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A new robotic spray technology for generative manufacturing of complex concrete structures without formwork

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Abstract

The robot-assisted manufacturing is introduced for many years in automated production areas, while the production of buildings still follows the traditional manual process. Using new possibilities of digital planning the construction industry demonstrated potential for the implementation of freeform architectures, which are only possible using expensive and only once usable formwork structures. This paper focuses on sprayed concrete technology for automated production processes to build up freeform concrete components. A study case of the production of a concrete wall by an industrial robot, equipped with a concrete spraying tool is presented in order to investigate the possibilities and tolerancing issues of this technique.

Keywords: generative manufacturing; concrete spraying; free form; formwork; robotic fabrication; digital process chain.

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1. Introduction

Sprayed concrete technology exists in Germany since the 1920s. The main fields of application are tunnel construction, rock stabilization and strengthening of old concrete parts. This technology could be used to produce freeform concrete structures for modern buildings.

While the current discussions in industrial production concern future developments of the subjects "industry 4.0", which means networking of production techniques, the so-called "smart factory" and the "human-robot cooperation", the construction industry has not even arrived in industry 3.0.

The digital revolution has indeed taken place in the construction planning offices in the form of powerful design, calculation, construction and simulation software. However, on the worksite high-quality materials and semi-finished products are still set "stone-on-stone" to each other or "seam-for-seam" welded together. These procedures incur large losses in quality and cost-intensive work processes. The practical construction is still dominated by standard system formwork, which means flat formwork elements to produce simple and mostly planar components such as walls. This discrepancy between the possibilities and complexity in the digital planning of sophisticated concrete structures and what can be implemented on site has been increasing steadily the last years.

A basic requirement to implement resource-efficient construction is an enhanced component performance through the interaction of external form and internal material structure. To achieve this component performance, it is necessary to provide a powerful manufacturing technology. In this paper the idea of the automated manufacturing of freeform concrete structures for modern buildings by utilizing spray concrete technology is introduced. This process should be explored in the future in a research facility which is currently under construction at TU Braunschweig. It consists of two portals, one with a concrete spraying industrial robot and another to carry a dynamic formwork.

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To approach the proceeding the state of the art shows the history of sprayed concrete and already realized building components. In this context the new research facility and its application is introduced. Finally, practical experiments validate the use of the robot assisted concrete spraying system.

2. State of the art

Sprayed concrete or “shotcrete” is a concrete which is conveyed in a closed tube line to a nozzle, from where it is pneumatically sprayed onto a surface and compressed by the impact energy. The shotcrete process is often referred to as "Torkretieren". The term has its origin in the German engineer Carl Weber who first registered the shotcrete process patent in Germany and founded the company Torkret in 1919. Aggregates, cement and water are transported with compressed air and sprayed onto a surface (Figure 1). The three steps conveying, compacting and the application procedures are performed in one operation [1].

Figure 1: „Torkretieren“ of a road in 1926 [Torkret GmbH]

Nowadays “shotcrete” is mainly used for the retrofit of concrete structures, facades and rehabilitation of historic concrete structures, as well as for rock consolidation and temporary support in tunneling systems. In addition to these conventional application areas there have been hardly any exploration into new areas of application, despite the advantages and potentials that shotcrete brings with it. The reasons for this lie mainly in the traditional manual process of spraying. To achieve good results, a high level of experience in the movement and usage of the tool as well as the suitable material mixture is required. Often too much or too little material is applied and sometimes the concrete composition of the coating layers is not particularly homogeneous. The attainable qualities in terms of geometric accuracy, as well as the visual and haptic surface qualities are significantly lower than those of poured concrete are.

