DESIGN, PROTOTYPING AND PROGRAMMING OF A BRICKLAYING ROBOT

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ABSTRACT

This paper presents the development of a Bricklaying Robot capable of building entire walls. This project was motivated by opportunity of automation in construction, which remains costly and inefficient. Several studies have described specialized robot for masonry works, most of them incorporating the human arm concept that requires complex programming and low productivity. In order to improve this model, an innovative concept of a short arm assembled into a lift platform was introduced in this paper. The robot was modeled in Solidworks®, followed by motion study and dynamic analysis to optimize the model. A prototype in 1/4 scale was built to demonstrate its feasibility, detecting and correcting flaws. The prototype was tested by programming servo motors using Arduino UNO hardware and C ++ code. Finally, robot kinematics was analyzed in a construction site scenario. Concordance between the virtual simulation and the experimental prototype results demonstrated the functionality and effectiveness of the proposed design. The invention of this Bricklaying Robot will represent a technological advancement in developing new mechanisms and codes, which may be responsible for increasing productivity and reducing risks of masonry construction. Future analysis of global bricklaying market might be conducted to prove its commercial viability.

Cet article présente le développement d'un robot de maçonnerie capable de construire des murs entiers. Le projet est motivé par une grande possibilité pour l'automatisation dans le bâtiment, un domaine qui reste malsain, coûteux et inefficace. Plusieurs recherches discutent des robots spécialisés pour les travaux de maçonnerie ; la plupart de ces robots utilisent le modèle du bras humain, une conception qui nécessite la programmation complexe et présente une perte de productivité. Cet article a pour but d'améliorer le modèle courant en explorant une nouvelle conception d'un bras court, assemblé comme une plate-forme élévatrice. Ce robot a été conçu en Solidsorks®, et une étude de mouvement et une analyse dynamique ont été menées pour optimiser le modèle. Un prototype à l'échelle 1:4 a été conçu pour démontrer la faisabilité du robot, tout en détectant et corrigeant ses défauts. Le prototype a été évalué par la programmation des servomoteurs, en utilisant du matériel informatique d'Arduino UNO et le langage de programmation C ++. Finalement, la cinématique du robot a été analysée en un scénario de chantier de construction. La fonctionnalité et l'efficacité de la conception proposée ont été démontrées par la concordance entre la simulation virtuelle et les résultats du prototype expérimental. L'invention de ce robot de maçonnerie constituera une avance technologique dans l'étude et le développement de nouveaux mécanismes et des codes informatiques, qui permettront d'améliorer la productivité et réduire les risques de maçonnerie. Une analyse de marché mondial de maçonnerie peut être menée à l'avenir pour vérifier la viabilité commerciale du robot.

INTRODUCTION

Several industries have undergone a complete automation process in the last century, especially in the agriculture, automotive, food, logistics, and machinery industries. However, unlike the previously mentioned industries, the construction industry is going through a very slow process of automation. While the production of industrial robots is increasing up to millions of units, there are only hundreds of robots in masonry works that are produced [1] .

Scientific literature suggests that masonry work is often related to human health and diseases. In 1999, a study assessing the occurrence of musculoskeletal disorders observed that 38% of the bricklayers in the Netherlands reported back complaints[2]. Many external factors to the bricklayer him/herself can have a considerable effect on productivity; Ultimately however, the average bricklaying rate of one human is 140 bricks/hour [3] . In addition to all the disadvantages of manual bricklaying, 1993 studies reported a lack of skilled labor in the German masonry construction industry[4]. Several studies observed a high rate of inefficiency in the masonry industry of different countries. For example, studies reported inefficiencies at approximately 68%, 50%, 40%, 7%, and 2% for firms in Spain[5], Canada[6], Portugal[7], Greece[8], and China[9] respectively.

It was proven that automation increases productivity and reduces the risk of work disorders in highly repetitive and physically strenuous tasks. Robotics have been consolidated with the most important technological advancement in the automation process. In Israel, a mobile robot for building interior walls was developed [10]. Meanwhile, a group of European engineers developed a robot called ROCCO, which used an algorithm to plan, move its arm, and work on complex bricklaying situations[11]. For the past 2 decades, Increasingly advanced electronics sensors are being used in building equipment[12]. Quality control and Tool Center Point (TCP) calibration are achieved by using vision systems, laser beacons and ultrasonic sensors[13]. Automated laying of conventional clay bricks and application of bonding material is investigated in the United Kingdom by means of a stationary gantry type robot[10].

