An integrated automatic wall concreting system

Andrzej Więckowski

Department of Civil Engineering, Cracow University of Technology, Cracow, Poland
** Corresponding author (andrzej@izwbit.pk.edu.pl)*

Purpose Ja-wa refers to the construction of reinforced concrete sandwich walls, with variable production capacity for small and large buildings or colonies of houses, with an integrated system of automatic design and control of one-sided concreting with ongoing control of implementation quality; in the context of sustainable development, it includes minimization of direct investments and management costs and limited capital intensity of the devices applied. The ja-wa is a unilateral application system for a wandering automatic machine. **Method** The method is characterised by inverted order of building partitions in comparison to standard methods. The manner of building partitions with the ja-wa system is, firstly, to install e. g. target curtain coating, or a pneumatic tent, or a facade cladding layer or insulation, which is a lightweight, single-sided stay-in-place formwork. This becomes the base for the construction part. The material is applied in layers using the 'wet-on-wet' method, which ensures their monolithic character. The material is placed at intervals allowing the use of the growing strength of the previously made layers in order to transfer loads from the coatings applied later. This allows the construction of even a massive barrier at low load of the forming surface by a lightweight, folding scaffolding system. The automatic, computercontrolled manipulator moves with desired speed at intervals and on a fixed route fitted to the design of the object and developed in the ACAD or according to the route of either an individual program or a route introduced for repetition. The computer also controls the preparation of materials, controls the time when layers should be applied to different points of the implemented layers, checks the technical quality of works performed and in case of incompatibility intervenes to stop the works. **Results & Discussion** The paper contains a general description of the ja-wa system, the analysis of conditions for timely incorporation of the construction material and a comparison of the properties of the proposed partition to other solutions

INTRODUCTION

ja-wa (ja-wa), or *unilateral application - wandering automation* system (in Polish: system *j*ednostronnej *a*plikacji – *w*ędrującym *a*utomatem) is a representative of the technology which envisages automation of some processes carried out at the construction site, when building sandwich walls. At the same time, ja-wa integrates the problem of adaptation of the design of the building in the area of automatic preparation of organisational and execution management solutions, as well as computer control of the auto manipulator erecting the walls, together with control of the progress of works, naturally including complex mechanisation of auxiliary works.

In typical solutions applied, on the structural layer of the load-carrying wall, performed in the first instance, insulation, protective, and other layers are installed. At ja-wa, the order of wall construction is reverse. First, the e.g. façade siding or thermal insulation layer (or the curtain or pneumatic tent layer), constituting light unilateral formwork, is stabilised. Next, the structural part is performed. The material is jetted in layers, with “wet-on-wet” method, allowing for their good monolithic nature. Material application at the appropriate intervals also allows for the use of growing strength of the layers made earlier to transport loads from the layers placed later. This allows for making of an even massive wall with little load on the formwork.

The main ja-wa equipment applied at wall erection is the automatic computer-controlled manipulator together with specialist rail device. The mobile rail device is a light scaffolding of assembly structure, which as a disassembled kit can be subject to reloading, warehousing and transport. The device features rail for the automatic manipulator, and serves to stabilise the light unilateral formwork, e.g. in the form of target thermal insulation layer of the wall. While riding on the device rail, the manipulator moves the nozzle that applies the material. The material prepared in the mixer-pump is pumped via the pipe to the application nozzle that remains in a casing which at the same time secures against dusting and losses, on the one hand, and shapes the surface, on the other. The control of the manipulator and the pump is performed by the computer, according to the programmed scope and method of the works.

