OUTLINES OF TWO MASONRY ROBOT SYSTEMS

Hannu Lehtinen, Esko Salo, Heikki Aalto

Technical Research Centre of Finland
Vuorimiehentie 5, SF-02150 Espoo

ABSTRACT

Functional requirements, technical specifications and economical feasibility on masonry robotic theme have been investigated. Two alternatives are discussed: a modular SCARA-based system and a six D.O.F. articulated configuration. Market prices of \$ 310 000 and \$ 350 000 respectively have been estimated for the systems with a payback period of 6 years with realistic partition wall sizes. Economic analysis shows that a critical factor in the feasibility of such automatic masonry systems is the partition wall size due to manual preliminary works, which require rather constant amount of time. To reach a proper technical and economical feasibility, partition wall as the end product has to be restricted. The results of the study will be used for planning future research projects.

1. WALL DEFINITION

The automatic systems are designed to build up simple partition walls with maximum height of 3.2 meters. Only certain lime sand bricks, i.e. 270*130*75 mm^3 with strict tolerances, are allowed. The traditional mortar is replaced by a special glue-like material. In this method, the joints are only 3 mm thin. This method is becoming more common in Finland, and it is promising for automation, since the mortar can be spread to bricks by dipping.

The wall is recommended to be plastered afterwards. The wall must be straight and may contain doors, windows and comparable openings. It can be in connection with the ceiling, crossing walls or columns. Flat bars should be provided after every 8th brick row for connecting the partition wall to crossing walls or columns. A narrow gap (20 - 40 mm) should be left between the highest brick rows of and the ceiling due to the creep of concrete slabs.

2. MODULAR SCARA-BASED SYSTEM

The preliminary designed modular system consists of 1) a three axis depalletizing gantry robot, 2) a brick conveyor, 3) a brick lift and 4) a moving masonry unit. This unit consists - quite similarly to BLOCKBOT [3] - of a carriage with positioning devices, a scissors lift, a bowl of mortar, a cutter station and a SCARA-robot attached to two linear servo tracks (Fig. 1).

The main principle is to divide the masonry process in functional blocks and automate them separately, but however in a manner, where all processes run in parallel; the brick moves further until it is attached to the partition. The parallelism of processes would enable short tack times; the goal is one brick in 10 seconds. This means a material flow of 360 bricks per hour. Other difficult problems were the requirement, that the systems is capable to lay also the last brick rows, and a limited capability to perform unmanned operation during breaks of human operators.

Bricks are normally delivered in Finland on pallets of 72 bricks weighing 350 kg. In the modular system, the bricks are depalletized to the linear conveyor by a simple gantry

