Robotic On-Site Construction Of Masonry

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Abstract

This paper presents the prototype realisation of a mobile bricklaying robot designed for use on the construction site and controlled by a skilled operator. The complete working process of automated masonry construction is described from the beginning of the brickwork planning based on the layout of the architect up to the robotic on-site construction of masonry. In particular the generation of the manufacturing data for the robot as well as necessary man-machine-interactions on the construction site are described in detail. First results using the robot for masonry construction are shown at the end of the paper.

1 Introduction

In Germany the construction industry is the largest private business section with a construction volume of about 570 Billion DM in 1996 and a contribution of 16 % to the gross national product [1]. In the last years the worse order situation in the German construction business and the increased competition caused by foreign companies with cheap construction workers leads to a strong cost crisis. Moreover structural problems like overaged workers as well as the traditional manual construction methods with low technical level increase this trend. This applies especially to the masonry construction which is with a share of about 90% of all wall surfaces the most important production technology used in residential buildings. In order to meet these challenges the development of innovative and efficient technologies like a bricklaying robot has been forced in Germany with the aim to reduce the physical strain on the bricklayer, to increase the productivity and quality of the masonry construction and to improve the standing of that trade.

In recent years, the authors presented the demands and performance characteristics of a mobile bricklaying robot [3] as well as necessary enabling technologies such as a modern configurable robot control system [4], feedback control strategies for electrohydraulic servodrives [9], robust application specific sensing equipment and sensor strategies [5, 7] as well as automated methods for application of bonding material and robust brick handling using a vacuum system [6]. A detailed cost analysis and the economical and technical feasibility of such technology is given in [2, 8]. In the meantime the prototype realisation of the bricklaying robot is completed and first successfully on-site tests are carried out.

After a brief technical description of the realized bricklaying robot the sequence of brickwork planning is presented in Section 3 of the paper starting from the architect's layout to the production data for the bricklaying robot. Based on these production datas Section 4 describes in detail the process of automated masonry construction as well as the tasks of the site staff and the modification and operation possibilities of the operator. Finally, first results of automated bricklaying with the realized prototype robot on different testing sites are shown.

2 Application oriented design of a mobile bricklaying robot

The prototype realization of the bricklaying robot is based on a commercial construction machine. Typical application fields of this commercial machine are the removal of slag in industrial smelting furnaces as well as demolishing work of all kinds. From that machine the bricklaying robot is built up by task-specific modifications and extensions, e.g. supplementary fitting of servo drive units, kinematic extension by a 3-axis robot wrist to increase the flexibility of the robot arm up to 7 degrees of freedom, integration of a technological unit for brick centering and mortar application as well as a sophisticated robot control system and several sensor systems for positioning and compensation of on-site tolerances. Figure 1 shows the schematic design of the bricklaying robot.

The tasks of this robot which will be operated on the construction site include picking bricks or blocks from prepared pallets, application of bonding material and erection of brickwork at high accuracy and quality. Such automated on-site masonry construction places additional requirements on the planning of the construction work, the necessary preliminary work and the working process carried out by the robot and a skilled worker acting as an operator.

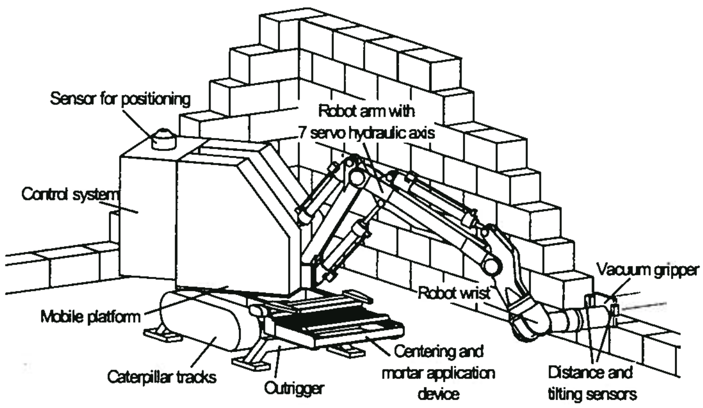

Figure 1: Schematic design of the realized bricklaying robot

3 Brickwork planning using a mobile robot

3.1 General aspects of programming a mobile bricklaying robot

The concept for programming and automated operation of a mobile bricklaying robot on the construction site must consider the following aspects:

- For the operation of a bricklaying robot data concerning the building, the material supply, the operation preparation and the production sequence has to be provided by the brickwork planning system.
- Large tolerance ranges of the floor dimensions, the material supply, the building components and the manual robot positioning on the floor must be considered and compensated.
- The operation positions of the robot are changed within short periods of time. The user-interface and the application program running on the robot control has to provide all conditions to immediately start and restart automatic production and to store the actual production status.
- The production task changes continuously. The wide range of possible masonry has to be realized within the brickwork planning system and to be projected into the application program. The application program has to deal with continuously changing and dimension tolerances within the working envelope of the robot due to the growing masonry and changing material supply.

