Strategic optimization of 3D concrete printing using the method of CONPrint3D®

M. Krause[a], J. Otto[a], A. Bulgakov[b] and D. Sayfeddine[c]

[a]Institute of Construction Management, Technical University of Dresden, Germany
[b]Institute of Construction Management, Southwest State University, Kursk, Russia
[c]Dept. of Mechatronics, South Russian State Polytechnic University, Novocherkassk, Russia
E-Mail: martin.krause3@tu-dresden.de, jens.otto@tu-dresden.de, a.bulgakow@gmx.de, daher@live.ru

Abstract –
The resource efficiency and labor productivity in the construction industry are still viewed critically. Concrete 3D-printing processes have the potential to significantly improve both factors. Currently, research activities in this field are growing rapidly worldwide, thus similar advances and market developments can be expected, as have already occurred in other sectors of the stationary industry. The TU Dresden relies on the development of the CONPrint3D® (Concrete ON-site 3D-Printing). It specifically relies on: established machine technology, the production of fully filled concrete structures, sustainable concrete formulations with a maximum grain size of up to 16 mm and the use directly on the construction site. In contrast to small-scale 3D-printing processes, the data processing chain for large-format 3D-printing with concrete still has considerable deficits. In order to depict the complex solidification properties of the building concrete, computer simulations are indispensable as a basis for the development of an optimized printing strategy. In this paper, investigations on the strategic process optimization of concrete printing using the method CONPrint3D® are presented. First, the relevant boundary conditions of concrete 3D-printing are described. Subsequently, calculation methods of the trajectory planning are presented.

Keywords –
3D-printing; Concrete; Optimization; Simulation; Continuous path control

1 Introduction

The concrete installation directly on the construction site is very labor-intensive and time-consuming. The costs of formwork accounts for a high proportion of the shell costs, at around 25 % to 35 %, and the construction period is largely determined by the formwork. [1] As a result, the development of a construction method without any formwork, which uses continuous 3D concrete printing, can yield great savings. In other industries, such as medical or aerospace industries, 3D printing technology has developed rapidly in recent years and is now being used not only for prototyping, but also increasingly for the manufacturing of marketable components.

Experts agree that the use of 3D printing technology in construction offers both significant economic potential and new architectural design. Economic considerations for CONPrint3D® resulted in cost savings of around 25 % and four to six times shorter execution times compared to conventional masonry construction. [2]

Compared to the stationary industry, the boundary conditions are completely different for computer-aided manufacturing in the construction industry. Changing environmental conditions (such as site location, subsoil characteristics or environmental impacts) makes it difficult to introduce automated production methods on site. The increasing digitization and establishment of new planning methods, such as Building Information Modelling (BIM), can ease the introduction of automated processes on construction sites. A BIM model already contains all the data necessary to control the machine technology. The BIM data only has to be prepared for an optimized construction process and converted into data formats which are readable for the machine.

The key process in data preparation is the "slicing" of the 3D model. The term means the division of the 3D object into two-dimensional layers having a defined layer height. While slicing the structure, important input parameters are defined for the printing process, such as the printing paths, printing speeds or the material discharge quantity. Subsequently, a machine control code, usually in the form of a G-code, is outputted. The optimization of the printing strategies is extremely relevant to ensure the efficiency of the process. The construction process is usually computer simulated before printing.

This paper discusses the 3D concrete printer as a robotic platform based on CONPrint3D®. In the 2nd section, the concept is presented. In the 3rd section, design requirements are described. In the 4rd section calculation methods of the trajectory planning are presented. The 5th section gives a small outlook.

2 CONPrint3D® Concept

Since 2014, an interdisciplinary team at TU Dresden has been researching the development of an innovative concrete construction process. Based on the principle of extrusion, load-bearing building structures are to be continuously produced by 3D shaping fresh concrete. Figure 1 shows the main components of CONPrint3D®.

