

INNOVATIVE SOLUTION OF MOBILE ROBOTIC UNIT FOR BRICKLAYING AUTOMATION

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Abstract – This study presents an innovative solution for a mobile robotic unit intended for the construction industry, the task of which is to automate time-consuming and burdensome masonry work performed manually using bricklayers. A ZSM mobile robotic bricklaying system (ZSM in Polish Zrobotyzowany System Murarski) was designed and developed in a demonstration version. The mobile ZSM consists of an ABB six degrees-of-freedom (6 DoF) industrial robot with a replaceable hydraulic gripper, a Hinowa tracked undercarriage with a hydraulic unit, hydraulic lifting and leveling module, a brick warehouse, a brick belt feeder, a mortar applicator, a control cabinet, and a control panel. Simulation tests were performed in a virtual ABB RobotStudio environment to verify the functioning of the robot and individual ZSM modules during the bricklaying process. ZSM control is based on the Siemens Simatic S7-1500 programmable controller in the fail-safe version, which supervises the correct operation of all devices. ZSM was tested under laboratory conditions and on the construction site. The robotic technological process of building a wall consists of the following stages: the robot grips the bricks, picks them up, manipulates them, applies mortar to them, and places them on the wall.

Key words – mobile robot, tracked undercarriage, bricklaying automation, operator interface

JEL Classification – O140, O320

INTRODUCTION

Research on the possibility of using automation and robotics in the construction sector relates to potential applications in masonry and plastering works and construction planning and management. With the move to Industry 4.0, robots have started to appear within the construction industry landscape. With labor shortages experienced in all countries, innovators are turning to robotics to help fill the gap in skilled bricklayers. One of the most well-known construction robots is the Hadrian X bricklaying robot, developed by FBR in Australia, which is mounted on the boom of a truck crane [1]. The work of this robot was limited to laying masonry blocks from outside. World reports on construction robots, particularly masonry (bricklaying) robots, are available only on websites in the form of general information regarding their applications. There is no explicit information on the methodology or research results for masonry robots. The implementation of advanced technology in construction using robots significantly accelerates

and leads to an improvement in the quality of the bricklaying and plastering work. Recently, productivity improvement has not been a major problem in the construction sector, but there is a lack of a sufficient supply of skilled construction workers. Currently, the construction sector is approaching a decisive period of rapid automation and robotization of traditional and innovative technological processes. Robotics is considered a potential solution for improving the efficiency of the construction industry. There have been many reports in the literature on the implementation of masonry robots. A study [2] presented research on the possibility of automating masonry. A masonry robot capable of autonomously building walls using cinder blocks is designed. In the paper [3], an experimental robotic masonry system and its relevant control modules were developed. Two control systems for different levels of robotic brick wall laying are described: local and global control. The local control system included three phases: gripping and handling, quality control, and brick placement. Global control integrates three local

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control subassemblies and the data flows between them. Pritschow et al. demonstrated an automated masonry construction process at a building site using a mobile robot [4]. Madsen analyzed the benefits and weaknesses of SAM100 (Semi-Automated Mason) cooperating with a mason, which smooths out excess mortar [5]. SAM100 is more effective for large box-shaped structures, such as warehouses. These structures were primarily composed of bricks and other masonry materials. An alternative method is panelization or prefabrication of brick panels in a plant environment [6]. Scientific and applied research that evaluates the potential use of robots in construction is essential. The mobile robot unit was developed as part of a European union-funded research project in the Department of Architecture at ETH Zurich in cooperation with an industrial partner [7]. A new direction for the development of fabrication technologies in construction largely focused on the integration of stationary industrial robots into off-site construction processes [8]. The second development direction is in situ construction with industrial mobile robots; it offers a wide range of architectural and construction potentials, which requires a solution that meets of many basic challenges. The production of potentially monolithic, large-scale building structures

requires advanced robotic manufacturing systems that can satisfy the associated material, construction, and architectural requirements. However, poorly structured construction sites require mobile robotic systems to be equipped with advanced mapping and control solutions that can cope well with uncertain conditions on the construction site. Although studies were used on automatic bricklaying, these projects have not yet been implemented in practice at construction sites.

1. MOBILE ROBOTIC BRICKLAYING SYSTEM

At the Kielce University of Technology, in cooperation with the industrial partner Strabag Ltd. an innovative research project aimed at designing, manufacturing, and implementing a mobile robotic bricklaying system ZSM was implemented [9÷14]. It is the first tracked mobile robot for bricklaying works in Poland, mainly for the bricklaying of facades and partition walls in office and residential buildings, as well as industrial halls. Strabag is a large international construction company whose core businesses are building construction, civil engineering, and transport infrastructure. Mobile ZSM is characterized by an innovative design solution (partially patented), the task of which is to robotize time-consuming and heavy masonry work traditionally performed by hand by bricklayers.

