On-Site Mobile Plastering Robot: A Practical Design Concept

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Abstract

This paper presents basic concepts and enabling technologies for a mobile plastering robot used on the construction site and controlled by a skilled operator. Economic aspects of the German plastering industry, requirements for semi-automated plastering, alternative robotic end-effectors, various kinematic structures as well as suitable drive technologies for a plastering robot are discussed in detail.

1 Introduction

Plastering is widely used as a finishing technology for both interior and exterior walls made from bricks, concrete or timber. While plastering of exterior walls provides heat insulation, sound absorption and protection against air pollution and weather, the application of plaster to interior walls improves the indoor climate by humidity regulation and serves the purpose of compensating inevitable tolerances of the brickwork, thus providing a clean, level surface for further finishing tasks. Special plaster material can also protect against fire or radiation. Currently plastering technology is used throughout the Western world, especially in the U.S., Japan, Australia, Israel and most Western European countries.

In Germany, plastering is mainly carried out by small to medium sized enterprises. Currently, there are approximately 8000 German companies involved in the plastering industry with a total industry turnover of around $13 billion per year. Due to spiraling labor costs, stagnant productivity levels and increasing competition, these companies are coming under severe economic pressure.

In response to these economic realities, the development of a robot for semi-automated application of plaster strives to achieve the following goals :

- Increased productivity through automated application and initial smoothing of the plaster.
- Improved worker health and safety through a reduction in the manual handling involved in the normally exhausting and repetitive plastering process.
- Through introduction of innovative technology the plastering trade will become a more attractive career choice.
- Improved plastering quality.

2 History and State-of-the-Art

Although plastering is one of the most physically strenuous jobs in building construction it was not before the early fifties that machines were developed which supported this strenuous task. The first machines to be developed were automated mixers which made the task of manual plaster mixing obsolete [1, 2]. The introduction of plastering machines such as RUMA 1, Putzmeister KS 1 [3] and Putzmeister Gipsomat [4] in the sixties was considered revolutionary and marked the beginning of a new era in plastering technology.

The development of the AMPA machine [5] was the first attempt to significantly increase the level of automation but this kind of equipment has never been accepted in practice. Automated spraying of mortar and paint has recently been demonstrated by means of the mobile articulated prototype robot TAMIR which had been developed in Israel [6] and a prototype of a cartesian robot which had been constructed in a Swedish joint venture between Swedish construction companies and universities [7]. Unfortunately these developments have been unable to provide a breakthrough in the plastering industry. Thus, even today, the plastering machines developed in the sixties such as [3, 4] are still considered to be State-of-the-Art.

Following surface preparation the plastering process is performed in three steps:

Step 1: Application of plaster to the wall.

Step 2: Formation of a (roughly) plane surface by leveling the plaster which had been applied to the wall.

Step 3: Finishing the surface in order to meet the given tolerances (e.g. maximum horizontal and vertical deviation of 8 mm at a measuring distance of 2.5 m according to DIN [8]).

While mixing and pumping of the plaster material is supported by a machine (see Figure 1), each of the described steps involves manual labor (see Figure 2). Movement of the heavy spraying nozzle (step 1) and distribution of the plastering material on the wall (step 2) are especially strenuous tasks for the operator.