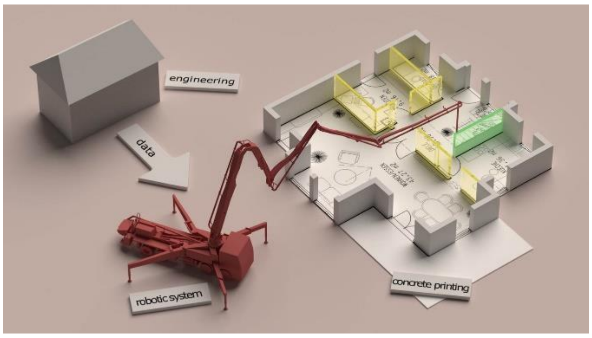


Fig. 1: Essential components of the concrete 3D printing process CONPrint3D®

As a mechanical platform, a modified truck-mounted concrete pump is used. Additional control technology and a newly developed print head ensure the continuous extrusion of the concrete and the geometrical precision on the construction site. The basis of the control process is a BIM-based planning. The necessary control data in the form of geometric data and material data are extracted from a 3D building model, then processed and transferred to the modified concrete pump. This allows the direct implementation of a previously created concreting plan in the machine control for automated movement. At the end of the geometrically precise distribution boom, the fresh concrete from the print head is laid out layer by layer with lateral shaping elements (see Figures 2,3). This is how the building is constructed using the layering principle.

Fig. 2: Geometrically precise installation of the concrete by modified truck-mounted concrete pump

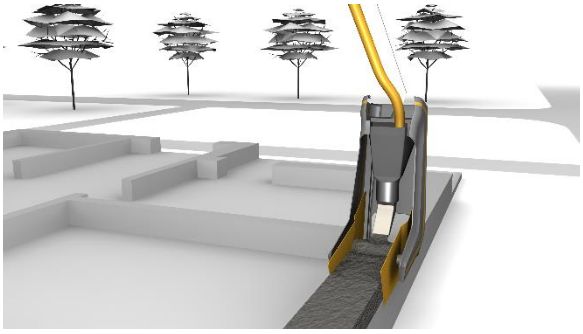


Fig. 3: Extrusion-based installation of fresh concrete using a newly developed print head

The research activities are clearly different from other global development work. The basic principles of the CONPrint3D® process are:

1. The execution takes place directly on the construction site (in-situ concrete construction).
2. The machine base represents a construction machine established on the market: the truck-mounted concrete pump.
3. Concretes with a maximum grain size of aggregates of up to 16 mm are used for the process.
4. Monolithic, fully filled concrete structures are created.

The research team of the TU Dresden consists of three institutes. The Chair of Construction Machinery handles the mechanical implementation. The Institute of Building Materials develops the special concrete technology. The economic implementation on the construction site and the productivity of the application as well as an optimized data management are ensured by the Institute for Construction Management.

Within a theoretical study, the feasibility of all three areas was initially ensured. Within laboratory tests on a scale of 1: 5 (see Figures 4 and 5), suitable concrete

Fig. 4: Concrete technological extrusion trials on a scale of 1: 5

Fig. 5: Printed concrete components for the investigation of the layer composite

recipes were developed, decisive strength values determined and the layer composite investigated. More detailed results are included in further contributions of the research team [2, 3, 4, 5, 6].

In a primary development step, CONPrint3D® aims to produce unreinforced concrete structures. The integration of reinforcement elements and other materials (eg. TGA installations, plaster or thermal insulation) is planned only in the long-term development. First of all, CONPrint3D® focuses on producing unreinforced walls directly on the construction site in order to replace traditional masonry and drywall construction. Thus, the main field of application of CONPrint3D® is in residential construction.

3 Design requirements

In the literature, Additive Manufacturing (AM) methods are often referred as 2½-D methods. The layers are generated in the x-y plane, the so-called printing plane. The layer thickness is usually constant. This creates the third dimension in the z-direction only by the superimposition of the individual layers. [7]

CONPrint3D® is characterized by the fact that the wall cross-sections are completely filled with concrete by a driving movement. In addition, sharp-edged 90° corners are to be generated. In other research activities, smaller concrete strands are printed resulting in round corners with small radii. The different methodological approaches are compared in figure 6.

In order to produce wall connections with CONPrint3D® in a force-fitting manner, conventional solutions already exist in masonry construction, which can be transferred. Accordingly, there are fundamentally three ways to produce force-fitting wall connections:

- Constructive gearing by alternating layer arrangement,
- Surrounding of the walls to be connected,
- Connection by stainless steel flat anchor systems.