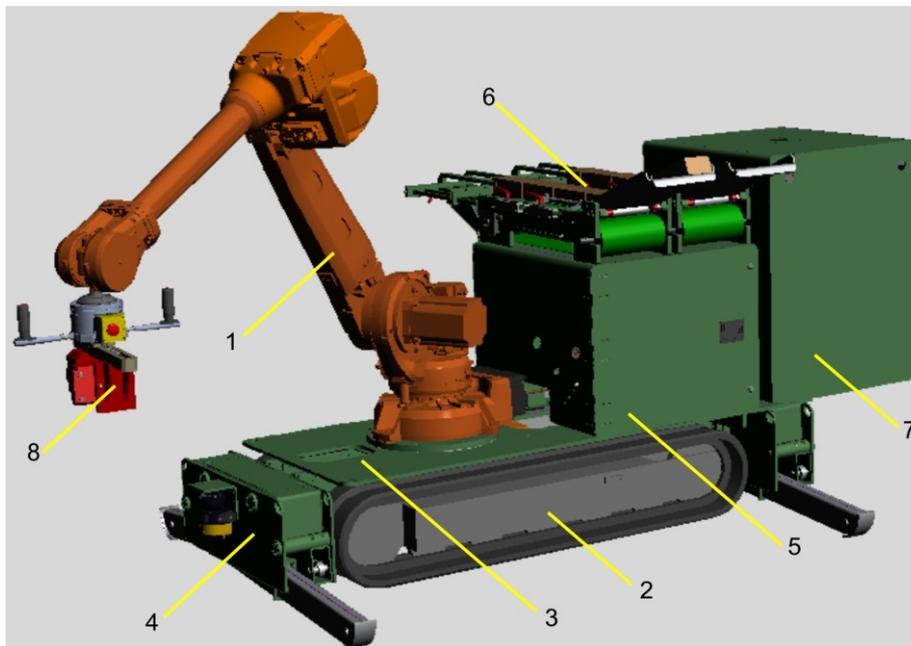


Fig. 1. 3D model of mobile ZSM: 1 – ABB industrial robot, 2 – Hinowa tracked undercarriage, 3 – base, 4 – hydraulic lifting and leveling module, 5 – hydraulic control unit, 6 – brick warehouse with a brick feeder, 7 – control cabinet with an operator panel, 8 – hydraulic gripper [15]

This ZSM project is designed for masonry technology classified as a “mobile masonry robot”. The main applications of mobile ZSM are facades and partition walls of offices and residential buildings, as well as industrial halls. The mobile ZSM enables the bricklaying of walls with dimensions limited to the working space of the robot. Mobile ZSM optimizes the time, cost, and efficiency of masonry work and reduces the amount of waste. Mobile ZSM is characterized by a new and innovative design solution, the task of which is to automate time-consuming and heavy bricklaying work traditionally carried out by hand by masons. The mobile ZSM consists of an ABB six-degrees-of-freedom (6 DoF) industrial robot with a replaceable hydraulic gripper, Hinowa tracked undercarriage with the hydraulic unit, hydraulic lifting and leveling module, brick warehouse, brick feeder, mortar applicator, control cabinet, and control panel. The

Hinowa tracked undercarriage with rubber tracks, owing to its highly maneuverable design, can efficiently move over longer distances between construction sites, shorter distances between operations, and positioning at the site of bricklaying. The built-up tracked undercarriage has been patented as utility models [13-14]. The 3D model of the mobile ZSM is shown in Figure 1.

Before starting the bricklaying work, the ZSM travels to the bricklaying site where it is lifted, leveled, and anchored. In the bricklaying process, the robot takes the bricks from the warehouse, places the brick under the mortar applicator, and lays the brick on the wall.

Simulation tests were conducted in a virtual ABB Robot Studio environment to verify the functioning of the robot and individual ZSM modules during the bricklaying process. A visualization of the bricklaying process in ABB RobotStudio is shown in Figure 2.

