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Application Specific Realisation of a Mobile Robot for On-Site Construction of Masonry

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Abstract

This paper reports the progress in research and development of a mobile bricklaying robot for use on the construction site. Its practical and market orientated design has been a key aspect of the project from the start.

1. INTRODUCTION

At the 10th ISARC in Houston, the authors presented a concept for a mobile robot for automated bricklaying on the construction site. The requirements of both this new production technology and of a modern high-end robot control system as the enabling technology were discussed in detail taking the national characteristics of masonry construction in Germany into consideration [1].

Realisation of this concept requires the integration of a variety of complex systems at a very high technical level. This can only be successful if an interdisciplinary approach is used, and if specific knowledge from different engineering sciences, especially from construction, robotics and information technology, is available. Therefore, a local consortium of four research institutes and ten companies covering the fields of bricklaying technology, mechanical engineering, hydraulics and control technology has been formed in South West Germany. Such synergy will be required to develop an automated bricklaying robot that is reliable, cost-efficient, and market orientated. The goal of the partners is to develop a prototype of this robot to prove the technical and economical feasibility of this new technology.

Exploitation and commercialisation of the research results have been key aspects of this project from the start. The following features demonstrate the commercial intentions: Practical and market orientated design by cooperation with industrial partners, modular development and design of the robot allowing reduced time to market, maximum product price of $150,000 US.

This paper discusses some aspects regarding the kinematic structure of the robot, closed-loop control of its hydraulic drives and proper sensor strategies.

2. KINEMATIC STRUCTURE OF THE BRICKLAYING ROBOT

Four different kinematic configurations are mainly used with industrial robots today: Polar, cylindrical, cartesian and articulated. Previous studies [2,3] showed that an articulated configuration is best suited for the manipulator of a mobile bricklaying robot as it is discussed in this context. When defining the working envelope and the final kinematic structure of the bricklaying robot the following requirements have been taken into consideration:

- constructing masonry at a maximum height of 2.5 m,
- changing the position and orientation of the Tool Centre Point (TCP) in a way which enables the robot to pick bricks or blocks from prepared pallets, to apply mortar and to place them at the location desired,
- reaching both the uppermost and the lowermost row of bricks within a wall segment of 5 m length,
- minimizing the number of changes of the robot's working position,
- robust and application orientated realisation.

Keeping these and other aspects in mind, a commercial construction machine with hydraulic drives has been chosen as a platform for the bricklaying robot (see Figure 1). It is characterized by a 4-degree-of-freedom (DOF) manipulator which is mounted on a mobile platform with caterpillar tracks and hydraulic outriggers. In order to fulfill all functions required, a 3-DOF robot wrist will be fixed to the manipulator. This results in a 7-DOF redundant kinematic structure which is shown in Figure 2.

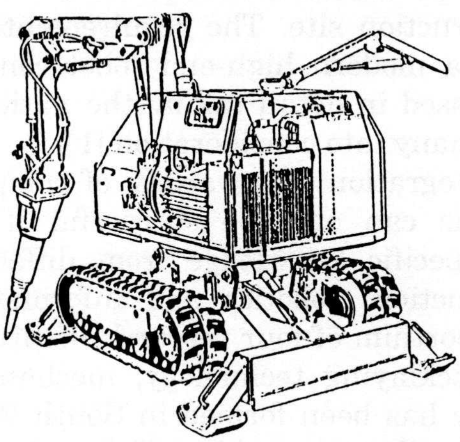

Figure 1. Commercial construction machine as a platform for a mobile bricklaying robot

