Robotized Method For Manufacturing Individual Concrete Elements With Specific Shapes

Tapio Heikkilä [a], Pentti Vähä [b] and Tuomas Seppälä[a]

[a] VTT Technical Research Centre of Finland Ltd, P.O. Box 1100, FI-90571,Oulu, Finland
[b]University of Oulu, P.O. Box 8000, FI-90014, University of Oulu, Oulu, Finland
E-mail: tapio.heikkila@vtt.fi, pentti.vaha@gmail.com, tuomas.seppala@vtt.fi

ABSTRACT

Wood and combinations of wood and plywood is the most traditional formwork in mould-based shaping of construction components. This kind of formwork usually doesn't include curvatures, but favours straight lines and sharp corners yielding in angular shape concrete building blocks. In this paper we describe a novel robotized method for manufacturing individual concrete elements with specific shapes. It is based on utilization of a digital 3D model of the target object, from which mould machining paths for the robot are stepwise created to prepare a mould made with hardened sand. Also casting of concrete blocks is described with an example.

Keywords – Mould making; manufacturing of concrete elements; automatic path planning; robotized method

1 Introduction

Mould-based shaping of construction components is still widely used in conventional construction although several modern manufacturing methods exist either commercialised or under experimental development. Conventional formwork usually doesn't include curvatures, but favours straight lines and sharp corners yielding in angular shape concrete building blocks. Today wood and combinations of wood and plywood is the most traditional formwork, although reusable wood or metal frames have been more popular in concrete construction. Flexible materials like fabric formwork have been applied as a building technology that involves the use of structural membranes as the main facing material for concrete moulds [1]. Unlike traditional formwork, the material is highly flexible and can deflect under the pressure of fresh concrete. The resulting forms exhibit curvature as well as excellent surface finishes that are generally not associated with concrete structures. Explorations in fabric-formed architecture include the architectural integration of structural and sculptural form provided by flexible mould material that can be found in student experiments and industrial design prototypes. Anyway, today there is an increasing need coming from the customer side to produce moulds for concrete elements with specific curved shapes.

In the last few years 3D printing has become a very common method for rapid prototyping in many industrial fields [2]. The evolution of this technology has also been an inspiration to test the same method on a bigger scale by using concrete as a material. The benefit of the method is the ability to produce complex 3D shapes easily. The shape of the concrete elements is designed using 3D CAD software. Then the element is manufactured automatically by using a portal type robot to deposit concrete very accurately layer by layer. Digital concrete manufacturing has also been studied, where manufacturing custom moulds for concrete elements is done using an industrial robot. In this approach, the mould is carved according to a 3D CAD model of the object. Custom-manufactured moulds can be made from foam materials that are low cost, fast and easy to mill. Contour crafting is a layered fabrication technology based on the distribution of concrete using a portal type robot with the aim of building the whole frame of a house automatically to form curved surfaces. In turn sand is used as a building material in D-shape robotic building system based on the principle of 3D printing, where a large-scale robot is used for moving the printing head. During the printing process a nozzle is used to deposit binder onto a layer of sand.

Robotic systems have found their way into the construction industry for component manufacture and the production of modular housing, e.g., for form working allowing flexible production of the concrete floor, wall and roof panels [3]. Typically the shape of prefabricated concrete elements manufactured with robotic systems have angular shapes. Also the openings in the element, such as doors and windows, have typically angular shapes. However, customers would also like to have different kind specific decorations to emphasise their uniqueness. Unique architectural designs are also rather common in public and commercial buildings. Residential buildings have to be very cost effective and this limits the freedom of the designer. With automation, the extra cost of customising can be reduced to a more affordable level. Furthermore old time buildings may encompass unique shapes to be renovated as they were originally. Hence in construction there is an increasing need for concrete building blocks encompassing specific curved shapes. Clearly there is a need for automated and robotised shaping methods enabling manufacturing of more customised structures (etc. concrete elements) when also the design of the structure will be done digitally and when all modifications can be done by altering the digital model of the product, currently more and more available from the Building Information Model (BIM) [2]. However, old buildings under refurbishment typically do not have BIM when the digital model can be produced by scanning the exciting piece with sensors like a laser scanner. Old public buildings may have decorations in railings, columns or bars, e.g. a face of a great man (historical figure), requiring refurbishment. When the 3D model information is available from the target objects, then the manufacturing of the product can be carried out automatically according to the digital design. In this paper we outline a robotized process for preparing and manufacturing concrete castings.