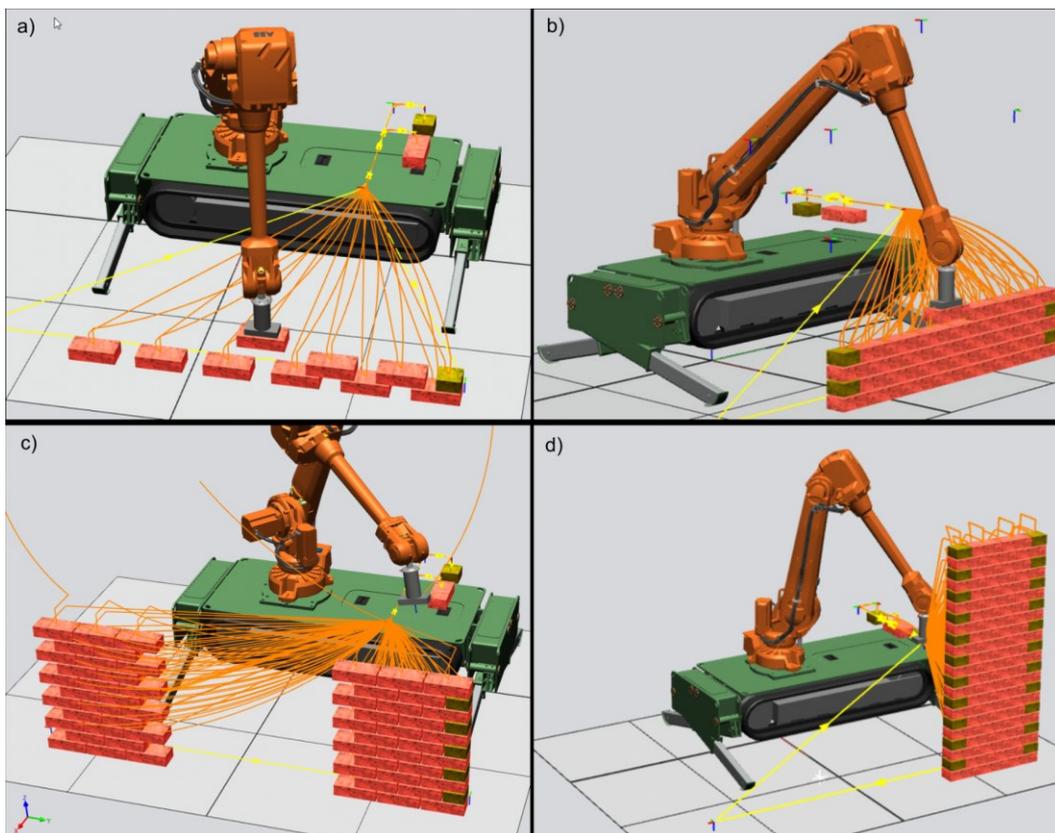


Fig. 2. Visualization of the bricklaying process in ABB RobotStudio: a) hit and miss brickwork, b) stretcher bond, horizontal wall, c) stretcher bond, hole in a wall, d) stretcher bond, vertical wall [15]

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During simulation tests, the following stages of the bricklaying process were verified: determining the variable working space of the robot, the length of the wall; division of the masonry lines for individual bricks/hollow blocks in the first layer, taking into account the width of the joints; determination of the robot's trajectory in accordance with the division into individual bricks and the method of placing bricks/hollow blocks in the wall and their arrangement in accordance with the division.

2. INDUSTRIAL BRICKLAYING ROBOT

Various robot models from several manufacturers were evaluated to select an appropriate industrial

robot for the bricklaying process. Due to the special application area of the robots in construction, the most significant factors influencing the selection of available robots are characteristic parameters such as range, payload, and dead weight. Ultimately, the ABB IRB 4600 - 40/2.55 type was selected from the range of robots evaluated. The ABB robot weight of 450 kg, a gripper load of 40 kg, a maximum vertical range of 3.055 m, a maximum horizontal range of 2.55 m, and repeatability of 0.06 mm. The six axes (6 - DoF - six degrees of freedom) of the robot manipulator are shown in Figure 3, and the axis parameter specifications are listed in Table 1.

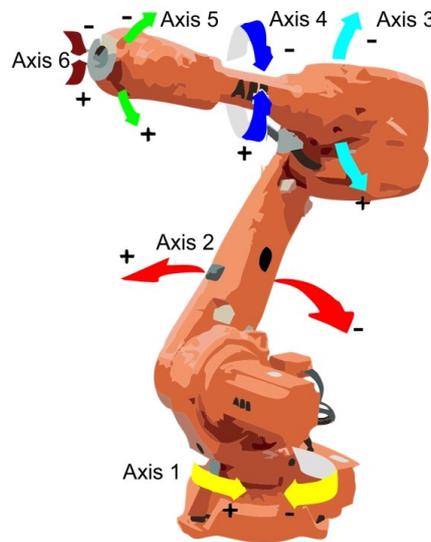


Fig. 3. ABB IRB 4600-40/2.55 robot axis

Table 1. Specification of the parameters of the robot axis ABB IRB 4600-40/2.55

Axis	Type of motion	Range of movement	Maximum axis speed
1	Rotation motion	+ 180° to - 180°	175°/s
2	Arm motion	+ 150° to - 90°	175°/s
3	Arm Motion	+ 75° to - 180°	175°/s
4	Rotation motion	+ 400° to - 400°	250°/s
5	Bend motion	+ 120° to - 125°	250°/s
6	Turn motion	+ 400° to - 400°	350°/s

The workspace of the ABB IRB 4600-40/2.55 robot is shown in Figure 4.

