

# DEVELOPMENT OF AN OPEN AND MODULAR CONTROL SYSTEM FOR AUTONOMOUS MOBILE BUILDING ROBOTS WITH FLEXIBLE MANIPULATORS

**Prof. Dr.-Ing. Klaus Feldmann,  
Dipl.-Ing. Markus Koch**

*Institute for Manufacturing Automation and Production Systems  
University of Erlangen-Nuremberg  
Egerlandstr. 7 – 9, 91058 Erlangen, Germany*

Abstract: Rationalisation efforts in the construction industry are more and more affiliated with the attempt to automate the building processes. This requires mobile systems, which can move themselves independently to their place of work and execute their job there. Apart from the development of suitable planning tools for the application of these systems, their control components must meet special requirements. These are first discussed in this paper. Subsequently, an overview of the current state of the art in the area of control engineering for robots and mobile systems is presented and a suggestion is made, how a modular control system for a mobile building robot could be structured. Finally a construction possibility for a manipulator is presented, which can assume handling operations in such a mobile building robot.

Keywords: mobile construction robot, mobile robot, open control system, modular control system, flexible manipulator, parallel manipulator

## 1 INTRODUCTION

The demands on the manufacturing process within the area of the building industry are constantly rising in order to enable competition with domestic and foreign companies. The requirement for high-quality products is the most important point of the value chain with the constraint of a careful and efficient use of the natural resources and the efficient employment of the workers. This requires manufacturing processes which are absolutely reliable and reproducible. That applies to the building industry as well as to all other areas of the production-related fields. Rationalisation efforts in the construction industry are more and more affiliated with the attempt to automate the building processes. Up to now, automated solutions are developed however in each case for each special building process. The repetition of development errors and the increased training expenditure for the users cause high development costs, which make an economic application of the automation systems often impossible. One possible solution for these problems is an open and modular control system for the construction robots based on a component system with modern industrial PCs.

In the following paper first the technical basic conditions for a mobile building robot are described

and afterwards, on the basis of the necessary system components for its control, an example of an open and modular control system is explained. Finally, a suggestion for an exemplary construction possibility for a manipulator is described, with which offers the requested flexibility to do the most different assembly works on the building site.

## 2 REQUIREMENTS OF CONSTRUCTION TO A MOBILE ROBOT

The development of mobile systems for the building industry presupposes an exact knowledge of the operating conditions, because these are particularly in the building industry very unfavourable. The following views refer all to the interior finishing, since there just a few automation solutions have been developed, but nevertheless large potentials for automation can be used.

In the interior finishing a mobile system is not directly exposed to unfavourable weather conditions like rain or snow. However the device can come into contact with splash-water and dust and can be exposed

strong variations in temperature. A further point, which is often neglected, is the transport of the device into the building. Devices for the interior work should fit into elevators and through doors, thus they have to be lower than 2 m and smaller than 0.9 m. Alternatively they have to be fast divided into smaller individual parts. It has proved that a transport into the building can not be ensured over load cranes, at least without complex advance planning, because scaffolds obstruct very often the access by the front. The manual transportation to the workplace would be ideal, since one could organise the transport very flexible and independent of elevators or load cranes. Because there are normally at least raw concrete soils available, the condition of the ground is well defined in the interior work. The application of a mobile system will be problematic, if raised floors (e.g. hollow floors) are already installed, the maximum payload of the floors must be considered particularly in this case.

The power supply turns out problematic, since no combustion engines may be used. Up to now the most meaningful alternative is the supply of electricity with a cable, however using mobile systems the danger of damaging the cable by overdriving is very high. Another possibility are battery-operated vehicles, however the operation of their tools and handling devices is more problematic then, as additional batteries increase the vehicle weight substantially, whereby the maximum payloads of the floors in the interior finishing could be exceeded. An interesting alternative within the area of the power supply could result from the further development of the hydrogen technique.

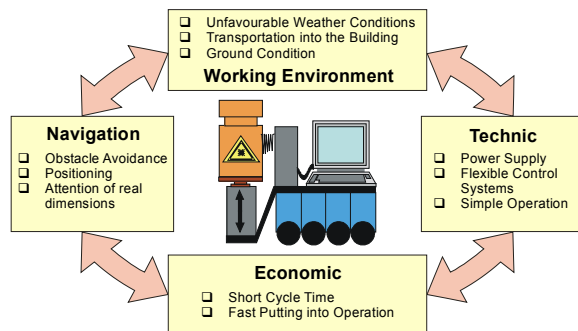


Figure 1. Requirements of Construction to a Mobile Robot

For each application of a mobile system the reliable recognition of obstacles is particularly important. It is to be expected that building robots will operate in next proximity with mechanics on the building site. In addition, stationary obstacles such as shoulders, openings in the building, ditches or installations etc. must be localised in time. The independent overcoming of the obstacles, without damaging the obstacles, is a substantial demand for an undisturbed operating.