In the next chapters we describe the planning and programming steps needed to program a robotic mould machining unit, as well as machining of the mould made of hardened sand and casting of the concrete, resulting in a concrete object with the desired 3D shape. All the phases are illustrated with an example and a test object and related data, including the casting experiments. We see that our experiences pave the way towards flexible and automatic production of concrete objects with specific and curvature shapes.

2 Modelling and programming for robotized mould machining

2.1 Planning and programming process

The key issue is to produce 3D moulds for concrete casting in a flexible way. We use hardened sand as mould material. Mould design and preparation is composed of several stages, starting from acquisition of the shape data for the target object and ending to casting of the concrete. Our approach for flexible mould manufacturing is outlined in Figure 1. We start with the digital model of the target object and the mould preform. The target shape of finalized mould is acquired by merging the models of the target object and the mould preform in a CAD system. After that the machining tool paths (NC programming) are generated based on the mould preform and target shapes with a CAM tool. This is further converted to a robot program and paths using models from the robot, tools and the robot cell. The resulted paths, their feasibility and characteristics in general will then be simulated with robot off-line programming tools and paths are corrected and revised if necessary. Finally the robot paths and program is uploaded to the robot controller for execution.

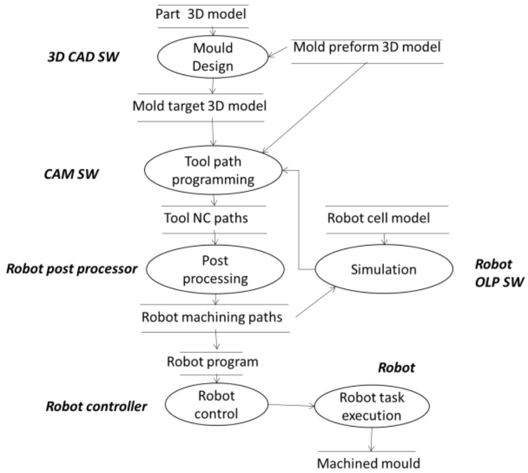


Figure 1. Functional architecture for planning and programming of robotized mould machining.

The planning and programming system was implemented with the following tools (see Figure 2):

- Mould design: AutoDesk Inventor®
- Tool path programming: ABB RobotStudio® Machining Power Pac
- Post processing of NC paths: ABB RobotStudio® Machining Power Pac
- Simulation: ABB RobotStudio ®
- Post processing of simulated robot programs: proprietary post processor on a Windows PC
- Robot + robot controller: KUKA KR110+ KRC2 robot controller

The planning and programming phases are described in more details below.

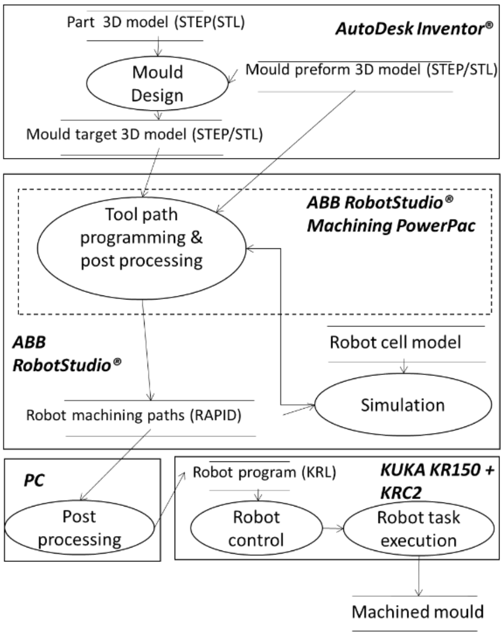


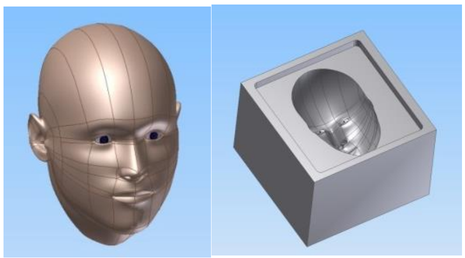
Figure 2. System architecture of planning and programming for robotized mould machining.

2.2 Mould design

A 3D digital model of the target object is required for manufacturing individual concrete elements with specific shapes. The target object may encompass any combination of curved and straight lines which should be represented in the model. In the case of new buildings the target object model can be taken from a construction planning data such as BIM [2]. BIM, a digital representation of physical and functional characteristics of a facility, covers e.g. geometry, spatial relationships, light analysis, geographic information, quantities and properties of building components, for example manufacturers' details. BIM provides reference values for dimensioning the prefabricated components as well as accurate locations of components on the building site. In our case BIM can be used to acquire the 3D shape and dimension information.

