**ORIGINAL PAPER**

# Cable Robotic 3D-printing: additive manufacturing on the construction site

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**Abstract**
This paper outlines an important step in characterizing a novel field of robotic construction research where a cable-driven parallel robot is used to extrude cementitious material in three-dimensional space, and thus offering a comprehensive new approach to computational design and construction, and to robotic fabrication at larger scales. Developed by the Faculty of Art and Design at Bauhaus-University Weimar (Germany), the faculty of Architecture at the University of Applied Sciences Dortmund (Germany) and the Chair of Mechatronics at the University of Duisburg-Essen (Germany), this approach offers unique advantages over existing additive manufacturing methods: the system is easily transportable and scalable, it does not require additional formwork or scaffolding, and it offers digital integration and informational oversight across the entire design and building process. This paper considers 1) key research components of cable robotic 3D-printing (such as computational design, material exploration, and robotic control), and 2) the integration of these parameters into a unified design and building process. The demonstration of the approach at full-scale is of particular concern.

**Keywords** Automation · Robotic construction · 3D-printing · Cable-driven parallel robots · Non-standard architecture · Computational design · Concrete

## 1 Introduction

Industrial robots are extremely useful to the field of architecture and construction (Brell-Cokcan and Braumann 2012). Not only can they lead to significant time and cost savings, but their ability to connect digital design data directly to the fabrication process enables the efficient and precise construction of non-standard structures. Yet traditional ground robots (such as serial industrial robots or other CNC manipulators) have workspaces limited by their scale of action defined by their arm lengths and thus considerably constrain the size of the workpiece they act upon (Bonwetsch et al. 2010a). However, cable-driven parallel robots (in short: cable robots) encompass such tight boundaries and

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**Fig. 1** 3D-printed façade made of carbon fiber reinforced concrete panels

can operate at much larger scales (Heidel et al. 2022). As a result, their use opens up entirely new possibilities for robotic construction, and, in particular, for applications at real-world building scales (see Fig. 1); the most evident and radical consequences is the ability to digitally oversee and control key aspects of design and construction, and the ability to freely manipulate building material in three-dimensional space (Barnett and Gosselin 2015).

Against this background, however, cable-driven robotic construction research is still in its infancy, and presents many theoretical, practical and methodological challenges. Those are for example, the need for advanced computational design processes, the efficiency of using non-standard building materials and constructive systems that are robotically configurable and the development of the (cable) robotic system, as well as the seamless integration into the building process. In order to develop a scheme for addressing these challenges, three research groups Faculty of Art and Design at Bauhaus-University Weimar (Professorship for Theory and History of Design 2019), the faculty of Architecture at the University of Applied Sciences Dortmund (Professorship for digital methods in architecture 2019) and the Chair of Mechatronics at the University of Duisburg-Essen (Professorship for Mechatronics 2019) collaborated to create a first experimental setup that allowed to flexibly employ cable robotic as well as conventional serial robots for large-scale construction (Willmann and Braun 2019). The resulting experimental setups produced a 115-panel carbon-reinforced concrete façade system. The applied flexible digital toolchain required many innovations, including the exploration
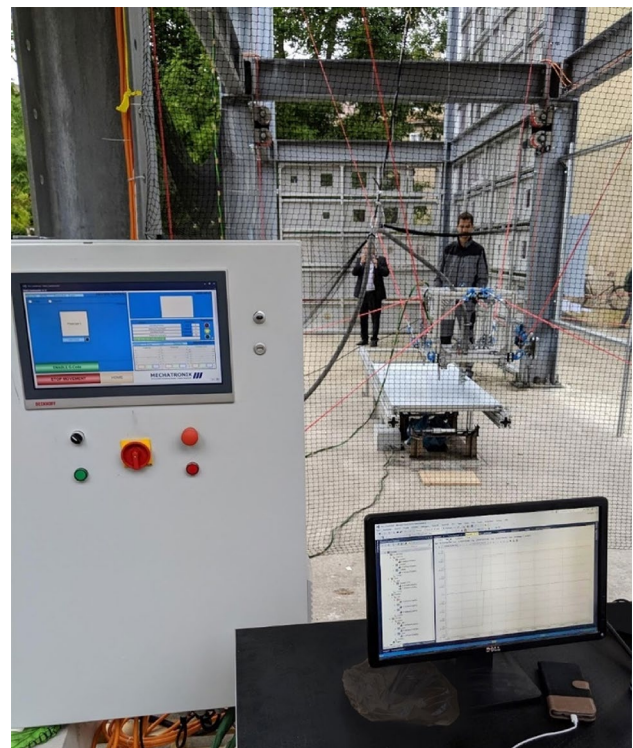