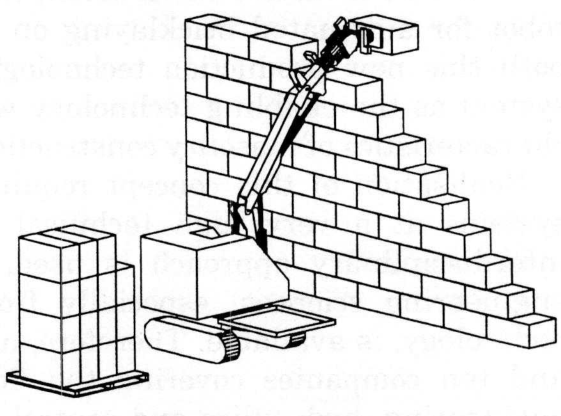

Figure 2. Automated bricklaying by a 7- DOF articulated manipulator

The additional degree of freedom allows to extend the working envelope, to avoid singular joint positions and to limit the maximum angles of the manipulator joints to proper values. A symmetrical structure of the wrist has been chosen because the manipulator will have to operate in all four quadrants of the platform coordinate system. Final optimization of the manipulator wrist is a comprehensive mechatronic task where not only the kinematic restrictions but also proper integration of the hydraulic drives and sensing equipment, details of the mechanical design and economical aspects have to be considered.

3. CLOSED-LOOP CONTROL OF HYDRAULIC MANIPULATORS

Due to their high power density and their robustness hydraulic drives have been selected for the bricklaying robot. Hydraulic motors together with gearboxes are used for the slew unit and the manipulator wrist, linear cylinder drives for the main axes of the manipulator [4]. The performance of the manipulator is negatively affected by the strong non-linearities of the hydraulic drives as well as by considerable parameter variations and disturbances caused by the movements of the joints. In order to assure high dynamics and sufficient positional accuracy modern digital feedback control strategies are applied [5].

3.1. Dynamic model of a manipulator axis

Modelling the manipulator kinematics and dynamics which is indispensible for the optimal design of the servo control loops will be illustrated using the example of a swivel axis with a hydraulic cylinder drive. The kinematic structure of the third manipulator axis is shown in Figure 3, its dynamic model is presented in Figure 4.