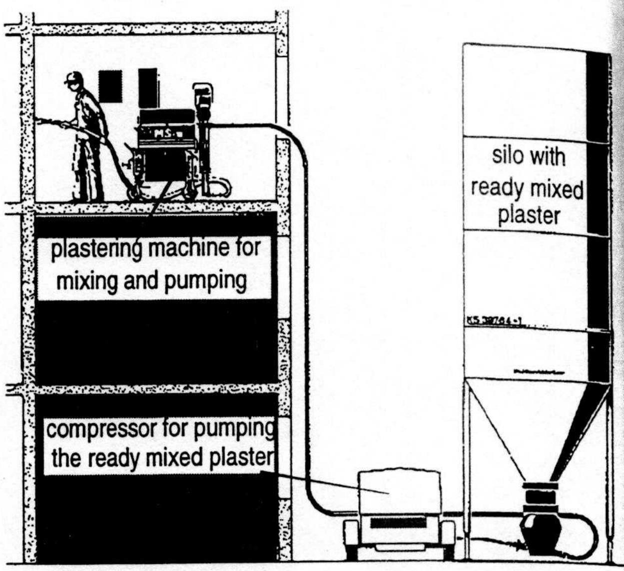
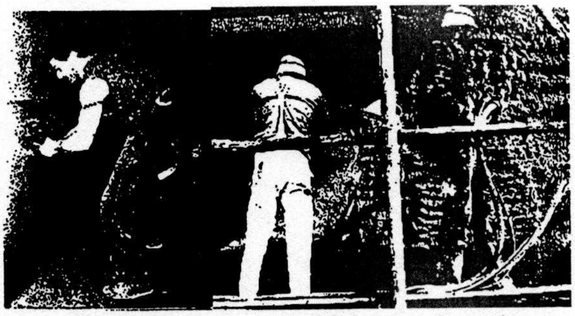


Figure 1: Plastering machine for mixing and pumping.



finishing spreading and leveling spraying

Figure 2: Manual plastering process.

The next section presents a description of the automated plastering scenario outlining the tasks to be carried out by the worker and plastering robot.

3 Automation of the Plastering Process

The main task of the plastering robot is the application and initial smoothing of plaster on the wall or ceiling and the removal of excess plaster material. The fine smoothing of the plaster is still to be carried out by the plasterer as the considerable level of expertise required is not achievable by a robot. The integration of the human worker in the automated plastering process is also necessary due to the complex working environment of the building site and mainly involves supervision and visual quality control.

The tasks of the human operator include:

- the positioning of the robot at the wall,
- determination of the required plaster thickness,
- initialization and monitoring of the automated plastering process and correction of any operating errors and
- repositioning of the robot to other walls, rooms and floors.

After commencement of the plastering process the robot will carry out the following tasks :

- measurement of the distance to the wall,
- tool positioning and motion control necessary for the defined plaster thickness,
- quantity control of the plaster mixing machine for a defined plaster flow,
- regular meandering motion generation and control for plaster application within the working envelope of the robot and
- automated motion of the robots working position along the wall.

While the robot is applying plaster to a wall or ceiling, the human operator has the following tasks :

- preparation of further walls and ceilings to be plastered,
- visual quality control of the plastered wall,
- manual refinement of edges, corners and niches of the plastered surfaces and
- fine smoothing of the plaster.

4 Requirements for an Automated System

Due to the versatility required for walls, ceilings and roof pitches and the high level of automation strict requirements are placed on the plastering material, the plastering tool and the automation components. Moreover, new handling tools are required for the plastering in order to enable automation of the plastering process. These requirements are summarized below :

Plaster Material

- *Good adhesion* to the wall over its complete area without the need for large application forces.
- *Extended time of use* after the plaster has been mixed in order to reduce the number of cleaning cycles.
- *High rigidity* in order to prevent plaster flow after application and initial smoothing.

Plastering Tool

- *A multi-functional tool* is necessary in order to apply and smooth the plaster.
- *Plaster thickness* for normal applications varies between 5 mm to 30 mm. For thin plastering a thickness of between 3 to 6 mm is standard. The plastering tool must be adaptable enough to apply plaster with these thickness.
- *Fast tool change* for plastering of large and small surfaces must be provided for.
- *High levels of plaster smoothness and angular accuracy* of the plastered surface are aimed for. Over a distance of 2.5 m a variation from a plane of less than 8 mm is to be achieved.
- *Set-up and cleaning cycle times* are to be kept to a minimum thus helping to increase acceptance in the building site environment.

Kinematic Structure and Control System

- *Mobility* is necessary due to the limited working envelope of the robot and the requirement that plastering of all walls on all floors of a building be possible. Thus the mobile platform must be able to climb and descend stairs.
- A *flexible working envelope* is required. In typical housing the walls, ceilings and roof pitches are to be plastered to a height of 3 m. For office buildings the working envelope should be extended so that a height of 4 m is attainable.
- *Compact dimensions* will allow the robot to pass through doorways and to work in small rooms. Overall robot dimensions are thus to be kept within a width of 0.7 m, a length of 1.1 m and a height of 1.9 m.
- *A lightweight modular structure* is necessary as no crane will available for transportation. Thus the robot must have a total weight of less than 500 kg.
- *Robustness* is of paramount importance because of the rough conditions on the building site, e.g. dust, heat, vibration etc.
- *A low-cost PC based control system* will be used for motion control, sensor signal processing and human-machine interface.
- *A simple human-machine-interface* will enable ease of operation for a skilled plasterer.