Generally, the bricklaying mechanism involves the concept of the human arm, as discussed in literature [4, 10, 11, 13]. This concept is based on a long arm with a vacuum gripper at the upper end, which is assembled onto a mobile base. Thus, this paper presents an innovative mechanism that moves each brick faster and injects mortar at the same time. Also, this project aimed to design, prototype, and program a new concept of short arm that is assembled onto a lift platform. It was necessary to calculate usual loads in the long arm concept to find out why they have heavier structures, resulting in over consumption of energy, high complexity of positioning programming and low productiveness. The new mechanism was tested, while the results were compared to the long arm concept to confirm its feasibility and whether the design allows for manufacturing of a lighter and more portable structure, which would have higher productivity in masonry works.

MATERIALS AND METHODS

Definition of the Robot's Concept and Tasks

The model was brainstormed based on a lift platform inside four-tubes column. An automatic gripper, which grabs each brick delivered by the flow rack and lays it on the wall after injection of mortar by nozzles, are assembled on the lift platform. A column must be assembled onto a mobile base with wells and tracks.

Design of Structure and Mechanism in CAD Software

The 3D model parts were designed through usual features of extrusion, revolve extrusion, and cut of Solidworks®. Tubes and steel sheet dimensions were based on standard commercial brochures. Steel ASTM A36 and AISI 1020 were defined as material for most of the components from Solidworks Materials Library. Then, an assembly document was created joining all parts through regular and mechanical mates. Finally, a technical drawing was generated from the assembly document with all dimensions and list of material necessaries to build the robot.

Kinematic Analysis

Structure was tested in Solidworks® to verify its behaviour during bricklaying process. Movements analysis were conducted using the tool Motion Study to verify if the short arm was the correct length and movement range while it grabbed each brick and moved it on the wall. Also, to set up the velocity of base movement, it was necessary to adjust the angular velocity of the arm. A 10-second video was recorded from the software Motion Study for analysis.

Prototyping of 1/4 scale robot

A prototype in 1/4 scale of the original concept dimensions was manufactured using aluminum beams, steel sheets, plastic components, three DC motors of 12V, and one servo motor of 5V.

Programming of movements of prototype

The movements of each motor were programmed using Arduino UNO® board and C++ code. Programming is based on state machine concept to control base and gripper movements at the same time.

Experimental tests and mechanism analysis

Tests were conducted with 1/4 scale bricks to measure velocity and acceleration of prototype. The movements of the robot were recorded in videos and analyzed in 2X slow motion using basic video software such as Movie Maker®. The results were compared to those from robots in observed literature.

RESULTS

The Design of a Final Structure and Mechanism

The 3D modeling of the Bricklaying Robot resulted in a model consisting of a four-tubed column that can be extended from 1.60 m to 3.00 m. Lateral dimensions were reduced to 500 mm x 500 mm, allowing the robot to pass through doors. The total weight of the structure was around 70 kg to ensure that the structure can be carried by a single worker (Figure 2).

Gripper Mechanism Was Conceptualized and Evaluated

The top end of the arm has an automatic gripper which was designed and analyzed in terms of forces and resistance during the process of picking up and moving each brick. The final mechanism design did not have any electronic sensor or actuator (Figure 3). Equation 1 represents the minimum force applied by each side of the gripper (GF) to hold one brick:

$$GF \geq \frac{\frac{W}{2}}{\mu} \ , \quad GF \geq \frac{\frac{2.7[kg]\, x\; 9.81\, [\frac{m}{s^2}]}{2}}{0.6} \ , \quad GF \geq 22.7 \qquad (1)$$

Where, an average red clay brick (4” x 8” x 2 1/4”) weighs 2.7 Kg and the friction coefficient (μ) between a rubber and brick surface (adopting concrete) is approximately equal to 0.6. Therefore, the GF must be ≥ 22.07 N to assure that LF=W/2. With this result (∑Fy=0) it was observed that the gripper mechanism was capable of holding one brick safely during movement.

The Prototype Was Built According to the 3D Model

The prototype in 1/4 scale from original dimensions was built using a technical drawing from Solidworks® (Figure 5). The materials that constituted the majority of the prototype included aluminium tubes, bolts, beams, steel sheets, and plastic components. It was not necessary to weld any structure. All parts were assembled using fasteners. Two gear motors and 1 servo motor were responsible for the movements. One Arduino UNO board and 4 batteries of 9V each were responsible for controlling the motors.

