Modelling of industrial robotic brick system

Ing. Vyacheslav Usmanov
Department of Construction Technology (K122), Faculty of Civil Engineering in Prague Thákurova 7/2077, 166 29 Prague 6 - Dejvice, Czech Republic

vyacheslav.usmanov@fsv.cvut.cz

Ing. Michal Bruzl
Department of Construction Technology (K122), Faculty of Civil Engineering in Prague Thákurova 7/2077, 166 29 Prague 6 - Dejvice, Czech Republic

michal.bruzl@fsv.cvut.cz

doc. Ing. Pavel Svoboda, CSc.
Department of Construction Technology (K122), Faculty of Civil Engineering in Prague Thákurova 7/2077, 166 29 Prague 6 - Dejvice, Czech Republic

pavel.svoboda@fsv.cvut.cz

Ing. Rostislav Šulc, Ph.D.
Department of Construction Technology (K122), Faculty of Civil Engineering in Prague Thákurova 7/2077, 166 29 Prague 6 - Dejvice, Czech Republic

rostislav.sulc@fsv.cvut.cz

Abstract – The paper will describe a design of functional model of a bricklaying industrial robot that is able to technically implement the complete process of bricklaying. The system will be created at a reduced scale and will be able to brick object. The robotic system for bricklaying will use special developed software which will convert the necessary data of mathematical model from BIM environment to format KUKA for industrial robots KRC4 and make optimal design of movements of the robotic arm. As a result will be developed: a functional model of the robotic bricklaying system including technology (de-palletizing, motion control, cutting and gluing bricks on the bond); Software for data migration (IFC -> KRC4), technical equipment (grip, applying mortar / glue, cutting bricks, control systems); control system including optimization processes (energy, time, material consumption).

Keywords –
Robotic; brick; system; BIM; IFC; robot; KUKA

1 Introduction

Industrial revolution 4.0 predicts that in 10 years the factories will be run by themselves and the productivity will increase by one third. Currently construction industry drops behind in using of robotic systems compared to other industrial branches, because of the difficulty of implementing various and dynamic work activities into robotic systems. Manual and mechanical work is usually being used in construction industry. Because of large number of injuries suffered and high extent of burden relocation by human strength during constructions, implementing of robotic bricklaying system is very topical. An attempt of implementing robotic systems into construction industry is very pressing, because of total absence of these systems in construction industry.

Currently there is no mobile industrial bricklaying robotic system available on the market. Up until now he have known mainly stationary robots used in industry for specific actions. There are robotic construction systems on moving machine basis, which can brick up liner objects (fence, wall). Due to large extents and weight they need a large workspace and because of that they are not universally usable for building spatial objects.

Focusing on development of industrial robotic systems means to put an end to unnecessary delays, ineffective use of material and energy, unnecessary health risks caused by hard working conditions. The aim of this research was to lower these problems to minimum or eliminate them completely by implementing robotic systems to construction raw and finishing processes. A functional model of bricklaying robot with mathematical modeling of optimal trajectory was the main and original part of the research. Some of the aforementioned parts (optimization procedures, video logs) were transferred into an internet application.

Created robotic bricklaying system with the help of uniquely developed software can convert needed data of mathematical model from BIM into format of industrial robots KUKA KRC4 and perform optimal suggestion of movements of the robotic arm. We also researched other factors influencing construction process:

- optimization of material consumption.
- optimization of costs and energy.
- efficient time management and optimal movement trajectory of robotic units.

2 Mathematical model and system concept

The Listed problems are partially removed by industrial bricklaying robotic system, which is the subject of the research. It is a system consisting of three main elements: robotic end device (grip, glue nozzle and brick cutting system), robotic arm and computer operating system (see Figure 1). All parts of the system are connected through data collector, which allows input and output information flow with following analysis. Robotic bricklaying model has the ability of adaptive and interactive system and it can react to changing environment and human factor. Bricklaying robot can be used for automatic walling of vertical constructions (supporting and non-bearing) based on model BIM. Because of high investment costs, the robotic system was created in lowered scale as a functional model.