- *Safety* for both worker and machine is to be achieved through use of suitable tools and practices
- *Economic operation* will only result if the performance of the human-machine-system is superior to that of the current plastering team consisting of three workers and plastering machine.

4 Automated Plastering - A General Design

Based on the general requirements presented above this section presents general design solutions for the plastering tool, the kinematic structure of the robot and the drive technology employed.

4.1 Alternative tools for automated plastering

The main task of the plastering tool consists of pumping of the plaster, even distribution on the wall or ceiling and initial smoothing of the applied plaster.

The same machine responsible for plaster mixing (from dry plaster and water) can be used to pump the plaster to the plastering tool. This pumping action can be further supported by tool rotation or by means of a secondary propulsion medium such as pneumatics.

Application of plaster to the wall can be achieved by means of undefined spraying, use of a roller mechanism or through the filling of partly or fully sealed chamber formed by the plastering tool itself. Initial smoothing of the applied plaster can be carried out by either scraping or cutting the excess plaster away. Figure 3 shows these principle methods with the different plastering tools suited for automated plaster application. Table 1 presents an evaluation of these tool concepts with respect to the main requirements for automation.

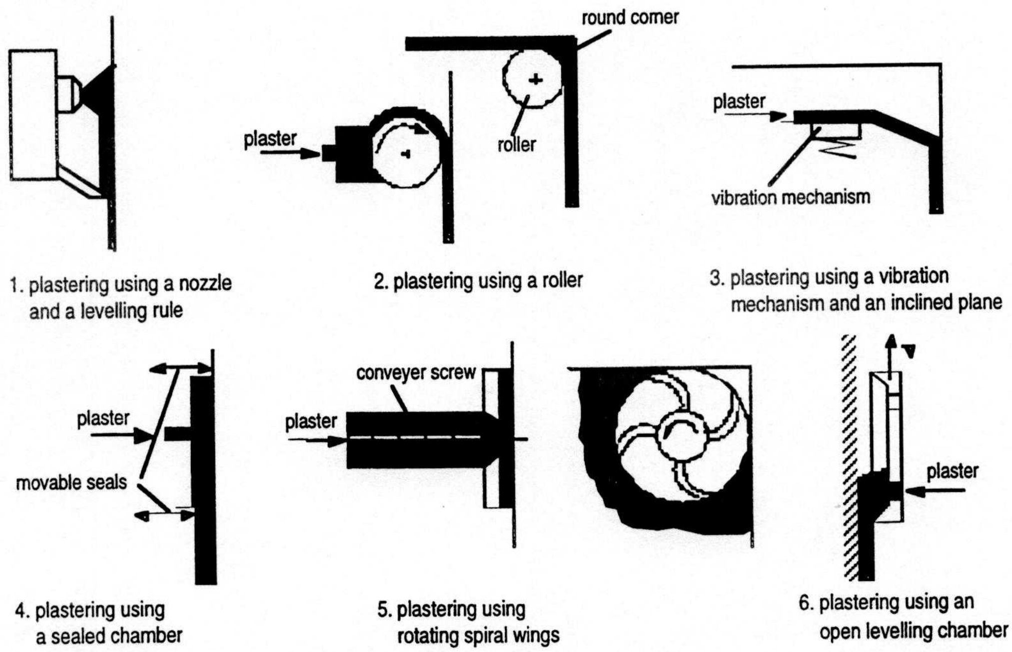


Figure 3: Methods for applying and leveling plaster.

