production machine is connected (DNC) to one workcell computer. The work cell controller is responsible for the optimal use of the machine within a given set of tasks generated by a global controller.

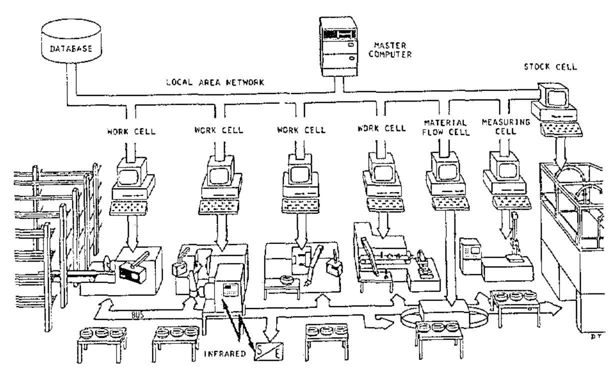

Figure 4: Flow of Information in the FMS of iwb

The workcell controller coordinates the charging and discharging operation with the mobile robot. In this concept the work cell controller can continue operation independent of the central coordination in case of faults. In addition, by doing the local coordination at local instances, the central controle computer can be more efficiently used for the optimization of the whole system.

The experiences with the above described system shows that mobile robots can improve the flexibilty of FMS. For future concepts the following capabilities will increase the use of mobile robots:

- free navigation in the shopfloor; the necessity of supports restricts the robot to certain places for operation, two robots can not work at the same time (e.g. part loading and exchange of tools or assembly of parts),
- automatic task oriented manipulation sequence generation; the robot needs not be idle because of the teach-in of new programms
- local control and coordination with other robots as long as no global decision is necessary.

These requested abilities leads to an autonomous mobile robot (AMR) for production enviroment. The design of such a robot has to respect the demands resulting from the desired use in production systems. This means that aside from the functionality of the robot, it has to support the total system optimum deduced from the economic targets of the mangement such as:

- short transit time,
- minimizing circulating capital costs and idle capacities,
- improving flexibility for product changes.

In general the globaly defined economic targets have to be achieved by the whole system. One of the most difficult problems is the optimum supply of manufacturing equipment for optimal exploitation of capacity and independence- a job to be done by the material flow system.

An analysis shows the distribution of different activities on a workpiece (figure 5) during the transit time on the shopfloor (see Wiendahl /5/). Only 1.2 % of the whole transit time is used for the actual manufacture of the workpiece - 98 % is used up by storing, transportation and waiting time before processing. The use of autonomous mobile robots is one step towards a better economic optimum.

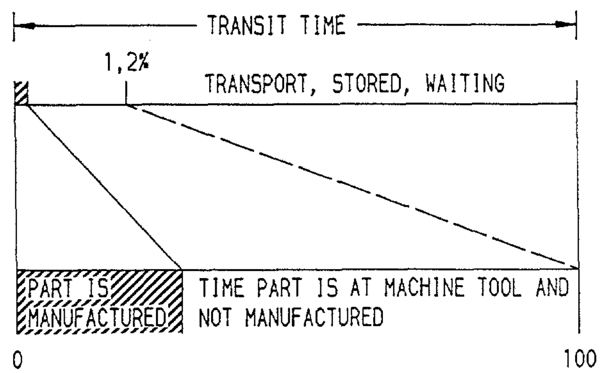

Figure 5: Timeparts of Transit Time

Further aspects to be achieved by autonomous mobile robots are a reduced setup-time of the robot by autonomous planning of the manipulation procedure and flexibility in case of changes in the shopfloor layout.

An autonomous mobile robot in an industrial production environment must execute its tasks under the restrictions and requirements of a global optimum of the whole system. This means that the local decisions of a real autonomous system (not only of robots!) have to conform to the global targets deduced from economic necessities.

3 The Structure of an AMR and the Project Structure

The basic functions of an AMR are:

- mobility and navigation
- manipulation
- system control.

A: system control, knowledge base design and hardware development

B: sensors for navigation and manipulation

C: planning and execution for locomotion and navigation.