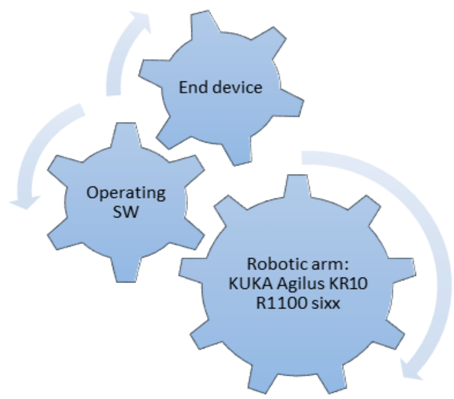


Figure 1 - Schematics of robotic bricklaying system

We will formulate basic steps of development of robotic bricklaying system (see Figure 2):

1. Choice of concepts and materials for modeling of bricklaying robot.
2. Specification of technological and economic aspects and demands during the process.
3. Development of SW for migration of data from BIM to KUKA KRC4.
4. Computer simulation of robotic system.
5. Design and manufacture of robotic end device (grip, mortar/glue fetching).
6. Design and manufacture of brick cutting device.
7. Design and programming of optimal procedures and robot movements.
8. Verification on functional model, quality control.
9. Elaboration of research report with user manual, internet application a video logs.

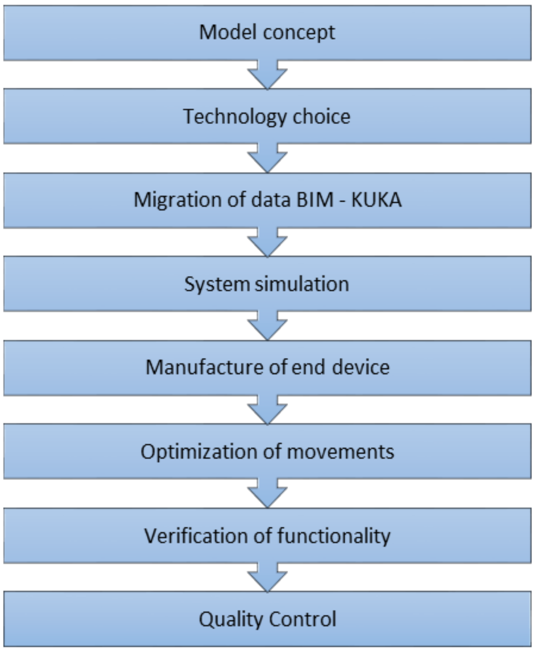


Figure 2 - Flow diagram of system development

Mathematical model and simulation were conducted in a special simulation SW Matlab Simulink [8] and subsequently verified by a simple example. Mathematical model is made from 4 parts: inputs, mathematical core, outputs and external influences [3], [4] (Figure 3). The system takes inputs from BIM, where construction objects are conclusively described (technical parameters, drawing documentation) and construction elements (size and weight of objects for walling). Subsequently developed converter (see further description) converts data from BIM into industrial robot KUKA KRL [9] and optimization SW performs a suggestion of efficient movements of robotic arm. Also, critical points and technical restrictions will be evaluated including possible collisions. The output of the system will be a list of optimized robotic movements according to following aspects: speed of object construction, energy consumption and environmental impact, quality of work [5].