An important option to acquire the 3D digital model for the target object is to have physical models as a source for shape information, like in renovation targets. When the physical model is scanned with a 3D sensor (scanning or profile measurements with additional motion provider) [2], the resulting point cloud can be transformed to 3D surface model to be utilized in the mould design. We use the simplest way from a structured point cloud to a 3D model: use STL converter tools, like the Point Cloud Library SW package [4].

There is also a third option for acquiring the 3D digital model, to rely directly on detailed design data. In our case we took a digital 3D model of a human face (or head) and a 3D model of a mould preform, i.e. hardened sand block and cut out the face model from the block model, resulting in a negative 3D image as the targeted mould surface profile (Figure 3). This mould model was then used in further planning and programming phases.



a) b)

Figure 3. Digital 3D model of the target shape (face) (a) and its negative 3D image (b).

2.3 Tool path programming

Tool path (or NC) programming creates the machining path points to gradually form the desired shape out from the mould preform. Tool path programming was made using a block model of the mould preform and the target mould profile with the negative face profile as inputs to the NC programming tool, ABB RobotStudio®, Machihing Power Pac [5]. The paths were created by correlating the source geometry (mould preform) and target geometry (mould target surface profile). In addition, the machining path type, approach directions, and overlapping were given. The form of the resulting paths was in RAPID language, ready to be used in the simulator tool or in ABB robots.

2.4 Post processing

Basically post processing would convert the NC program generated by the CAM SW to the robot program. In our case, during the tool path programming the results were already automatically post processed by the ABB RobotStudio®, Machining Power Pack tool to the robot program format, i.e. RAPID robot program language. The generated machining path included ca. 10000 path points. This needed to be converted, to the target language of our robot, i.e. KUKA KRL and also divided to smaller path segments with max size 500 path point per a segment. This was done using our proprietary converter tool SW running on MS Windows PC.

2.5 Simulation

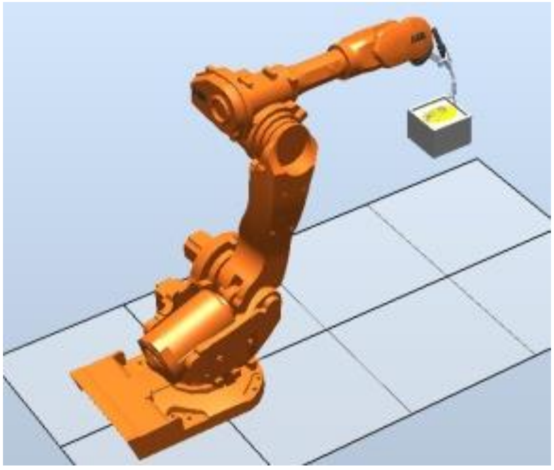


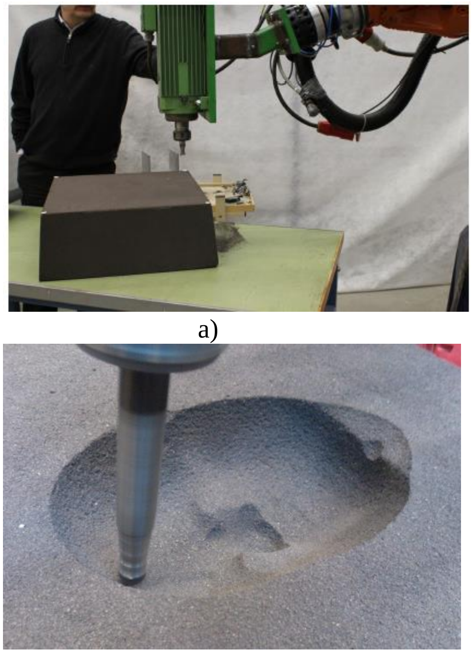
Figure 4. Simulation of the robot machining paths in ABB RobotSudio® software

The post processed paths from the ABB RobotStudio®, Machihing Power Pac were simulated in the RobotStudio® to check the feasibility of the paths wrt. reachability and joint constraints (Figure 4). The initial values for the mould fixture position as well as TCP correction were also included in the simulations. The exploitable axis configurations of the robot were checked including approaching and departure points. For the test object no change was necessary for the paths.

3 Robot Task Execution

After getting post-processed CAM data as a robot program or parts of the robot program as path segments, the robot requires two variables to be defined to be able to utilize results of locating measurements of the target object. First one is the actual location for the work object which can be defined by teaching or measuring it in robot coordination system. Second one is exact definition for tool centre point (TCP) which is defined by 6 or 7 parameters from robot flange (x,y,z, ,a,b,c for KUKA robots, x,y,z,q1,q2,q3,q4 for ABB robots).