**Fig. 2** Cable robotic 3D printer and control interface

of new computational designs and a unique material system, and the development of a specific cable-driven robot setup (see Fig. 2) to extrude cementitious material according to a precise digital blueprint. In this context, a key research goal

for cable robotic 3D-printing is not only the design of complex structures, but also the (digital) simulation of material processes and robotic manipulation. This includes real-time assessment of material tolerances, the integration of robotic extrusion parameters and the development of corresponding computational simulation routines.

While it remains to be seen whether cable robotic 3D-printing will emerge as a viable building technology, the demonstration successfully illustrated how cable robotic construction becomes tangible to design and architecture, and addressable at real-world scales. The demonstration described subsequently delivered the following insights: first, because cable robotic systems manipulate material directly on site, there is no need for additional formwork or scaffolding for people or material. Second, such structures can be built according to highly complex design propositions: the robot operates under the explicit guidance of digital data sets, and can extrude the material exactly where it is needed, and in the sequence that is required. Third, the cable robot's mechanical setup is flexible and its work capacity scalable: while conventional serial robot arms are limited to operating on small components (being smaller than the machine), cable-driven robots can operate at considerably larger scales, either in prefabrication settings or directly on the construction site. Fourth the mechanical principle of cable robots employs motor-driven winches and cables, where all of those components that are already known and established on today's construction sites, e.g. by cranes. Each of these characteristics lends cable robotic 3D-printing the potential to pave the way for new avenues of (large-scale) additive manufacturing in design and architecture that are currently not possible with standard robotic systems.

In the next section (Sect. 2) we present the context of our work, outlining the state-of-the-art and specific approaches related to this research. Section 3 presents a scheme for exploring cable robotic 3D-printing, suggesting essential research parameters, ranging from algorithmic design, to material and fabrication, and to robotic control, mechanical design and corresponding periphery. In Sect. 4, a detailed description of a first experimental setup is presented, which was demonstrated at the Bauhaus Centenary in summer 2019 and leaded to the Lessons Learned. Our conclusion and outlook are presented in Sect. 5.

## 2 Context

Cable robotic construction is a novel area of research which experiences growing interest. First this section gives a general overview of robotic construction in architecture. Next we discuss the specific context of our research, and describe current attempts to deploy cable robots for full-scale construction, and for 3D-printing specifically.

In fact, research on robotic construction dates back to the early 1980s (Warszawski 1984). There have been several attempts to develop mobile bricklaying and construction robots for the usage on site, the most advanced of them being the ROCCO (Andres et al. 1994) and the BRONCO (Dalacker 1997) projects. The motivation behind this research was to improve the productivity of building construction (Bock and Langenberg 2014), mainly by utilizing the machines' ability to handle an increased payload as compared to humans. Although highly advanced, these developments did not find access into the market since they were not flexible enough to adapt and react in different design situations (Bechthold 2010; Bonwetsch et al. 2012). In the course of the shift towards digital fabrication technologies, research groups and universities, such as (Ficca and Iwamoto 2009; Gramazio and Kohler 2019; Menges and Schwinn 2012; Schodek et al. 2008), have set up research facilities for non-standard construction with industrial robots. Elevating robotic fabrication towards a constitutive design and construction tool, they have proven that the use of robotic technology beyond traditional industrial automation is clearly feasible (Bonwetsch et al. 2010b).

Concurrent to these advances in the application of robotics for non-standard construction processes is a growing interest in the exploration of three-dimensional deposition and/or extrusion techniques to aggregate material into most diverse geometric configurations (see Fig. 3), including, for example, concrete, wood, stone, earth, clay or plastic (Henke and Treml 2013; Henke and Talke 2016; Khoshnevis and Bekey 2002).