The different building processes, which are applicable for an automation, make the most different demands at the accuracy of navigation and positioning of the automation solution. Within the area of service robotics there are numerous basic approaches, which enable a navigation in unknown environment, however none of the algorithms so far presented allow a positioning with an accuracy of a couple of millimetres.

While in outdoor work the use of GPS or DGPS would be a very good solution, this cannot be used in the interior work, since the satellite signals are not received failure-free. Laser-Systems (theodolites) are still very expensive for the moment, so that in this point is still a large development potential. A further problem to the work accuracy is the specification of the bias points. If these are to be determined on base of a CAD-plan, an alignment between the planned and the real dimensions of the work space is urgently necessary.

A further problem is the small degree of technical training of the future users. In order to keep the restraining threshold low in handling the automatic control engineering, the operation of the devices should be possible without complex training course expenditure.

The economy of future automation solutions is likewise a large problem. The devices should indicate long operation times and short downtimes, what presupposes a matured control system and a process planning for the building project adapted to the devices. The economy of past prototypes was questioned again and again by the low wage level of workers from low wage countries, which particularly often take over the monotonous activities as subcontractors.

### 3 STRUCTURE OF OPEN, MODULAR CONTROL SYSTEMS FOR AUTONOMOUS BUILDING ROBOTS

In this section the basic structure of an open, modular control system for autonomous mobile robots is described. The software components are introduced afterwards in the next section

#### 3.1 Structure of Open, Modular Control Systems based on Industrial-PCs

Openness is today a frequently used term in the automatic control engineering. Generally openness means that automation components offer intervention and combination options the user [3]. This presupposes the introduction of suitable standards, which do not have to be inevitably standardised however, but

can also be established as De-facto-standards. The basis for an open system was founded by IBM introducing the concept of extension boards with the development of the PC.

Therefore the user can profit from the large hard- and software supply of the market. He can also get rapidly a substitution of damaged hardware components. More and more control problems can be processed on a single processor with the rapidly increasing efficiency of the PC technique. The programming of the PC takes place over wide-spread programming tools, the familiar appearance of applications enables a high acceptance and a fast training of the future users. Therefore the industrial PC could become generally accepted in the automatic control engineering in the last years.

In the software area the operating system has a key position. In control engineering above all the real time ability applies as absolutely necessary. Real time describes in this case not the speed of operation, but the ability of a system to react on special events within a predictable time interval. It is an obligatory condition that this reaction takes place at all events and independently from the present system workload. The temporal tolerance limit can vary thereby depending upon the application.

In the PC world the operating system Windows was established as standard, which features a familiar graphic appearance of the user interface, but does not have real time possibilities. For this reason several expandabilities were developed to enable real time functionalities for applications in control engineering, either on base of supplement software or over additional hardware components.

A further advantage when using industrial PCs are the standardised interfaces, which enable the linking of the automation solution to superior control components and simplify in addition the integration of external hardware components. Glossary words in this context are dynamic data exchange (DDE), the integration of external objects with object linking and embedding (OLE), linking different applications at the field level with OLE for process control (OPC) or the open data base interface with open database connectivity (ODBC) [3].

Thereby, industrial PC were established as the base for open, modular control systems and combine meanwhile the required real time ability with the familiar appearance of graphic user surfaces. So such a system is also the basis for the control system of a mobile building robot.

### 3.2 System Components for an Autonomous Mobile Construction Robot

Considering the control system of a building robot it must be differentiated between the controlling of a

mobile system and the controlling of a robot or a manipulator.

Control systems for manipulators or robots process normally a pre-set program, the bias points are directly given to the robot by teach-in. In addition the robot needs to react only in a very limited way to its environment, normally it needs only information whether its tools and its workpieces are available in the correct form and at the correct place. The newest generations of control systems for robots already use the control systems on the basis of industrial PCs described in chapter 3.1.

Mobile systems must get along in their environment independently and move without collisions from their start to their goal. This requires on the one hand different sensors to recognise the environment of the system and on the other hand a very flexible control system, because of the permanently changing application environment of the mobile system - in particular in the building industry.