Fig. 6 left: Approach of CONPrint3D®
right: Extrusion of smaller concrete strands with round corners and subsequent concrete filling [8]

The examination of the geometric requirements reveals that three different categories of wall connections can be distinguished:

- Corner joints,
- T-connections,
- Intersections.

In this article, the constructive execution of corners is to be considered more closely. The non-positive wall connection should be made by constructive gearing. Table 1 describes the printing structure of force-fitting corners.

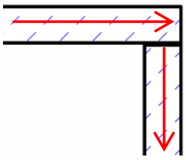
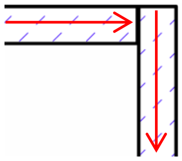
Wall connection	Layer 1, 3, 5, …	Layer 2, 4, 6, …
Corner		

Table 1: Printing-strategy to produce a force-fitting corner

In order to produce a force-fitting corner connection by constructive gearing, two different printing paths are required, which repeat alternately over the entire wall height. In contrast to other global research activities, which track strands pressure, only one printing path is to be developed, thereby followed in every layer.

In order to create a wall corner connection with the given geometry of the CONPrint3D® printhead (see Figure 7), certain movements must be considered. This is illustrated in figure 8.

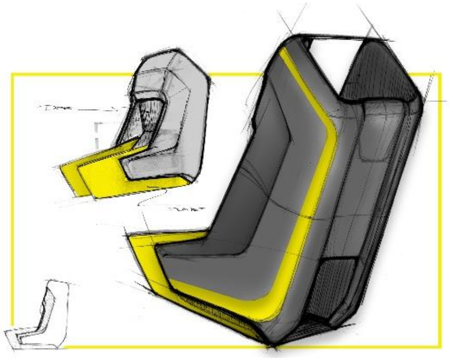


Fig. 7: Design of the printhead [3]

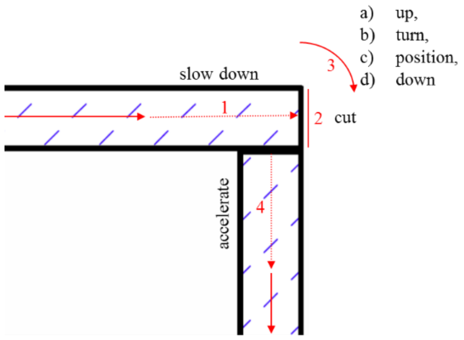


Fig. 8: Movement of the printhead at a corner

In the area of the recesses (door and windows) no material is discharged. The soffit is realized by a) decelerating, b) Cutting off the concrete, c) Driving without material discharge, or d) accelerating with material discharge. Above the windows, a prefabricated lintel is inserted similarly to the masonry construction. The layer height depends on the nozzle opening and the printing materials. With CONPrint3D®, layer heights of 5.0 cm can be reliably achieved.

4 Planning the Trajectories of the Printer

The task to develop the trajectories of the end effector motion of a manipulator is reduced to describing a sequence of motions in the plane X_P, Y_P parallel to the plane X_0, Y_0 of the robot coordinate system. The Z_P coordinate does not change within one stacking cycle, and then increases by an amount Δh, corresponding to the thickness of the stacked layer.

Figures 9 and 10 show examples of floor plans for different monolithic objects. As can be seen from the diagrams in figures 9 and 10, the trajectories of motion are either a set of rectangles or circles. When constructing the static frame of an apartment house (see Figure 9), it is necessary to formulate an array of coordinates of points on the basis of the building plan and to determine the sequence of traversal of rectilinear sections.