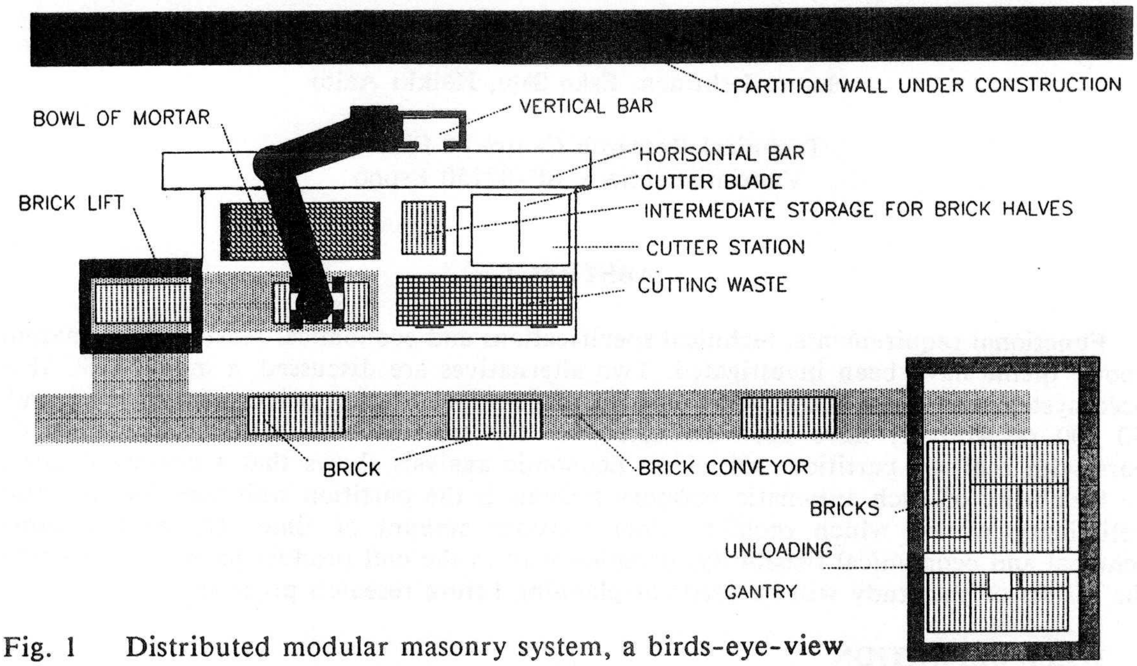


Fig. 1 Distributed modular masonry system, a birds-eye-view

robot with two servo-controlled degrees of freedom. The lifting movement can be pneumatic, that is also used in the suction cup gripper. Simple tactile sensors in the gripper can be used to control the vertical movement. If one hour unmanned operation is required, the depalletation station has to be equipped with a pallet storage of four pallets and a pallet changer.

The low-mounted conveyor transports the bricks along the partition wall to the carriage. The conveyor is assembled by attaching short modules to each other with snap connections. It acts also as a natural safety barrier and possibly leads electrical power to the carriage. The brick moves from this long conveyor to a short conveyor attached to the carriage to be trasported upwards. This movement is carried out by a lift like cage, that moves attached to five cables. Four of these cables guide the cage. They are reeled according to the height of the upper automatic masonry work platform of carriage. The brick is pushed from the cage and it will slide to a position where it can be gripped by the masonry arm. The lift can elevate the brick as up as the needed 2.5 meters.

2.1 Masonry operations

The masonry movements are carried out by a SCARA (Selective Compliance Assembly Robot Arm) robot attached to two linear servo-controlled tracks. Most suitable SCARA robot will be selected and slightly modified for the system. The horizontal track is attached to that edge of the masonry platform, that is close to the partition. The second axis of SCARA is needed to bend the arm behind the vertical slide. It is attached to the horizontal one. The desigh of the carriage and the lifting mechanism affects to the length of this slide. The SCARA is attached to a platform moving on the vertical slide.

The carriage should be able to move linearly along the wall. The carriage could use external position measurement systems like "Laser Positioner" [1] or so called dead reckoning, where internal sensors connected to wheels and steering mechanisms are used to estimate the position of the carriage. In that case the gradually increasing position error should be zeroed by special markings on the floor or the long conveyor. The distance from the partition wall or from the laser plane generated parallel to it and alignment along it can be controlled by turning front or rear wheels. This turning angle can be very limited, since only small corrections are needed. Even three possible angles for the wheels may be sufficient. The wheel angle control needs data from two distance sensors. The laser plane is mostly for minor corrections of the masonry movements of the arm securing the wall straightness.

The carriage is equipped with a lifting mechanism, that elevates the upper masonry platform to optimum height. A scissors lift could be the best choice. The lifting mechanism is not moved during masonry arm movements. It has not be lowered either during the movements along the partition.

The principle of the position measurement system is to locate accurately the carriage and, by combining the internal measuring systems, to measure the position of the brick during masonry insertion. The arm can be then moved close to the position of the previous brick with accurately enough to be controlled further by the force/torque (F/T) sensor of the wrist.

The bricks are dipped into a bowl of thin seam mortar by the SCARA. With a proper design of the bowl, mortar can be evenly spread to two planar surfaces of the brick by using linear movements in two degrees of freedom. The extra mortar is wept as the remaining mortar is grooved. For the bricks inserted to corners an additional wrist rotation of 180 degrees has to be used in order to spread mortar also to the third surface. Spreading mechanisms onto bricks and a gripper, that could both spread mortar during insertion and be usable with cut bricks and narrow corners, were noticed quite impossible.