3.2 Generation of the production data for the bricklaying robot

The process of production data generation for the bricklaying robot can be divided in the following 3 main sections:

- Geometrical data preparation of the construction project,
- Elementation of the walls in single bricks or blocks and
- Generation of the production data for the bricklaying robot, the operator and the floor preparation.

Before the automatic brickwork construction can be carried out by the robot, the layout datas of the construction project are needed for each floor in the brickwork planning system. The layout datas can be generated by manually inputs of the walls and openings for each floor of the building or by loading existing CAD-datas from the architect and processing these datas to a 3 dimensional model. Important data like the wall heights, the opening dimensions, the heel of parapet, the wall thickness etc. must be set manual if nonexistent. Additional it is possible to put special built-in units into the walls, like headers or U-blocks, to consider that these areas are ignored during wall elementation.

After the geometric generation of the 3 dimensional model from the layout plan, the next step is to assign the materials and corner connections to the walls on the floor. This is supported by databases with typical brick materials, brick dimensions and wall connections. Based on the standard DIN 1053 and the target to minimize the cutting bricks, the wall elementation in single bricks is done automatically for the selected floor and the given brick size. However a manual modification possibility is necessary for this elementation to change the levelling layer or to define special brick dimensions. After the elementation several walls are combined to production groups for the bricklaying robot. The brickwork planning system divide such a production group in several wall segments considering the working envelope of the bricklaying robot and the wall elementation. (A segment is characterized as a section of one or more walls the bricklaying robot could complete from a single working position.)

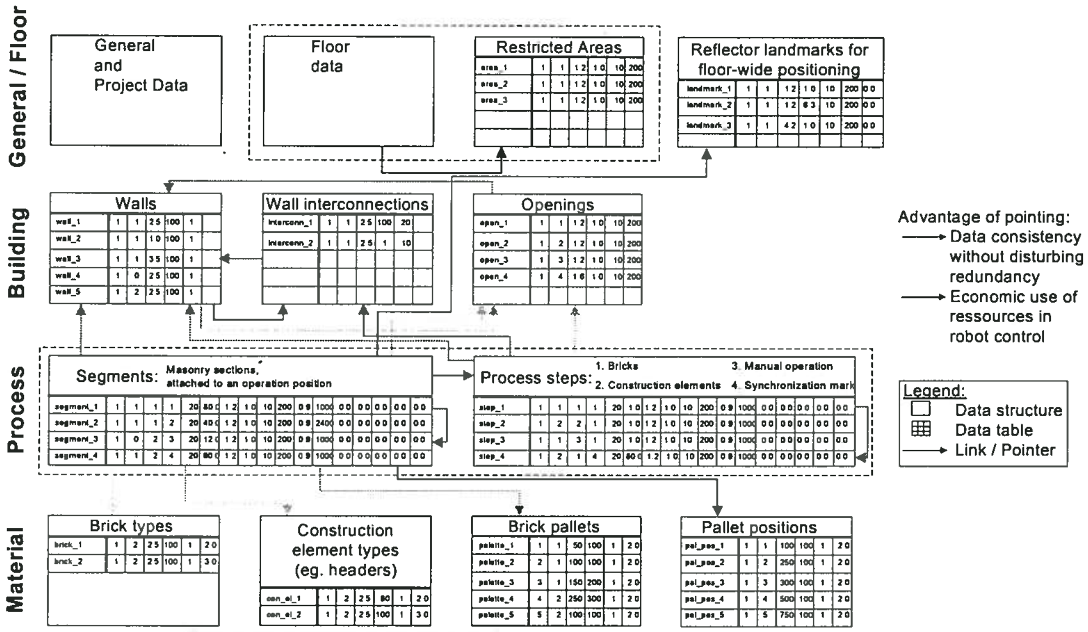

Figure 2: Structure of the data interface between the brickwork planning system and the bricklaying robot

Out of the segmentation process for each wall segment results the belonging robot working postion, the pallet set up positions and the measuring positions for determination the manually layed first brick layer and wall edges within the wall segment (like openings, begin and end of a wall or segment connections). After that the production data for the bricklaying robot can be generated an stored in a file for each wall group. Figure 2 shows the structure of this file and the included data.