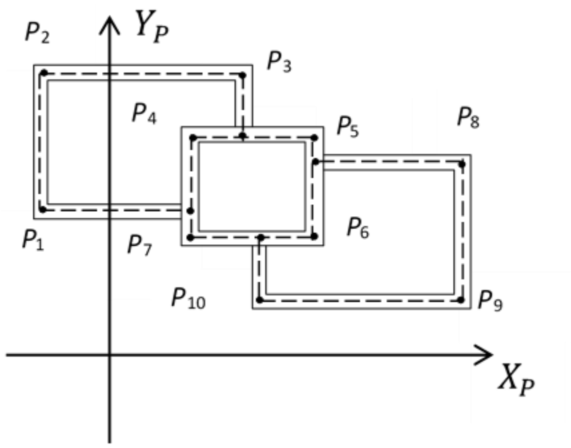


Fig. 9: Static frame of an apartment house and the trajectory of motion of the end effector

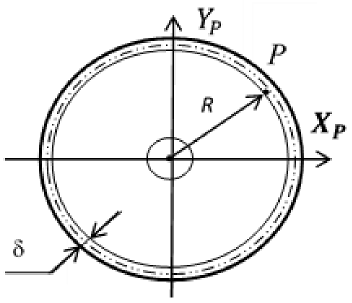


Fig. 10: Plan for a monolithic tower and the trajectory of motion of the end effector

Each section can be described by equations of the form:

- for sections parallel to the X-axis

$$X_0 \to P_{jS}(x_{jS}, y_{jS}), P_{jE}(x_{jE}, y_{jE})$$

$$y = y_{jS} V y_{jE} \to x_{jS} \le x \le x_{jE}; \qquad (1)$$

- for sections parallel to the Y-axis

$$Y_0 \to P_{iS}(x_{jS}, y_{jS}), P_{iE}(x_{jE}, y_{jE})$$

$$x = x_{iS} V x_{iE} \to y_{iS} \le y \le y_{iE}. \qquad (2)$$

When building tower-type structures, the printer is placed on a telescopic carrier platform in the center of the structure. Therefore, its trajectory is a circle (see Figure 10) of radius R_{0P} lying in the horizontal plane X_P, Y_P:

$$(x - \Delta x_{0P})^2 + (y - \Delta y_{0P})^2 = R_{0P}^2,$$

where $\Delta x_{0P}, \Delta y_{0P}$ – is the deviation of the load-bearing platform from the design axis of the erected structure. These parameters are automatically controlled by laser control systems and are entered into the robot control system. Planning of movements of robots is performed in generalized coordinates. This means that for each section of the trajectory of the nozzle, it is necessary to obtain a temporal law of variation of each generalized coordinate of the manipulator, which provides the required motion, i.e. it is necessary to formulate for each sector a vector

$$q(t) = [q_{1i}(t), q_{2i}(t), \dots, q_{ni}(t)],$$

where i is the number of the trajectory section and n is the number of degrees of freedom of the manipulator.

Solving the tasks of movement planning of the working body for manipulation robots with a nozzle on the final link is performed in the following sequence. In the general case, at the beginning of the task, it is necessary to formulate the laws of the change in the time of the position and orientation of the working member and the speed of its movement:

$$\begin{cases} tr_i(t) = [x_i(t), y_i(t), z_i(t)], \\ v_i(t) = [v_{xi}(t), v_{yi}(t), v_{zi}(t)], \\ \psi_i(t) = [\theta_i(t), \varphi_i(t), \beta_i(t)], \\ \omega_i(t) = [\omega_{\theta i}(t), \omega_{\varphi i}(t), \omega_{\psi i}(t)], \end{cases} \quad (3)$$

where $tr_i(t), v_i(t)$ – are the position and velocity vectors at the current time t when moving on the i-th section of the trajectory; $\psi_i(t), \omega_i(t)$– are the orientation and angular velocity vectors on the i-th section at time t.

The above equations can be directly used to obtain the temporal laws of variation of generalized coordinates. However, in most cases, this problem is unsolvable in explicit form. Another important use of equations (3) is the accuracy control of the result by means of the degrees of freedom. In the general case, any rectilinear portion of the trajectory of the grasping movement with uniform motion at a speed $v_i = \lfloor v_{vi}, v_{yi}, v_{zi} \rfloor$ can be described by the vector:

$$tr(t) = \begin{bmatrix} x_S + v_{xi}t \\ y_S + v_{yi}t \\ z_S + v_{zi}t \end{bmatrix} \rightarrow \begin{bmatrix} x_{Si} \le x_i \le x_{Ei} \\ y_{Si} \le y_i \le y_{Ei} \\ z_{Si} \le z_i \le z_{Ei} \end{bmatrix}, \quad (4)$$

where x_{Si}, y_{Si}, z_{Si} – are the coordinates of the starting point of the trajectory; x_{Ei}, y_{Ei}, z_{Ei} – are the coordinates of the trajectory end-points.