At present, one can observe advanced works on automated construction robot systems for construction of entire buildings, as well as their complexes. The systems integrate the following functions: work organisation planning, operating time control, material consumption and quality of the works. Examples of the developments include the following systems. AMURAD (AutoMatic Up-Rising Construction by ADvance Technique[1]) is a completely automated system, where after the completion of the top floor – first, automatic servos push the entire storey upwards, and the following lower floor is erected in its place, etc. On the storeys erected, finishing works are performed. SMART System (Shimuzu Corporation)[2] features temporary rood equipped with transport devices and a machine for erection of structural steel frames and casing walls of the building, with automatic welding and control systems. The automatic mechanism raises the roof upwards using special lattice masts. ABSC (Automated Building System Construction), which is a fully automated system for construction of steel skeletal buildings, uses the working platform that rises, but is supported on previously completed storeys. A concept for building construction that has development potential is CC (Contour Crafting), using an automatic gantry that moves on rails and features a nozzle laying and forming the material, as well as a device for assembly of reinforcement and installations. When the nozzle moves, first, the curved or straight edges of the walls are formed, which, as lost formwork, is filled with the material during the next cycle of nozzle move.

The systems envisage automatic construction of entire buildings, usually high buildings. As a consequence, such method of construction of entire buildings in the 1:1 scale requires development of certain automatic factories that carry out production in a large space, but also high at the site. Due to the need for precise movements of specialised gantries, with a set of adjusted cooperating equipment, their weights are significant, reaching even beyond several hundred tonnes. These area also very expensive solutions. The ja-wa system naturally does not meet the precondition of complex automation, but it also basically facilitates work with much lower outlays.

This study covers the general characteristics of ja-wa and the equipment applied, together with execution of an exemplary wall using the automation manipulator moving on systemic rail.

INTEGRATION OF PLANNING, EXECUTION AND CONTROL ISSUES

A distinct feature of automated systems for building construction is the general use of IT technologies. Similarly in ja-wa, when using databases and knowledge, there is automatic integration of automatically performed computer calculations and analysis in the area od documentation generation upon direct adaptation of the building design, developed in typical software, e.g. AutoCAD, determining outlays on labour, materials and equipment operation, as well as financial and environmental outlays (in the context of building life), as well as management planning, work organisation and transport logistics, site management, as well as the schedules for preparations and execution of the task. There is also an automatic management system comprising databases of identified production and material resources, preparation of prefabricated items, transport and execution of works at the site, as well as sales, functioning online according to the principle of on-going monitoring 'in situ', which is used for data processing at the centre and for decision-making at the decision-maker's site. Tele-transmission allows for on-going cooperation of the centre with continuous research and determination of the most favourable current solutions, appropriate for the currently occurring conditions at the site for work execution by the manipulator, with complex use of the computer for controlling robot operation, namely its launch, work control, as well as stoppage and monitoring, safety control and quality of the execution.

Below is the selected fragment of analyses related to environmental outlays. Due to incomplete information on the value of materials and products, which carry the prices, an important issue refers to the analyses considering the environmental impact of the building during its entire life cycle, namely sozo-economic analyses. Such analyses, apart from cash flow, consider environmental outlays from the moment of planning the building, through programming and designing, as well as construction of the building, including its long-term use, with significant outlays related to e.g. heating/air-conditioning, including renovations, modernisations, and finally its physical elimination. Naturally, this includes the entire sphere of impact, material and equipment used in this period, the prior production of which was often also related to high environmental costs.

In reference to a building facility, the sozo-economic model of analysis can be formulated as follows, [20]:

- (sozo-economic) criterion:

$$B_I + B_e = \sum_{t=0}^{n} \frac{CIF_t - COF_t}{(1+k)^t} - \sum_{t=0}^{n} \frac{oe_t}{(1+k)^t} \geq 0 \, ,$$

- Conditions:

$$B_I, \; CIF_t, \; COF_t \geq 0 \, ,$$

where:

- updated as of present with discount rate at level k:

B_I - economic benefits for the entity due to investment (*investing benefits*), PLN,

B_e - *environmental benefits*, PLN,

- cash flow from the business in year □ include:

CIF_t - *cash inflow*, PLN,

COF_t - *cash outflow*, PLN,

oe_t - *non-assessed environmental outlays*, PLN,

- are determined for the full life cycle of the building, from the first plan, corresponding to commencement of action in year $t = 0$, throughout the period of building presence, until the completion of the last control activity in year $t = n$.