3. BUILDING A TRACKED UNDERCARRIAGE

A conventional Hinowa rubber track undercarriage (model PT20GL) was selected as the mobile robot platform (Fig. 5). Specifications of the PT20 model: 2000 kg maximum total weight (machine +

undercarriage), 1935 mm length, 1100 mm width, 250 mm track width, 370 mm track height, 5 + 5 rollers. Two Bravini hydraulic orbital geared motors CTM1022 + BRZV (geometric displacement 80.4 cm³/rev, maximum flow rate 65 L/min, maximum pressure 210 bar, maximum speed 119 rpm, maximum torque 1280 Nm) were used for the tracked undercarriage drive. The CTM 1022 series geared

motors were specifically designed for small-track drives (maximum weight 2500 kg). These units feature a planetary gearbox (one reduction stage), fail-safe brake (optional), built-in motor, and braking valve (optional). The track undercarriage is powered by a hydraulic power supply unit. The tracked undercarriage

can move forward and backward at a speed of 0.56 m/s, the maximum slope of the driveway $\pm 15^\circ$, and maximum lateral inclination $\pm 8^\circ$.

The tracked undercarriage was built-up with a robot support plate to which the lifting and leveling module (HLL) was attached to the front and rear (Fig. 6).

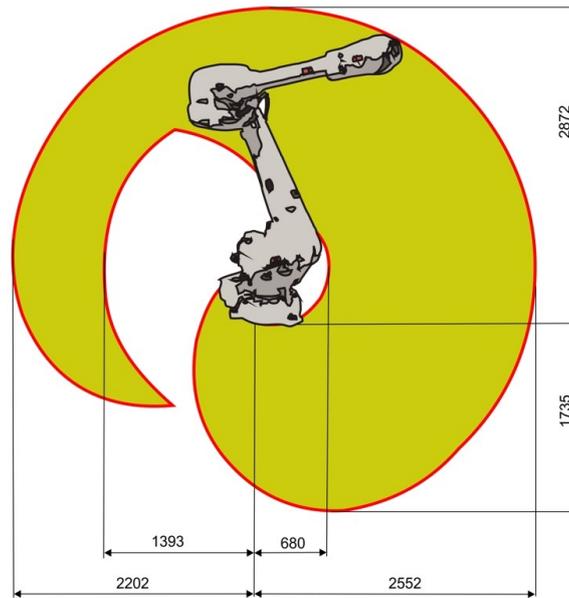


Fig. 4. Dimensions of the workspace of the ABB IRB 4600-40/2.55 robot in mm

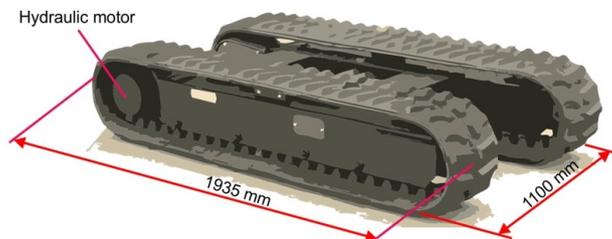


Fig. 5. Overall dimensions of Hinowa PT20GL tracked undercarriage

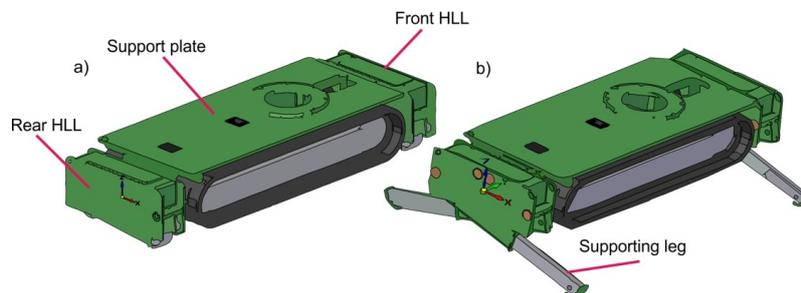


Fig. 6. Built-up tracked undercarriage : a) folded support legs, b) extended support legs [15]

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Two HLL modules were used to stabilize the robot's position during automatic bricklaying. A single HLL module is constructed using two hydraulically lifting support legs mounted on a cross system. Leveling occurs in two stages: maximum extension of the supporting legs by means of short-stroke actuators, and lifting and leveling of the supporting legs by means of lifting actuators. In the first stage, the actuators extend the supporting legs without external load until they come in contact with the ground. In the second stage, the lifting actuators pressed the supporting legs until the tracked undercarriage was raised to the required height. Once leveled, the legs are locked mechanically.