These functions and their subfunctions (e.g. global and local navigation) are interconnected by a global knowledge base. These subprojects are divided into (see figure 6)

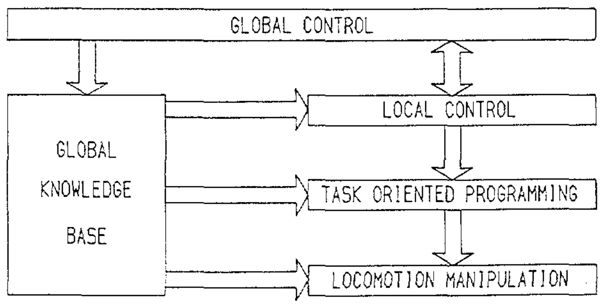

Figure 6: Functions of AMR

During the first three years of the project the following aspects will be analyzed:

- the integration of an autonomous mobile system into production environment
- how to structure the knowledge base
- what kind of multiprocessor architecture base and communication structure is necessary for efficient knowledge base implementations (see Helling /5/)
- the autonomous navigation and locomotion in the shopfloor environment (see Freyberger /6/, Kampmann /7/)
- the autonomous manipulation of tools and workingpieces.

At the end of those first three years of research a prototype of an AMR charging and discharging machine tools will be built.

4. System Control and Manipulation

The following chapter will describe the subprojects the iwb is working on.

4.1 Control of Autonmous Mobile Robots

There are three major duties for a system control supervising several AMRs:

- control of several AMRs (global)
- control of one AMR (local)
- coordination with other production units.

The tasks of the AMRs are deduced from the production plan of a given period. This production plan is based on the global economic goals stated by the management. Usually the optimum aimed at is not the system's absolute optimum, but a relative optimum according to the demands of the market. Of course this relative optimum does not lead to an optimal use of each single unit.

Therefore the local optimum is not the appropriate criterium for the decisions of the AMR's system control. To build a real autonomous system there must be further criteria to bring decisions closer to the planned system optimum. Without this criteria there will be no useable AMR for production environment.
The demands of behaviour in favour of the system optimum and the capability of bringing autonomous decisions closer to a corresponding optimum includes the question: what is the necessary global knowledge for AMRs according to the decision levels. This knowledge asked for has to be structured like this (figure 7):

Level I: Knowledge and decisions to execute a task.
Level II: Knowlegde to make decisions which are not detrimental to the total system goals.
Level III: Knowledge to decide on questions concerning the whole system.

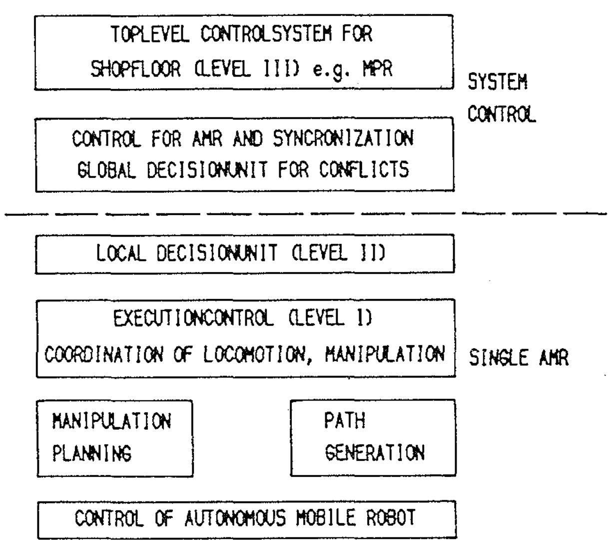

Figure 7: Levels in Controlsystem of AMR

Level I. This is the basic knowledge of an AMR. With this local knowledge the system controls simple action sequences like "go to the store, take the specified tool and go to a specified machine".

This execution oriented knowledge also includes simple decisions like avoiding collisions during locomotion.

Level II. Problems not concerning the whole system are decided by the autonomous system control. Such problems are jobs of the autonomous system that can be carried out correctly in spite of complications, e. g. by choosing another way to the goal. In the first phase of the project some criteria for such decisions are chosen, such as:

- the job can be terminated
- the execution finishes in a given time interval.