The F/T sensor can be used to check the amount of remaining mortar by weighing the brick before and after dipping. Dipping will stain also the visual side of the brick, but coating afterwards is anyway a normal praxis with thin joint masonry. Natural requirement for the dipping station is that the level of the mortar in the bowl is controlled within some limits. Using a small mixer unit, where water is mixed to mortar powder, may be the most convenient way to keep the bowl filled. The cisterns could be manually filled on system requests by operators.

2.2 Other functions and accessories

A cutter station is needed due to openings and corners. A simple storage station for a brick half should be used. Cutting rests will slide to waste bin, that is emptied by the operator after being fulfilled.

The best grip of brick is from above, in the insertion direction. For the narrow gap (20-40 mm) between the wall and the ceiling, a special gripper with linkage has been suggested, Fig. 2. The operator changes it to the arm, when the partition is getting close to the roof. The fingers on the opposite side of the wall are so short, that it can be withdrawn through the gap. A strain gauge based force sensor has to be integrated to the linkage. In order to reach evenly the gap of 20 to 40 mm, the thickness of mortar layer may be varied during the last brick rows.

The weight of the moving carriage will be about 1000 kg. It should be designed so that, some components can be disassembled and reassembled quickly in order to enable transportation in narrow corridors and reduce weight of one transported unit. However, in the first place, such partitions are selected, to where transportation does not cause any problem.

2.3 Description of work

A following work cycle and durations have been estimated for the masonry arm: movement to fetch location (2 s), gripping (0.5 s), dipping (1 s), removing extra mortar and grooving (1.5 s), movement to insertion location (2 s), insertion (1 s), contact sensing and position correction (1 s), releasing and withdrawing movement (1 s); thus totally approx. 10 s. This estimation is used for designing the other components of the system. In the economic analysis this work cycle has been estimated to last 12.5 seconds.

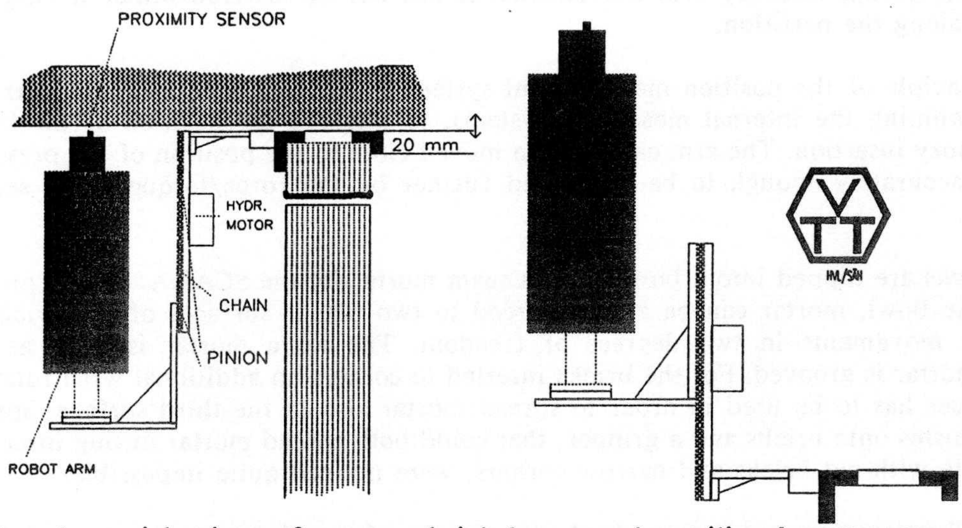


Fig. 2 A special gripper for upper brick layers under ceiling inserting the highest brick under ceiling and ready to fetch another brick

An operator and an assistant are needed to install and run the system. The operator is specially trained to do the necessary measurements for installation and take care of man-machine communication. The assistant will help in mechanical installation and take care of material flow during operation.