Our robot is equipped with a milling tool spindle attached to the end of the wrist. This kind of milling tool is rather heavy requiring a big and rigid robot able to move the tool accurately. The mould preform was introduced to a fixture in the robot cell and calibrated values of the mould preform location and TCP were set into the machining program of the robot. The mould preform was composed of hardened sand, Figure 5a.



a)

b)

Figure 5. Robot starting the mould milling (a) and resulting mould shape (b).

The robot machined the final shape to the mould, Figure 5b. During machining the pull-out loose sand material was removed manually with a vacuum cleaner. Running the machining path with ca. 10000 points took place about 30 minutes.

4 Casting of concrete objects

When the mould is complete, the mould surface must be coated with a substance like spackle so that the concrete would not adhere to the mould. Coating with spackle was most promising in our experiment to prohibit concrete sticking in the hardened sand. After the mould was milled and coated the concrete was poured into the mould. Thereafter the concrete was dried the casted object removed from the mould. In the case some spackle remains on the surface of the casted object, the spackle can be removed with a water spray. In this way the object is clean and gets its distinctive shape. The method was demonstrated in our laboratory by casting several concrete blocks (an example in Figure 6). The experiences clearly show that this method makes it possible to automatically produce distinctive building elements including curved or plentifully changing straight shapes. In our case we used only one milling tool with a substantially large end radius, and this resulted in smoothened details in the mould surface, also seen clearly in the casted concrete object surface. However, using tools with smaller end radius more details can be brought up to the final shape.

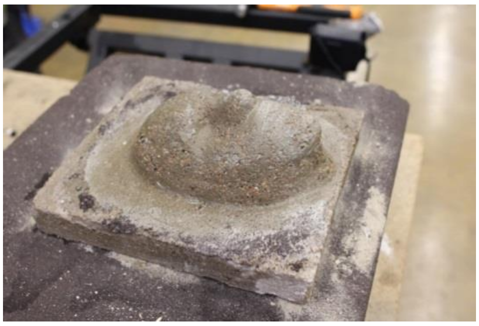


Figure 6. A casted concrete object with specific curved shapes of the target.

5 Conclusions

In this paper we have described a robotized method with example castings for manufacturing individual concrete elements with specific shapes. Robotized methods require a digital model of the object for manufacturing individual concrete elements. In the case of new buildings the detailed design model can be taken directly from designers or more generally, from a construction planning tool such as Building Information Model (BIM) is today. In prefabrication BIM can be exploited in the manufacturing of components e.g. to give component dimensional information for automatic fabrication of moulds with required shapes and openings. Regarding old buildings which do not usually have BIM, the digital model can be produced by scanning the exciting piece with a 3D sensor, like a laser scanner. After scanning the path planning and programming SW tools will be used to generate target 3D models for further programming and planning phases.

Digital fabrication of customised structures of buildings or even the whole frame of the building and unique designs of shapes or surface decorations are one promising area of robotics in construction. Although the example presented here is still under research, it has its prerequisites in some applications to be commercialized. At first these kinds of products will be niche products, but they will become more common. These kinds of diverse casted concrete blocks will enter the construction marked when producing concrete decorations to pillars or columns or making concrete seats or garden decorations.

6 Acknowledgements

The authors would like to thank the VTT Technical Research Centre of Finland for giving the opportunity to do this survey study. The authors would also like to thank Mr Ville Lämsä and Mr Matti Annala for their assistance in programming and robot machining tests.

References

[1] Veenendaal D, West M. and Block P. History and overview of fabric formwork: using fabrics for concrete casting. 2011 Ernst & Sohn Verlag für Architektur und Technische Wissenschaften GmbH & Co. KG, Berlin, Structural Concrete 12 (2011), No. 3. pp. 164 – 177.

[2] Vähä P, Heikkilä T, Kilpeläinen P, Järviluoma M and Heikkilä R, Survey on automation of the building construction and building products industry. VTT TECHNOLOGY 109, Kuopio 2013, ISBN 978-951-38-8031-6, p. 82.

[3] Bock, T. Construction Automation and Robotics. In: Robotics and Automation in Construction, In-Tech, October 2008, Croatia. Pp. 21–42.

[4] Rusu, R B, and Cousins, S, 3D is here: Point Cloud Library (PCL) International Conference on Robotics and Automation, 2011, Shanghai, China, (2011).

[5] RobotStudio® Machining PowerPac, Increased engineering efficiency within machining applications. Data sheet, ABB 2014, 2 pages.