The great advantage of the spraying process lies in the flexibility of the application, in particular in the production of complex geometries with thin material layers. The construction company of engineer Ulrich Müther has applied the sprayed concrete technology for various shell structures as well as for the construction of bobsleigh runs. For the construction of the bobsleigh run in Oberhof (Figure 2) concrete was sprayed on separate curve sections of wire grating without using a mold. A very fine mesh size was used in order to prevent the concrete mass from slipping down the inclined surface. This technique was so convincing that shortly thereafter all tracks were built in this method.

Figure 2: Shotcrete method used for the construction of the bobsleigh run in Oberhof [Torkret GmbH]

Many domes, like the planetarium in Wolfsburg, were produced with the shotcrete method. On a self-supporting and reinforced rod network, a tightly woven wire mesh was braided. The concrete was applied with the wet spraying technique in layers and in ring formations without the use of additional formwork, Müther [2].

Another recent example in manual concrete spraying for freeform architectures was tested at the TU Vienna [3]. With the help of pneumatically-assisted molding as semi-permanent formwork, sculptural forms were produced. A newly developed concrete recipe made it possible to cover the air cushion with a thin layer of concrete and thus produce viable concrete sculptures.

As formwork is immanent for the process of spraying concrete, it is necessary to take another technology in consideration. With the method of “slip forming” (Figure 3) a dynamic formwork is used instead of static formwork.

Figure 3: Slip forming of rain water drainage [5]

The formwork is moved hydraulically to extrude complex concrete elements in a continuous production process on a building site. The concrete is poured, simultaneously consolidated and finished with a high surface quality and low tolerances. The investment into complex constructions for formwork can be dramatically reduced by this method and significant time savings can be realized. This technology is widely used to generate horizontal or vertical structures such as chimneys, columns, walls, multi-story buildings and street pavements. As the machines for this process are constructed for specific geometries with a preset profile, they cannot be adapted to generate freeform shapes. At the ETH a first approach has been done to combine a robot with a dynamic slip form to generate columns [4].

The developments in generative processes in the field of concrete construction related to printing processes where concrete structures are built up in layers from bottom to top are presented in Lim et al. [6]. Classic layer-based printing processes can produce concrete components without scaffolding and free from any necessary mold. With this method, concrete can be applied differentiated by the distribution of hollow chambers. Material is used where it is needed structurally. The limitations of this method are, as with all layer printing methods, problems in the production of high-quality surfaces, in the integration of necessary tensile reinforcement and the anisotropic component behavior created by the layering process.

The present project described in this paper will build on the exploration of existing manual processes for concrete spraying and is aiming to develop it further towards an automated, generative method. The objective is to enable new and forward-looking perspectives in the field of generative construction methods. By combining spraying technology and slip forming technology the geometrical limitations of static formwork are aimed to be overcome. While generative processes are established in mechanical engineering, in the building construction industry basic research is still necessary to achieve the described application procedure. The reasons for this lie in long process cycles, complex component requirements, major component dimensions and lack of process chains. As first generative research, efforts tend to mono-functional processes like 3D layer printing the focus of this project is on the development of combined processes and methods for the generative fabrication of effective graduate material systems without the need for further formwork. As in traditional applications of sprayed concrete on site, the inhomogeneous surface qualities are acceptable for industrial prefabrication of architectural elements a new process has to be developed to get high surface qualities with low tolerances.

3. Steps towards automated freeform spraying of concrete

At TU Braunschweig a research facility is planned to transfer advanced production technologies from car and plane manufacturing into the building industry. It is planned as a near market system and combines proven and affordable fabrication technologies to a high performance system. This system is capable to handle very complex processes cooperatively and works well at rough environmental conditions. By combining flexible robotic components and precise and robust machining systems, a huge bandwidth of applications will become available for the building industry. The facility will be unique in its capabilities and will have a great impact on the future fabrication of architecture. Although one of the first processes, besides low tolerance milling processes, will be the additive concrete spraying of architectural elements in cooperative operation of the two portals, the future use of the facility will be much more flexible in exploring materials and procedures.

