Robotic mechanical design for brick-laying automation

Zakaria Dakhli1 and Zoubeir Lafhaj*

Abstract: This paper investigates the potential for automation of masonry work. A brick-laying robot was designed and the robot's design criteria were such that it should be able to construct a wall using cinder blocks autonomously. The paper outlines considerations for the entire process of implementing the robot, from material input and stock management to construction process by the robot itself. The design included the functioning of the brick-laying robot's head. Finally, comparisons were made in terms of cost and time efficiency between the robot and traditional methods for masonry assembly. The results revealed that the designed robot optimized time and cost deliverables with a noticeable waste reduction and an increase in productivity.

Subjects: Applied Mechanics; Automation; Robotics; Mechanical Engineering Design; Architecture; Building and Construction; Building Techniques

Keywords: automation; industrialization; bricks; construction robot; masonry

1. Introduction
One of the main challenges the construction industry faces is a low productivity compared to other industries (Fulford & Standing, 2014). Productivity could be understood as the ratio of the output to the input of a given process. The construction sector uses a considerable number of resources (human resources, materials, equipment, etc.), and waste occurs along the construction value chain until the final delivery (Koskela & Rooke, 2007). (Warszawski & Navon, 1998) reports the main problems the construction industry faces. Labor efficiency is low and work quality and control are insufficient which result in a high accident rate onsite.

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PUBLIC INTEREST STATEMENT
In recent decades, a new trend has led the construction industry towards automation by integrating new technologies and substituting site operations with more secure and efficient ones in terms of cost, time, and quality. The construction industry has a large number of accidents (about 9% of total work accidents in France and 60% of construction workers who experience an accident at work are unable to return to work again). The suggested Robotic Mechanical Design in this paper develops a framework for automating the laying of bricks. This automation has also a social dimension since it improves the working conditions of traditional masons and prevents potential health risks and discomfort. It also reduces waste on the building site by eliminating the risk of breakage of concrete blocks and loss of cement during the construction of the walls.
O’Brien, Formoso, Ruben, and London (2008, chap. 1) highlighted the differences between manufacturing and construction sectors. The gap results in different characteristics: the manufacturing industry relies on mass production, a reduced variability of supply, continuous improvement and integration of efficient logistics while construction is a limited production (few projects a year) and is highly fragmented (Howell, 1999): several actors work on the same project which make management and tasks definition a subtle process. During the last decades, performance improvement hasn’t been the main concern of the construction sector, probably because there was, until recently, no model (philosophy, methodology, tools) that takes into account all the interfaces in the act of building. Currently, the construction sector is about to know a decisive period: new technologies are introduced rapidly, however, the understanding of the construction as a global process (not separate phases) should be in line with the introduction of those technical innovations.

Bock (2015) pointed out that labor productivity in the industry, especially in the manufacturing industry, is continuously rising whereas labor productivity in construction has been decreasing for decades. Figure 1 reveals the frequency of accidents (with absence) for 1,000 employees in France. Construction is the leading sector in terms of absence related to work accidents, followed by the wood and service industries.

1.2. Robotics in construction
Robotics are viewed as one potential solution to improve the construction industry efficiency (Castro-Lacouture, 2009). Robotics offers process automation and reliability thanks to sensors technologies (Väähä, Heikkilä, Kilpeläinen, Järviluoma, & Gambao, 2013). The lack of robotics in civil engineering could be linked to product features and complexity (Project size, lifetime and uniqueness, versatile construction environments) and the weak capital budgets in R&D and the reluctance of strategies related to construction automation. Other research studies assessed the potential use of robots in construction (onshore oil and gas industry y (Shukla & Karki, 2015), bridge construction (Oh et al., 2009)…).

Industrialization is also enabled thanks to robotics and automation. According to Richard (2005), industrialization is based on quantity. The author presented five levels of industrialization: prefabrication, mechanization, automation, robotics and finally reproduction.

In the same context, Jensen, Olofsson, and Johnsson (2012) conducted a research study to automate the design of modular construction using the parameterization technique. The approach consists of streamlining the construction product components to make modularization more achievable.

Figure 1. Frequency of accidents (with absence) for 1,000 employees in France.
Source: PLFSS (2015).
The construction sector could not be fully automated using the current available technologies. The human factor is a prominent cause (Navon, Kelly, & Johnston, 1993). This may also be explained by:

- Automatic manufacturing technologies are not suitable for construction projects and designs.
- A low quantity of the finished products; restrictions on materials that might be used by an automated system (regulations and construction norms).
- Low economic attractiveness due to an expensive automated equipment.
- The issue of soil (and the environment) that changes for each site.

Robotics in construction is a large field of study due to the multidisciplinary trades that constitute the act of constructing. Bridges for instance is a type of construction subjected to various robotic automations. Oh et al. (2009) developed a robot for bridge inspection and (Lorenc, Handlon, & Bernold, 2000) for maintenance. Bridges are difficult to access and the need for robots for diagnostics and reparation is highly demanded.

