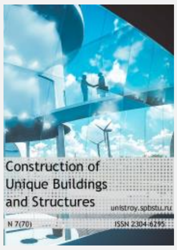
Строительство уникальных зданий и сооружений. ISSN 2304-6295. 3 (78). 2019. 7-22

Construction
of Unique Buildings and Structures
journal homepage: www.unistroy.spbstu.ru`



doi: 10.18720/CUBS.78.1

Автоматизированный способ кладки с оценкой характеристик его производительности и качества

Automated masonry method with evaluation of its productivity and quality characteristics

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КЛЮЧЕВЫЕ СЛОВА

Строительная автоматизация;
аддитивные технологии;
мелкомасштабные модели;
каменная кладка;
робот-манипулятор;
3D-принтер; качество кладки;
технологии строительных процессов;
технологии будущего;

KEYWORDS

Building automation;
additive technologies;
small-scale models; masonry;
robotic arm;
3D-printer; masonry quality;
building process technologies;
technologies of the future;

АННОТАЦИЯ

В статье представлен способ использования шарнирного робота-манипулятора со строительным 3D-принтером для автоматизации кладки кирпича с использованием традиционного водоцементного раствора. В статье поэтапно описаны все действия, которые нужно проделать с роботом-манипулятором для того, чтобы построить кирпичную колонну, схожую с реальной, без использования рук. Колонна, по предварительным данным, должна выдерживать максимальную нагрузку, примерно равную той, которую выдержала бы колонна из того же материала, но сделанная человеком. Позже сравниваются свойства 6-ти построенных кирпичных колонн, половина из которых построена роботом, а другая часть – человеком. Также рассмотрены все достоинства и недостатки автоматизированного метода возведения каменных конструкций. В ходе работы были выявлены такие показатели, как время кладки, предел прочности конструкции, а также их сравнение с показателями конструкций, возведенных физическими усилиями.

ABSTRACT

The article presents the way of using articulated robotic manipulator with building a 3D printer for automation of brick masonry using traditional water-cement solution. The article describes in stages all the steps that need to be done with a robot manipulator in order to build a brick column, similar to the real one, without the use of hands. The column, according to preliminary data, must withstand a maximum load approximately equal to that which would withstand a column of the same material, but made by man. Later, the properties of 6 built brick columns are compared, half of which is built by a robot, and the other part – by a man. All advantages and disadvantages of the automated method of construction of stone structures are also considered. In the course of the work, such indicators as masonry time, structural strength, as well as their comparison with the indicators of structures erected by physical effort were revealed.

Содержание

1. Introduction

Nowadays, almost every industry is rapidly increasing its productivity through automation, but constructing sector is lagging behind the use of automatic technology [1, 2]. Today, the way to fully automate and mechanize the masonry process has the ability to introduce new technologies, which every year will receive more and more opportunities by creating various updates and modifications. Therefore, in the future, humanity will completely get rid of the need to carry out the construction of walls manually.

The idea of full automation is that by including an articulated robot in construction process you can completely bricks abandon lay in the traditional way (masonry is deal by mason). Due to special language, it will be possible to program robot’s «arm» so that it can transfer bricks to necessary place using pneumatic gripping, you just need to indicate the initial position of this brick. Currently, each articulated robot has a special sensor, which helps to determinate position of the desired objects on the ground [3, 4].

Based on many different publications on this topic we can conclude that this masonry method has remained in the patent stage. Automation is a kind of simplification of work for a person: automation of production documentation [5, 6], a method for remote systematic control of constructing equipment and others. For example, some specialized building companies have developed prototype of robots for only one application (a robot for painting bridges, a robot for blasting cocreate, a robot for placing rebars, a steel-skeleton welding robot, a robot for roads maintenance and etc.) [7,8].

Currently, the need for low-rise construction of industrial and civil facilities is increasing. Such objects in many cases are made of brick or aerated concrete masonry [9-11]. In developed countries the volume of such construction is already higher than the volume of construction of massive objects from reinforced concrete. In the near future, similar processes can be expected on the territory of the Russian Federation. The advantage of additive block technologies is the absence of technological breaks in waiting for concrete to set, and the greater availability of material.