3.3 Data-Interface between the Brickwork Planning System and the Robot Control System

The contents of the ASCII-data-file transfered from the brickwork planning system to the robot control are used to generate the robot commands for bricklaying. The file describes the geometric data like the walls, the wall interconnections and the openings to provide all aspects of the building model needed for verification and visualization on the construction site. Further informations about the used materials like brick types, pallete size and pallet positions are described also in the data-file as well as all relevant data needed for the bricklaying process itself.

The data-interface is organized as a database in the form of multiple lists for all kinds of objects and links between these objects, that can be found in the bricklaying process and the environment. The principal structure of the database is shown in Figure 2. Another feature are the geometric relations between the objects to be found on the construction site. These geometric relations are described in Figure 3 by means of different coordinate systems and guarantees an easy description and modification of all defined objects in the database. Moreover the application program can switch between these coordinate systems for easy position calculation and motion generation.

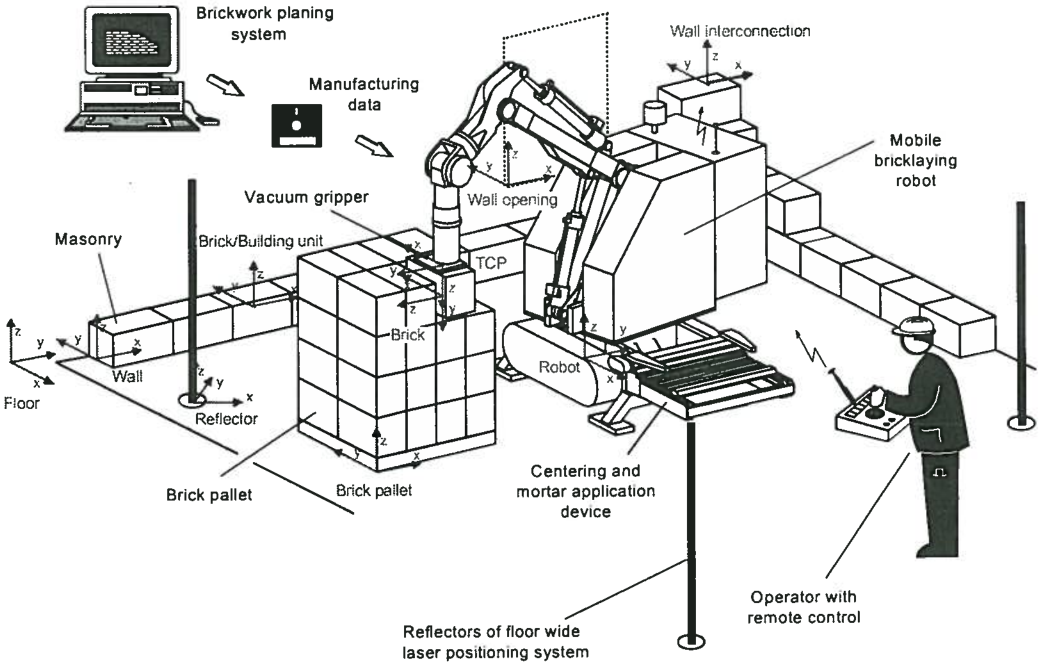

Figure 3: Mobile bricklaying robot and geometric relations between the objects on the construction site

4 Working process and Man-Machine-Interaction

4.1 Requirements to the application program and the operator control unit

The following list describes the major requirements to the application program:

- The application program must generate the robot commands for motion out of the data-file from the brickwork planning system and has to control sensor and actor peripheral devices of the mobile bricklaying robot.
- Immediate recovery of the bricklaying process after any kind of interruption must be enabled by continuous storage the actual state of production environment (eg. number of bricks on the palletes) and production progress.
- The application program must be controled by an application-specific user-interface. The operator needs simple and standardized commands to control the application. Planned and actual data concerning production environment and production progress must be visualized.

To meet the above mentioned requirements an enhanced programming interface is necessary as well as specialized application programs fully integrated into the robot control system to have full access to internal data and functions (like transformation algorithms, axis limits, etc.).