1.3. Masonry robots
Bryson, Maynard, Castro-Lacouture, and Williams (2005) developed “RoboPaver”, a 1:20 scale prototype concrete paving robot. The latter contains sensors and data collection tools in order to work as autonomously as possible and is designed to operate in difficult environments.

Warszawski and Navon (1991) discussed in details robots intended to perform Interior-Finishing Works. They presented an overview of the interior-finishing robot development process and proposed a preliminary design for the robot set of activities to perform the work. In the same context, Spath and Andres (1997) investigated the use of robots for interior trade works in construction. They proposed a kinematical concept of a robot for interior building trades and a specific process automation for the cutting of wall slits in masonry on construction sites.

The present research focuses on the masonry work. The latter has been a field of investigation for a number of research projects (Cavieres, Gentry, & Al-Haddad, 2011; Spath & Andres, 1997). Masonry work is one of the most arduous jobs in construction (Hess, Weinstein, & Welch, 2010; Vink, Miedema, Koningsveld, & van der Molen, 2002) since it includes a mason standing, kneeling and lifting. In addition, the mason works almost exclusively outside and undergoes the weather conditions (rain, wind, heat, humidity...). The mason sometimes works in height scaffolding or in trenched soils which may put his life in jeopardy.

In the last two decades, some research projects focused on the development of a bricklaying robot (Pritschow, Dalacker, Kurz, & Zeiher, 1994). Bricklaying work follows predefined steps and thus is favorable for automation. However, the process cannot be fully automated and requires the supervision of a worker nearby to adjust/control the robot. Tan, Mohan, and Watanabe (2016) stressed the importance of the environment when designing a robot. They support the idea that robot level of autonomy should be in line with the environment (actively/passively/not assisted environment). For that, the authors proposed a framework to help categorize the robot/environment interaction.

The latest technologies for masonry work automation that came out recently concern:

- The Australian “Hadrian X” ROBOT (Pivac & Pivac, 2016) that closely resembles to a truck crane (Figure 2). The robot is capable of laying the bricks with a high accuracy thanks to a laser guidance system. It is also able to work on almost any block size. The advantage of such a design is the flexibility in mobility: the robot can work under difficult circumstances linked to the environment.
• SAM100 (Semi-Automated Mason) from Construction Robotics (Podkaminer & Peters, 2015): the robot successfully passed the prototyping phase and is now commercially available. Figure 3 shows the utilization of SAM100 onsite. This robot is by far the most complete masonry robot realized until now. It can lays bricks with precision and includes the binder in the process of laying as well. SAM100 is capable of laying 800–1,200 bricks a day. The robot performs in a straight line with a limited height capacity. SAM100 costs around 500,000$ (442,030 €).

Other research projects focused on a specific design problematic of the automation process. For instance, (King, Bechthold, Kane and Michalatos (2014) explored the automation of tile placement using a variety of mathematical algorithms and image based methods. Their analysis led to the conclusion that installation costs for both robotic and manual placements are similar, but robotic methods add customization in the possible patterns. Bock, Stricker, Fliedner, and Huynh (1996) focused on the “software” part of the brick laying robot design.
Those cited research projects focused on the “functional” aspects: placement, pattern recognition, software, etc… However, the design part of the robot isn’t provided and detailed in literature. For SAM100, the design is based on an articulated arm as found in previous research projects (Bock et al., 1996; Pritschow, Dalacker, Kurz, & Gaenssle, 1996). The “HADRIAN X” is based on a variant of the articulated arm supported by a truck-crane robot.

In this article, we explore a different design alternative for the brick-laying robot. Design could greatly impact the efficiency of the robot and its cost. This article provides insights on the importance of the design phase when building a robot intended for construction.

The proposed design in the next chapter achieves the following goals:

• An increase in maximum construction height possible by the brick laying robots.
• An improvement in cost by design.

A design of a masonry robot, called “brick-laying robot” is achieved and explained throughout the next sections of the paper. At first the technical design is presented. After that, the design of the laying head and its functioning is discussed. Finally, the analysis of the robot is viewed in comparison with the traditional masonry construction method in terms of time and cost efficiencies.

2. Research methodology
This study was conducted with an industrial partner. The latter is specialized in building construction and is interested in brick-laying process automation in Construction. The results shown in this paper concern the first part of the Project. Those results describe the Robotic mechanical design for brick-laying automation.

The design was co-developed with the industrial partner in order to fit the needs (construction time and cost gain compared to the traditional masonry work).

The general framework of the technical/mechanical solution is developed according to Table 1.

We start by showing the general view of the proposed solution. The choice of the materiel (a specific type of bricks) is then justified. Mechanical considerations are discussed and the robot mobility system described meticulously. The reason for adopting a mechanical mobility is by large more economical and feasible. Finally, analysis of the automated solution was conducted and comparison with the traditional masonry work.

3. Overall system design
The system is designed to guide the brick-laying head along the walls and to supply the head laying with blocks and cement (Figure 4).
The construction of a wall with this system is achieved through three steps as described below:

(1) Stock processing;
(2) Construction;
(3) Material deposit.