The Results of Kinematic Analysis

Operation of the prototype combined different movements sequenced for moving and positioning

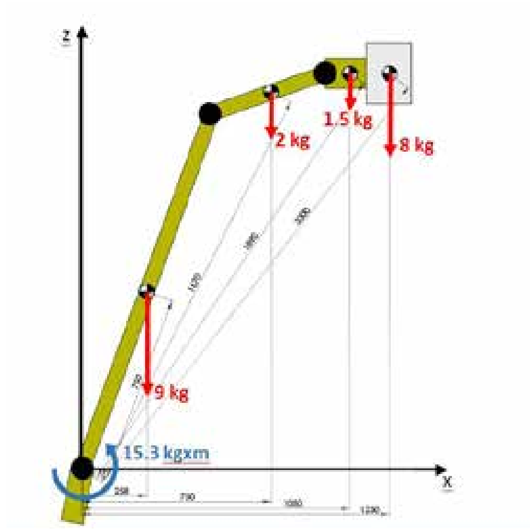

Figure 1:

Usual concept of robot for masonry works which design is based on human arm. *Average weight of a brick and estimated weight of manipulator components were used in the calculus of momentum on the base articulation.*

Figure 2:

Proposed design for innovative Bricklaying Robot is more compact. *3D model was generated in Solidworks through part modeling and assembly. It was simulated using Motion Study tool and optimized until this final design, which is more portable, lighter, cheaper, quicker, and more efficient than long arm bricklayer concept.*

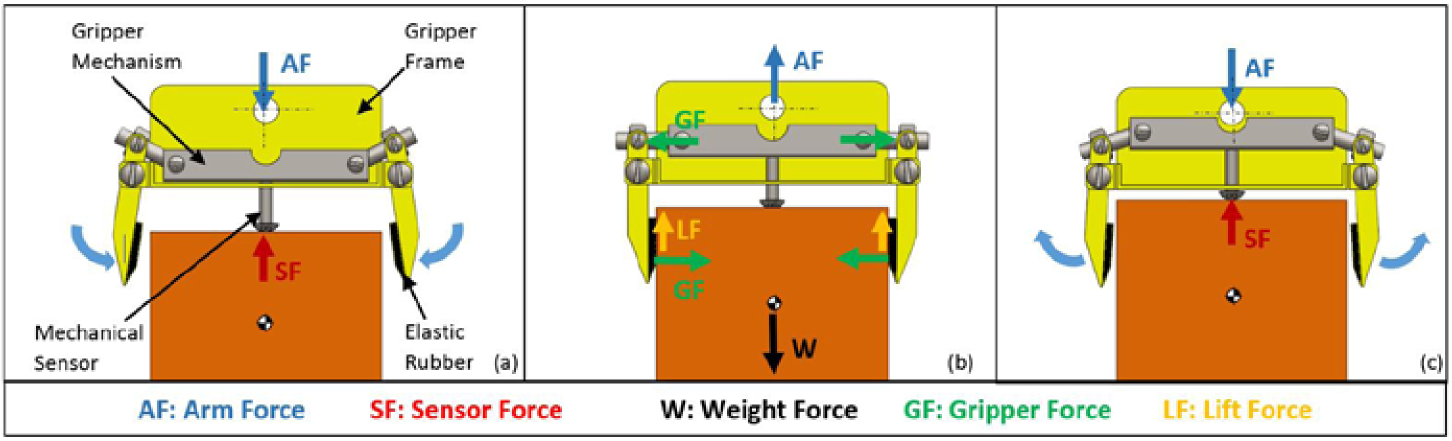

Figure 3:

Automatic gripper mechanism is able to grab and hold a brick. *(a) Gripper approaches over the brick; mechanical sensor starts touching its upper face with sensor force (SF) and closes the holders. (b) Free body diagram where LF is the frictional force due gripper force (GF) and roughness between contact surfaces (μ), W=2xLF. (c) Releasing movement occurs after higher contact force on mechanic sensor during pressing the brick on the wall.*