For an efficent working process with the bricklaying robot a flexible user oriented and robust operator control system is necessary. This operator control system must enable robot movements to change the working positions, to start, to modify and to interrupt the automated bricklaying process as well as trouble shooting and error recovery. The hardware requirements to the operator control system are in detail:

- Robustness: The bricklaying robot will be operated under rough environmental conditions. Therefore a robust design for the operator control system is necessary.
- Mobility: The operator control system must be outside the robot envelope and moveable because of the changing robot working positions.
- Visualization: To make the programming and operating of the bricklaying robot easy-to-use, a user oriented menu operation and visualization is required.
- Size and weight: The operator control system must be carried by the operator, therefore a small and lightweight design is necessary.
- Interface to the control system: A remote control is required, that the operator is indepentend of the robot location.

To fulfill all these requirements the operator control system is splitted in two parts (see Figure 4). A lightweight portable control panel with the functions for operation without disturbances and a mobile control desk with a graphical display for modification of the brickwork planning, visualization of relevant data, error recovery and a joystick for manual robot movement.

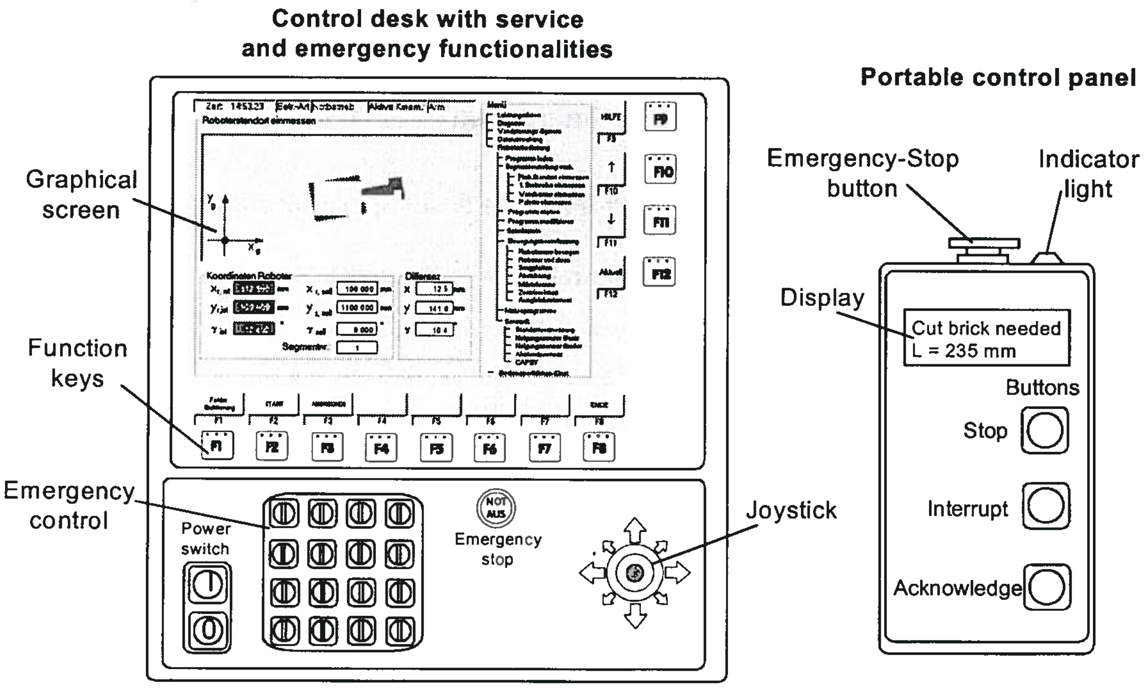

Figure 4: User control system for the mobile bricklaying robot

4.2 Operation and control of the working process

After the bricklaying robot is placed on the floor the whole system is controled through a graphical user-interface and additional control elements. First of all the actual data file is loaded for the next walls to realize on the floor. The preparation of the automated bricklaying could be separated into several steps.

- Determination the actual working position of the robot relative to the coordinate-system attached to the floor.
- Determination the exact location and stack height of the next used brick pallet.
- Detection of the exact wall position and orientation as well as existing openings within the wall.
- Automatic bricklaying sequence including depalletizing, brick centering, mortar application and exact brick positioning within the wall.

These steps are provided by different display masks within the user-interface (see Figure 5) and separated application programs. Every application program provides data to be visualized through its display mask.