The hydraulic power unit (Fig. 7a) consists of a Siemens SIMOTICS M compact asynchronous servomotor type 1PH8103-10002-0GA1 (speed 1000 rpm, torque 35 Nm, power 3.7 kW) and a Hydro-LEDUC fixed

displacement piston hydraulic pump with bent axis type XPi 12 0523820 (geometric displacement 12 cm³/rev, flow rate 24 L/min, maximum pressure 380 bar, maximum speed 3150 rpm, maximum torque 76 Nm). A brick warehouse with a brick feeder is attached to the hydraulic power unit (Fig. 7b). The brick warehouse was adapted to various building materials with a length of up to 600 mm and a working width of up to 400 mm. The brick feeder was an electrically driven belt conveyor. The belt conveyor speed is 8 m/min, adjustable from 4 to 200%. The minimum load on the conveyor belt was 20 kg/m. The presence of building material in the feeder was controlled using capacitive sensors.

The hydraulic power unit and brick warehouse with a brick feeder (Fig. 8), control cabinet (Fig. 9), and ABB industrial robot (Fig. 10) were mounted on the tracked undercarriage.

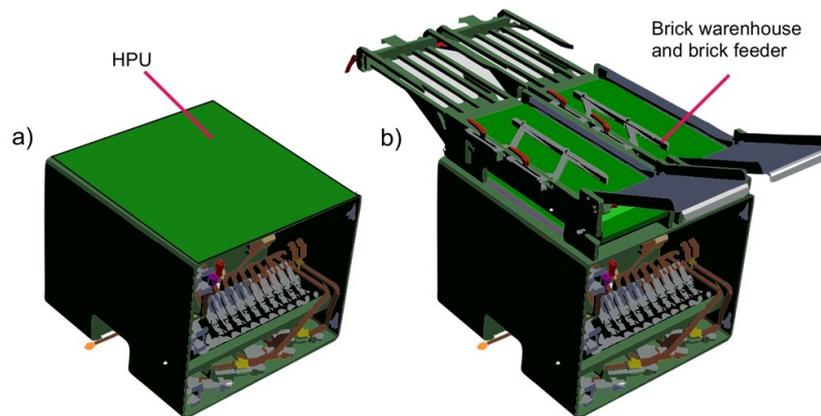


Fig. 7. Design elements: a) hydraulic power unit (HPU), b) hydraulic power unit and brick warehouse with a brick feeder [15]

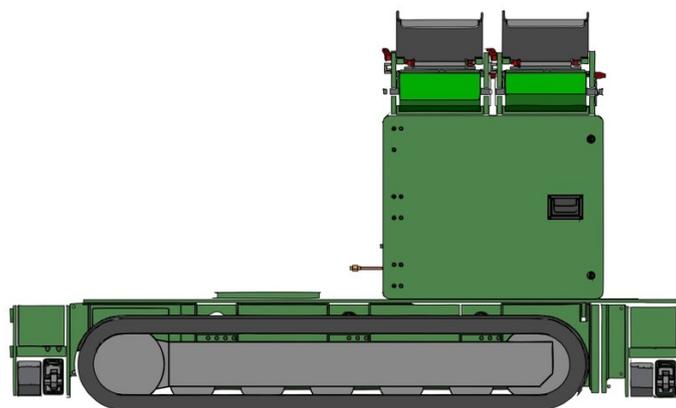


Fig. 8. Hydraulic power unit and brick warehouse with a brick feeder mounted on the tracked undercarriage [15]

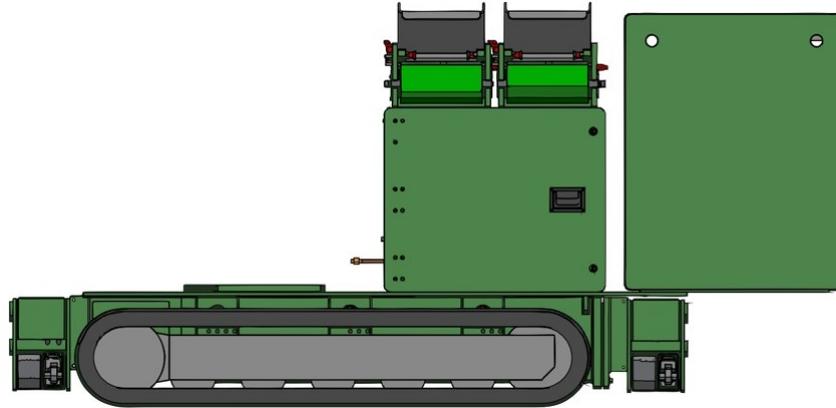


Fig. 9. Control cabinet mounted on the tracked undercarriage [15]