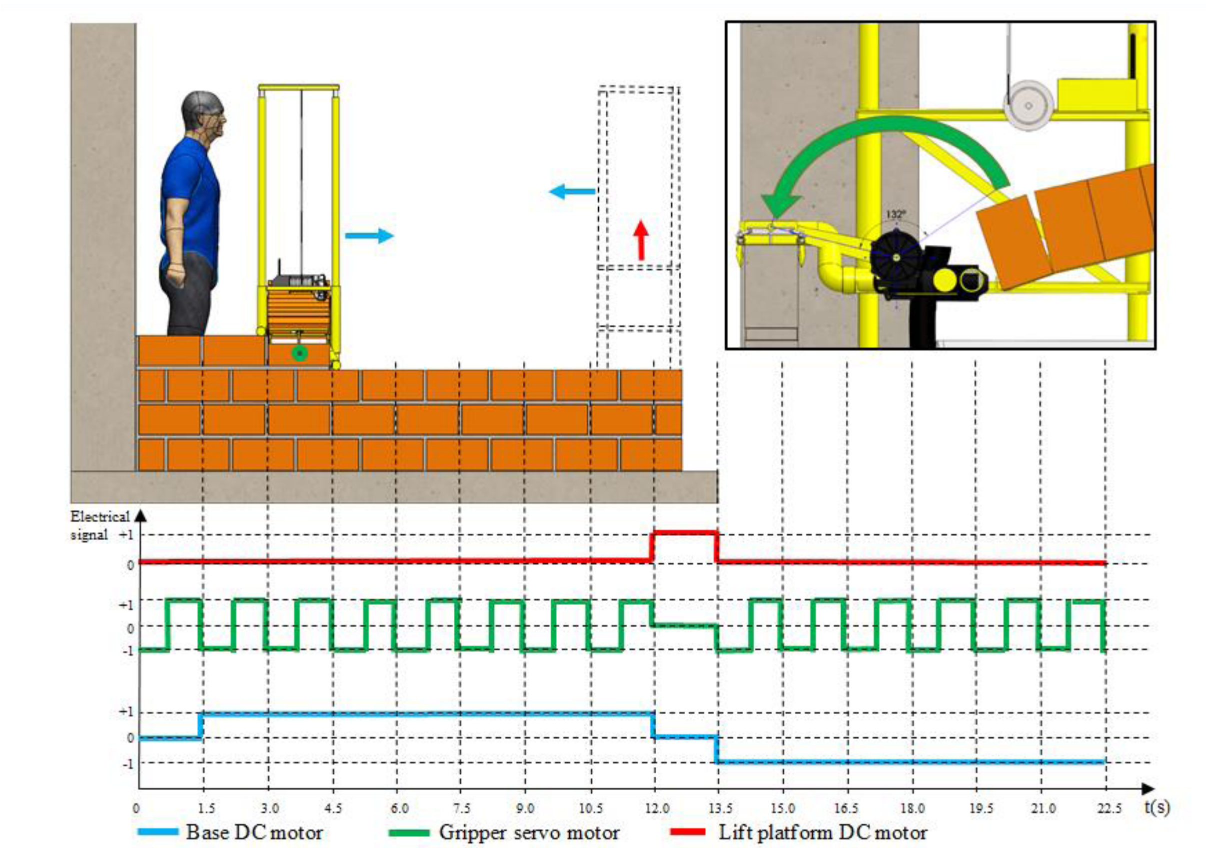

Figure 4:

Graph describing the programming of robot's movements. *The three motors are programmed together using only one control hardware and one code based on State Machine principle. The movements were synchronized according the time as the graph presents. While base DC motor moves constantly forward, gripper servo motor moves in an oscillatory way.*

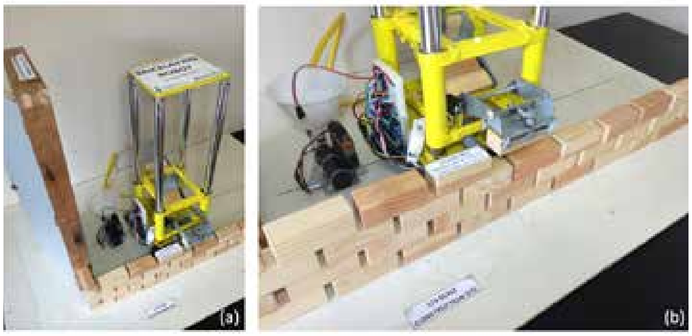

Figure 5:

***1/4 scale prototype working on construction site scenario. (a)** Prototype was built according technical drawing dimensions divided by 4. Structure is made from aluminum. (b) Lift platform, gripper mechanism, Arduino UNO board and mortar pump are presented.*