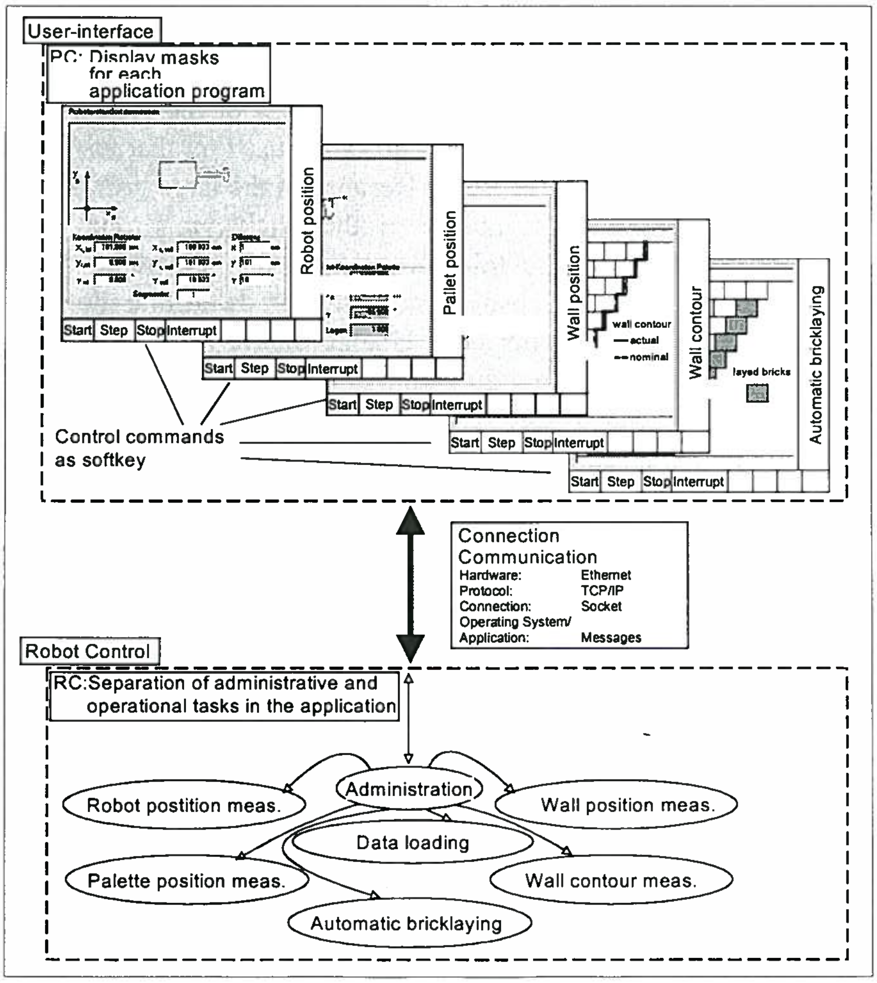

Figure 5: Application programs and interface between the user and the robot control system

The operator starts the first three preparation steps separately to guarantee maximum supervision until the actual production environment is known to the application program. A set of control commands represented by softkeys (see Figure 5) allows to start, to stop, to interrupt and to continue regular operations. The final step after preparation is the start-signal for automatic production. After that the operator is responsible for material supply, execution of manual production steps and error recovery.

After the end of operation caused by the program, an interruption or an error the actual status of the production database is stored. After restart of operation not only the planned data is loaded but also the last stored actual data. The aspect of error recovery needs special attention. If a fatal error occurs including total loss of state data, the data describing the production environment is extracted through the standard preparation steps mentioned above. After that the recovery of production progress is possible.

5 Practical site tests and the results

To verify the site-suitability of the bricklaying robot several field tests have been carried out under very different conditions.

On a building yard for teaching purposes the on-site use of the bricklaying robot was demonstrated the first time. Areated cement blocks are used on that test site to build up a test floor with the robot on a paved ground. Because of the large ground unevenness of about 6 cm at a length of 2 m the ability of the bricklaying robot was shown to determine and to compensate these tolerances using the integrated sensor systems. However these tolerances makes it absolute necessary to determine the wall height and the end of the last wall segment after each change of the working position. Figure 6 shows the bricklaying robot on the building yard and the environmental conditions.