The diagrams below present each step (Figures 5–7):

4. Material input for the brick-laying robot
For this study, standard cinder blocks (50 × 20 × 20 dimensions) were used as an input material. Accordingly, the brick-laying robot must have an advance of 50 cm to lay the cinder blocks, and a vertical movement of 20 cm in order to shift between the rows of finished blocks.

The method of thin joints is preferred for the bricklayer robot. The method appeared in the 90s and had big advantages over the classic masonry method. Indeed, it is similar to bonding technique; instead of having joints with a thickness of ten millimeters, thinner joints are required thus the use of...
A particular type of bricks is required. Those bricks are called rectified bricks due to the mechanical rectification on their upper and lower sides with dimensional tolerances of one millimeter.

The advantages of these rectified bricks are:

- Ten times less mortar than normal bricks (so much less water consumed and less waste).
- Less difficulty in the assembly.
- At least 20% of gain in time.
- Improved thermal performance.
- Clean and steady performance.
- Price: 26€/range of rectified bricks.
- Existing Dimensions (L × W × H): 15/20/30/50 × 20 × 15/20/25 cm.

The success of thin joints assembly technique is not exclusively contingent upon time saving. Figure 8 reveals the traditional masonry method, requiring 7.5 kg/m² of cement binder and the thin joints masonry, requiring only 2.5 kg/m².

5. Technical design

5.1. Structure

The proposed technical design for the basic structure of the brick-laying robot is a scissor lift. The latter is a folding system which is easy to transport and requires little labor for installation (compared to other alternatives). This solution has been inspired from aerial buckets, commonly used in the construction field to lift people or loads.

The advantages of this system include:
• Intrinsic stability of the equipment -> no need for stabilizers within the range of normal heights.
• Can lift fairly heavy loads.
• Spacious Platform.
• Certain devices are being designed to enable the extension, depot or orientation of the platform.
• Use a relatively small surface of the ground to hold.

In contrast, the disadvantages are:

• Requires the use of a tank transporter to carry these devices over long distances;
• Requires clean and hard floors with no slope, gutters (etc.).
• Presents a shearing risk when the platform descends, especially if the scissors are not well protected.

Before using the machine, the stability of the ground must be ensured (flat ground, no hills...), the soil must be hard enough to withstand the machine (the lifting platform, scissors, bricks....).

The drive controls are located in the working platform (at the chassis). Hence, once the robot is on site, it can be programed for self-movement.

5.2. Robot mobility
The aerial bucket has a support frame which is movable when the platform is raised. The robot is not completely autonomous: a skilled worker is needed to ensure the controls (height, translation, etc.).

In the context of this research, the aerial bucket should be adapted to have the drive controls in the chassis instead of the cabin. Therefore, the platform commands should be moved to the platform; an operation that will bring additional costs, which are not accounted for in the conducted cost study later in the article.

5.3. Stock processing
A stock of bricks and cement (mixed in advance) is put in place at the mobile platform.

For a chosen aerial bucket, the platform maximum capacity is 950 kg and that of the unit constituted by the laying head and the conveyor system is 100 kg. The stock could therefore contain more than 45 normal blocks of 17 kg. Thus intermediate stock containing 45 blocks each can be set up in advance on site and moved to the mobile platform using a forklift. The latter has a maximum capacity of 900 kg.

A small cement mixer will also be assembled on the working platform and is intended to operate autonomously (using a pump).

5.4. Handling system for bricks
We found that a conveyor system is a convenient solution to deliver bricks to the brick-laying head.

5.4.1. Robot-arm manipulator
A manipulator arm is designed to move building materials (bricks, plasterboard...) to the conveyor system (Figure 9).

5.4.2. Robot-laying head
The main design challenge was to imagine a system that can handle smoothly the large and heavy agglomerated blocks. The system requires devices that are able to accommodate, move down, and place on average a 20 kg blocks.
For example, a clip closing over the block that slides along the vertical axis would be perfectly suited for the descent of chipboard block but it would face many problems during the brick-laying phase. Indeed, the ends of the clip would be trapped between the bloc and the built wall. Furthermore, cement might grip and harden on the clip thus reducing substantially the accuracy of the laying. This solution, which seemed at first glance simple and convenient, arises complex problems.

The proposed brick-laying head is shown in Figure 10 and the followed process is described in Figure 11. In the next section, we first present the functioning and the system modelling (blocks accommodation (onset)). After that, we present the system that moves down the blocks and place them for the descent (descent).
6. Onset system

6.1. Functioning

The onset system intends to accommodate the blocks so that they are properly put in place for the descent while ensuring a set of requirements (Table 2). Accommodating a new block should be possible as soon as the previous one is evacuated from the working area. The onset system involves three stages:

- Accommodation and positioning of the block.
- Initiation of the descent.
- A Return to the starting position.

Since the brick-laying head is intended to work in building sites, a special attention should be paid to avoid using components that are too sensitive to water, dust, or gravels (we limit the number of actuators and electronic sensors in favor of simple mechanism and springs).