Figure 4 shows the design of the research facility with its two portal structures sharing one square workspace with the dimensions of 9m x 17m x 3m. The left Portal is a stiff 5-DOF linear robot with an integrated milling head. The right Portal has 9-DOF with 3 linear Axes combined with a commercial 6 axes industrial heavy payload robot of Co. Stäubli. The kinematic of the this portal will be very flexible when it comes to such complex spraying operations and allows the operator to control on the one hand the distance between tool and part and on the other hand the orientation of the tool. In addition to the kinematic structure, the system consists of a highly adjustable concrete pump that provides the needed amount of concrete and a cleaning system that reclaims the used water.

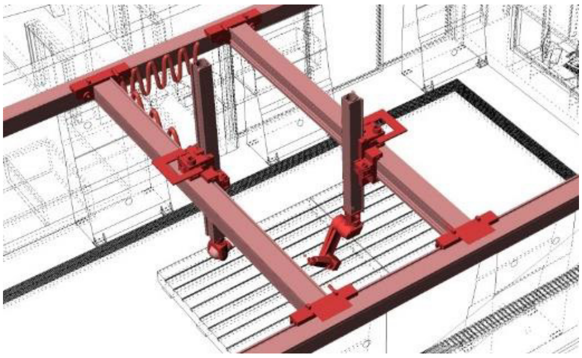

Figure 4: Design of the research facility at TU Braunschweig

The biggest challenge in this purpose is to handle with low viscosity of sprayed concrete and the necessity of a fast curing at a certain point on the component. To meet this challenge many different sensors are included, for example a short range 3D-laser triangulation scanner is combined with a 3D vision system to measure the surface finish of the manufactured part. In addition to that the machine controller uses several long range scanners to detect the dimension und the shape of the whole manufactured component (Figure 5). As manufacturing conditions at spraying of concrete are rough all sensory is robust encapsulated.

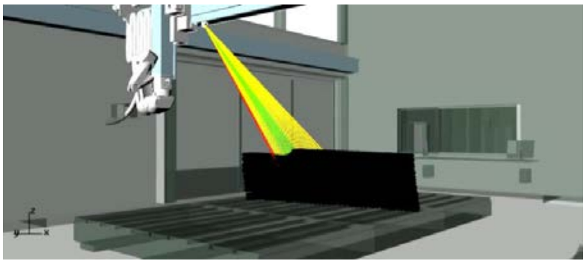

Figure 5: Long range laser scanner on portal structure of research facility

Since, in the initial experiments shotcrete is used, it is necessary to investigate possible occurring component tolerances regarding the dimension accuracy. The reason for this is the highly inhomogeneous material, which is applied in an air stream through an injection mold on a formwork element. Concrete, or in this case shotcrete, is a building material which is produced as a mixture of binder and an aggregate. For the artificially produced rock, the binder cement is often used. The aggregate usually consists of gravel and sand. Adding water causes the binder to react chemically, causing it hardens and a solid, particulate mixture is produced. As the aggregate is a natural product the properties of the concrete mixture differs by charge and has a big impact on the geometrical distribution and tolerances at the target. The evolving challenge is to set the process automatically so that one part of the concrete adheres to the component and on the other hand is sufficiently liquid so that it can be processed in the shotcrete process. The charge based behavior of the material has to be compensated by predictive simulations and an adaptive production process to get low surface tolerances.

3.1. Additive manufacturing of geometrically simple and planar wall elements

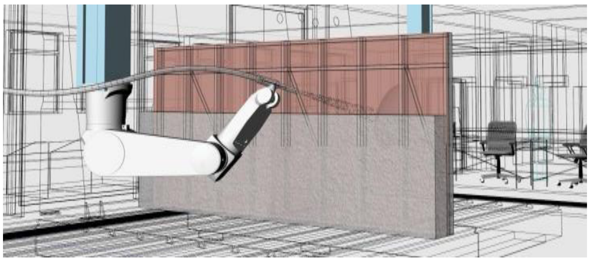

Figure 6: Automatic shotcrete application with flat opposing formwork

The first steps towards a fully automated process, as shown in Figure 6, is the production of geometrically simple and flat wall elements with opposing formwork.