Requirements	Plastering tools					
	Roller	Rotating spirals	Nozzle with leveler	Vibration method	Sealed chamber	Open chamber
Compensation of masonry tolerances	o	+	o	+	+	+
Smoothness of application	-	+	-	o	+	+
Avoidance of waste material	--	-	--	-	++	+
Plastering of difficult areas (corners, niches etc.)	o	o	++	+	+	+
Plastering of walls, ceilings and roof pitches.	+	+	+	-	+	+
Robustness	+	o	o	+	-	+

++ ideally fulfilled + well fulfilled o partly fulfilled - hardly fulfilled -- not fulfilled

Table 1: Evaluation of tools for automated plastering.

The evaluation shows that while the nozzle tool is best suited for plastering of difficult areas such as corners and niches a large amount of material waste is to be expected if an uneven finish is to be avoided. In contrast, the chamber solution offers smooth and economic plastering, whereby the open chamber solution is more robust due to the lack of moving parts. Based on these considerations, the open chamber plastering tool has been chosen as the most suitable for automated plastering.

The following section discusses the kinematic structure of the robot which must be capable of movement along the walls and ceilings of a building.

4.2 Kinematic Structures for a Plastering Robot

In order to meet the mobility criteria in a building site environment, a mobile platform capable of climbing and descending stairs is necessary. The best solution is offered by the caterpillar drive which is robust and capable of overcoming inclines of up to 40°.

To facilitate automated plastering the following degrees of freedom are required for robotic manipulator:

- Two degrees of freedom are required for plaster application in a plane for a single robot working position.
- A further degree of freedom is required to compensate for tilting of the mobile robot and thus enable parallel motion of the plastering tool with respect to the wall or ceiling.
- For fine distance to wall control and tool orientation two further degrees of freedom are necessary for situations where the required accuracy cannot be achieved by means of the mobile platform.

Figure 4 illustrates the necessary degrees of freedom for plaster application with a cartesian robot.

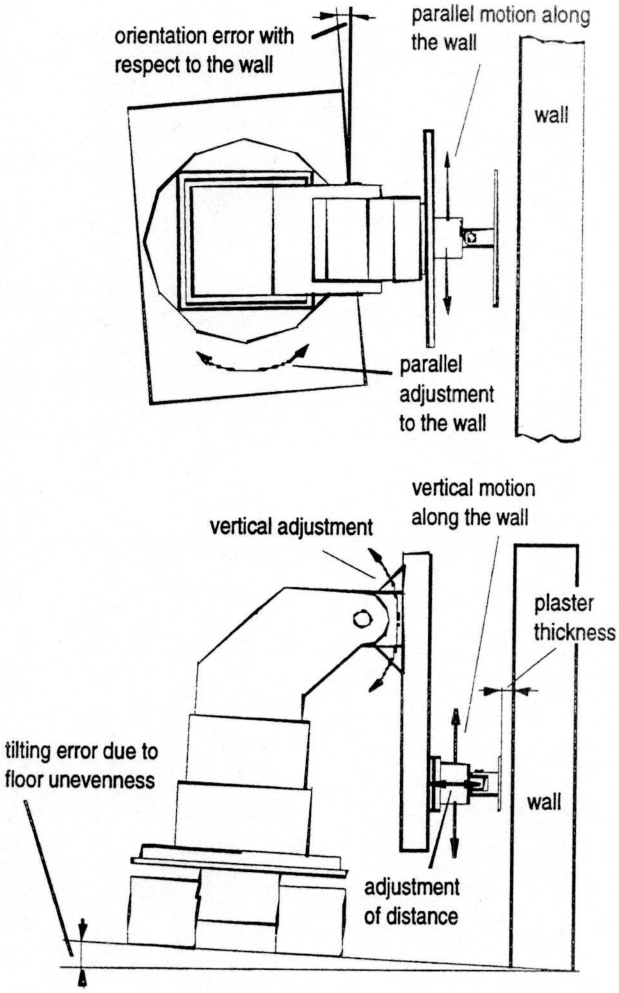


Figure 4: Some examples of a mobile plastering robot.