The position measurement systems are installed at first. The depalletation station is followed by the long conveyor, that is completed after the carriage is moved to correct starting position. The operation can start after parametrization of the partition and filling the depalletation station and mortar cisterns. One hour 10 minutes installation time by two persons is assumed for the system.

The assistant installs the flat bars and other requisites, when the system requests them according of the entered model of the partition. The system may ask similarly the installation of frames for doors and windows. Thus, in a sense, the masonry system is "semi-automatic".

3. MASONRY SYSTEM BASED ON SIX D.O.F. INDUSTRIAL ROBOT

Complexity of the presented modular system and international experience on multipurpose interior robots as at Technion, Israel [2] inspired another solution, Fig. 3 (a GRASPmodel). According to this alternative, a standard six degrees of freedom industrial robot and two pallets of bricks are mounted on a freely moving carriage. The robot controller is connected to carriage with approx. 15 m long cables.

The whole carriage will be lifted slightly up on mechanical feet, before it starts the construction process. This is due to stability reasons; the rapidly moving arm would cause easily oscillations for the carriage.

As the robot arm and the pallets are lifted up approximately one meter, the robot arm can reach up to 3.2 m. The mortar unit and cutter station are also attached to the lifted part of the carriage.

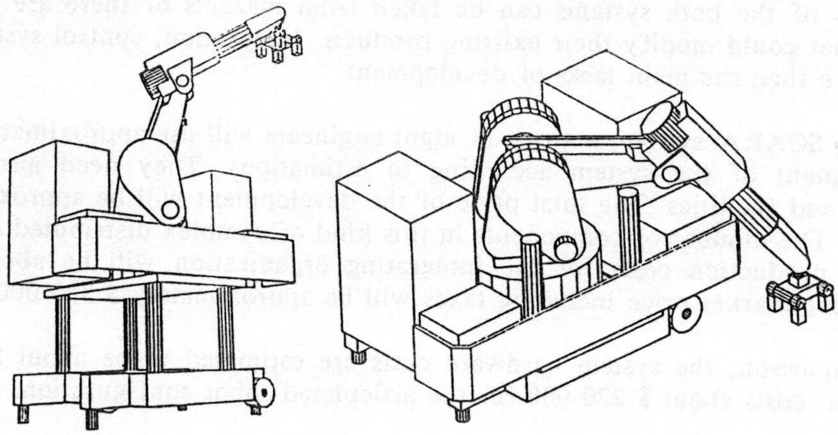


Fig. 3 A general purpose robot doing masonry work on carriage

Also this system has to be equipped with a special tool with one moving joint for the upper brick layers close to the ceiling. The mechanism of this gripper is much simpler than that of the previous case. The same F/T sensor may be used in both cases and probably also with an automatic tool changer. The inclination and distance from the nominal partition plane of the brick before insertion can be controlled by using a laser plane parallel to the wall and two detectors at the gripper.

A six d.o.f. articulated robot has several advantages compared to the SCARA-based system described in the previous chapter:

- the system consists of only two components: carriage and controller connected with cable; installation is thus faster
- the number of degrees of freedom is decreased
- no special mechanism are needed to lift the brick
- the main components of the system could also be used for other robotized interior construction works.

Also disadvantages exist:

- the tact time may be slower due to reduced parallelism and elevation of the carriage on wheels for moving the carriage
- the weight and size of the carriage will increase.

The installation of the system is in many sense similar as in the previous chapter. The main difference is loading pallets to the carriage. This is in the first place made manually by lowering the mechanism and moving the carriage with pallet forks under the pallet. This may be automated later on by mechanism that elevates the fork a few centimeters. Since the carriage will be most probably similar to three-wheel forktrucks with good movability, the pallets could be fetched from some meters distance.

The other tasks suitable for this type of configuration are sealing, smoothing, plastering, grinding and painting. They require, perhaps, higher speed, but similar reach and accuracy capabilities, but the mass to be lifted can be smaller. Therefore the racks for the brick pallets could be used as storage for other process material.