The necessary components such as an automated injection tool (end effector), CAx simulation tools, control (path planning) and material application methods will be developed in close cooperation between interdisciplinary working groups consisting of mechanical and civil engineers. Following the successful integration of all components, first attempts using shotcrete will show the feasibility of this technology. Hereby, layer by layer concrete will be applied to a one-sided shell construction.

Together with these first attempts another main topic of this project is the path planning for the tool itself. Until today a prerequisite for high part quality is the experience of the person who guides the tool. Based on this manual process the aim is to better understand the interaction of the tool, control and path geometry that can be used for more complex and fully automated processes. With well-tuned system characteristics, it is possible to control the tool simultaneously with the path planning and the mixture preparation.

3.2. Additive manufacturing of geometrically simple elements without opposing formwork

Figure 7 shows the second step for the manufacture of concrete structures, which will be the manufacturing of simple elements without opposing formwork. These wall components are developed by integrated simulation tools taking into account the tolerances These tools make it possible to derive path geometries from the model directly.

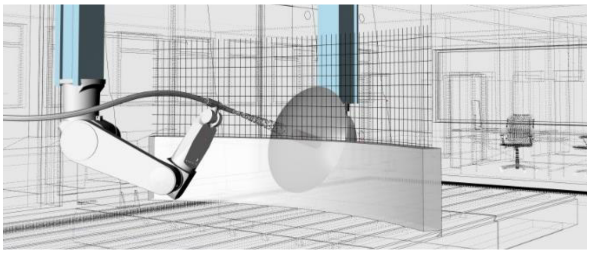

Figure 7: Formwork-free shotcrete application with counter-plate guide

To test the path geometry algorithms, the manufacturing of unilateral curved prototypes is implemented. In this case, a conventional flat and static formwork is not required. Rather, the specific application will be set-up with only using a dynamic plate held by the second kinematic structure of the facility (Figure 7) opposite to the robot. With this, it should be possible to produce arbitrary curved components with different thicknesses. Three different manufacturing strategies will be examined: The first strategy is to apply the concrete purely additive. The second involves the use of knitted textile or web-like support structures. In the third manufacturing strategy a so-called traveling formwork is used, which moves in synchronism with the application process. Based on the results of these production strategies, the best processing method can be evaluated for further research.

3.3. Additive manufacturing of geometrically complex, curved wall elements with high surface quality

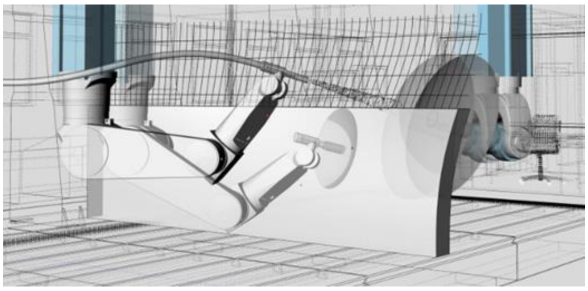

Figure 8: Combined smoothing process of concrete structures

The last expansion stage will be additive manufacturing of geometrically complex and curved wall elements without opposing formwork with high surface quality (Figure 8).

The advantage of a variably adjustable material quantity is studied in simulations and experiments. In process online measurement and verification of actual geometries with the mentioned optical sensors is a crucial aspect of this work, to coordinate the expanded regulation of variable material quantities while spraying. At this point an about two axes curved wall element (s-curve) in 1:1 architecture benchmark can be produced with maximum complexity. To this end, the new generative, formwork less method is used which dispense with conventional solid formwork. A high surface quality with low tolerances are produced through combined mechanical smoothing methods, iterative sensory monitoring of the production process and simulative prediction models of the material behavior.