Environmental benefits B_e considered represent the value of public welfare, as value of their existence "as such", which is lost in the environment due to construction of the building, including materials and equipment used for its construction and during use. The value of existence is described as follows: "Even if a particular unit is not a consumer of environmental resources..., it may attach specific importance to its value and existing welfare. It may also derive satisfaction from the very fact of existence of such welfare and their availability to people living at present and in the future," [22]. It is a value that results from the very fact of existence of the environment in its natural state, e.g. of a mountain without its defect caused by collection of a mineral to produce cement, or steel.

In turn, non-assessed environmental outlays oe_t represent the value of external effects caused by the building facility, and which are not considered in

cash flows CIF_t and COF_t. Non-assessed environmental outlays oe_t due to raw materials consumption constitute the value of the irrevocably collected mineral with distortion to the natural state of the environment, which is "usually neglected".
It seems that for an objective complex assessment of the solutions, similar extended analyses are necessary.

LIST OF EQUIPMENT

The main equipment ensuring partial automation of the wall construction processes in ja-wa includes: systemic rail and automatic manipulator, as well as dosing-mixing unit with a pump, and material tank.
Systemic rail device features a rail for moving automatic manipulator along the walls constructed, Fig. 1.
The device is characterised with high mobility. The complete device is disassembled into two flat elements which, together with the manipulator, are entirely subject to reloading and transport. The device is a type of systemic light scaffolding with fixed, jointed and sliding connections of particular parts. This allows, depending on the needs, for quick assembly or disassembly of entire segments corresponding to two neighbouring walls in the building constructed (without the need for disassembly into individual parts).
At the site, the device is transported and set with the crane of the transporting vehicle or with a crane at the site. Elements: 1.1 – are opened, 1.2 – slided and set appropriately to the form of walls performed.
The device also serves for initial stabilisation of unilateral lost formwork - 1.3, e.g. in the form of target thermal insulation layer of the wall, which is kept in the planned position by top sprags - 1.4 stabilised on the poles of systemic scaffolding.
The automatic manipulator, namely robot with inbuilt computer and controller together with the applicator, serves for jetting the material, and possibly for shaping the surface of the layer made.
The controller, according to the programme corresponding to the design of the building constructed, ensures robot's passes and shift of the applicator, according to the route required, with the consecutively placed layers and with finishing of the wall surface. According to the programme, the computer monitors the course of the process, controls and analyses the times of material preparation and jetting in particular layers and places of the wall constructed.
The manipulator with inbuilt computer and controller - 1.5, moves on the rail of the rail device - 1.6, along the wall constructed, while upwards and downwards within the extent of the storey height, on its own vertical frame - 1.7. Material ejector with casing - 1.8 is placed on the applicator plate. The casing protects against material losses, and the texturizing element serves for possible levelling of the layers and for surface finishing.
The dozing-mixing unit with a pump and the material tank are placed at the wall opposite to the place from where the manipulator begins jetting (this allows for shortening the feed pipe by half). The unit collects components from the tank and, after preparation, pumps them to the ejector.

