The analysis of factors influencing on efficiency of applying mobile bricklaying robots and tools for such analysis

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Abstract. Automation and using robotic means allows increasing industry efficiency, including construction. At the same time, important factors of applying such means are profitability and adaptability. The paper considers the basic parameters influencing the economic and technological efficiency of applying mobile bricklaying robots. The main aspects for comparing manual and automated labor are showed based on the acting standards and technical features of operation of such robots. It is offered to use a coefficient showing the ratio of brickwork volumes for bearing walls and for partitions of a constructed object for evaluation of efficiency of applying a bricklaying robot. As most buildings differ from each other, the modeling software for automated evaluation economic and technological parameters of construction is offered. Such software will include a model of operation of a bricklaying robot and will evaluate efficiency of different combinations of manual and automated labor during bricklaying.

1. Introduction
Automated and robotic systems are being actively integrated as innovations in many industries [1], including construction industry that is traditionally less equipped with automatics than many other spheres. Developing systems for automatic building using bricks and blocks is one of actual tasks. Papers [2, 3] show the basics of feasibility study of applying mobile robotic bricklaying systems. The general view of the mobile masonry robot is shown in the figure 1. The main idea of such complex is providing less costs and risks of bricklaying process compared to manual labor and theoretically unlimited length of the built object due to mobility of the machine.

The key factors that influence on introduction of new technologies, including robotic systems, in construction are profitability and compliance with production technology. There are also some factors that may reduce efficiency of the considered robotic systems:

- the need for the technological processes accompanying the bricklaying process, such as installation of heat-insulating elements, making windows and doors openings;
- using fractional parts of bricks and blocks (1/2, 1/4, 3/4, etc.);
- complex planning solutions of the built objects, including numerous corners and columns, that cause slowdown of a robot’s operation.

The presence of the mentioned factors makes it necessary to study the efficiency of operation of the mobile bricklaying robot taking into account the conditions of the building process.
2. The factors influencing the efficiency of a mobile bricklaying robot

There are different ways of organization of building process at the construction site [4]. So, it is necessary to consider several groups of factors that determine the best ratio of manually implemented brickwork and brickwork implemented automatically using the robot.

The most significant factor includes the ratio of brickwork volumes of bearing walls and partitions and the ratio of costs of their building. According to the Russian standards for multi-story construction [5], bearing walls are walls with thickness 1.5 blocks and more (380 mm, 510 mm and more). Partitions are walls with thickness 0.5 or 1 block (120 mm and 250 mm). So, there are three main types of using the bricklaying robot:

I – building all brickwork with robot, including outside and inside bearing walls, partitions (figure 2a);

II – building only outside and inside bearing walls, when partitions are built manually (figure 2b);

III – building only outside bearing walls, when inside bearing walls and partitions are built manually (figure 2c).

Searching for the best ratio of using robot and manual labor should be implemented on the basis of analysis of time and costs for the both variants, taking into account the algorithm of the robot operation.

Figure 1. The general scheme of a mobile masonry robot: 1 – brickwork, 2 – robot’s base, 3 – chassis, 4 – bricks supplying device, 5 – manipulator).

Figure 2. Types of using a mobile bricklaying robot.
The standard time for building different types of brickwork are taken from the standard documentation [6], according to which laboriousness of a 1 m$^3$ of brickwork (394 standard bricks) using manual labor is:

- for bearing walls – 5.66 human-hours;
- for partitions – 1.44 human-hours.

Building the same amount of brickwork using the mobile bricklaying robot takes 0.5 hours at its maximal productivity of 800 bricks per hour.

Bricklaying robot efficiency depends not only on a brickwork volume, but also on spatial configuration of walls. As the bearing walls are thicker than partitions, the manipulator working area cover more blocks. It results in reducing movements of the whole robot, increasing the laying speed and the total productivity. Productivity of the bricklaying robot provides significant advantage in building time in comparison with manual labor when building thick straight walls, usually external bearing walls. On the other hand, this advantage reduces when building thin walls with big amount of turns, such as bathrooms, toilets, little storerooms, etc. Such conditions require many implementing many maneuvers and accompanying movements by robot and reduce its productivity.