Table 2. Special requirements for the onset system

| Special requirements                                      | Consequences                                      |
|-----------------------------------------------------------|---------------------------------------------------|
| Simple systems, easy to maintain                          | Systems easy to dismantle without specific tools   |
| Resistant systems: resists to heavy loads, water, and dust | Limited number of electronic devices              |
| Security                                                  | Irreversible system, can detect failures          |
The proposed solution for the onset system consists of two metal strips - of few centimeters wide and about fifty centimeters in length- that support the cinder block from the two sides. The block accommodation phase is completed when the block gets off the conveyor and brings the blocks to the laying head. A stop sensor is installed to prevent the blocks from advancing too far. This stop sensor also identifies the block position when initiating the descent.

Figure 12(a) presents the modelling of the accommodation phase when the block is positioned and ready for decent. Figure 12(b) shows the next step: the descent of the block activated when the block holder rotates.

Only one side is shown since the system is symmetrical. The frame 0 and the unit 1 remain fix until the block B reaches the stop position. Once reached, the laying phase begins. In the kinematic diagram shown in Figure 13, the sliding pivot is not permanent and is composed of an axis 2 (drives in translation) and a bore in the work piece 1 (Figure 14). Thus, when axis 2 is completely removed from the bore, part 1 rotates freely around the pivot and drops the block. The latter can be received by the descent system.

Once the block begins its descent and is no longer in the working area, we enter the position of the “re-initialization” phase. This position is made possible by the presence of two springs designated by red circles in Figure 14.

A torsion spring is placed on the pivot shaft in connection with unit 1 and frame 0. This modelling helps to bring the unit 1 to its initial position after the descent of the block. The spring stiffness should be low enough to allow the block descent (20 kg) yet high enough to bring the whole unit 1 (<1 kg) to its position.

A compression spring is placed between shaft 2 and frame 0. This spring brings the axis 2 to the bore so that the system supports the weight of a new block.
This system was chosen for two main reasons:

- Its operation is relatively simple and requires few devices (it is therefore an economical solution).
- It requires, by and large, two stop sensors and one single actuator.

The first stop sensor is used to detect the presence of a block in the system. When set to 1, the block is in place. It is possible then to launch the actuator. The latter allows removing the axis 2 from the bore and thus bringing down the block. Once the block is down, the system returns to its original position thanks to the two springs.

The choice was made to install a second stop sensor that detects the presence of axis 2 in the bore. When axis 2 is detected, the system is ready to welcome a new block on the descent system. This second sensor is not essential: a timer could be used to fix the re-initialization time. However, such device can’t account for events such as blockages or bottlenecks. Accordingly, a second sensor is used for a physical confirmation that notifies whether the system has been well reinitialized.

7. Lowering and laying system

7.1. Functioning

Figure 15 presents the system located under the onset system which is responsible for receiving the blocks and moving them down to build the wall. The system should be able to let go the blocks without moving them, and if possible without any contact with the mortar put between the block and the already built wall. Finally, this system is expected to build with 90° angles without difficulties as well.

The system consists of a roller on both sides of the block as seen in Figure 16. The rollers are connected to springs and exert considerable pressure on the block which creates the retaining friction. The rollers move down the block and have the particular advantage of placing the block directly on the wall already built without any contact with the seal.

Once the block is positioned on the wall, it is still tightened by the rollers and the laying head will therefore rise with a slightly lower speed of descent than the block’s speed. This not only allows clearing the roller block, but also pushes the placed block. Furthermore, the head should be set up
before asking for a new block. Thus, this phase uses an existing movement and does not constitute an overtime loss.

The objective is to achieve a total tangential force at least equivalent to the block mass in order to prevent slipping. This force depends directly on the normal force and on the coefficient of friction that we seek to maximize. The normal force depends solely on $\Delta L$ and the stiffness of the springs.

Finally, if we sum the lengths, the total width of the system is related to the length of the springs, the angle $\alpha$, and the thickness of the block.

In practice, there are two pairs of rollers (one above the other) that get a block at the same time that it receives a new one. Moreover, since the block is linked to two rows of rollers, it ensures the horizontality of the block during the descent.

In brief, two main difficulties arise when designing such a system:
The rollers may move laterally for a small distance while a connected motor drives them to the frame.

The rollers from each side of the block have different rotation directions. Thus, it is better to have only one motor (for cost savings) and to be sure that the movements of the rollers are synchronized.

The proposed solution for the first problem is to place a pulley on which a flexible drive belt is mounted on each roller shaft. The belt will be driven by a pivot connection with the tree frame.

The proposed solution for the second problem is to use conical gears. The latters are mounted on a shaft, which drives two other shafts that can pivot relatively to the frame. Finally, the use of a pair of spur gear, to reduce the rotational speed at the rollers level, is suggested.

Figure 17 reveals the operating diagram of the lowering system. The selected engine is a worm gear with a low yield; the reason for this choice is that the system should be irreversible, otherwise even in case of emergency stop, a block may rotate the rollers and fall on site (for a security purpose).