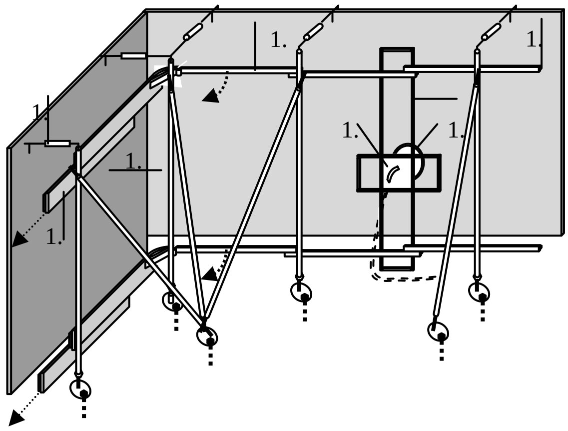


Fig. 1. Corner of the concrete walls constructed and systemic rail device with the automatic manipulator, description in the text

EXAMPLE OF WALL CONSTRUCTION

In ja-wa, with 'reverse' order of the works, e.g. thermal insulation layer is set as the first element, Fig. 2. Elements - 2.1, from thermal insulation material are of the storey height (with floor thickness) and of modular length. They feature locks - 2.2, to improve the joint, and at the same time ensuring good facing of the surface of neighbouring elements. From the external, façade side, in the glue layer - 2.3, the reinforcement mesh is embedded - 2.4, together with overlaps - 2.5, to bond the joints. On the internal surface of elements 2.1, a thin glued adhesive layer is made - 2.6. The elements, acting as light unilateral lost formwork, may feature profiled groves on the internal side, with appropriate cross-section, for the purpose of forming poles in them - 2.7, ring beams, and possibly ribs to stiffen the wall. Elements prepared in the auxiliary production plant have lashing points - 2.8, passing across the entire thickness, for the purpose of anchoring the entire thermal insulation layer in the structural layer performed later. In the lashing point terminals, there are sockets for stabilisation and gauging of the structural reinforcement of the wall - 2.9 (which, after installation, additionally stiffen the forming element). Stabilisation of the elements with sprags to the poles of the systemic rail device ensures their precise gauging against the robot's driving rails (cf. Fig. 1).