So, the ratio of brickwork volumes for bearing walls and for partitions influences on the bricklaying robot efficiency. Numerical analysis of the efficiency can be based on the following equation (1):

$$K_{EF} = \frac{V_{BW}}{V}$$

where $K_{EF}$ is a coefficient showing the ratio of brickwork volumes for bearing walls and for partitions;

- $V_{BW}$ is the brickwork volume for bearing walls;
- $V$ is the total brickwork volume in a building.

Finally, evaluation of bricklaying robot efficiency is based on costs for building a certain construction that can be expressed in a price for laying one block. According to the acting standard [6], the price for laying 1 m$^3$ (394 standard bricks) of brickwork is:

a) for external walls:
- 1232 RUR – for manual labor;
- 311 RUR – for a bricklaying robot.

b) for partitions:
- 307 RUR – for manual labor;
- 311 RUR – for a bricklaying robot.

The more detailed analysis of prices is shown in [3], including the approach to calculation costs of laying bricks by a robot.

Another factor influencing on the efficiency of a bricklaying robot is the production technology itself. The technological aspects of building of blocks using mobile robotic systems are described in more details in [7, 8]. The construction technology requires implementing the accompanying technological processes, such as installation of heat-insulating elements, making windows and doors openings.

The showed above difference in efficiency of a bricklaying robot for different building configurations requires a selective approach to determining the scope of work for a bricklaying robot and manual labor. Such approach should take into account the robot limitations. As most buildings differ from each other, it is necessary to have special instruments for evaluation of the best ratio of manual and automated labor. Such instruments should be able to simulate such types of work, evaluate its labor input and costs and compare different types of labor organization for a certain building. The approach to creating such instrument in the form of software including the model of operation of a mobile bricklaying robot is described below.

3. The approach to modelling the robot operation

The aim of modeling the operation of the bricklaying robot is evaluation of time for all the required operations taking into account the described factors. For such modeling it is necessary to know the
required time for each operation implemented by the robot. Also, the modeling can be implemented with different accuracy of describing the corresponding processes, so the following approaches can be used:

- The approach when time for each operation is determined based on averaged kinematic calculation of the robot’s subsystems (manipulator’s movements, movements and maneuvers of the robot itself);
- The approach when time for each operation is determined based on dynamic calculation of the robot’s subsystems (dynamics of the robot’s drives taking into consideration the acting loads) and taking into account the time for data processing in the robot’s controllers (images processing, trajectory calculation, etc.).

The second approach is more accurate. At the same time, such accuracy is unnecessary for the basic evaluation of robot’s effectiveness in combination with manual labor. So, the first approach can be used for this purpose. The more detailed description of such approach and its basic implementation is described below. The full results of modeling and its discussion will the topics of the upcoming papers.

The developed software for the described modeling imitates robot movements at the construction site during bricklaying. The process is modeled in time and considers the following time factors:

- time for direct laying blocks for a certain thickness wall;
- time for maneuvers of a robot, namely:
  - moving along walls during bricklaying;
  - moving along walls without bricklaying;
  - turns.

Total robot working time in the model is calculated by summing the times for all operations required for a certain walls configuration. It also should be noted that robot movement algorithm also affects the bricklaying time. The simplest algorithms following along all walls contour. The more complex algorithms may include moving away from the walls contours for faster travel between sections of a map. Comparison of different algorithms and their influence on the robot efficiency will also be held and described in upcoming articles.