4. Preliminary experiments for robot-assisted concrete spraying

4.1. Scope of assessment and experimental setup

Preliminary experiments have been carried out in order to evaluate the feasibility of the proposed concept for robot assisted generative manufacturing with shotcrete. The goals of this experiment were to observe the process-properties of robot-assisted shotcrete applications and to study the surface finish and the material application accuracy to gain insight to the measurement and tolerancing properties of this process. The experimental setup is shown in Figure 9. A commercially available industrial robot "UR5", made by *Universal Robots* was equipped with a spray gun using a rubber nozzle with 15 mm diameter. The robot was chosen due to its adaptability and easy implementation for different applications and a CAD/CAM Software interface that was already established for another application. The spray gun was supplied with concrete from a hose with a diameter of 50 mm and a length of 1200 mm connected to a simplified concrete pumping system suitable for laboratory testing. A vertical wooden panel was used as the formwork for the experiments.


Figure 9: Experimental setup for concrete spraying with UR5 robot

The pumping system consisted of a 30 l concrete reservoir, a piston for pressurizing the reservoir, powered by an 80 mm pneumatic cylinder, and valves for manual adjustment of pneumatic pressure. This experimental setup enables the manual adjustment of the concrete mass flow rate with good accuracy. Additionally, an easy exchange of different shotcrete mixtures is possible to rapidly perform several trials. This setting has similar material transportation properties to a conventional concrete pump that will be later used in the large-scale facility.

The spray gun was equipped with an additional valve to inject compressed air directly into the nozzle in order to adjust the material flow behavior exiting the nozzle. During shotcrete spraying, the shotcrete viscosity and the quality and distribution of the applied shotcrete on the formwork was observed. The rebound rate was measured in order to evaluate the influence of path motion and the characteristics of the wet-mix shotcrete (WMS) mixtures. The weight of the material stuck onto a 500 x 500 x 10 mm³ wall area and the material that bounced off were measured using a conventional scale. The rebound rate was then calculated using Equation 1:

$$R = \frac{W_r}{W_r + W_w} \text{ x } 100 \qquad (1)$$

Where R [%] is the rebound Rate, W_r [g] is the weight of the rebound, and W_w [g] the weight of material that was applied on the wall.

4.2. Experimental procedure

Three wet-mix shotcrete (WMS) mixtures were prepared with variable water-to-cement ratio (w/cm) of 0.4, 0.5 and 0.55, with a cementitious content of 2187 kg/m^3, with a maximum coarse aggregate size of 1 mm. The fined-grained shotcrete consisted of Portland cement and quartz sand and was free of shrinkage [7]. The WMS mixtures were prepared using a conventional pug mill mixer suitable for laboratory testing. After 8 minutes of mixing, a good viscosity was reached and the concrete was filled into the reservoir of the pumping system. The spraying experiments were conducted within a period of 10 minutes. At first, manual spraying experiments were conducted in order to find suitable systems parameters. The pressure of the pumping system was varied between 4.0–6.9 bar and the pressure at the nozzle tip between 4.5-6.0 bar. The different WMS mixtures where applied for 80s in circular movement and the quality of applied wet-mix shotcrete was evaluated subjectively (Figure 10).


Figure 10: Surface structure of the dried shotcrete

The adjustment of the process parameters proved to be difficult due to the small process window for shotcrete application. In the laboratory a small aggregate size was used. It is expected, that the difficulty in setting the right process parameters will increase with the aggregate size.

After adjustment of the system parameters, robot assisted concrete spraying was tested. The robot was programmed with a linear path motion, with a superimposed circular component with a diameter of 50-100 mm. One rotation of the circular motion corresponded with 20 mm distance in the linear direction, parallel to the formwork. Additionally, the motion was programmed to position the nozzle perpendicular to the plane of the coating surface. The velocity of the robot was fixed at 200 mm/s.