One of the most important issues in engineering is the speed of construction of buildings. Despite all of these advantages, there is an unexpected lack of research and development related to the implementation of articulated robots in the construction industry [12-14], which is currently possible. To date, in scientific and industrial research, they are only approaching the creation of full-fledged robots for the construction of masonry structures, which allows us to conclude that this scientific direction is new [15]. Moreover, research is mainly carried out from the perspective of designing the robots [16-18], while research from the perspective of civil engineering is practically not conducted.

At the moment, a small number of companies are engaged in the creation of special robots that are capable of laying bricks. The main brands that have similar ideas to us are Fastbrick Robotics и Construction Robotics. Types of robots are presented on the pictures 1 и 2 respectively.

Picture. 1. Hadrian X

Hadrian X was patented in 2008 and built its first house in 2019. More than $ 36 million was raised to create the model. The problem of this robot is the inability to lay a brick using standard mortar.

Григорян Э.А., Суровенко В.Б., Семенова М.Д., Кормалова К.Д. Автоматизированный способ кладки с оценкой характеристик его производительности и качества // Строительство уникальных зданий и сооружений. 2019. № 3(78). С. 7-22. DOI: 10.18720/CUBS.78.1

Picture. 2. SAM 100

The most advanced technological solution is 3D building printing in the field of automation today [19-22]. It is well known that the basic principles of this method of construction are the same, regardless of the model of 3D printing or 3D printing of a full-sized building. Both of them require five basic processes [23], including the creation of a 3D model. In addition, these processes also include the generation of an STL file, planning slicing and paths, writing machine code, printing. That is why the use of these devices in a certain sequence can give us the most promising type of automation and also more accurate and profitable.

Thus, if we combine a 3D printer and an articulated manipulated robot, we will be able to supply cement mortar to the brickwork and we will place bricks with a manipulator with the necessary sequence directly on the mortar. The main problem is checking the rationality of the construction a 3D model. Also it is quite possible to modify the mortar due to chemical additives [24-26] to obtain a higher compressive strength of the structure.

The purpose of the experiment is to evaluate the speed of masonry in an automated way and its quality characteristics. As a result, the construction object (in this case, the column) should have similar compressive strength and less time spent on its creation. At the moment, the task is to show not only the possibility of using robots, but also their profitability in a construction site.

2. Materials and Methods

Методы1 During the research, the Mitsubishi RV-2AJ articulated robot equipped with position sensor and pneumatic grippers was used as a manipulator (pic. 3). Ceramic solid bricks with a scale of 1:10 with respect to the dimensions of a standard full-size brick were chosen as building materials. And also, we used a special gypsum-based mortar with an average hardening rate, which replaced the water-cement mortar in this experiment. The ultimate goal of this experiment was to build a brick column similar to a real one, without using hands. The column, according to preliminary data, had to withstand the maximum load. This load is approximately equal to that which a column made of the same material could withstand, but created by man. The 3 columns were made using the manipulator and 5 columns were built manually. The tests were carried out for central compression with fixation of the maximum load.

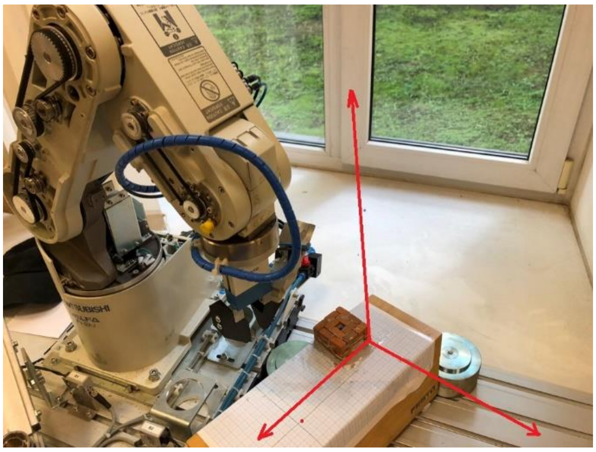
Picture 3. Mitsubishi RV-2AJ

Grigorian, E., Surovenko, V., Semenova, M., Kormalova, K. Automated masonry method with evaluation of its productivity and quality characteristics. Construction of Unique Buildings and Structures. 2019. 3(78). Pp. 7-22. DOI: 10.18720/CUBS.78.1

The initial step was to connect this manipulator to a computer and control it using a programming language. This model is controlled using the MELFA BASIC IV language. The manipulator was not created for construction work, so many functions in its language were missing, such as the required number of optical sensors. But for an experiment with bricks on a scale of 1:10 this robot was an excellent tool for research. It is worth pointing out that the manipulator has the same error both in working with miniature bricks and with real ones, unlike human hands (pic. 4).