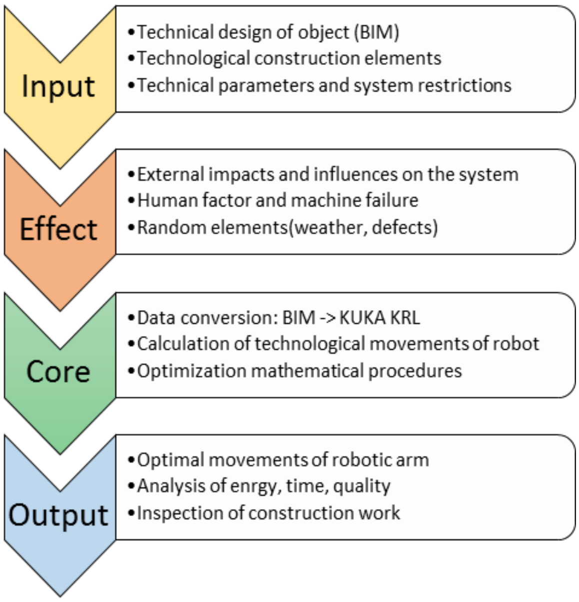


Figure 3 - Mathematical model of robotic bricklaying system

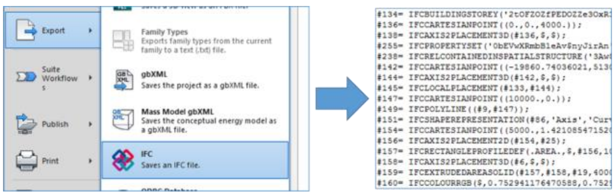
3 Converter BIM (IFC) -> KUKA (KRC4)

Building Information Modeling *(BIM)* is a modern intelligent process for creation and management of projects based on model [10]. It eases the transfer of information in process of designing of the project, construction and usage of building. It allows the creation and managing of projects of ground and engineering infrastructure buildings - faster, more economically and with lesser environment impact.

It was decided to use technical drawings from IBM as a pattern for input system, which definitively determine the need for functioning of the information system. Following chart (see Table 1) describes the concept of developed converter in 6 steps. For between-step format standard IFC was used.

Step 1: Model creation (BIM)

Step 2: Model export to IFC format



Step 3: Parsing IFC file

```
#257= IFCRELDEFINESBYPROPERTIES('1aSfmB5efCDA_Q
#222= IFCCARTESIANPOINT((19860.74036021,-4980.8
#132= IFCAXIS2PLACEMENT3D(#6,$,$);
#133= IFCLOCALPLACEMENT(#32,#132);
#134= IFCBUILDINGSTOREY('2tOFZOZfPEDOZZe3OxR3jb
#136= IFCCARTESIANPOINT((0.,0.,4000.));
#138= IFCAXIS2PLACEMENT3D(#136,$,$);
#255= IFCPROPERTYSET('0bEVwXRmbBleAv$nyJirAn',#
#238= IFCRELCONTAINEDINSPATIALSTRUCTURE('3Aw$FV
#142= IFCCARTESIANPOINT((-19860.74036021,5130.8
#144= IFCAXIS2PLACEMENT3D(#142,$,$);
#145= IFCLOCALPLACEMENT(#133,#144);
#147= IFCCARTESIANPOINT((10000.,0.));
#149= IFCPOLYLINE((#9,#147));
#151= IFCSHAPEREPRESENTATION(#86,'Axis','Curve2
#154= IFCCARTESIANPOINT((5000.,1.42108547152020
```

- coordinate system (clockwise Cartesian coordinate system) ($WORD)
- matrix of coordinate points [X, Y, Z] ($BASE)

Step 4: Processing of points

- robot placement ($ROBROOT);
- verification of robot reach ($TOOL -> $BASE);
- setting of priority points (movement direction) ($BASE);
- task assignment.

Step 5: Files creation .DAT/.SRC (KUKA KRL)