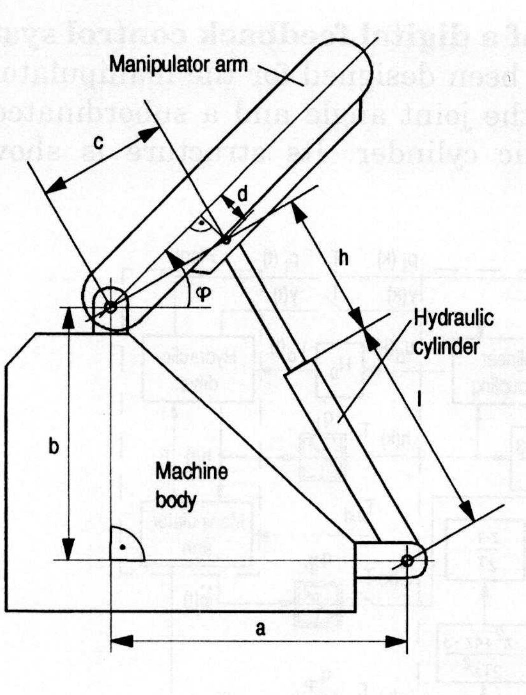

Figure 3. Kinematic structure of a manipulator axis

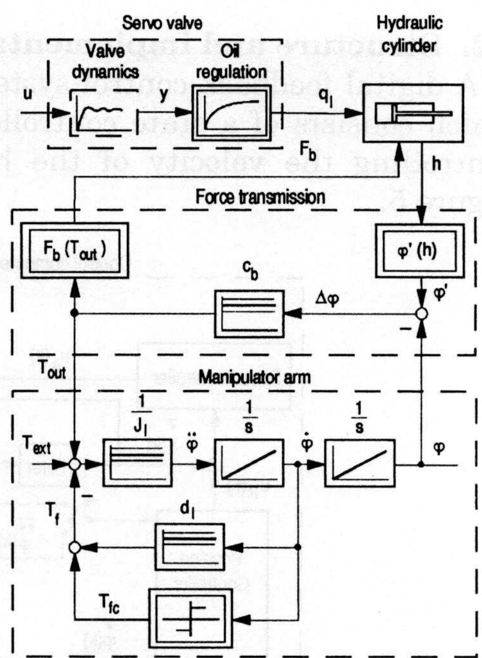

Figure 4. Dynamic model of a manipulator axis

Due to the extremely stiff mechanical design, the manipulator link is assumed as an ideal rigid body represented by its effective inertia J_l. The dynamics of the manipulator joint is characterized by the friction constant d_l, the coulomb friction torque T_{fc} and the resulting stiffness c_b which represents the elasticities of the bearings. The linear movement of the cylinder results in a rotational movement of the manipulator arm according to Figure 3. Supposing infinite stiffness c_b, a non-linear kinematic relation is established between the piston stroke h and the resulting joint angle φ' which is given by the following equation:

$$\varphi' = \arctan\frac{a}{b} + \arcsin\frac{d}{c} + \arcsin\frac{(l + h)^2 - \left(a^2 + b^2 + c^2\right)}{2\,c\,\sqrt{a^2 + b^2}} \tag{1}$$

The performance of the manipulator axis described above is characterized by the following features:

- strongly non-linear flow characteristics of the servo valve,
- non-linear friction of the cylinder (stick-slip effect) and the joint (bearings),
- variable eigenfrequency of the hydraulic cylinder depending on the piston stroke,
- low damping of both the hydraulic and the mechanical subsystem,
- considerable parameter variations and disturbing forces due to the movements of the other joints.

In order to eliminate the non-linear effects and to assure satisfactory dynamic performance efficient closed-loop control algorithms have to be applied.

3.2. Structure and implementation of a digital feedback control system

A digital feedback control system has been designed for the manipulator axis which consists of a state controller for the joint angle and a subordinated loop controlling the velocity of the hydraulic cylinder. Its structure is shown in Figure 5.

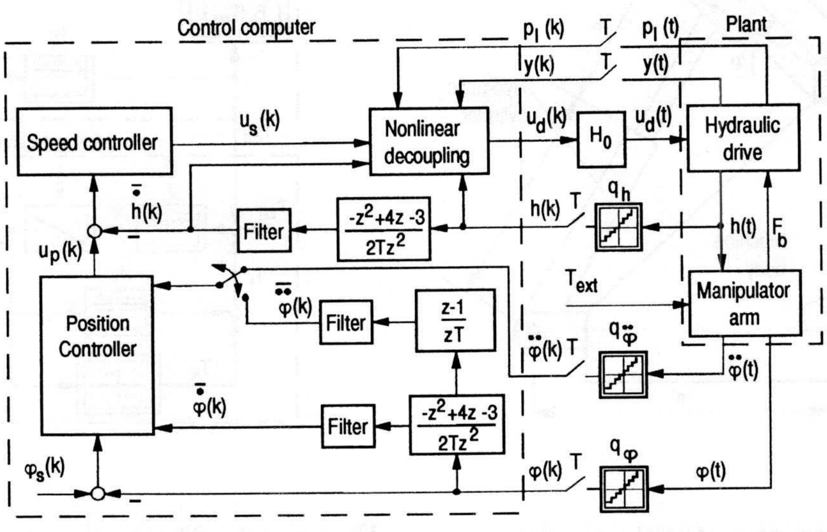

Figure 5. Structure of the feedback control system for a manipulator axis

Digital measurement systems with high resolution are available for both the joint angle and the cylinder stroke. The velocity signals which are also required as inputs to the controllers can be obtained by digital differentiation of the respective position signals. In order to reduce inevitable quantization errors, digital filtering is provided. The angular acceleration is usually estimated by double differentiation of the joint angle. Multiplication of the quantization errors and a considerable loss of dynamics are, however, substantial disadvantages of this approach. The best way to overcome those difficulties is direct measurement of the angular acceleration by means of a proper sensor. Such a sensor which is based on the physical principle of magnetic induction is currently being developed and will be tested in the course of the research project. Compensation of both the non-linear characteristics of the servo valve and the variable stiffness of the hydraulic cylinder is done by proper decoupling algorithms which are applied to the controller output.