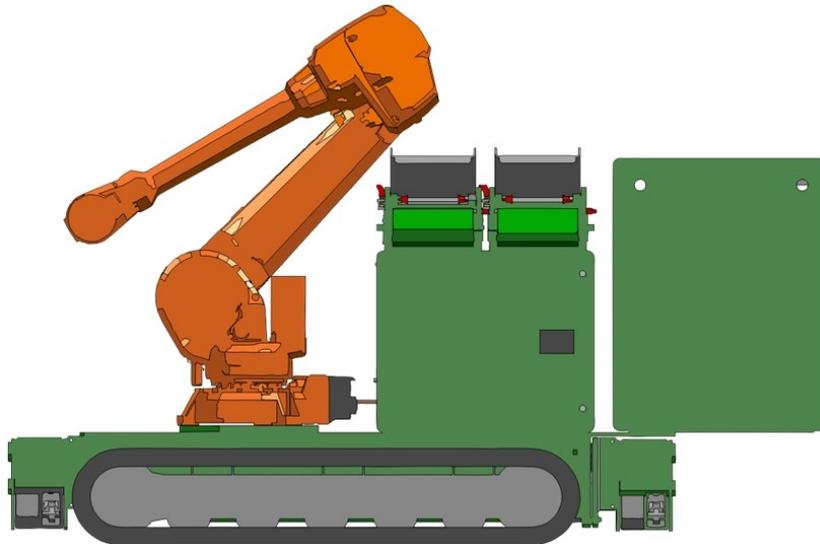


Fig. 10. ABB Robot mounted on the tracked undercarriage [15]

4. CONTROL CABINET AND OPERATOR PANEL

The view of the control elements with the operator panel on the control cabinet is shown in Figure 11.

The ZSM control is based on the Siemens Simatic S7-1500 programmable controller in the fail-safe version, which supervises the correct operation of all devices, powers electrical installations and inverters, and transmits digital and analog signals. The controller communicated constantly with the control system of the robot. The control system uses a Profinet communication network. To control the ZSM, control elements of electrical, hydraulic, and mechanical

systems were used. The Siemens Simatic HMI operator control panel enables visualization of communication between the operator and controller that manages the operation of the ZSM. After being powered on, the panel with the application developed based on WinCC Advanced V16 software will be started. The control system based on the Human Machine Interface (HMI) panel consists of several screens that can be called up using the associated buttons. When starting the control system, the start screen of the operator control panel was displayed with a menu bar with function screens, as shown in Figure 12.



Fig. 11. View of the control elements in the control cabinet: 1 – HMI operator panel, 2 – automatic control cycle start button, 3 – control mode switch, 4 – automatic cycle STOP button, 5 – control cycle indicator light, 6 – emergency STOP button, 7 – emergency STOP reset button [16]

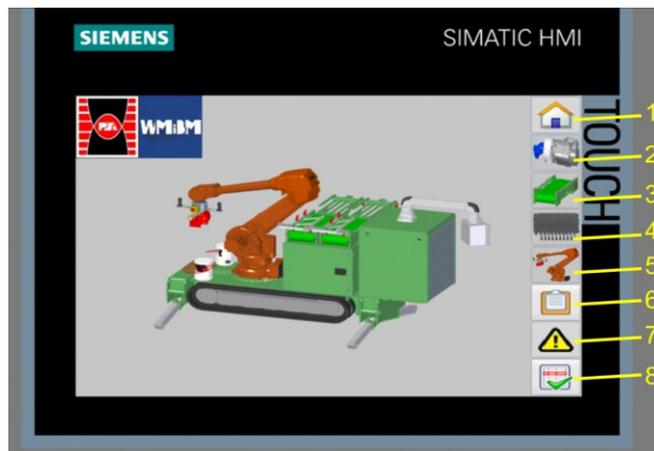


Fig. 12. Start screen of the operator control panel: 1 – home screen, 2 – hydraulic power supply screen, 3 – construction materials feeder screen, 4 – track undercarriage drive screen, 5 – robot screen, 6 – technology process procedure screen, 7 – failure screen, 8 – failure reset button [16]