Picture 4. Work with manipulator

The second step in the work was to establish the correct position of the coordinate axes for more convenient operation using the position sensor installed in the robot. The position of the axes was chosen in such a way that the «arm» of the manipulator had the ability to move to these limits (pic. 5.).

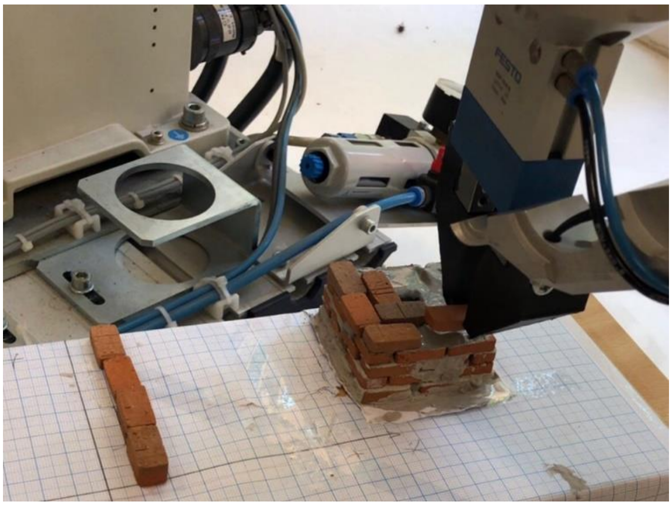


Picture 5. Coordinate axes

The third step was to set the start and ends coordinates of each brick. Since the starting position of the bricks is the same it did not take much time (because bricks are fed using a conveyor feed, but in this work, we had to confine ourselves to one manipulator without a tape, so the initial coordinates were also set for each brick with an offset down). The end points for each brick are different, so their own position was selected and recorded. After that, the second layer of the column was laid out taking into account the size of the brick with a displacement by a distance equal to its half. Also the height of each layer was taken into account.

The last step was to write the program which helped move the manipulator from one position to another (MOV command), grabbed and lowered bricks (HOPEN 1 and HCLOSE 1), set a certain percentage of the maximal speed (OVRD 10) and paused between movements depending from their need (DLY 1). After writing each command, we were convinced of the accuracy of constructing the first layer of the column. Then we set a command to the cycle of the same actions with a shift and we poured a mortar between the construction of each layer. Later this mortar hardened and strengthened the structure (pic. 6).

Григорян Э.А., Суровенко В.Б., Семенова М.Д., Кормалова К.Д. Автоматизированный способ кладки с оценкой характеристик его производительности и качества // Строительство уникальных зданий и сооружений. 2019. № 3(78). С. 7-22. DOI: 10.18720/CUBS.78.1



Picture 6. Column construction process

3. Results and Discussion

In total, 3 brick columns were made at the presented configuration (2.5x2.5 brick's size, height – 12 row). Then, central compression tests were performed using a hydraulic press (pic. 7).

Picture 7. Tests of brick columns of automated assembly after damage

Due to the data obtained after tests conducted with the columns, we have identified strength indicators of the columns of automated and manual assemblies, their differences and properties.