The map for robot operation in the described model is based on a masonry plan and considers a walls configuration. The map resolution should be at least half brick size. In the modeling software the map is an array of the corresponding size. The values of the array elements are numbers of bricks in the corresponding wall place. E.g., a fragment of a map with the outside bearing wall with thickness of 2 blocks and the adjacent partition with thickness of half block will be described as follows (figure 3):

```
  0 1 0 0 0 0 0 0
  0 1 0 0 0 0 0 0
  0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0
  4 4 4 4 4 4 4 4
  0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0
```

**Figure 3.** The initial fragment of the map.

A current robot position at the map is described by coordinates X and Y stored at the corresponding variables of the program. The coordinates are indexes of an array’s element corresponding to the robot position. Orientation of the robot also should be taken in account due to the fact that the robot turns during operation and its turns take time. In most cases walls are orthogonally oriented, so the model should have 4 main orientation values multiple of 90 degrees of the robot turn.

The described model contains the simplest robot movement algorithm described above. In such model robot moves along the non-zero elements of the array. Robot movement is modeled by changing its coordinates X and Y. The robot’s path is stored in another array including the successive coordinates of the robot movement, as well as its orientation for each position.

Passing the map by the robot model also includes modeling bricklaying. As the robot’s manipulator has a certain direction, bricklaying is modeled according to the robot current orientation in the model.
A “laid brick” is marked by multiplying the corresponding array’s elements by -1. So, the fragment of the map shown above after modeling will be modified as follows (figure 4):

\[
\begin{array}{cccccccccccccccc}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & -1 & 8 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & -1 & 8 & 0 & 0 \\
8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & -1 & 8 & 8 & 8 \\
-4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 & -4 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}
\]

**Figure 4.** The processed fragment of the map.

The processed fragment contains the following designations:
- negative numbers – laid blocks;
- elements of value «8» – positions visited by the robot;
- zeros – map points without blocks and not visited by the robot.

In a certain layer all blocks will be laid when all corresponding array elements values are negative. This is also an indicator for the end of the algorithm execution.

Total robot work time is calculated by summing times of operations at each step with the coefficients for setting the ratio between such times:
- KL for laying blocks time;
- KM for moving during bricklaying time;
- KI for moving without bricklaying time;
- KT for turning time.

So, the results of the whole modeling are:
- path of the robot;
- total robot work time expressed in conventional time units (can be scaled to the real time units).

The graphical modeling result for a conventional building is shown in the figure 5. The building contains an external bearing wall with thickness of 2 blocks and partitions with thickness of 1 block. Laying of only one layer of blocks has been modeled for demonstration of the modeling software operation. In the figure black is for the laid bricks, white is for the positions visited by the robot, gray is for positions without blocks and not visited by the robot. For demonstrational purpose all coefficients KL, KM, KI and KT are equal to 1. The figure 5a shows the modeling result with all brickwork made by robot, the figure 5b – only external bearing walls made by it. The first case requires 81 conventional time units, the second – 39.

**Figure 5.** Modeling results.

The further improvement of the described model will be:
- refining time coefficients and their mutual influence (for example, in the case of simultaneous motion and bricklaying);
improving movement algorithms, including the ability to process wall structures not adjacent to external bearing walls (separate elements at the map requiring passing to them not along other walls), as well as selecting the best algorithms in terms of time. Such algorithm can be based, for example, on the D* [9] or LPA* [10] algorithm;

introducing economic factors described above into the model.

4. Conclusion
The paper shows the basic factors that should be taken into account for organization bricklaying process in construction using mobile bricklaying robots and for obtaining their maximal efficiency. These factors include the ratio of brickwork volumes of bearing walls and partitions, spatial configuration of walls and partitions, presence of other elements such as heat-insulation, armature, that should be mounted manually. The more detailed study of influence of such factors on efficiency of applying mobile bricklaying robots will be based on modeling of the corresponding technological processes. The described approach to such modeling includes considering the most significant factors, such as walls thickness, its spatial configuration, speed of work of robot’s elements and systems, movement algorithm. The further work will be for improvement of the model accuracy, including more accurate modeling of operations implemented by a robot.

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