The hydraulic actuator is a high-quality control cylinder which is controlled by a robust direct drive servo valve. The high dynamic performance of the valve itself is achieved by electronic feedback control of the valve stem position. Eventual dead volumes are minimized by mounting the valve directly on the cylinder. For measuring the piston stroke a linear absolute measurement system with synchronous serial interface has been integrated into the piston rod. The acquisition of the joint angle is performed with a high-resolution digital incremental encoder.

A modern transputer system featuring application specific control algorithms and high computing capacity is used as a control computer [6]. The system may be operated from a personal computer which is connected to the processor board via a link interface. A Dual Ported RAM is available for communication and data exchange with the robot control system.

4. CLASSIFICATION OF SENSOR CONCEPTS

The shell geometry of the building to be constructed which is provided by the architect and the desired brick or block formats are the basic entry information for the automated construction of masonry. Based on both those geometrical data and the technological requirements given by the bricklaying process, the exact coordinates of every single brick within the masonry structure can be found in a world coordinate system which is defined by the ground floor and a vertical straight line. The dimensional tolerances of the bricks will not be considered at this stage of planning.

In order to achieve precise positioning at a given accuracy, the actual position and orientation of each brick must be determined and compared to its reference position. Generally this may be done by using high-precision surveying instruments such as total stations or theodolites which allow precise measuring of absolute positions with respect to the world coordinate system. Such systems, however, are not always suited for the use during the construction process due to their high complexity and sensitivity. As the cost of such instruments is usually very high, they will not be considered any further.

An alternative method is the separate determination of the platform position $\boldsymbol{r}_{\mathrm{P}}$ within the world coordinate system xyz, the TCP position $\boldsymbol{r}_{\mathrm{TCP}}'$ within the coordinate system x'y'z' which is local to the mobile platform, and the brick position $\boldsymbol{r}_{\mathrm{S}}''$ within the gripper coordinate system x"y"z" (see Figure 6). The brick position $\boldsymbol{r}$ in the world coordinate system is given by the equation

$$\boldsymbol{r} = \boldsymbol{r}_{\mathrm{P}} + \boldsymbol{r}_{\mathrm{TCP}}' + \boldsymbol{r}_{\mathrm{S}}'' \qquad (2)$$

The problem of TCP calibration, i.e. determination of the vector r_S'', has been addressed in several publications (e. g. in [7]) and will not be discussed in this paper which focuses on the calculation of the vectors r_P and r_{TCP}' by using proper sensor systems. In this context it is important to know that the robot is operating from a stationary position during the bricklaying process itself. Hydraulic outriggers support the mobile platform in order to guarantee sufficient mechanical stability to prevent the robot from tilting. The platform will only move after a complete wall segment has been finished. Therefore, the platform position r_P has to be determined only once after the robot has reached a new working position whereas the calculation of the TCP position r_{TCP}' has to be done for every single brick.

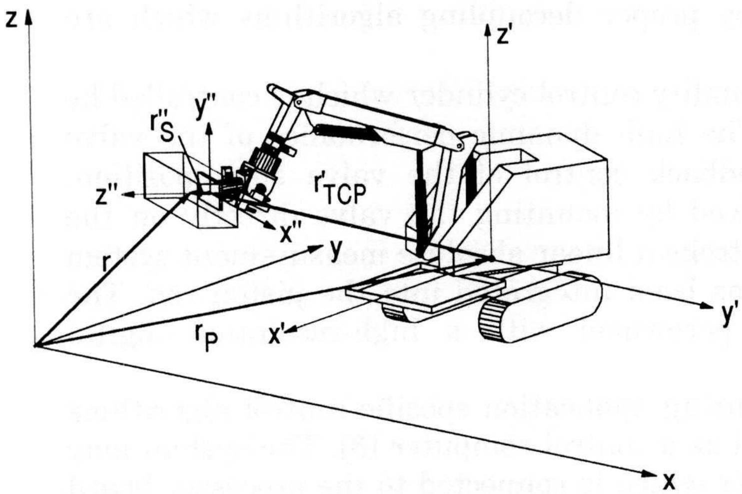

Figure 6. Different coordinate systems for calculating the brick position

Calculation of r_P and r_{TCP}' by using only internal measurement systems (e.g. incremental encoders) is affected by different sources of error:

- slip of the caterpillar tracks,
- elasticities and flexibilities in the manipulator links and joints,
- dimensional tolerances of the bricks and blocks,
- dimensional tolerances of the ground floor as well as of the masonry which has already been constructed.