7.2. Modelling and realization

One problem not obvious at first glance is the mounting of the rollers’ shaft. In addition to being rotated by the belts, those rollers are engaged in a linear motion during the springs ‘compression. This movement is made possible by the presence of parallelepiped pieces that can be identified in Figure 17. These parts drive the rollers in rotation and are in a sliding connection with the frame. A bent plate forms this sliding connection. The springs in turn are to be placed between the casing and the parallelepiped pieces.

The belt, which is placed on the two rolls, is not a drive belt. Rather, it helps guide the blocks between the two stages of rollers, and serves to increase the coefficient of friction between the block and the rollers. Indeed the coefficient of friction between the block and the roll is inversely proportional to the minimum force required to support the block.

7.1.1. Rollers shafts

Two pads located inside the bores of the parallelepiped bars guide the roller shafts. A pulley is arranged on the shaft so as to accommodate the belt. The roller shaft consists of two fretted parts: in
order to avoid processing too big cylinders during the metal turning phase, we simply drill a room and fit an axis within. As the torque being transmitted here is 20 Nm, the hooping is a sufficient solution for savings in terms of material and machining.

7.1.2. Rectangular pieces
Rails, manufactured using bent plate screwed to the frame, guide the pieces on which the axes of the rollers are mounted. A blind hole, which does not pass through the whole piece, is provided in order to allow room to accommodate the spring that maintains the block. Reinforcements are provided to connect the top and the bottom rail of each parallelepiped piece.

7.1.3. Transverse axis
The transverse axis corresponds to the axis 2 in the diagram. It aims to enable simultaneous motion of the rollers on each side of the block. As we have already seen, the two conical gears put in place above this axis move the rollers with the same speed in two different directions. Moreover, since the two pinions are mounted in opposition, the axial forces are canceled. The use of a pair of spur gears reduces four times the motor’s speed. Specifically, it can reach an on-load speed of 40TR/min with a 5 Nm torque.

Since the ratio of conical gears’ torque to drive pulleys’ torque is 1, the block descent velocity is 4.2 cm/s.

For a couple of 20 N.m, we would prefer a higher on-load speed, however, since this speed is very close to the 5 cm/s velocity initially planned, we accept the current economical prototype.

7.1.4. Cement deposit
The rectified blocks were chosen mainly because the tolerances related to their dimensions are much lower than those related to the ordinary blocks. Another benefits related to the use of rectified blocks is that a thin layer of seal can substitute the traditional cement binder. Therefore the mass of the binder for transportation is low. Moreover, the seal can easily grip on the concrete thus allowing the seal to be directly applied under the block if desired. Rather than using an articulated arm that removes the seal, we chose to use the block movement in the conveyor to remove the seal; this operation represents a significant savings in sensor and actuator.

As discussed before, the conveyor delivers the block to the onset system. However, during the delivery process, the block travels on a roller that is dipped in a tank containing the seal. The underside of the block (in touch with the roller) will therefore be covered by the seal as shown in Figure 18. The roller is not as large as the block, accordingly, the blocks’ edges will not be soaked by the seal, which otherwise would have impeded the functioning of the onset system.
The casing is made of folded sheets on which are fixed the various systems described above. Sheet metal is being used in order to minimize the mass.

For vertical binding of the blocks, the seal is deposited via a pipe linked to the laying head as described in Figure 11.

8. Construction time analysis

From the three stages of construction defined in this study (Figures 5–7), a building time analysis was conducted for various types of aerial buckets. Those different aerial buckets are characterized by various working heights thus can be adapted to different projects.

The building time analysis was conducted on four commercially available aerial buckets:

- ID #1 (working height: 34 m).
- ID #2 (working height: 15.30 m).
- ID #3 (working height: 12 m).
- ID #4 (working height: 6.35 m).

As mentioned before, the aerial bucket “ID #1” has a good working height to load capacity ration and therefore allows to build very high buildings. However, the aerial bucket “ID #4” has other interesting advantages: its height when folded allows to move through standard doorways; an overall length of 1.88 m and a width of 0.76 m that accesses congested areas. Thus, such a platform offers the possibility to construct interior bearing walls.

Table 3. Wall’s characteristics

| Number of layers | 12 |
|------------------|----|
| Number of cinder blocks per layer | 6 |
| Total number of cinder blocks | 72 |

Table 4. Building time analysis for the three studied aerial bucket

|                      | ID #1  | ID #2  | ID #3  | ID #4  |
|----------------------|--------|--------|--------|--------|
| Working height (m)   | 15.30  | 12.00  | 6.35   | 34     |
| Ceiling height (m)   | 10.00  | 4.35   | 32     |        |
| Maximum payload (kg) | 750    | 300    | 270    | 1,000  |
| Length of a cycle (rise and fall) (seconds) | 50 | 83 | 35 | 120 |
| Maximum translational speed (km/h) | 3.8 | 3.5 | 4.5 | 2.4 |
| Translational speed with charging load (km/h) | 0.800 | 0.900 | 0.500 | 0.200 |
| Maximum climb speed (km/h) | 1.102 | 0.434 | 0.447 | 0.005 |
| Time of horizontal advance of the machine (a 50 cm step) (min) | 0.04 | 0.03 | 0.06 | 0.15 |
| Elevation Time Platform (a 20 cm step) (min) | 0.01 | 0.03 | 0.03 | 2.40 |
| Capacity (number of cinder blocks) | 30 | 10 | 10 | 45 |
| Laying time of the brick’s laying head (min) | 72.00 | 72.00 | 72.00 | 72.00 |
| Translation time (min) | 2.25 | 2.00 | 3.60 | 9.00 |
| Elevation time (min) | 0.12 | 0.30 | 0.30 | 26.40 |
| Climb/descent time (min) | 5.00 | 22.13 | 9.33 | 8.00 |
| Dispense time stock (carriage) (min) | 3.00 | 8.00 | 8.00 | 2.00 |
| Total time (h) | 1.38 | 1.75 | 1.56 | 1.96 |
An example is the construction of a wall that is 2.4 m in height and 3 m in width. The construction characteristics of the robot are deducted and presented in Table 3.