A mobile building robot finally represents a synthesis between the two systems, since it does not only have to arrive independently at its destination, but has to execute there also different handling or assembly operations. Its basic structure is shown in figure 2.

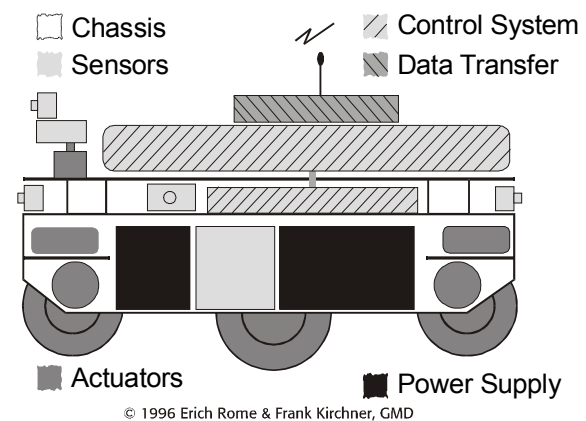


Figure 2. System Components of an Autonomous Mobile Construction Robot

Using the robot for interior work, the power supply will be supplied electrically by batteries or cables. The actuators can likewise be available in most different implementations. Beside electrical engines above all hydraulic or pneumatic cylinders can be used. The sensors represent a determining size for the efficiency of the system within a mobile building robot. Sensors are used both for the diagnosis of internal system states (e.g. number of turns of the engines, temperature of the resources, ...) and for the acquisition of external signals. E.g. it is necessary that obstacles in the surrounding field of the robot are detected reliably and under all conditions. The selection of the sensor technology is particularly critical for the accurate position determination of the robot. Communication with the user is done with a man-machine-in-

terface which is simple to use with a graphical user guide and an extensive help system. The necessity for a radio-based data transfer, similar as a manufacturing control system, is conceivable for a future integration into a building site control system.

All of these items are finally co-ordinated by a control system. This system must indicate on the one hand real time functionality and on the other hand a graphical user-interface. The individual functions of this control system are described in the following section.

## 4 FUNCTIONS OF THE CONTROL SYSTEM FOR A MOBILE CONSTRUCTION ROBOT

After the requirements as well as the components of a control system and the possibility of its implementation with industrial PCs were described in the preceding sections, now the functions of the control software are discussed. Figure 3 shows the functions and interfaces of a control system for autonomous mobile robots [4], its most important subfunctions are briefly described in the following.

### 4.1 Planning

The planning component forms the highest level of a control system for mobile robots. It generates, according to the complex task given to the robot, in the ideal case the appropriate control sequences. This requires however a high technical expenditure, therefore the planning component for a building robot will be limited rather to the function of course planning.

With the dedicated control procedures one must differentiate between a navigation in unknown and well-known environment. If the environment of the mobile system is well-known, above all model and card-supported procedures are used. By sensor data from the environment recognition the environment of the vehicle is realised and the taken up image is set to the coincide with the stored model. With measured distances to known points of the card the position of the robot can then be determined quite exactly.

In unknown environment the robot orients itself only with the help of sensor data from the environment recognition and mostly produces during its movement a card of its environment, which can be used for later activities again. This procedure does not enable the movement to an accurate target position, but the robot can explore its environment without collisions.

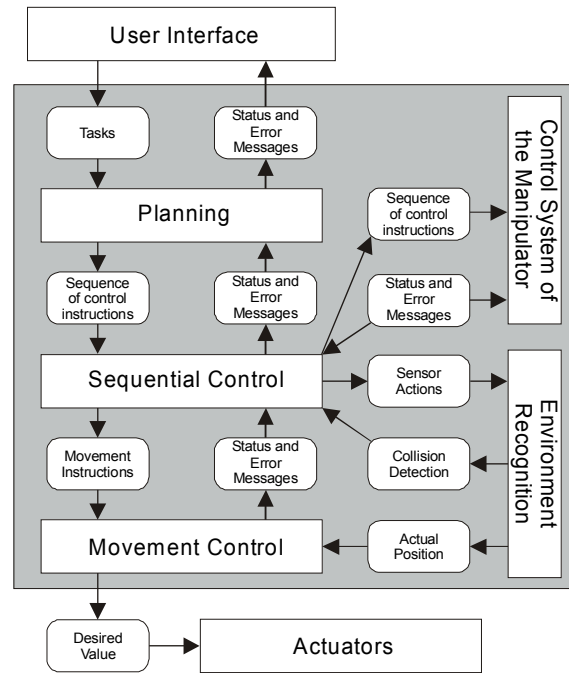


Figure 3. Functions of a Control System for a Mobile Construction Robot [4]

### 4.2 Sequential- and Movement Control

The sequential control coordinates the execution of the demands of the planning component, the monitoring of their correct execution and the reaction to error conditions [4]. It forms thus the central function of a control system. The error handling still represents such a complex topic that an automatic reaction to the occurring errors appears hardly realisable, therefore this function of a building robot is particularly limited to acoustic and optical signals to the user.