5. TECHNOLOGICAL PROCESS PROCEDURE

Before starting the technological process, a bricklaying wall was designed based on the laser measurement readings. The parameters entered into the control program through the technology process procedure screen (WALL screen): wall length, wall height, wall angle, brick length, brick width, brick height, vertical joint thickness, and horizontal joint thickness. The next step is to design the order of laying the bricks on the wall using the CHOOSE BRICK screen. Parameters entered into the calculation program: sum of all bricks in the wall, a sum of the whole brick in the wall, a sum of half of brick in the wall, number of brick layers in the wall,

index of the current brick in the wall, index of the current row. The technological process of selecting a building material in the manual programming mode includes the steps of the procedure shown in the flowchart Figure 13. Choose the WALL screen to-the-wall design; choose the START BRICK button to control the order in which the bricks are stacked in the wall; choose the GET BRICK button to pick up the entire brick from the feeder; choose the GET HALF BRICK button to pick up the half brick from the feeder; choose the WAREHOUSE button to calibrate the brick position in the feeder; select the GRIPPER button to activate the robot and gripper to pick up bricks, select the AUTO button to start the automatic brick-laying cycle in the wall.

6. ROBOTIC BRICKLAYING TEST

During robotic bricklaying under laboratory conditions and on the construction site, single-layer walls with thicknesses of 8, 12, 15, 18, and 24 cm were bricked using Porotherm cell blocks or 900 class aerated concrete blocks, and different sizes of

single whole or half bricks. The robotic technological process of building a wall consists of the following stages: the robot grips the bricks, picks them up, manipulates them, applies mortar to them, and places them on the wall. The individual stages of the robotic process of bricklaying a partition wall are shown in Figure 14.

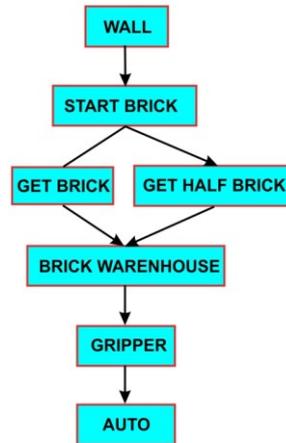


Fig. 13. Flow chart of the technological process procedure in manual programming mode

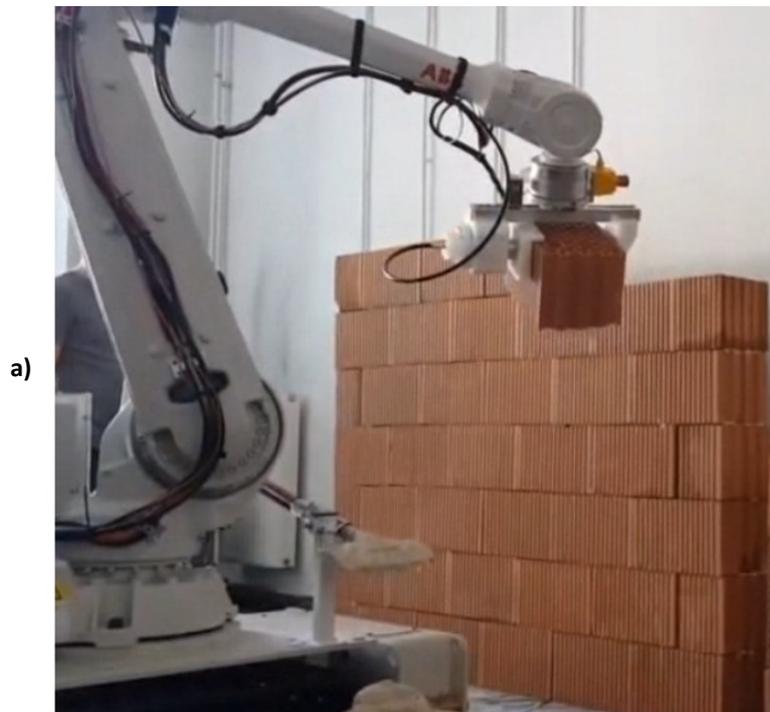


Fig. 14.a View of the bricklaying process on a partition wall: industry robot while bricklaying [16]



Fig. 14.b View of the bricklaying process on a partition wall: lay bricks on the wall [16]



Fig. 14.c View of the bricklaying process on a partition wall: apply mortar to the bricks [16]