It was also defined in the tender specification that the paving speed of the brick-laying head $V_p$ be equal to one block per minute ($V_p = 1 \text{ blc/min}$). The vertical and horizontal translation speeds of each aerial buckets are provided by the manufacturers. From these data, we could calculate the building time of the wall using the Bricklayer Robot (Table 4).

The results are very satisfactory for the Bricklayer Robot although many rooms for improvement are available. For the traditional construction method, we estimate that one man/women needs 1 h of work to build 1 m² of wall. Hence, in order to build the 7.5 m² wall, we need one mason as well as 7.5 h with the traditional method is needed.

The current study indicates that by automating the processes, it is possible to reduce this time by more than a half.

9. Cost analysis
Labor and the waste costs are estimated using the standard method. Data were gathered from a French construction company by exploiting the ratios of cost to time required to build an edifice. The hourly rate for construction corresponds to 36 €/Hour for the Paris region and to € 32/Hour for other regions (Without Taxes). It is also important to take into account that; in general, builders are working in teams of two.

Managing waste is also resource consuming. The Bricklayer Robot is fully automatic and is designed to produce 0% waste. As for the standard methods, there are costs related to waste disposal. By and large, it takes about 0.80€ to manage 1 m² of waste during the first stages of construction (excavation and structural work) and about 2.10 € to do so during the secondary stages (finishing work, electricity, plumbing...).
In this context, the Masonry Robot reduces the cost and saves time by cutting waste (no broken bricks for example). Dump trucks are not necessary to evacuate waste anymore and workers don’t need to allocate time and energy for cleaning and putting garbage in dumps.

For Masonry Robot, costs can be divided into different parts as revealed in Figure 19.

At this stage of the research project, we still lack information about the system operation. Improvements are to be made in the future to increase the accuracy of the estimated costs.

Various costs should be covered in this preliminary analysis. If this list is not exhaustive, it tries, however, to capture the main costs that will eventually show up during the process. Next is an estimation of each cost category.

9.1. Fixed cost
The Masonry Robot’s fixed costs represent the manufacturing costs of the different components that constitute the robot: aerial buckets, cement mixer, conveyor system, manipulator arm, brick-laying head, and rails.

Those components have been described in previous sections of this paper. Table 5 expresses the average costs estimated using available data on the current market.

The cost of the mechanical manufacture of the laying head is approximately 600 €. By adding other costs that cover the automatic parts, labor, and design, a total cost of the laying head of 5,000 € is reached.

9.2. Electricity cost
The aerial buckets “ID #2” was chosen for electricity costs estimation. The aerial bucket works using a 24 V-255Amp/h batteries. This cost analysis also accounts for the functioning of the conveyor system, the manipulator arm, and the brick-laying head. Table 6 presents the power of each element.

Since the cost of one kWh of electricity in France (in 2015) is € 0.16660, the estimated electricity cost is 1.13288 €/h.

9.3. Labor cost
For the automated construction using the Masonry Robot, two workers are needed: one responsible for controlling the machine and the other responsible for reloading the stock. Here, the same hourly rate for labor was used since this rate takes into account the different levels of workers’ qualifications. Thus, it was considered an hourly rate of € 36/H for the Paris region and 32 €/H for the other regions.

| Table 5. Fixed costs of the Masonry Robot |
|-------------------------------|--------|
| **Model**                      | **Price (€)** |
| Aerial bucket                  | 15,000.00 |
| Cement mixer                   | 287.00   |
| Conveyor system                | 1,940    |
| Manipulator arm                | 1,000    |
| Brick’s laying head            | 5,000    |
| Vertical rails                 | 98.00    |
| Total                          | 23,325.00 |
9.4. Maintenance cost

When building a wall using the standard method, health problems may arise. As for the discussed automated method, the breakdowns require the allocation of a maintenance cost.

Maintenance includes the costs of the different corrective and preventive actions necessary to maintain the installation’s availability and security level.

As regard this cost analysis, since the designed robot has not been used yet, we can only estimate the maintenance costs using the average costs fixed in usual maintenance contracts. We thus sought data from the maintenance contracts available in a regional research mechanical laboratory in France. In general, this cost represents 3–5% of the total machine cost. To manage the worst scenario, we considered a maintenance cost of 5% of maintenance cost is considered.