$ROBROOT, $TOOL, $BASE

.DAT

```
;ENDFOLD (USER EXT)
;ENDFOLD (EXTERNAL DECLARATIONS)
DECL BASIS_SUGG_T LAST_BASIS={POINT1[] "p5                    ",
"PDAT1                    ",CONT[] "                    ",CP_VE
",SPL_NAME[] "S0                    ",A_PARAMS[] "ADAT0
DECL E6POS XP1={X 146.914566,Y 135.745819,Z -12.2283487,A 83.62067
DECL FDAT FP1={TOOL_NO 3,BASE_NO 3,IPO_FRAME #BASE,POINT2[] " ",TQ
DECL PDAT PPDAT1={VEL 100.000,ACC 100.000,APO_DIST 100.000,APO_MOD
DECL E6POS XP2={X 58.7224655,Y 23.5809097,Z -12.4140739,A 82.92398
DECL FDAT FP2={TOOL_NO 3,BASE_NO 3,IPO_FRAME #BASE,POINT2[] " ",TQ
DECL LDAT LCPDAT1={VEL 2.00000,ACC 100.000,APO_DIST 100.000,APO_FA
50.0000,EXAX_IGN 0}
DECL E6POS XP3={X 23.6995068,Y 81.2394409,Z -11.8915625,A 82.92398
DECL FDAT FP3={TOOL_NO 3,BASE_NO 3,IPO_FRAME #BASE,POINT2[] " ",TQ
DECL LDAT LCPDAT2={VEL 2.00000,ACC 100.000,APO_DIST 100.000,APO_FA
50.0000,EXAX_IGN 0}
DECL LDAT LCPDAT3={VEL 2.00000,ACC 100.000,APO_DIST 100.000,APO_FA
```

movements, tasks

.SRC

```
;FOLD PTP HOME  Vel= 100 % DEFAULT;%{PE}%MKUKATPBASIS,%CMOVE,%VPTP,%
$BWDSTART = FALSE
PDAT_ACT=PDEFAULT
FDAT_ACT=FHOME
BAS (#PTP_PARAMS,100 )
$H_POS=XHOME
PTP  XHOME
;ENDFOLD
;FOLD LIN P1 Vel=2 m/s CPDAT4 Tool[3]:fix1 Base[3]:hne_lev;%{PE}%R 8
$BWDSTART=FALSE
LDAT_ACT=LCPDAT4
FDAT_ACT=FP1
BAS(#CP_PARAMS,2)
LIN XP1
;ENDFOLD
;FOLD LIN P2 Vel=2 m/s CPDAT1 Tool[3]:fix1 Base[3]:hne_lev;%{PE}%R 8
```

Step 6: Import of files .DAT/.SRC to robot KUKA

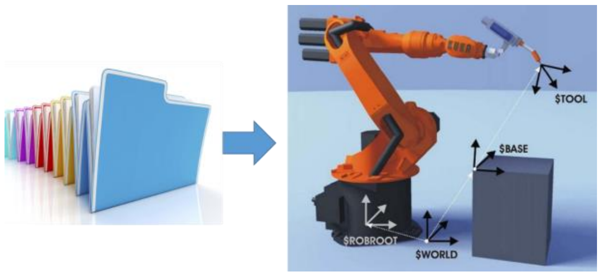


Table 1 - Concept of converter BIM -> KRL

IFC (The Industry Foundation Classes) is an open neutral file format supporting sharing of data on BIM principle, which allows communication between individual participants of construction process and their software BIM tools. Specification IFC is registered as an international standard ISO 16739:2013. Current formats are IFC 2x2, IFC 2x3 (2006), IFC 4 (2013) [10].

Industrial robot system KUKA uses its own programming language KRL, which is derived from group of basic languages C++. Because the programming language KRL [9] has limited options, the system core of the converter was designed in language C++, which transfers format IFC into format KUKA KRL, which is comprehensible for the robot. We are interested in the level of support bearing construction elements (drawing documentation, critical coordinates and intersections of surfaces) and technical parameters of construction elements (size, weight, strength characteristics). BIM system saves needed information and data into IFC format. Then the converter takes and processes the data and saves it into .SRC and .DAT files accessible also for the robot [9]. Industrial robot, which will be in external automated mode or awaiting input parameters, will begin to conduct the technological process. We presuppose that the sequence of movements of technological process will be optimized according to pre-determined optimization parameters.

4 Optimization of robotic movements and trajectory

Very important part of the system is the optimal design of movement for obtaining needed technological process. Optimization is made through converting outputs of BIM system (technical drawings and description of construction elements) based on the following parameters:

- speed of object construction.
- energy consumption.
- environmental impact.
- quality of work.
- malfunctions quantity and influence of random factors.