4. ECONOMIC ANALYSES

4.1 System development costs

It is very difficult to estimate development costs of new automation. Most of the components of the both systems can be taken from markets or there are manufacturers of them, that could modify their existing products. Integration, control system and programming are then the main tasks of development.

For the SCARA-system, a group of eight engineers will use approximately three years in development of the system according to estimations. They need also development equipment and facilities. The total price of the development will be approx. $ 2.5 million in Finland. The number of components in this kind of complex distributed system is quite large. The production costs for the integrating organization will be about $ 220 000. Therefore the market price including taxes will be approximately $ 330 000.

In comparison, the system hardware costs are estimated to be about $ 200 000 and development costs about $ 220 000 for the articulated robot configuration.

4.2 Work cycle analyses

As for the basis of the economic feasibility justification, work method description, work rate data, work costs and some predictions of future salary and productivity were collected, Table 1.

Expected cycle time of the discussed robotic systems is expected to be:

- 12.5 s/brick normally
- 25.0 s/brick in the neighborhood (about 30 cm) of the ceiling.

The robotic system (MR) is maintained by one operator and one assistant (masonry robot group, MRG), who have the same salaries as shown in Table 1.

In the following calculations, three partition wall sizes are analyzed:

1. 2.0 m * 2.6 m= 5.2 m2
2. 5.0 m * 2.6 m= 13.0 m2
3. 11.0 m * 3.2 m= 35.2 m2

Estimated data for the work process of the second wall type is presented in Fig. 4 and summary of the work rates, and costs for each wall type is in Table 2.

In these cases, MRG is thought to work 11 months per year, 160 hours per month. The system will be in duty approx. 80 percent of working hours of the MRG; the rest is used for transportation, maintenance and other non-productive tasks. By comparing the achievements of the current work group and MRG's results, one can estimate the capital costs that can be invested in such a robotic system. The estimated work savings, which equal to the amount of money possible to invest in MRG, are presented in Figure 5 as a function of the wall size.

4.3 Market potentials in Finland

There are about 4000 masons in Finland. Rapidly increasing number of them (nowadays approx. 10 percent) are working in small subcontractors, that usually can not invest for experimental automation. The large construction companies are willing to get rid of all own construction machinery. They may, however, own daughter companies that rent construction equipment.

420 000 m^2 partition walls of lime sand bricks are produced every year in Finland. It is assumed, that 25 percent of them could be constructed by an automatic system. The yield of automation will be so good, that about twenty systems could do the work needed.

The share of large partitions is very small. The system can not be transported only to large partitions. The average size of partition is about 10 m^2. Therefore as the base for payback evaluation is used the 13 m^2 partition sizes. Then the payback period would be about 6.5 years. This does not sound economically very intersting. Small companies could, perhaps, run the system in two shifts, which would increase the economical potentials.

5. CONCLUSIONS

One possible semiautomatic masonry system has been analyzed both technically and economically. The key issues of related technology have been considered and partial solution suggested. Many of the suggested solutions can be used as components in the future masonry systems. Due to complexity of the initial suggestion another system has been outlined.

According to the economical evaluation the masonry automation cannot be considered economically interesting today, however, technical evaluation projects are recommended.

6. ACKNOWLEDGEMENTS

This paper is part of VTT's research programme "Information and Automation Systems in Construction". The basic work is done as a part of the Norwegian-Finnish co-operative feasibility study, which was funded by Technology Development Centre, Nordisk Industrifond and 15 Finnish enterprises.