9.5. Other costs

Other costs are:

- Secondary equipment: electricity, instrumentation, etc. An average of 1,000 € of secondary equipment to guaranty a good functioning of the robot.
- Carriage of the robot’s components to the construction site: as stated earlier, a truck will ensure the transport of equipment and materials. Knowing that the cost for renting a truck is 750 €/day, we have a total cost of 1,500 € per site (if we consider only one round trip for each site is needed).
- Assembly works of the main and secondary equipment. The assembly and the disassembly of the main equipment and the secondary equipment each require two worker for one day (8 h). Considering the hourly rate of € 36 for a worker, total cost is € 1,152 per site.
- Site Preparation: since the realization of construction projects requires site preparation even without using a robot, the use the Bricklayer Robot does not add significant site preparation costs.
- Indirect expenses to cover the contingencies. A 5% allocation is considered for the Robot’s fixed costs to cover those expenses. In other terms, we put aside 1,166.25 € to cover the indirect expenses.

9.5. Comparison: Bricklayer Robot vs. traditional masonry method

As noted earlier, it takes less than two hours to build a 7.5 m² wall using the Masonry Robot. Thus, the assumption is that the robot can build approximately 3.75 m² of wall per h.

To make the comparison between the Bricklayer Robot method and the traditional method, we consider a typical model site, a square building of 6 floors (R + 5) 10 × 3 m (height × width). The four facades sum up a total surface of 720 m² (windows’ surfaces are neglected).

Such a site requires 192 working hours using the automated building method as opposed to 720 h using the traditional masonry method. The results are summarized in the Tables 7 and 8:
The overall construction cost of this model site is approximately 19,000 € with the bricklayer robot. In contrast, the construction cost of the same model site is estimated at 28,000 € with the traditional masonry method (additional labor and waste costs).

This result demonstrates the profitability of the masonry robot compared to the traditional method. Table 9 resumes the conducted comparison between the traditional masonry method and the brick-laying robot.

### 10. Conclusion

Global interest in automating the traditional masonry work is increasing. In this study, a brick-laying robot was designed and assessed in terms of cost and time efficiencies. The overall system design was presented and explained following in terms of:

- Material input and the stock management.
- The brick-laying process.
- Technical design: the structure, robot mobility, the brick-handling system.
- The brick-laying head functioning and modelling.

Finally, a comparison was performed between the traditional masonry method and the designed brick laying robot. The latter can perform in a pace of 3.75 m²/h compared to 1 m²/h for the traditional method. The results also reveal a significant gain in construction cost. Indeed, the robot requires about half the cost of the traditional method. While the economics of such an automation is revealed, future research should focus more on the removal of technical locks of the brick-laying head in line with on-site work conditions.

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### Table 7. Total fixed cost for the brick's laying robot

| Description                                      | Amount    |
|--------------------------------------------------|-----------|
| Fixed cost of the machine (€)                    | 23,325.00 |
| Maintenance costs (5%)                           | 1,166.25  |
| Indirect expenses (5%)                           | 1,166.25  |
| Total                                            | 25,657.50 |
| Total – Robot amortization for 20 constructions   | 1,282.88  |

### Table 8. Total variable costs of the brick’s laying robot per site

| Description                                      | Amount    |
|--------------------------------------------------|-----------|
| Electricity (€)                                  | 217.51    |
| Secondary equipment (instrumentation)            | 1,000.00  |
| Transport                                        | 1,500.00  |
| Assembling and dissembling                       | 1,152.00  |
| Staff (one technician and one mason)             | 1,3824.00 |
| Total                                            | 17,693.51 |