The last criterium is necessary because the actions of the AMR always have to be synchronized with the actions of the production unit served. As long as this service can be done within a specified time interval, the actions of the other system units are not influenced or disturbed. Conflicts between several autonomous robots,

"which one is passing through a lane first or the priority at crossings"

are also part of this category of knowledge and decisions. These sort of problems are treated in level II as long as there is a solution satisfying the jobs of each AMR involved in the situation. For level II decisions the AMR has to

- plan a possible action sequence
- compare a planned action sequence with the situation
- coordinate action plans of different AMRs.

From this decision scope the knowledge of level II can be deduced. Here we find a set of knowledge which will also be meta-knowledge for level I knowledge and action.

Level III knowledge and decisions are necessary if a task cannot be finished. Usually lack of free capacities or of alternative jobs for the unserved manufacturing unit induce delays in the production. In this case a changed shopfloor schedule for the influenced part of the system must be generated.

The shown structure of knowledge leads to a location of decision and knowledge. Level I is to be found on every autonomous system. Level II is divided:

- decisions which need no further information or planned actions (actual position belongs to the environment!) of other components are made localy on the AMR,
- decisions which need information about other systems' planned action are made with the help of the global part of level II.

In this global part knowledge is prepared and decisions concerning more AMRs are made. Interaction with other machines is planned and synchronized, e.g.:

"put part in machine, wait for signal, part fits, now remove hand".

The signal "part fits" is transferred by a realtime mechanism in the knowledge base.

The global system control, including the following functions, is the first to be implemented:

- distribution of task to different AMR
- synchronization with other production equipment
- permanent control of actual status
- conflict solution of several AMRs

The structure is divided in 4 layers (figure 9). The top layer is the interface to production planning and control system (e.g. MRP, level III).

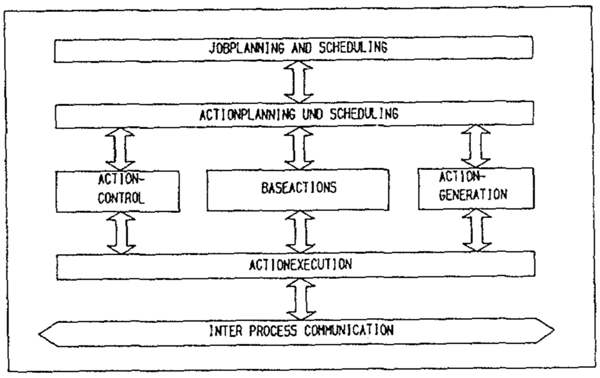

Figure 9: Layers of Control System

The production tasks for the whole FMS are scheduled. The next layer plans the necessary actions for AMR to execute the production tasks. The action control starts the single tasks and supervises the execution. The module "Baseactions" describes the basic actions, which are available in the "Actionexecution" module. The module "Actiongeneration" generates situation dependent actions and combination of actions sequences with the help of the basic actions. New actions are loaded in the "Actionexecution" module. The execution of actions can be performed automatically, several actions can be performed at the same time. The Inter- Process- Communication transports (IPC) requests and responses to and from the devices.

The generation of basic actions (without the graphic modules) and the execution system is written in PROLOG. The IPC is implemented in Modula- 2 for VAX/VMS operation systems. With the IPC every node in a network is reachable. A Prolog-Modula interface connects via IPC all AMR in the production system.

4.2 Manipulation and Sensors

Level I (see above) executes the tasks given. In this level the operation sequences are generated and the execution is controlled. The process of generation and execution of a manipulation sequence (here: loading of the machine) will be discussed in detail.

According to the known geometry of the workpiece, machine and robot hyponotic trajectories and points are generated. This sequence of robot actions is not yet adapted to the actual position.

Like this the planning of the manipulation can be done while the robot is moving. The planned robot movings will be veryfied by simulation. After reaching the final position a special laser sensor measures the exact position of the robot in relation to the machine. This sensor is developed for this special purpose in shopfloor environment (see Karstedt /9/). It is started by the specifications of the machine (figure 10).

With this specification the sensor knows where to scan for a reflecting mark on the machine. If the machine mark is found exactly, the sensor puts the exact position (tolerance 0,1 mm) directly into the global knowledge base.

The prepared robot sequence is adapted or, if the position of the whole robot is to be corrected before, the measuring cycle is restarted.