When planning the movements of concrete printers along rectilinear trajectories, the areas can be in the form of arcs of a circle. A characteristic feature of building robots is that the working planes are usually parallel to the planes X_0Y_0 (P_{XY}) (see Figure 11).

Consider the basic relations for the description of movements. When the robots operate in the plane parallel to the plane Z_0X_0, the motion along the arc of the circle is described by a system of equations of the form:

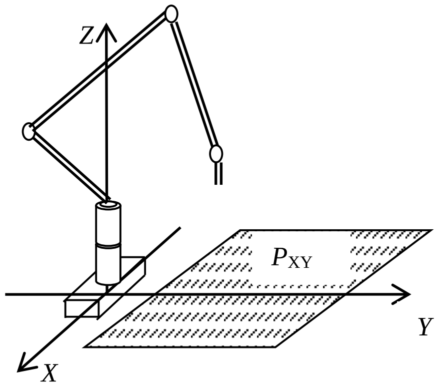


Fig. 11: Location of the working surface in the robot coordinate system

- option 1

$$\begin{cases} x = x_r + R\ \sin\omega t \\ y = y_r = const \\ z = z_r + R\cos\omega t \end{cases} ; \begin{cases} v_x = \omega R\cos\omega t = v\cos\omega t \\ v_y = 0 \\ v_z = -\omega R\ \sin\omega t = v\ \sin\omega t \end{cases}$$

$$\rightarrow 0 \le \omega t \le \pi; \quad (5)$$

- option 2

$$\begin{cases} x = x_r + R\ \cos(\pi - \omega t) \\ y = y_r = const \\ z = z_r + R\sin\omega t \end{cases} ; \begin{cases} v_x = v\ \sin\omega t \\ v_y = 0 \\ v_z = v\ \cos\omega t \end{cases} ;$$

$$\rightarrow 0 \le \omega t \le \pi; \quad (6)$$

where R – is the radius of the trajectory section; ω – is the angular velocity of motion; x_r,, y_r, z_r – are the coordinates of the center of the circle. If the motion is carried out in the plane X_0Y_0, then it is described by a system of equations of the form:

- option 1

$$\begin{cases} x = x_r + R\ \sin\omega t \\ y = y_r + R\cos\omega t \\ z = z_r \end{cases} ; \begin{cases} v_x = \omega R\cos\omega t \\ v_y = \omega R\ \sin\omega t; \\ v_z = 0 \end{cases}$$

$$\rightarrow 0 \le \omega t \le \pi; \quad (7)$$

- option 2

$$\begin{cases} x = x_r + R\ \cos(\pi - \omega t) \\ y = y_r + R\sin\omega t \\ z = z_r \end{cases} ; \begin{cases} v_x = \omega R\sin\omega t = v\sin\omega t \\ v_y = \omega R\cos\omega t = v\cos\omega t \\ v_z = 0 \end{cases}$$

$$\rightarrow 0 \le \omega t \le \pi; \quad (8)$$

In many cases, when planning the movement of the manipulator after describing the trajectory of motion in the form (4), the length of the trajectory or the path of motion is determined. In the case of rectilinear sections, the coordinates of the boundary points are $P_S^{(i)}, P_E^{(i)}$:

$$l_{tr}^{(i)} = \sqrt{\left(x_E^{(i)} - x_S^{(i)}\right)^2 + \left(y_E^{(i)} - y_S^{(i)}\right)^2 + \left(z_E^{(i)} - z_S^{(i)}\right)^2} \quad (9)$$

where i – is the number of the section. For arcs of a circle lying in the plane X_0Y_0, based on the coordinates of the boundary points $P_S^{(i)}, P_E^{(i)}$ and the arc radius R, the length of the trajectory l_{tr} is calculated in accordance with the equation:

$$l_{tr}^{(j)} = \int_{x_S}^{x_E} \sqrt{1 + y(x)}\, dx \ \rightarrow \text{plane } X_0Y_0. \qquad (10)$$