In order to identify and eventually correct all those errors it is inevitable to apply external sensor systems which provide the robot control system with all necessary information about position and orientation of both the mobile platform and the TCP. Taking the rough environmental conditions of the construction site into account, robustness and simplicity must always be remembered as key features of all sensor components.

Determining the coordinates of the mobile platform must be considered as a 3–dimensional problem. This is due to the fact that neither the ground floor nor the platform itself can be expected to be exactly horizontal with respect to the world coordinate system. The task may, however, be simplified if both the z-coordinate z_P and the tilt angles α_P and β_P of the platform are known. α_P and β_P may easily be measured using a 2-axes tilt sensor while z_P can first be assumed to be constant. If this assumption turns out false, z_P can be approximately measured by a distance sensor which may be fixed to the mobile platform. Application of elementary transformation algorithms yields then a 2-dimensional problem where only the position coordinates x_P, y_P and the heading γ_P of the platform are yet to be determined.

The simplest way of determining the position and heading of the mobile platform is odometry, i.e. measuring the angular position of both the driving wheels and the slew unit by using internal measurement systems (e.g. incremental encoders) located at the respective drives [8]. This method will just allow for a rough determination of x_P, y_P and γ_P. This is due to measurement errors caused by the slip of the caterpillar tracks. Especially the calculation of γ_P will be negatively influenced by those errors. In order to yield sufficient accuracy a gyroscope may be used in addition [9].

A substantial increase in accuracy can only be achieved if measurement systems are used which provide a geometrical relation between the robot itself and its environment on the construction site. For this purpose active sensor elements are fixed to the robot measuring a set of distances or angles relating to artificial or natural landmarks which are located at known positions in the surroundings of the robot. Examples for such sensor systems and a comprehensive evaluation of their characteristic features are given in Table 1.

Table 1
Evaluation of selected sensor systems for the determination of the position and heading of a mobile bricklaying robot

	Overall Accuracy	Accuracy of γ_P	Robustness	Effort for preparation	Effort for signal processing	Cost
Theodolite/ total station	+	none	-	-	--	--
Incremental encoders (odometry)		-	+	++	++	++
Odometry plus gyroscope	o	+	+	++	+	o
Video camera (image processing)	o	o	--	+	--	--
Laser scanner with reflectors	+	++	o	--	+	-
Distance sensors	+	+	o	++	o	+

(Ratings: ++ best, + good, o medium, - bad, -- worst)

A rough estimation of $\boldsymbol{r}_{TCP}'$ can be found by calculating the forward transformation of the manipulator based on the measurement of the joint angles. Distance sensors, tilt sensors and passive compliance elements can be used to make proper corrections.

Different sensor systems have been set up and have undergone various testing procedures so far. The evaluation of the experiments according to the criteria stated above is still going on and will be completed in the near future.

5. CONCLUSIONS

In order to increase the productivity of masonry construction, a mobile bricklaying robot for use on the construction site is currently being developed by a German consortium. The robot is based on a commercial construction machine and is characterized by its low weight and compact overall dimensions, offering both high movability and flexibility. Some key aspects of the hardware concept, especially the kinematic structure of the robot, the modern transputer-based servo control system and positioning strategies using simple and rugged sensor components have been discussed in this paper. To date feasiblity studies and specification of the above mentioned individual system components have been carried out by the various consortium partners. The complete system integration is currently underway.

6. ACKNOWLEDGEMENTS

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