### Table 9. Construction analysis of the traditional masonry method and the brick’s laying robot

|                                      | Traditional method | Brick’s laying robot |
|--------------------------------------|--------------------|----------------------|
| Construction time (m²/h)             | 1                  | 3.75                 |
| Construction cost (€)                | 28,000             | 19,000               |
| Cost of waste evacuation (€/m²)      | 2.9                | Towards 0            |
| Difficult work conditions            | Yes                | No                   |
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References
Bock, T. (2015). The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. Automation in Construction, 59, 113–121. https://doi.org/10.1016/j.autcon.2015.07.022
Bock, T., Stricker, D., Fliedner, J., & Huynh, T. (1996). Automatic generation of the controlling-system for a wall construction robot. Automation in Construction, 5, 15–21. https://doi.org/10.1016/0926-5805(95)00014-3
Bryson, L. S., Maynard, C., Castro-Lacouture, D., & Williams, II, R. L. (2005). Fully autonomous robot for paving operations. In Construction research congress 2005 (pp. 1–10). Reston, VA: American Society of Civil Engineers.
Castro-Lacouture, D. (2009). Construction automation. In S. Y. Nof (Ed.), Springer handbook of automation (pp. 1063–1078). Berlin: Springer. https://doi.org/10.1007/978-3-540-78331-7
Cavieres, A., Gentry, R., & Al-Haddad, T. (2011). Knowledge-based parametric tools for concrete masonry walls: Conceptual design and preliminary structural analysis. Automation in Construction, 20, 716–728. https://doi.org/10.1016/j.autcon.2011.01.003
Fulford, R., & Standing, C. (2014). Construction industry productivity and the potential for collaborative practice. International Journal of Project Management, 32, 315–326. https://doi.org/10.1016/j.ijproman.2013.05.007
Hess, J., Weinstein, M., & Welch, L. (2010). Ergonomic best practices in masonry: Regional differences, benefits, barriers, and recommendations for dissemination. Journal of Occupational and Environmental Hygiene, 7, 446–455. https://doi.org/10.1080/1545962X.2010.484795
Howell, G. A. (1999). What Is Lean Construction – 1999. In 7th Annual Conference of the International Group for Lean Construction, Berkeley, USA, 26–28 July. 1999.
Jensen, P., Olofsson, T., & Johnsson, H. (2012). Configuration through the parameterization of building components. In Automation in Construction, 23, 1–8. https://doi.org/10.1016/j.autcon.2011.11.016
King, N., Bechthold, M., Kane, A., & Michalatos, P. (2014). Robotic tile placement: Tools, techniques and feasibility. Automation in Construction, 39, 161–166. https://doi.org/10.1016/j.autcon.2013.08.014
Koskelo, L., & Rooke, J. (2007). The TFV theory of production: New developments. In For Lean Construction, No. July, pp. 2–12.
Lorenz, S. J., Handlon, B. E., & Bernold, L. E. (2000). Development of a robotic bridge maintenance system.

Automaton in Construction, 9, 251–258. https://doi.org/10.1016/S0926-5805(99)00040-0
Novan, R., Kelly, P. W., & Johnston, D. W. (1993). Human factors in introducing on-site construction automation. Journal of Construction Engineering and Management, American Society of Civil Engineers, 119, 801–812.
O’Brien, W. J., Formoso, C. T., Ruben, V., & London, K. (2008). Construction supply chain management handbook. Retrieved March 6, 2014 from http://books.google.com/books?id=ZZW7bO500kUC&pgis=1 https://doi.org/10.1007/978-0-387-74662
Oh, J.-K., Jang, G. O., & H., L. J. H. J., S., Yi, B.-J., Moon, Y. S., ... Choi, Y. (2009). Bridge inspection robot system with machine vision. Automation in Construction, 18, 929–941. https://doi.org/10.1016/j.autcon.2009.04.003
Pivac, M., & Pivac, M. (2016). Fastbrick robotics. Retrieved from https://www.fbr.com.au/ PLFSS. (2015). Programme de Qualité et d’Efficience “Accidents Du Travail/Maladies Professionnelles”. Retrieved from https://www.securite-sociale.fr/IMG/pdf/rapport-pqe_atmp.pdf
Podkarmin, N., & Peters, L. S. (2015). Construction robotics. Retrieved from https://construction-robotics.com/
Pritschow, G., Dollocker, M., Kurz, J., & Geenslis, M. (1996). Technological aspects in the development of a mobile bricklaying robot. Automation in Construction, 5, 3–13. https://doi.org/10.1016/0926-5805(95)00015-1
Pritschow, G., Dollocker, M., Kurz, J., & Zeijer, J. (1994). A mobile robot for on-site construction of masonry. Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS’94) (Vol. 3, pp. 1701–1707). Piscataway, NJ: IEEE. https://doi.org/10.1109/IROS.1994.40762
Richard, R.-B. (2005). Industrialised building systems: Reproduction before automation and robotics. Automation in Construction, 14, 442–451. https://doi.org/10.1016/j.autcon.2004.09.009
Shukla, A., & Karki, H. (2015). Application of robotics in onshore oil and gas industry—A review part I. Robotics and Autonomous Systems, 75, 490–507.
Spath, D., & Andres, J. (1997). Concept of a robot for interior building trades by the example of wall slits in masonry. Automation in Construction, 6, 205–214. https://doi.org/10.1016/S0926-5805(97)00004-6
Tan, N., Mohan, R. E., & Watanabe, A. (2016). Toward a framework for robot-inclusive environments. Automation in Construction, 69, 68–78. https://doi.org/10.1016/j.autcon.2016.06.001
Vahia, P., Heikkilä, T., Järveläinen, P., Järviöuma, M., & Gamboa, E. (2013). Extending automation of building construction—Survey on potential sensor technologies and robotic applications. Automation in Construction, 36, 168–178.
Vink, P., Miedema, M., Koningsveld, E., & van der Molen, H. (2002). Physical effects of new devices for bricklayers. International Journal of Occupational Safety and Ergonomics, Taylor & Francis, 8, 71–82. https://doi.org/10.1080/10803548.2002.11076515
Warszawski, A., & Novan, R. (1991). Robot for interior-finishing works. Journal of Construction Engineering and Management, American Society of Civil Engineers, 117, 402–422.
Warszawski, A., & Novan, R. (1998). Implementation of robotics in building: Current status and future prospects. Journal of Construction Engineering and Management, American Society of Civil Engineers, 124, 31–41.