In the general case, when the trajectory section is curvilinear and described by the equation of a plane curve $f(x, y)$, then the trajectory length is calculated as an integral:

$$l_{tr} = \int_{x_S}^{x_E} \sqrt{1 + df(x)\,/dx}\,, \qquad (11)$$

where $df(x)\,/dx$ – is a continuous derivative of a function on a section $x_S \leq x \leq x_E$. For a spatial curve given in parametric form

$$x = x(t), y = y(t), z = z(t) \rightarrow t_S \leq t \leq t_E,$$

the length of the trajectory is expressed by the formula:

$$l_{TR} = \int_{t_e}^{t_s} \sqrt{(x(t))^2 + (y(t))^2 + (z(t))^2} \qquad (12)$$

The total length of the trajectory consisting of n sections is defined as the sum of the lengths of these sections:

$$L_{tr} = \sum_{e=1}^{n} l_e$$

Knowing the length of each section of the trajectory, and the technology-limited speed of their execution, the time of passage of each section and the whole trajectory as a whole is estimated preliminary:

$$T_{tr} = \sum_{e=1}^{n} t_e = \sum_{e=1}^{n} \frac{l_e}{v_e}$$

Having planned operations at the seizure level or tool, it is necessary to build a program for changing the generalized coordinates of the manipulator and at the same time to verify the practical feasibility of the planned movements on each section of the trajectory. When planning in Cartesian coordinates, on the basis of the dependences $tr(t)$, $v(t)$, the values of the generalized coordinates $q_i(nT)$ at discrete instants of time, as well as the velocities $\dot{q}(nT)$, which are used to form the control actions in the next control step are determined. However, this approach requires, at each step of the control, the solution of inverse kinematics problems and significant computer time, which does not always allow real-time operation of the control system. In this regard, when controlling the robot, it is recommended that the motion planning be performed in generalized coordinates. In this case, for each boundary and node points of the trajectory, on the basis of the solution of the inverse position problem, generalized coordinates characterizing the configuration of the mechanism at these points are determined. For each coordinate, the constraints and realization of movements are checked by the executive-level management system. Planning of movements in this case ends with the construction of functions $q_i(t) \rightarrow i = 0,1,2...,n$ with the necessary condition $q_i(t_j) = q_i^{(j)}(j = 0,1,...,m)$. In this case, the planning is carried out in real time and the controlled variables are directly generated.

The planned trajectory $q_i(t) \rightarrow t_S \leq t \leq t_E$ forms a continuous path of movement for the manipulator arm. Continuity and fluidity of the tool movement are mandatory requirements for the movement of the robot. When robotizing this operation, one needs carefully to plan not only the movement of the tool, but also its speed and acceleration of movement [9,10].

5 Summary and Outlook

Concrete 3D printing processes have high economic potential. Initial cost-effectiveness considerations for CONPrint3D® are likely to result in building cost savings of approximately 25 % and significant reductions in execution time compared to conventional construction methods. In the first part, the article dealt with the special features of CONPrint3D® and considerations on the motion profile of the printhead. In the second part, mathematical basics of the Trajectory Planning of the Printer were presented.

The path planning is carried out taking into account the restrictions on the continuity and smoothness of the trajectory and also in accordance with a given set of constraints on the position, speed and acceleration of the generalized coordinates at the reference points of the trajectory. When solving the problem of planning the trajectories of motion, sections of acceleration and braking of the printhead are provided. Planning of the trajectory is carried out in space and time, which ensures the passage of the printhead the nodal points of the working space at a given time period. The solution of the planning task is determined by the appointment of the robot, its kinematic characteristics, performed by the technological operation and the technical environment conditions.

In order to achieve the process-reliable construction site application, adapted 3D printing strategies have to be developed and implemented in a continuous digital process chain. Digital data preparation and processing is currently not ready for application. As part of the research project digiCON^2 (digital CONcrete CONstruction), an adapted data management system for CONPrint3D$^{®}$ is being developed (duration 01/2018 to 12/2019, funding provider: Federal Ministry of Education and Research). The aim of the international research project is to complete the digital process chain from BIM to machine-specific optimized G-Codes. At the Technical University of Dresden, research will continue to be carried out in order to achieve the goal of construction site application.

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