Table 1. Small-scale masonry brick test results

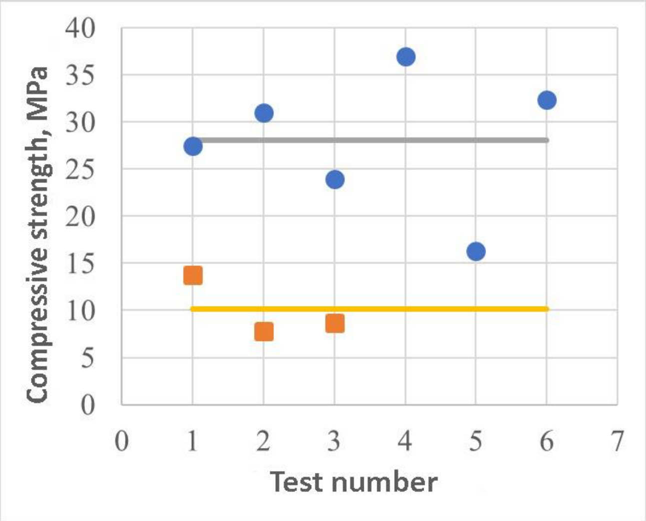
№	Assembly type	Sizes, sm		Breaking load, kg	Compressive strength, MPa
		a	*b*		
1	automated	5,2	5,2	3800	13,8
2	automated	5,2	5,2	2150	7,8
3	automated	5,2	5,2	2400	8,7
4	manual	5,0	4,9	8100	32,4
5	manual	5,1	5,2	4400	16,3
6	manual	5,0	5,0	6100	23,9

Grigorian, E., Surovenko, V., Semenova, M., Kormalova, K. Automated masonry method with evaluation of its productivity and quality characteristics. Construction of Unique Buildings and Structures. 2019. 3(78). Pp. 7-22. DOI: 10.18720/CUBS.78.1

It is clearly seen that in this test, the samples collected using the robotic arm showed significantly lower strength. This is due to the fact that bricks were not tamped and positioned and also horizontal joints were formed manually.

It is also noticeable that samples collected in an automated manner have close strength indicators. This cannot be considered absolutely reliable due to the small number of samples tested. however, due to equivalent assembly operations, it can be assumed that all samples collected by the manipulator will have similar strength and deformability.

The test results are presented in graphical form for clarity (pic. 8).

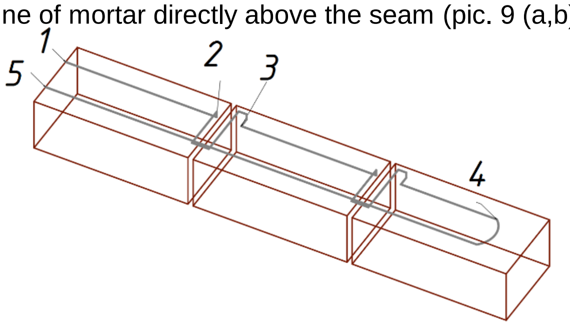


Pic. 8. The results of compression tests of manually collected samples, (●) and in a semi-automated method using the manipulator (■). Lines represent averaged values. (Vertical: compressive strength, MPa; horizontal: test number)

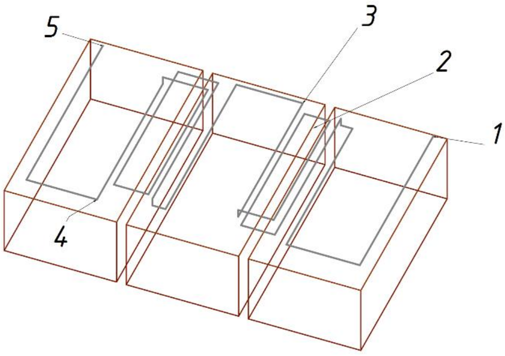
Given the height of the brickwork in our study (meaning a hand-assembled column), their compressiveman strength and deformability are similar to those mentioned by Massimiliano Gei and Diego Misseroni in their article [11], where the author, in addition to compressive strength, also considers bending resistance, thereby obtaining a clearer picture of the load on the column. At the same time, the experiment demonstrated a wider applicability, which must be supplemented by a large amount of experimental data as part of further research.

A traditional 3D printer extruder provides a mortar with a fairly narrow strip. The formation of a horizontal seam can be achieved by feeding the mortar to the brick in 2 lines and compressing it with a brick installed on top. The formation of a vertical seam is a more difficult task. Ehe solution to this problem may be to supply an additional line of mortar directly above the seam (pic. 9 (a,b)).

a)



b)



Picture. 9. The sequence of supplying the mortar to the masonry with an extruder 3D printer. a) Half brick masonry; b) Masonry at 1 brick. 1 – Start of mortar supply; 2 – An additional layer of mortar for the top row of bricks; 3 – Supply of mortar to the 2nd brick; 4 – Turn the extruder, start moving in the opposite direction; 5 – End of trajectory, end of mortar feed.