The movement control transfers the elementary movement messages given by the sequential control e.g. travelling straight ahead or driving along curves, into a temporal operational sequence of desired values needed by the drive. In addition the given pieces of way must be interpolated according to the possibilities of the underlying chassis kinetics. Additionally the support by sensor signals of the environment recognition is possible in order to drive around an obstacle.

### 4.3 Environment Recognition

The environment recognition represents the most important component under safety-relevant criteria. It gathers messages from both external sensors like measured distances to obstacles, and internal sensors, like speed measurement or temperature levels, and analyses the collected data. There are sensors for

obstacle recognition in many different technical designs, either on optical (infrared, laser scanners or camera systems), acoustic (ultrasonic) or tactile base. Which sensor is used, depends on the height of the possible investment, the range, the accuracy and the desired rate of the obstacle recognition.

For a building robot the exact determination of the current positioning is of substantial importance. It was already mentioned above several times that for this purpose many different solutions are conceivable, particularly for the positioning in the interior work however is still a large development potential available. Further research is necessary on the one hand with respect to economical sensor systems, which can measure the distances without large installation expenditure over distances of up to 50 m with an accuracy of 1 mm. Currently there are only laser systems able to meet this requirements, these are however very expensive and require usually additional accurate in-measured reflex baffles spots at the walls. On the other hand a possibility must be developed of being able to allow the alignment between the real building site and the given CAD-data.

An economical possibility would be the guidance of the robot along a guideline, which is attached either at the soil and detected with optical sensors, or which is produced with the help of a laser. Then the deviation from the line can be detected with photodiodes. For positioning the distance in direction of the guideline toward one reference point must be measured additionally, this could be done for example by a laser distance measurement.

## 5 IMPLEMENTED CONTROL SYSTEM FOR A MOBILE CONSTRUCTION ROBOT

Following the preceding investigations in this section the structure of an open and modular control system for a mobile building robot, which performs assembly tasks in the interior work, is discussed. The functionality of the first design was already presented in [1] and in [2] and is only briefly repeated here.

The robot's task is the accurate attachment of hangers with anchor bolts into the concrete slab. The anchor bolts have to be set with a tolerance by  $\pm 5$  mm around their debit position. Figure 4 shows the robot in front of the laboratory of the institute FAPS.

The structure of the implemented control system shows figure 4. It is not implemented on a single processor, the control surface was realised under Windows NT on one processor and the real time operating system was implemented with RTKernel on a separate computer. The two systems communicate with each other via the serial interface.

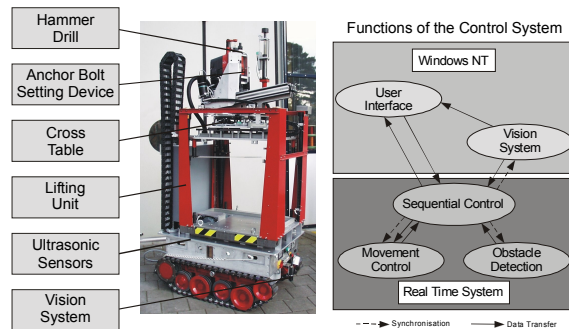


Figure 4. Control System of a Mobile Construction Robot for the Interior Work

The individual functional modules presented in chapter 4 are realised in RTKernel as tasks, i.e. as parallel running programs, and are described only briefly. In this case the planning component gives the appropriate movement instructions to the sequential control depending upon the position of the robot to the guideline, prepares the outputs on the user interface and processes the inputs of the user. The flow control coordinates the temporal allocation of the individual program runs and the data exchange between the tasks. Each task is executed all 20 ms.

The environment recognition consists on the one hand of altogether 14 ultrasonic sensors with a measurement range up to 4 m for obstacle avoidance. On the other hand either an image processing system or the beforehand described system with a laser beam is used for the guidance of the vehicle on the guideline. The user can choose among different operating modes over a user interface based of ergonomic criteria arranged on a touch screen. Error messages and critical operating conditions are also indicated on the screen in a form easy to understand.