Figure 6:

***Frames sequence of one brick lying during 1.5 seconds.** The first image shows the arm approaching on the upper face of the brick. The second frame presents the gripper applying force and holding the brick. The brick moving is shown by the third frame and the fourth frame is the final movement of the gripper, when it releases the brick on its final position on the wall.*

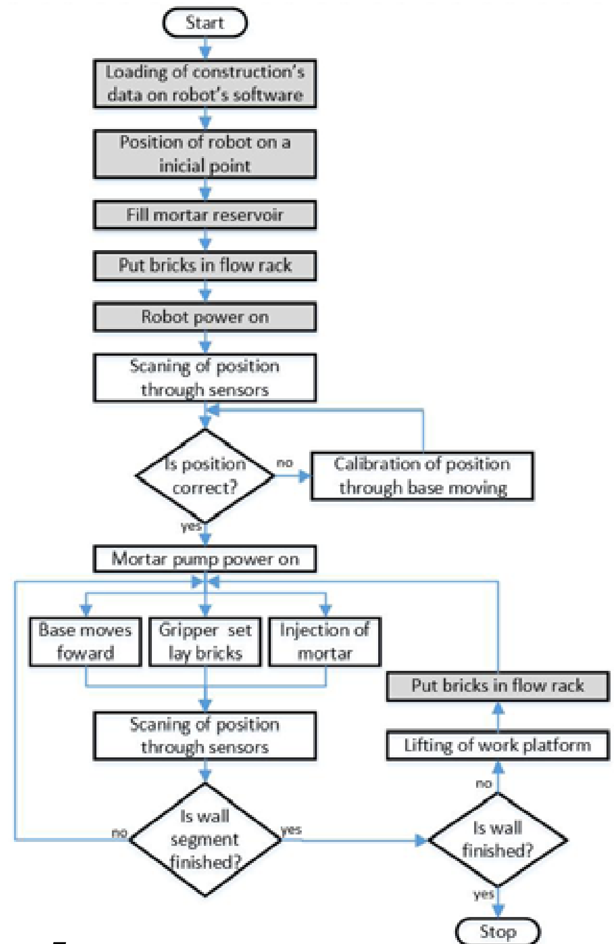

Figure 7:

***Flowchart describing the sequence of operation of the robot.** Bricklaying Robot must be the most automatized as possible. Steps in gray are represented by human actions and in white by robot action. Hard and repetitive tasks are clearly done by robot.*

each brick. While the base moved straight forward, the bricks slid down and were picked up by the gripper. Mortar was injected by nozzles onto bricks in the wall and the gripper lay each brick over the mortar layer. After each tier was completed, the base stopped moving forward, while mortar pump paused during 1.5 seconds, and the platform was raised to the equivalent height of 1 brick (2 1/4"). Then, the robot started moving backward, continuing the bricklaying function. The previewed frequency of the machine was 1 brick per 1.5 seconds. Figure 4 describes the sequence movements of each motor of time (seconds) versus electrical signal, except the mortar pump; this graph also guided the process of the robot's programming.

Test Outcomes from Experimental Prototype

Figure 6 displays the frames of the recorded video during tests with the Bricklaying Robot prototype. The average frequency of work measured in the first test was approximately 1 brick per 1.51 seconds. The information below was measured from prototype tests after timing calibration.

- Arm displacement: Backward = 59.10°; Forward = 69.39°; Total = 128.49° = 2.24 rad
  Arm timing: Backward = 820 ms; Forward = 810 ms;

Total= 1630 ms = 1.63 s
Arm speed = 78.82°/s = 1.3742 rad/s

- Base speed = 41.3 mm/s = 0.0413 m/s
Each cycle is being completed within 67.31 mm (41.3 mm x 1.63 s = 67.31 mm). Considering that each prototype brick is 67.00 mm long, the linear space for completing one cycle is sufficient according these measurements.
- Elevator displacement: 20 mm
Elevator delay: 1.52 s
Elevator speed: 13.2 mm/s = 0.0132 m/s

The prototype confirmed that the gripper mechanism worked the same way it was designed; that applied force was enough to hold and move a brick. Dynamic analysis on the computer resulted in well dimensioned components that can work under the required loads and speeds. Programming of prototype movements resulted in a refined C++ code that was based on State Machine. Tests demonstrated that it is possible to have a high level of automation of the bricklaying process with low human interference. However, data loading, initial positioning of the robot, and refilling of materials are the only tasks required by humans (Figure 7).