Technological process must be strictly respected with the lowest possible deviation from required quality and technical instruction of construction work. Optimizing parameters may be evaluated also based on a multiple-criteria decision.

With the help of simulation in program Matlab Simulink [8] and based on outputs of optimizing SW we will receive several possible solutions, which will fulfill given task. Not all of the permissible solutions will lead to optimal and efficient solution. We have to assign optimization criteria in advance and find the most efficient solution. All permissible solutions may create in graphic form an optimal curve, where global, respectively local extremes will be the sought solution of the problem.

There are many fast converging optimization methods [7]. After evaluating several methods it was decided to use the theory of convex polyhedron for a group of optimal points of linear optimization task. Each evaluating parameter can be assigned importance by using coefficients from 0 to 1. The sum of all optimization coefficients equals exactly „1“. If we have a group of permissible points, we can draw a polyhedron in space, where the sides or apexes will create the optimal solution. In mathematical expression the maximum value of parameter will definitively determine the result of the problem. If we include several evaluating parameters into the task, this method allows the search for a complex solution of the problem:

$$\max F(x) = \sum_{i=1}^{k} p_i \, x_i, \text{ [-]}$$

where p – weight coefficient, [-];
k – number of evaluating system parameters, [-].

In the next chapters of the article a detailed description of aims, methods and results of the research work will be provided. Also, the way of realization of modeling and simulation of technological construction processes of bricklaying will be explained.

5 Technical and technological aspects of the bricklaying process

5.1 Bricklaying done by a man

During the bricklaying the first layer of bricks is put on a perfectly horizontal and coherent layer of base mortar of minimal depth of 10 mm. The first important step is height location of baseplate (ceiling) in places where the walls are going to be. The correct location is made after the melting of isolation strips to the underlay in the place of the wall. During the leveling, the highest point is set and from this it is determined how to lay the first layer of bricks. After the setting of height the mortar bed is applied and straightened, where it is needed to pay attention to the correct consistence of the base mortar. After the application the mortar is straightened by aluminum lath.

The first layer of bricks is set directly into the mortar bed. The exact straightening of bricks will be achieved by percussion of masonry hammer or rubber hammer. The level will be checked by water-level and masonry cord which holds the level. This way we will brick up the whole wall. If a brick does not fit exactly, we can break it on demand by percussion of masonry hammer.

Approximately 1 centimeter wide gap is left between the bricks. These vertical connective gaps are filled by mortar. The surplus mortar from connective and storing gaps is let to flow downwards on the wall and is removed by a trowel. To achieve the correct adhesiveness of mortar to bricks we will also wet the upper part of bricked wall. We will apply mortar on the damp surface to create horizontal storing gap and the bricks are placed into it from the corners using the masonry cord. If we are adding a new partition to the current supporting structure, it will be tied by chiseled pockets, or by putting a reinforcing iron into the gap in the new wall and by drilling it to the main wall.

5.2 Bricklaying done by a robot

5.2.1 De-palletization

Automated de-palletization can be made with robotic arm or with portal robots. It is the opposite of palletization process, where the products are removed from palette and placed in their spot (in our case a robotic arm for walling is used). The information was obtained with the help of video files and photo documentation from actual de-palletization performed by a man on a construction site, which led to creating the trajectory for unloading the material. It was necessary to create a trajectory for precise removal of the walling elements from the palette to avoid collision with neighboring material on the palette. An electromagnet was used as the gripper in our model (see Figure 4), which is in on-off mode depending on the movement and action it is currently doing. Moreover, all the bricks were adjusted by creating a groove on the surface and inserting of a small metal plate. The development of the gripper for real brick blocks will be a part of the future research.