## 6 DEVELOPMENT OF A FLEXIBLE MANIPULATOR IN LIGHTWEIGHT CONSTRUCTION

The robot described above could be used more flexibly and the economy could be improved, if more than only one assembly process could be executed. Therefore instead of the rigid structure of the present technology module a handling system would be necessary, which should be on the one hand flexible and as lightweight as possible and on the other hand it should enable large handling forces. This apparent contradiction is overcome by a kinetics, which is discussed lately in form as "binary manipulators based on Stewart-platforms".

Such systems are based on Stewart platforms connected in series, whereby so far pneumatics or hydraulic cylinders are used predominantly. These actuators are able to carry large payloads, but they are

normally just used in their two end positions. Therefore the entire manipulator can execute only discrete movements, which may lead to problems for some assembly tasks, such as welding. Continuous cylinders, like electrical cylinder, would be more suitable. They would enable an infinitely variable adjustment of the platforms. The calculations for the construction of such systems are extremely complex and extensive. Thus there are world-wide so far only a few calculation programs, which can calculate the position of the platforms for several platforms connected in series and the cylinder forces occurring with it. For continuous cylinders against it there still no such tools available, which can compute the desired results in a reasonable computing time.

Therefore at the institute FAPS a simulation tool was developed, which supports the construction of such robots, consisting of platforms with continuous cylinders.

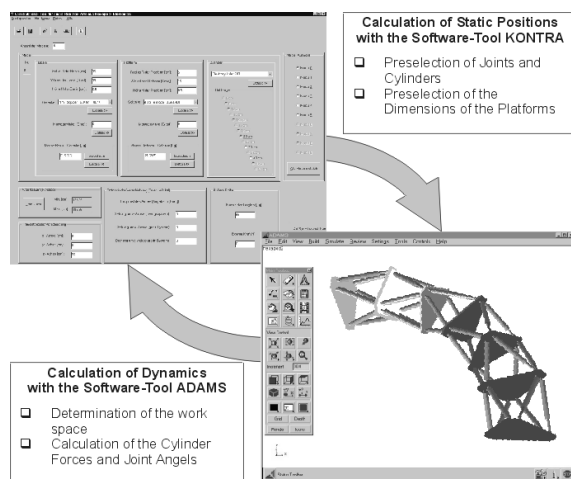


Figure 5. Calculation Tools for a Flexible Manipulator with 6 DOF

In order to keep the expenditure of computing time small and to minimise the optimisation steps which have to be executed, the system is divided into two sections. The first section is a software tool with name "Kontra", which determines the occurring forces on the cylinders in a certain position of the platforms on the basis of data bases for different cylinders and joints. Additionally the joint angles are calculated, in order to determine the optimal mobility of the joints. Altogether manipulators with up to 10 platforms can be calculated with this program. These calculations run very fast and one receive immediately a specification concerning whether the desired selection of the cylinders and joints can hold the static position.

As soon as a configuration is found with this tool, which accomplish the static requirements, the second part of the simulation tool can be used. It concerns the multi-body simulator routine of "Adams", which can calculate movements of certain items, deforma-

tions and the loads occurring with it in the model. A post processor was integrated into the tool "Kontra", which translates the substantial features extracted from the data bases for the cylinders and joints into a model description for "Adams". This model can be loaded into "Adams" and the desired movement can there be simulated. Thus one receives all cylinder forces and joint angles in the dynamic case and can additionally calculate the complete work space of the manipulator.

The combination of these two aids enables now an efficient design of a manipulator which is to be used in the next time for the application on the building robot presented above.

## REFERENCES

- [1] M. Koch „Chances, obstacles and a possible trend of automation in construction from the point of view of the German construction industry“  
Proceedings of the 17<sup>th</sup> ISARC 2000, Taipeh, Taiwan  
September 18 – 20, 2000
- [2] M. Koch „A Mobile Robot System for Assembly Operations at Interior Finishing“  
Proceedings of the 15<sup>th</sup> ISARC 98, pp. 93–102,  
Munic March 31 – April 1, 1998
- [3] M. Wenk „Verdrängt der PC die SPS?“  
Technica 3/98 pp. 12-15, 1998
- [4] Gerhard Drunk „Sensor- und Steuerungssystem für die leitlinienlose Führung automatischer Flurförderzeuge“ Springer Verlag, Berlin 1990