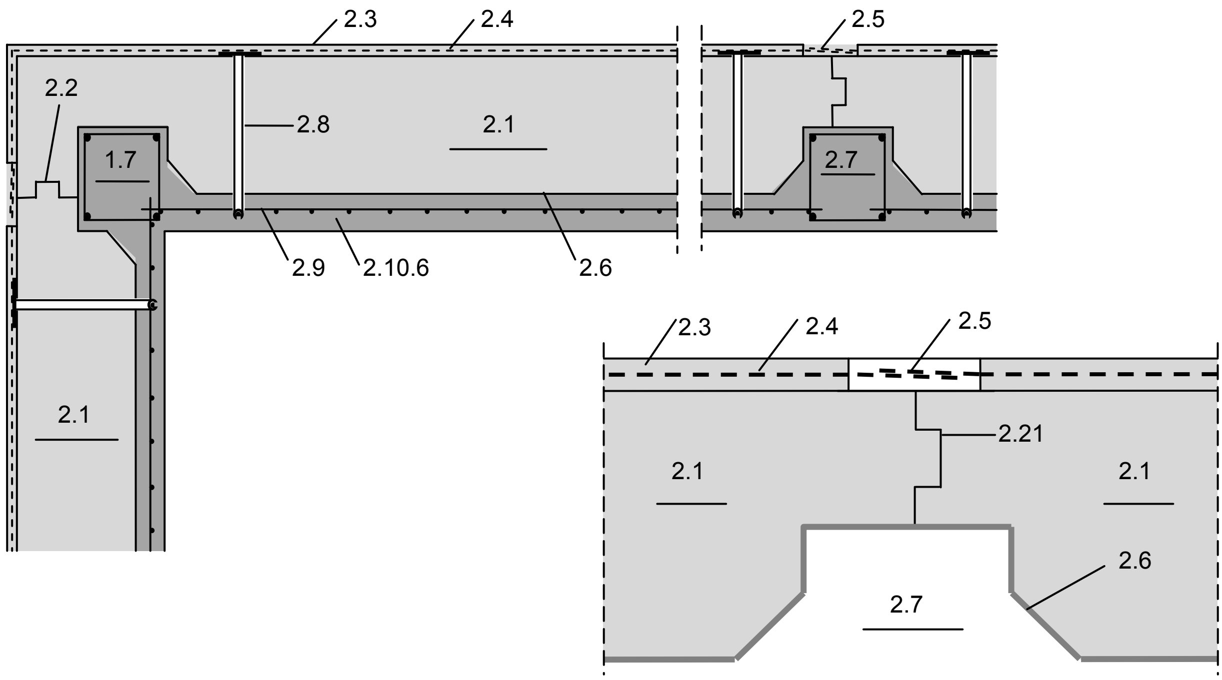


Fig. 2. Example of light outer wall, description in the text

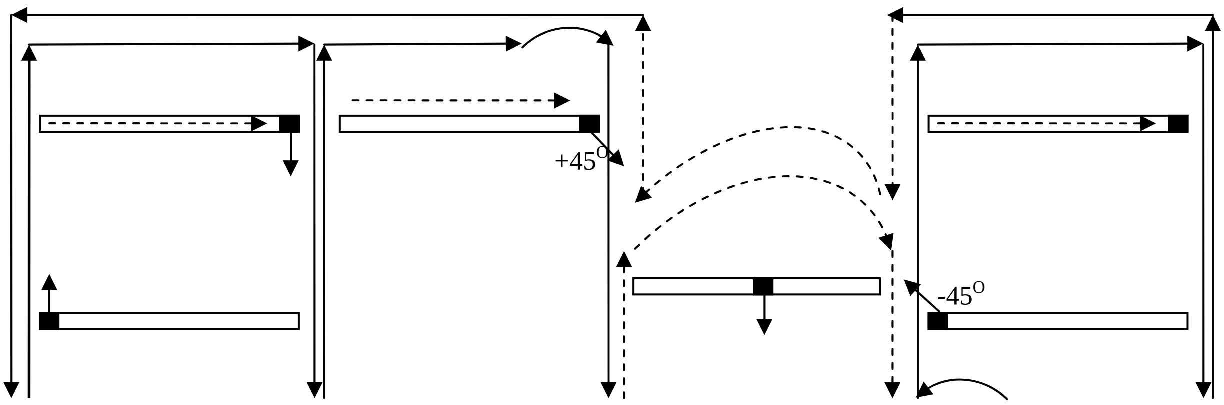
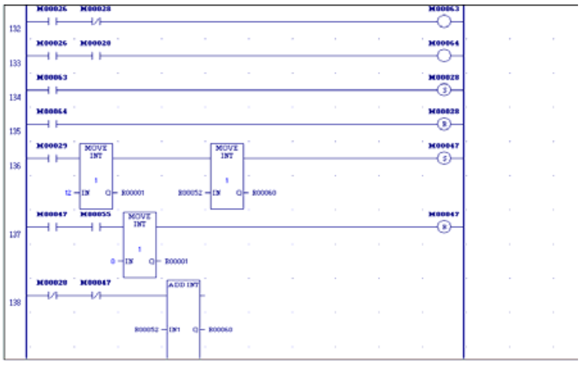


Fig. 3.

Material laying

Material is laid and thickened by jetting, using the energy of the plume of high-velocity particles. The device begins jetting from the centre of the wall opposite against the dosing-mixing unit with a pump and material tank. This allows for reducing the pipe length to the half of the wall made (unfolded).

When building light walls with bearing, skeletal structure and a thin wall between the poles (cf. Fig. 2), Poles and ring beams (possibly ribs) are made first. The material is placed in layers. Jetting is performed e.g. from the bottom of the pole vertically upwards, and then the ring beam horizontally, next pole vertically, down and upwards, ring beam, etc. At the corner pole, the ejector turns at the angle of 45° and jets the material at the pass downwards, next the manipulator moves to the neighbouring wall, sets the ejector at the angle of 45° and ejects the layer at the same corner pole, moving the ejector upwards, further on again moving to the ring beam, pole, and until the end of the wall. Similar jetting of the layer in the ring beam is observed in the return pass. As a result, after each complete cycle (pass and back) of the manipulator, two layers of the material are placed. Fig. 1 presents a fragment of the ejector route and elements of the programme for the applied PLC controller of series VersaMax Micro, type IC200UDR064-AB.