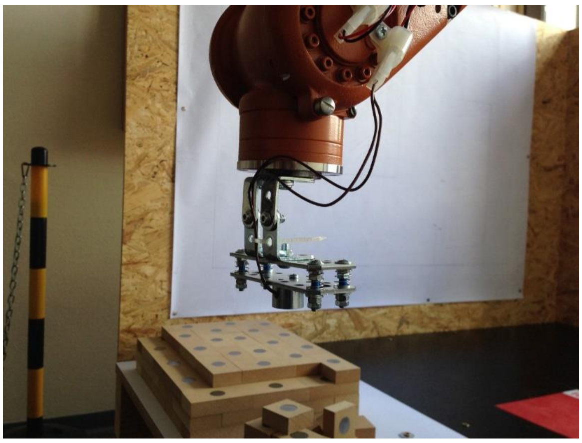


Figure 4 – Gripper of the walling robot (electromagnet)

In our model, two kinds of palettes were used. The first type simulates whole walling elements (100mm x 50mm) and they are placed on the palette in the way they are distributed by the manufacturer. On second palette there are halves of walling elements (50mm x 50mm), which are used for beginnings or ending of the wall, to ensure proper bonding of bricks (see Figure 5).

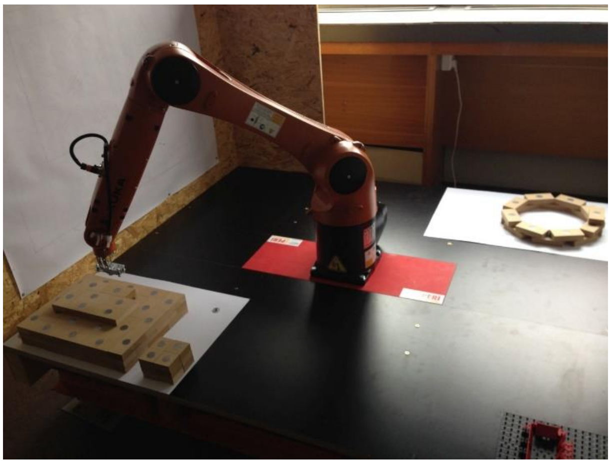


Figure 5 – De-palletizing by the robot (two pallet types – on the left)

Each walling element must be calibrated after the extraction from the palette. This is made via calibration model, into which the brick is put after de-palletization, straightened and again gripped to be put into the wall. The main reason is to eliminate inaccuracies and small deviations that are created by incorrect holding of the brick by the gripper. These inaccuracies would have a negative impact on the flatness of the wall.

5.2.2 Robotic bricklaying

After the removal and calibration of the walling element from the palette, it is allocated to the exact spot where it should be by the instructions of the 3D. Robot abides by the same principles as a man, it starts bricklaying from the corner of the wall, it chooses half a brick for correct linking, it does not put bricks where there should be an open space.

The walling elements must be suitably arranged. They have to be tied up in layers of the wall or a pillar, so that they act as a one monolithic supporting element. To ensure proper binding of the wall, bricks in height not over 25 mm should be bound to length equal to higher of value 0, 4 times height of walling element or 4 mm and bricks higher than 25 mm to length equal to higher of value 0,2 times height of walling element or 10 mm. In corners or places of wall connections, the length of binding of walling element should not be lower than its width. If the walls cross, one is let to go through and the second will be bricked up. In the next layer it is vice versa, second is let to go through and the first is bricked up (see Figure 6).

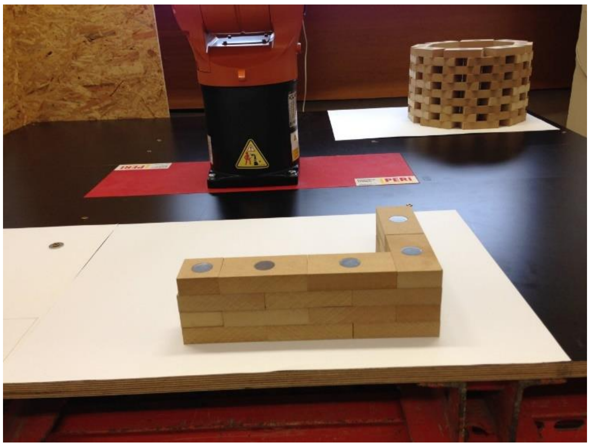


Figure 6 – Intertwined masonry in the corner of the wall

Advantages:

- Time saving.
- Faster construction (only necessary technological breaks).
- Higher quality (geometric precision, complexity, accuracy, flatness)
- Lower construction costs.
- Protection of human health in risky locations.
- Allocating of large and heavy elements.