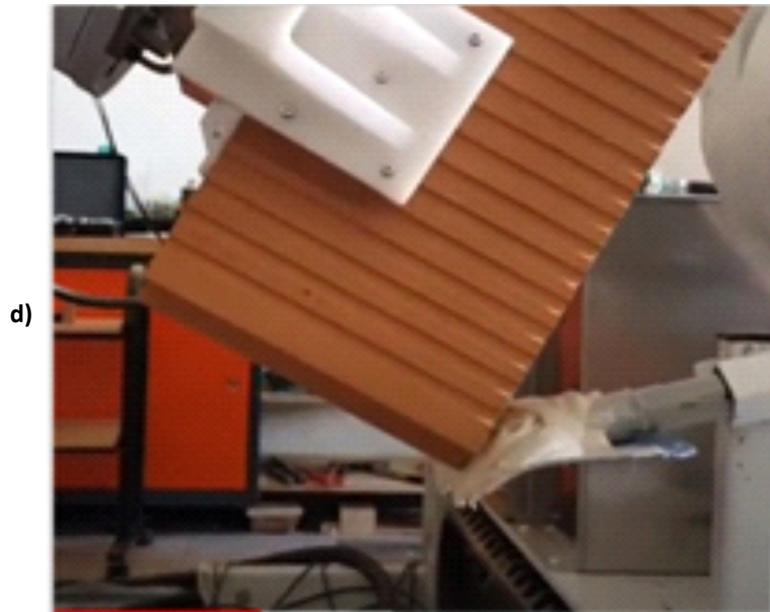


Fig. 14.d View of the bricklaying process on a partition wall: apply mortar to the bricks [16]

Examples of bricklaying tests were performed under conditions similar to those in the proving grounds.

1. Wall bricklaying was performed using 24 x 24 x 59 cm cell blocks with mortar feeding into two planes (horizontal and vertical). Mortar feeding tests were carried out for various target joint thicknesses. The safety of the robot system was tested.
2. Bricklaying tests were carried out with the application of glue mortar on cell blocks. Mortar was applied to two surfaces of the block. The homogeneity and thickness of the glue layer as well as its loss were checked. The densities of the glue mortar samples were determined. The technological time was determined for the required mortar feed.
3. Vertical and horizontal wall positioning algorithms were verified using a laser measuring sensor. Vertical and horizontal deviations of the wall from the wall axis were checked.

CONCLUSIONS

The first innovative ZSM mobile robot bricklaying system in Poland was built in cooperation with an industrial partner Strabag. Mobile ZSM has been successfully tested in laboratories and construction sites and is currently in the industrial implementation phase. This is a new configuration solution for a mobile robotic unit in the construction industry the task of

which is to automate time-consuming and burdensome masonry work performed manually by bricklayers. The developed HMI operator panel includes all functions required to control the individual ZSM units, such as the hydraulic drive of the tracked undercarriage, hydraulic lifting and leveling module of the robot support platform, electric construction material belt feeder, mortar applicator, industrial robot, hydraulic gripper. The HMI operator panel enables visualization communication between the operator and controller which manages the work of all mobile ZSM units during the bricklaying process. The design, manufacturing, testing, and implementation of mobile ZSM was carried out in a research project supported by grant number POIR.04.01.02-00-0045/18-00 "Development and demonstration of a robotic bricklaying and plastering system for use in the construction industry" by the National Centre for Research and Development in Poland within the framework of the Smart Growth Operational Programme 2014–2020.

INNOWACYJNE ROZWIĄZANIE MOBILNEJ JEDNOSTKI ROBOTYCZNEJ DO AUTOMATYZACJI MUROWANIA

W artykule przedstawiono innowacyjne rozwiązanie mobilnej jednostki robotycznej na potrzeby branży budowlanej, której zadaniem jest automatyzacja czasochłonnych i uciążliwych prac murarskich wykonywanych ręcznie przez murarzy. Zaprojektowano i opracowano mobilny zrobotyzowany system murarski (ZSM)

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w wersji demonstracyjnej. ZSM składa się z robota przemysłowego ABB o sześciu stopniach swobody (6 DoF) z wymiennym chwytakiem hydraulicznym, podwozia gąsienicowego Hinowa z agregatem hydraulicznym, modułu hydraulicznego podnoszenia i poziomowania, magazynu cegieł, podajnika cegieł, aplikatora zaprawy, szafy sterowniczej i panelu sterowania. W środowisku wirtualnym ABB RobotStudio przeprowadzono szereg testów symulacyjnych w celu weryfikacji funkcjonowania robota i poszczególnych modułów ZSM podczas procesu murowania. Sterowanie mobilnym ZSM oparte jest na sterowniku programowalnym Siemens Simatic S7-1500 w wersji fail-safe, który nadzoruje poprawną pracę wszystkich urządzeń. ZSM został przetestowany w warunkach laboratoryjnych i na budowie. Robotyczny proces technologiczny budowy ściany składający się z następujących etapów: robot chwytka cegły, podnosi je, manipuluje nimi, nakłada na nie zaprawę i umieszcza je w ścianie.

Słowa kluczowe: robot mobilny, podwozie gąsienicowe, automatyzacja procesu murowania, interfejs operatora

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