The type of kinematic structure engendered by a robot is defined mainly by the configuration of either rotary or translational axes. In principal four different kinematic configurations are mainly used by industrial robots [9]: polar, cylindrical, cartesian and articulated. The main difference between these four types is the shape of their working envelopes whereby the size of the working envelope is defined mainly by the length of the individual link components. Table 2 presents an evaluation of these kinematic structures with respect to the requirements of the automated plastering process. This evaluation shows that polar kinematic structures are least suited to the task of automated plastering - mainly due to their spherical working envelopes. Articulated kinematic structures offer better performance due to their flexibility and compact structure. The drawback of this kinematic type is the elaborate control system required for motion control. Cylindrical kinematic structures offer limited effectiveness due to the shape of their working envelope, which limits overall accuracy. The most suitable kinematic structure is the cartesian robot which is most suited to the planar work surfaces offered by walls and ceilings. The control system complexity is also kept to minimum due to the inherent geometric correlation. The main disadvantage is the intrinsically large size of the cartesian kinematic structures.

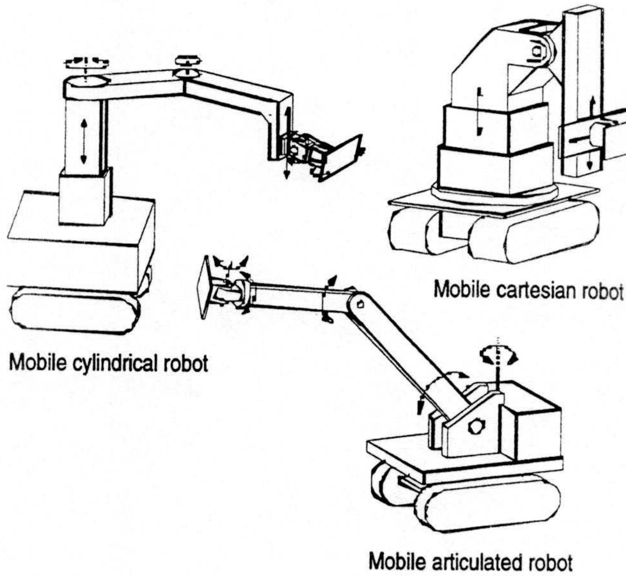


Figure 5: Examples of a mobile plastering robot.

In order to meet the motion requirements of automated plastering, drive technology offering slow, even and exact motion are required. Electro-mechanical and electro-hydraulic drive systems are thus compared in the next section.

Evaluation criteria	Kinematic configuration			
	Cartesian kinematic	Cylindrical kinematic	Polar kinematic	Articulated kinematic
Required degrees of freedom	3-5	4-5	4-5	4-5
Suitability of working envelope	+	o	--	-
Compactness	-	o	+	++
Accuracy	++	+	o	o
Simple control system	++	+	-	-
Simple sensor integration	+	o	-	-
Flexibility	o	o	+	++
Simple collision monitoring	o	o	-	-
low costs	o	o	-	-

++ ideally fulfilled + well fulfilled o partly fulfilled - hardly fulfilled -- not fulfilled

Table 2: Evaluation of different kinematics for the automated plastering process.

4.3 Drive Technology

Both electro-mechanical and electro-hydraulic drives fulfill the motion requirements of the plastering robot. Table 3 shows a comparative evaluation of these drive technologies against the major requirements for the plastering robot application.

Requirements	electro-mechanical	electro-hydraulic
Low weight	o	o
Small dimensions	o	o
High power density	+	++
High peak power capability	++	o
Controllability	++	-
Compact and robust control unit	o	+
High efficiency	++	-
Long service life	+	o
Reliability	+	+
Low cost	o	o
High stiffness	+	-
High dynamics	++	+
High positioning accuracy	++	+
Environmental friendliness	++	--

++ ideally fulfilled + well fulfilled o partly fulfilled - hardly fulfilled -- not fulfilled

Table 3: Evaluation of drive principles for a plastering robot.

The evaluation according to Table 3 shows that hydraulic drives are only superior in terms of power density and robustness of the control units (usually servo valves). The major drawbacks of hydraulic drives are their inferior controllability, low efficiency, low stiffness and the environmental impacts caused by possible oil leakage.

Modern electro-mechanical brushless technology, however, is more suited to meeting the demands of an automated construction application like plastering. A section through a standard brushless motor is presented in Figure 6. A schematic of an electronically commutated synchronous AC motor with permanent magnetic field excitation is shown in Figure 7.