Disadvantages:

- Manipulation space.
- Ability to adjust.
- Purchase price.

6 Analysis of energy and time consumption

Based on the example case, which contains a cut of construction work (part of wall construction in corner and a round chimney), an analysis of time and energy consumption was created. Also we analyzed the strain of six motors/transmissions of the robot.

The comparison was made for two states:

- without smoothing and without optimization of movements.
- with smoothing and optimization protocol in place.

Environment of WorkVisual offers a graphic comparison of different states in the form of graph (see Figure 7) and it can compare time and energy consumption or the strain of the robot.

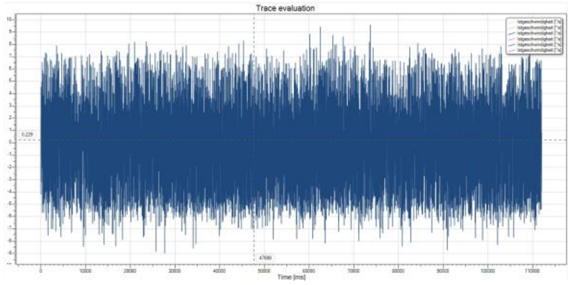


Figure 7 – Observation and analysis of robot movements in environment Oscilloscope in WorkVisual

Subsequently a calculation and a comparison of states were made. As it is obvious from Table 2 and Figure 8, the developed optimization algorithm enabled a more efficient robot deployment on construction site.

Parameter	Before	After
I. Time [s]	1250	1130
II. Consumption energy [Wh]	945	869
III. Max angular velocity [′/s]	1050	941
IV. Average angular velocity [′/s]	380	354

Table 2 – Comparison of states before and after optimization

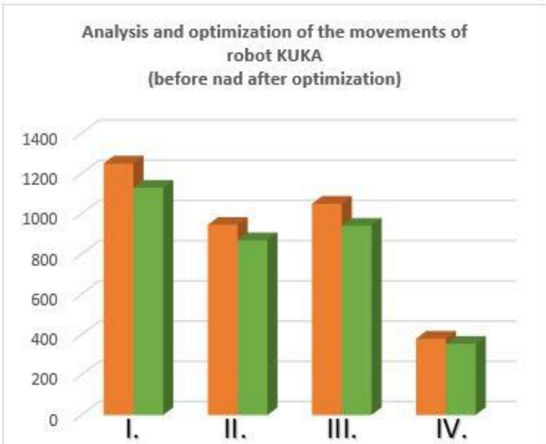


Figure 8 – Comparison of states before and after optimization

Using of optimization algorithm showed efficiency 7-9%, which has a very positive effect for deployment of robots on construction sites. Wear and tear of robot transmissions will be lowered, time of task completion will be lowered.

7 Conclusion

Development of walling robot should mostly contribute to implementing of robotization and automatization to construction industry, which is completely different from industrial production due to constantly changing work space. Robot can work nearly without a break, it is only forced to follow technological breaks. Human can only place 300 – 500 bricks a day, robot can place 800 – 1200 bricks a day, which increases the productivity. The primary aim is not to entirely replace a human mason by a robot, but to increase the productivity of bricklaying in combination human – robot. Robot eases the work by lifting heavy burdens, frequency of repeating individual processes, higher quality etc., but it still cannot react and evaluate crisis situations on construction site the same way a human can.

In the next phase of development of the bricklaying robot we want to focus on a bonding material, in which it seems to be more economic to use foam instead of mortar. For this to work it will be necessary to develop or upgrade the gripper in a way that it is compatible with the walling gripper.

Furthermore, we want to examine wall cutting. When a non-standard situation on the walling occurs, robot can locate, cut and place the brick into the free space. This will be made by a modified circular saw, which will be a part of the robot.

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