In this case, the seam is formed both due to gravity, and due to the extrusion of the mortar into the seam with a brick laid on top. For masonry in 0.5 and 1 brick, an extruder nozzle can also be used, which ensures the

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supply of mortar in an even strip equal to the width of the masonry, with additional thickenings in the weld zone. However, when laying thicker seams are located in different directions and their formation is more convenient to perform using a linear extruder.

Picture. 10. A row of masonry before feeding the solution with a 3D printer

During the experiment, the mortar was poured into the masonry rows using a 3D building printer (pic. 10). Mortar mixtures were prepared with a water-cement ratio of 0.35 to 0.8 with various mobilities determined experimentally (table 2).

Table 2. Test results for cement mobility

W/C	0.35	0.4	0.5	0.6	0.7	0.8
CD, см	0.5	3	4.5	6	8	10

For each mortar, the pouring time was calculated according to the schemes in pic.9. The pouring time was determined by the set speed of the 3D printer funnel, which was selected empirically based on the maximum possible speed to ensure a continuous supply of mortar to a number of bricks. The workability of bricks was also determined for each mortar. Since there is currently no combined brick and mortar feed tool, the second row bricks were laid manually. Masonry was carried out in one step in order to maximize approximation to automated laying. The mortar was extruded with brick, forming a horizontal and vertical seam. Part of the mortar was squeezed out of the masonry, so an excess was formed due to the uneven distribution in the seam. Presumably, from such surpluses, it is possible to approximately evaluate the quality of the masonry and the workability of the brick to the mortar seam of this mobility. The results are summarized in table 3.

Table 3. The results of the experiment for applying the mortar to the masonry

CD	0.5	3	4.5	6	8	10
Half brick time for masonry	20,5	14,3	14,3	12,1	12,6	12,6
Filling time for masonry in 1 brick	28,2	17,9	15,5	13,4	13,4	13,4
The mass of excess mortar, kg (workability)	0,4	0,12	0,16	0,13	0,05	0,12
The initial mass of cement paste, kg	3,82	3,65	3,3	2,97	2,69	2,31
The relative amount of surplus, %	10,5	3,3	4,8	4,4	1,9	5,2

The results show that the shortest pouring time for mixtures with a mobility of 6-10 cm. But the least excess is formed in mixtures with a mobility of 3 and 8 cm. Mortar with a mobility of 4.5, 6 and 10 cm also have low surplus rates. A mortar with a mobility of 0.5 cm showed the worst results in all points, from which it can be concluded that it is unsuitable for automated masonry. Optimum mobility is 6-8 cm. The greatest fillable of vertical joints was found in mortars with a mobility of 8-10 cm. However, due to the fact that the first row of masonry was

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performed without a substrate seam, it can be assumed that under real conditions mortars with a mobility of 5-6 cm will also be suitable for the formation of vertical seams.

Despite the fact that Izabela Hager talked about the only prospective use of a 3D printer in the construction industry [22], as a tool that prints walls from a special solution, Table 3 clearly shows that the method of using a 3D printer directly as a solution supplying tool is no less useful for masonry.

4. Conclusion

According to the results of experimental reteaches of the technological cycles of the robotic arm and the 3D printer, the execution time of each operation of erecting stone structures in an automated manner was determined. Also, the estimated operating time of the existing masonry positioner was obtained. The obtained data on the execution time of operations are used to build productivity models and assess the economic efficiency of combined tools.

The practical use of the articulated robotic arm in brickwork is quite feasible. Problems arose in only three directions:

- lack of devices tamping bricks so that the mortar can fully fix;
- the mobility of the manipulator and the aspect ratio should be different from those used in our studies. If you consider that a full-sized brick has a scale that is 10 times larger than the layout, a proportional manipulator will have invalid sizes;
- the use of traditional water-cement mortar to strengthen the brickwork, instead of glue, which cannot perform all the functions needed by the supporting structures.

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