7. REFERENCES

1 Ochi T., Mio K., A positioning system for mobile robots in construction applications ("Laser Positioner"), proceedings, 5th Int. Symp. on Robotics in Constr., June 6-8, 1988, Tokyo, pp. 333-340

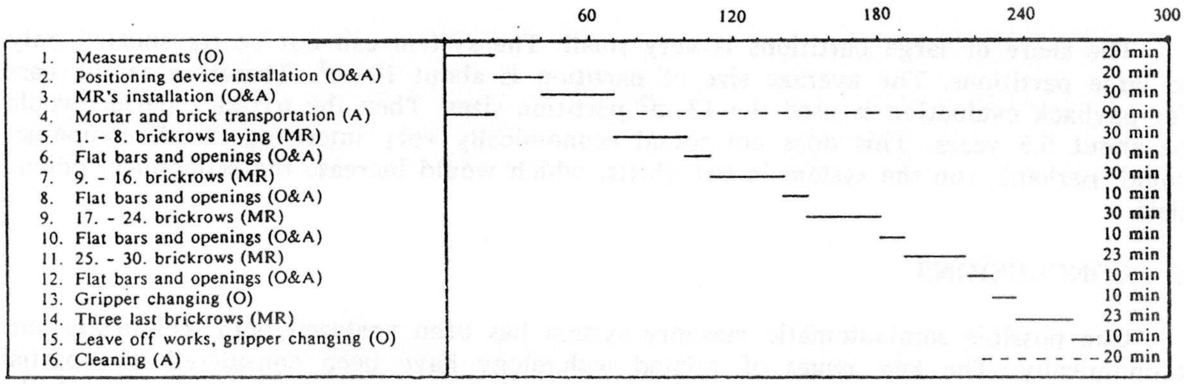
2 Warszawski A., Issues in the development of a building robot, proceedings, 5th Int. Symp. on Robotics in Constr., June 6-8, 1988, Tokyo, Japan, vol. I., pp. 17-26

3 Slocum A.H., Schena B., Blockbot: a robot to automate construction of cement block walls, Robotics 4 (1988), pp. 111-129

Table 1. **Work rates and costs of the present brick works in Finland.**

Work group
- brick layer (BL, craftsman): measurements, brick laying, finishing works
- construction worker (CW): brick and mortar transfers, scaffolding, leave off works

Work rates (partition walls, including minor pauses and interruptions):	
- BL	0,74 h/m2
- CW	0,74 h/m2
Work costs	
- salary of the brick layer	15,50 USD/h
- salary of the construction	9,40 USD/h
- social security expenditures	65 %
Total costs	
- BL 1,65 * 15,50 * 0,74	18,90 USD/m2
- CW 1,65 * 9,40 * 0,74	11,50 USD/m2
- BL+CW 1,65 * (15,50 + 9,40)	41,09 USD/h
Totally	**30,40 USD/m2**



O=operator, A=assistant, MR=robot.

Figure 4. Scheduled work cycle in case II (partition wall 5,0 m * 2,6 m).

A	B	C	D	E	F	G	H
5,2 m2	3,2 h	32	0,615	25,27	5,13	2290	1050
13,0 m2	4,5 h	50	0,346	14,22	16,18	4070	55000
35,3 m2	8,6 h	73	0,244	10,04	20,36	5770	107000

A Wall size [m2]
B Total time [h]
C MR's utilization -% during the work cycle
D MRG's work rate [h/m2]
E MRG's work costs D * $41,09 [$/m2]
F Difference to manual work E - $30,40 [$/m2]
G Annual work achievements 0,8*11*160h/D [m2]
H Annual work savings G*F - 0,2*11*160*$30,40 [$/year].

Table 2. MRG's estimated work rates and costs.

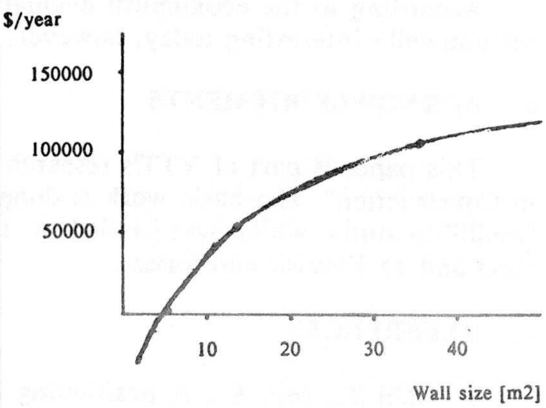


Figure 5. Estimated work savings per year as a function of the wall sizes.