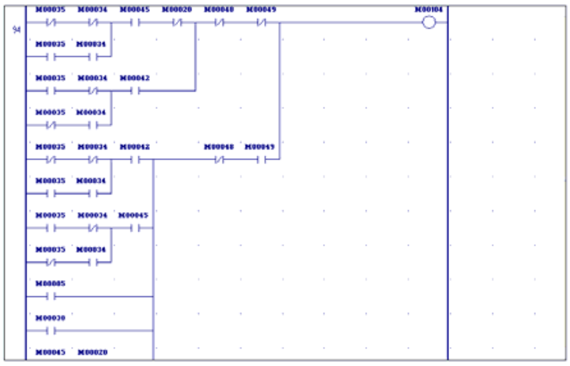


Fig. 4. Fragments of the ejector route when performing poles and ring beams in wall corners and elements of the programme for PLC series VersaMax Micro, type IC200UDR064-AB, description in the text.

The material for the entire wall surface is also jetted in layers, in the form of belts with the height of the storey. After completion of the first belt, the robot moves by its width and places the next belt, again moves in the same direction, places another belt, etc., until the last belt connecting to the first belt of the layer is made (or until the entire wall is covered with a layer from the beginning to the end). The robot returns to the start place in an idle run. It begins laying the next layer, starting from the place of the first belt (previously made) with the shift by half of the width (of the belt), observing the same order of laying as in the case of the belts in the first layer. The first layer, adhesive one, is the thinnest, of 0.1 ÷ 0.3 cm thickness, the next of approx. 1.5 cm, while the last, facing layer – of 0.7 cm, with the surface smoothed or with external texture made. Also, a painting layer can be placed.

CONCLUSION

Characteristic features of ja-wa include the following:

- integration and facilitation of executive documentation preparation, with calculations and analysis made automatically by the computer according to the developed programme, based on direct adaptation of the building design, developed in e.g. AutoCAD, for the case of well-known and described limitations upon work performance by the automatic manipulator, determining labour, material and equipment operation, as well as financial outlays (in the context of building life cycle and environmental impact), as well as planning of management, work organisation and site management, together with the schedule for preparations and task execution.
- significant use of IT technologies, including for performance of continuous research and determination of the most favourable current solutions, appropriate for the currently occurring conditions at the site for work execution by the manipulator, with complex use of the computer for controlling robot operation, namely its launch, work control, as well as stoppage and monitoring, safety control and quality of the execution.
- The solution is characterised with little involvement of technical means, namely small weight, and low capital intensity of the equipment, in the form of the following computer-controlled equipment: light automatic manipulator, which “wanders” along the systemic rail device and dosing-mixing unit with a pump.
- The concept of a robot “wandering” along the mobile rail device ensures precise execution of activities at a large space without the need to apply long booms and massive stabilising structures, characterised with high material and capital intensity.
- The reverse order of the works allows for performance of a complete wall with lower outlays on labour, materials and equipment operation, as the complete wall is performed in one technological line, more favourably than in standard solutions, when first the structural layer is made, while in another cycle, i.a. the thermal and protective layers are performed, with the need to apply another external scaffolding.
- man is favourably freed of physical work and deals with equipment operation, with labour reduction to programme launch.

References

1. Cousineau, L., Miura, N., “Construction robots: the search for new building technology in Japan”, *American Society of Civil Engineers,* ASCE Publications, 1998.
2. Maeda, J., “Development and Application of the SMART System”, *Automation and Robotics in Construction*, Elsevier Science B.V. , pp. 457 – 464, 1994.