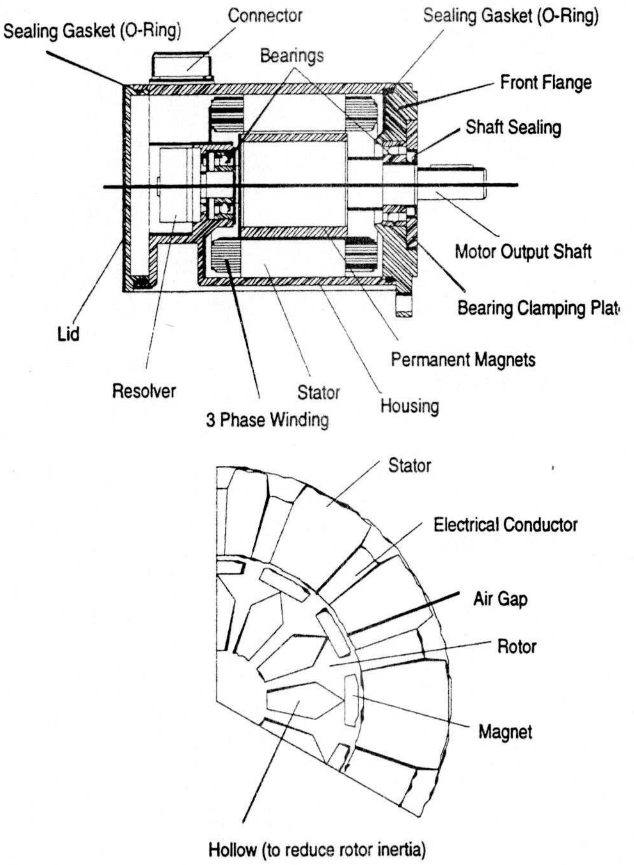


Figure 6: Section through a standard brushless servomotor.

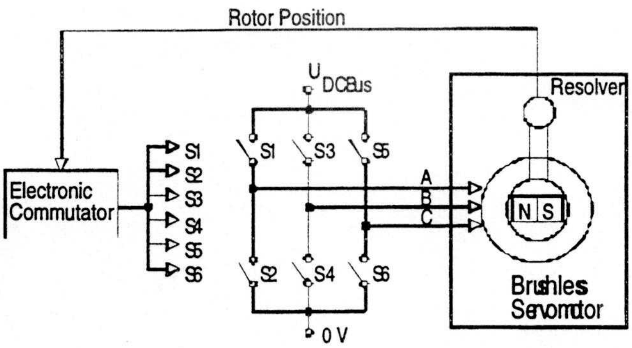


Figure 7: Brushless servodrive schematic.

The following key features apply to the brushless technology:

- Samarium Cobalt high energy magnets on the rotor,
- embedded thermistor for temperature monitoring,
- sinusoidal induced voltage for optimum slow speed characteristics and higher efficiency,
- brushless analogue resolver requiring no electronics in the motor,
- die-cast aluminum, light-weight housing,
- sealed pre-loaded bearings with high-temperature grease for long service life,
- protection class IP 65,
- optional permanent magnet holding brake,
- consistently high torque from standstill to rated speed and
- IGBT power transistors ensuring low losses and reliable operation.

Even the use of simple current, speed and position control loops will guarantee smooth motion control.

5 Conclusions

Following a short description of the economic situation in the German plastering industry, a summary of the automated plastering process and its requirements on key components was presented. In answer to these requirements solutions plastering tools, kinematic structures and drive technology suited for a plastering robot were presented.

Future activities will be directed toward the design of plastering tools and the development of a prototype robot in order to test solutions discussed in a practical setting. A further important point is the integration of sensor systems into the overall design that measure the plaster thickness, the wall tolerances and allow the detection of structures such as pipes, windows and doors.

Further analysis has shown that the basic kinematic structure of the plastering robot is also suited to the tasks of tile laying, painting of walls and ceilings as well as for general handling tasks in interior finishing. Suitable tools and sensors are however application specific.

6 Acknowledgments

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