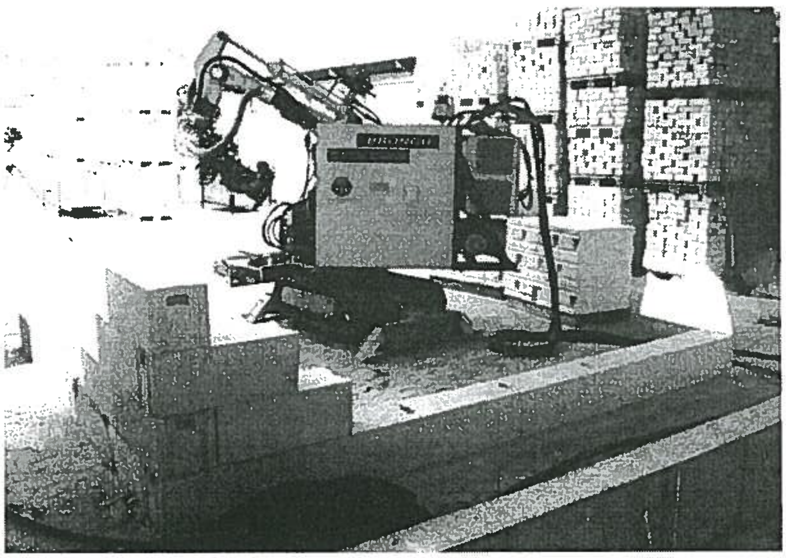

Figure 6: Bricklaying robot on a building yard

On another building site the use of rubbed bricks for bricklaying could be demonstrated by the bricklaying robot. Although the weather conditions like drizzle and tempratures down to -5°C are not very optimal a garage was built up with the bricklaying robot. Figure 7 shows a sequence of bricklaying with the robot building this garage.

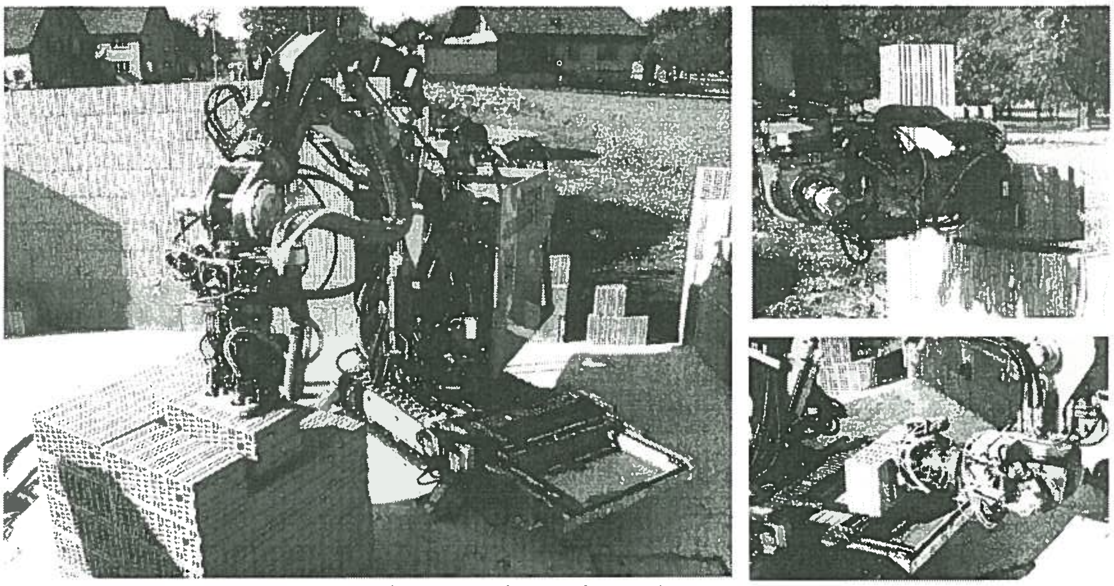

Figure 7: Building a garage with the bricklaying robot

6 Conclusions

In this paper a concept for automated bricklaying on the construction site by means of a robotic man-machine-system has been presented. Therefore a brickwork planning system has been described to generate and modify the production data for the robot as well as the necessary interface to the robot control system. Based on the man-machine-interactions on the construction site the requirements for a user oriented control panel have been defined. A possibility to meet these requirements by splitting the control functions in two panels have been presented.

The use of the bricklaying robot on the construction site has been verified by trials on different test-sites. Future research will include further extensive experimental site-tests, investigation aimed at the enhancement of speed and accuracy of the automated bricklaying process.

7 Acknowledgments

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