DISCUSSION

A bricklaying Robot must be light, mobile, easy to operate, compact, precise, quick, and commercially viable. Based on the robots presented by literature, it is possible to conclude that they have many physical features to improve upon in order to achieve the previously mentioned qualities. Although they are mobile and accurate, they require a more robust structure, which makes them heavy and large. The concept based on a long arm produces a considerable distance between the main load (brick) and base articulation, causing high moment load (Figure 1). It is possible to state that the overload on articulations due high momentum causes high angular inertia values, which obligates designers to reinforce the arm structure and limited the speed of operation. Due to the extra weight of arm structure, in most of cases, they are equipped with hydraulic or pneumatic actuators that are characteristically slow (Figure 1). Another disadvantage to these systems is that they require the pump and valve installation of pumps that take up space and add additional weight to the robot. In the case of electronic servo motors installation, the amount in degrees of freedom in a multi articulated arm results in complexity of programming. In addition, they are very expensive and commercially unviable for small and medium-sized constructors.

The results from 3D modeling presented an innovative and simple design which solves many of the difficulties of masonry construction that preclude the use of robots, such as mortar injection on the wall during bricklaying, size reduction, simplification of movements, and operating facilitation. Kinematics analysis proved that expected movements are possible to be executed by the mechanism. Speeds were defined and tested to achieve the maximum productivity without quality loss. A prototype was built and programmed in a relatively easy way, proving that the concept is viable. The first design of mortar pumping system did not work as expected because its pressure loss due gaps between screw and tube wall. The pump system does not work for high viscosity fluids such as mortar or concrete, and because of that, it was redesigned. The second concept of pump is based on a peristaltic pump with a flexible hose made from latex that generates the pressure required for mortar pump. The experimental tests with the prototype observed the automatic gripper mechanism working at a rate of 1 brick per 1.5 seconds, or up to 2400 bricks per hour upon assuming a non-stop operation. When comparing prototype production rate to the average bricklaying rate of one human (140 bricks/hour), this projects suggests that the robot is time efficient, low energy consuming and cost for construction.

The Bricklaying Robot is presented as a real competitive equipment compared to the existing robots available in the markets. Due to design improvements, it was proved that the shorter arm can lay bricks with the same precision of the long arm concept, with the advantage of being quicker and capable of injecting the mortar at the same time. Concordance between virtual simulation and the experimental prototype proved the feasibility of the innovative automatic gripper. The structure is easier to build and the programming of its movements are less complex compared to the usual concept. With all these design improvements, it is possible to increase considerably the productivity, the efficiency, and reduce cost, accident risks and waste of masonry construction, turning it more sustainable.

FUTURE DIRECTIONS

The innovative mechanism was tested and worked as designed, except the mortar pumping system. The next directions for the Bricklaying Robot will be defining the correct design for mortar pumping system based on peristaltic pump; this concept will be developed and tested. The loads on articulations and structures need to be evaluated to determine the correct shape, materials, bolts, bearings and manufacturing processes. To proceed with this evaluation, the Working Model 2D software will be used. The installation of sensors for closed-loop system is very important for positioning scanning of the prototype and quality improvement of the bricklaying process. After assuring that prototype is working and injecting mortar as it is supposed to do, all components will be listed and budgeted to know the final cost for manufacturing an original scale prototype; this is essential because it determines the commercialization feasibility.

ABBREVIATIONS

μ	Friction Coefficient
2D	Two Dimensions
3D	Three Dimensions
AF	Arm Force
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
DC	Direct Current
GF	Gripper Force
h	Hours
Kg	Kilograms
LF	Lift Force
m	Meters
N	Newton
ROCCO	Robot Assembly System for Computer Integrated Construction
s	Seconds
SF	Sensor Force
TCP	Tool Center Point
V	Volts
vs.	Versus
W	Weight Force

KEY WORDS

Bricklaying Robot; Masonry Construction; Automation; Mechanical Design; Prototyping

ACKNOWLEDGEMENTS

This work is supported by the Brazilian Government with funds of Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq). Programming of Arduino UNO board used in prototype was conducted by Isaías Junior, Electrical Engineering student. This project was assisted by Professor Kamran Behdinan and master student Yasaman Saeedi at Department of Mechanical & Industrial Engineering of University of Toronto.

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