To apply these movements for more complex freeform shapes a direct "easy to use" interface between the robot controller and the 3D CAD software Rhinoceros/Grasshopper was established. By loading a freeform shape, consisting of a single complex surface, path points for the movement are generated automatically by rows and circular movements are added to the main paths. Parameters as distance to surface, speed of motion and diameter of circular movements can be changed dynamically. The process is simulated offline in the virtual CAD environment and robot commands in UR Script are generated automatically and can be sent to the controller.

4.3. Results and Discussion

The manual adjustment processes to achieve good sprayability resulted in a wet-mix shotcrete mixture with a water-to-cementitious ratio of 0.4 combined with a pressure of 6.5 bar in the pneumatic cylinder of the pumping system. This resulted in the best sprayability in correspondence to the other chosen parameters. Additionally, the best quality of the applied wet-mix shotcrete could be reached with a pressure of 5.2 bars at the nozzle tip. Those parameters were used for robot-assisted concrete spraying. The robot-assisted shotcrete process resulted in a uniform application of the concrete and a heterogeneous concrete structure was achieved.

The surface structure of the finished shotcrete, as shown in Figure 10, was quite rough. It can be seen that, in order to achieve small surface tolerances, additional finishing steps will be necessary. It was possible to program the motion to build a desired shape. Additionally, the process could be implemented with a low rebound rate of about 8%. Despite of the good initial behavior, variations in quality during concrete spraying were observed. This is because a pumping system without a control loop was used resulting in an unequal concrete mass flow. This circumstance had such a great impact, that an influence of the robot’s path parameters on the application quality could not be observed. The Process of robotic shotcrete application was shown to result in an heterogeneous material application. This has to be addressed for the production of components, or at least has to be considered in the design of workpieces for this process.

In summary, our results show that robot-assisted concrete spraying has a great potential for generative fabrication of freeform concrete parts. For further research a concrete pumping system with a more sophisticated control loop has to be used in order to enhance build up quality. Such a system will be implemented in the demonstrated research facility and additional experiment for optimized path motion for generative manufacturing will be carried out.

5. Conclusion and Outlook

This work demonstrated a new technology concept for robot-assisted generative manufacturing of concrete parts. The proposed setup of the combination of a 5-DOF and the 9-DOF portal structure in one workspace will enable complex and flexible manufacturing strategies, which are necessary for generative manufacturing of concrete parts. The proposed manufacturing strategies include formwork-less shotcrete application using a counter-plate guide, automatic shotcrete application for flat opposing formwork and a combined smoothing process for concrete structures.

The feasibility of the proposed concept was validated in an experimental setup using an industrial robot. The robot was equipped with concrete spraying technology and used for generative manufacturing with a flat opposing formwork. A generative manufacturing process with a low rebound rate of about 8 % could be implemented with standard shotcrete mixtures.

These experiments also have shown what kind of challenges have to be faced to get this process completely automated. Especially the heterogeneous material deposition and rough surface structure need to be addressed. As these originate from the sensitivity of the spray process, closed loop process control will be an important topic in the future. We envision a simulation based approach to the material deposition problem: by estimating the material accumulation beforehand and using closed loop control to guide the spraying process it should be possible to achieve smaller part tolerances. The proposed manufacturing technology for large scale production of building members by this tested method is under construction at the Institute of Structural Design in Braunschweig, Germany and will be used for further experiment and a wide span of research projects in near future.

The preliminary investigations showed that the main challenge in developing an automated process for concrete spraying would be a concept to get low surface tolerances by a highly unpredictable production process. As expected conventional optical sensors for inline measuring will get to limits by the rough environmental conditions and new ways of sensorial adaption for the spraying tool as virtual sensors have to be developed. Before the physical concrete spraying the material distribution has to be simulated with a prediction model to get acceptable tolerances.

6. Acknowledgement

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