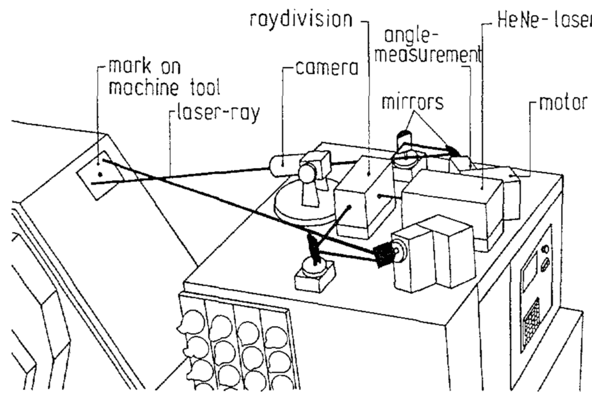

Figure 10: Laser Sensor for Position Measuring

A faultfree simulation run of the robot program with the exact coordinates is the last step before execution. The simulation checks for:

- collisions
- kinematical restrictions.

The simulation module is based on the interactive robot simulation system USIS (see Wrba /10/, figure 11, figure 12).

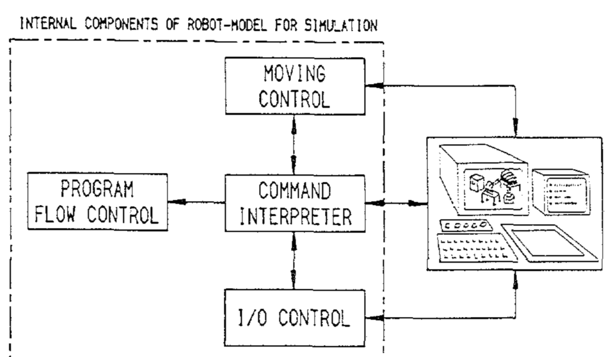

Figure 11: Structure of Interactive Robotsimulation USIS

In this system geometrical and functional descriptions of the robot are held for several tasks in the planning and programming of flexible assembly cells:

- graphic I/O support,
- measuring of geometrical and functional values,
- placing of assembly cell components, like robots out of a library
- motion of the robot in accordance to his model,

- generation of robotprograms,
- test of programs in realtime

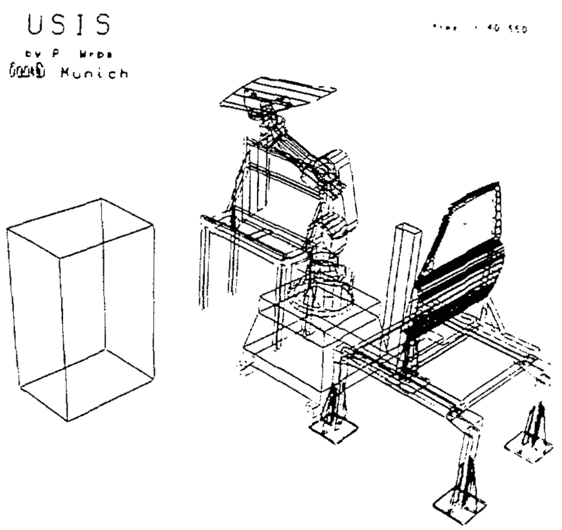

Figure 12: Simulation of an Assembly Cell with USIS

The execution of a simulation run is controlled by an interactive user. For the use in AMR the geometric and functional models are extracted and converted into the global knowledge base. A collision module is added (solid model) to the simulation package first. To control and direct the simulation, an expert system directly interacts with the simulation instead of a human being.

5. Summary

The presented project of an AMR shall improve the economic value of highly automated manufacturing systems. Therefore "autonomy" means adapation of the behaviour to given global goals by the means of local decisions of the AMR and application of the principles of distributed processing in order to increase availability and fault tolerance of production systems.
Different levels of the decision structure and the control hierarchy are defined for the AMR. On the execution level the simulation of manipulation sequences is used by the planner to verify generated manipulation action.

After this basic development the project will continue with

- learning by experience and simulation on the different levels
- parallel execution and preparation of tasks with a multiprocessor architecture.

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