When linked with robotic machinery (Gramazio and Kohler 2008), such 3D-printing processes satisfy the requirements for customization, efficient and waste-free fabrication (Willmann et al. 2014). Also the fact that such additive processes are statically indeterminate during fabrication (Athanassiadis et al. 2014; Dierichs and Menges 2012; Oxman 2010), can now be addressed by the exploitation of powerful digital design, simulation and fabrication tools, leading to highly informed, fabrication-stable, non-standard constructions, even when the design information and/or material process is highly complex (Yuan et al. 2016).

Although research into the combination of robotic fabrication and additive manufacturing—such as robotic 3D-printing—is constantly progressing, and although powerful computational design tools and advanced material systems are becoming increasingly available (Brell-Cokcan and Braumann 2013), a large number of approaches are still centered around the use of standard industrial manipulators (Nof and Rajan 2007), being heavily constrained in terms of scale and application. The digital process chain allows a flexible use of different robotic manipulators, and novel topologies such as cable robots offer radically new possibilities, since

**Fig. 3** 3D-printing of a carbon reinforced façade panel
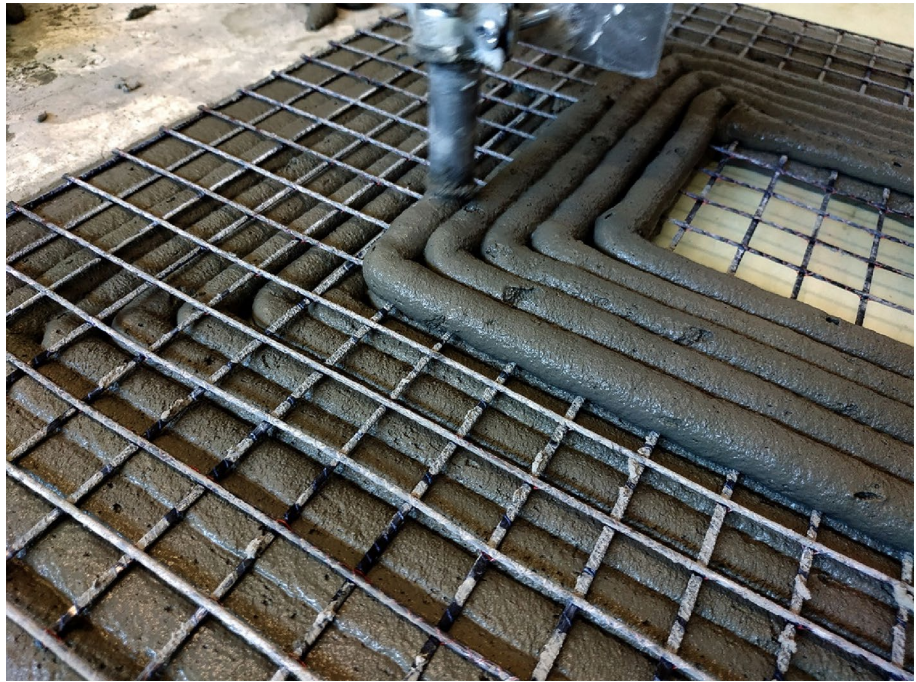




**Fig. 4** A cable robot prototype as a storage and retrieval system at the University of Duisburg-Essen

they do not have such tight boundaries (Kraus 2016) and can be installed flexibly (Boschetti and Passarini 2017) to perform non-standard construction purposes at considerably larger scales (Barnett and Gosselin 2015; Landsberger 1985; Rodríguez 2011). They are commonly applied in carrying and/or positioning objects in space, such as (Bruckmann

et al. 2018), three-dimensional crane operations, ultra-fast positioning routines (Pott et al. 2013), and are able to manipulate material at long distances and heights, for example in a warehouse storage and retrieval system (see Fig. 4).

In the field of robotic construction, cable robots have been demonstrated for automate façade installation (Iturralde et al. 2020) as well as automated masonry, where the latter includes research on suitable software tools to bridge from BIM data to robotized execution (Bruckmann and Boumann 2021; Heidel et al. 2022).

With regards to 3D-printing, a first (artistic) example in combining a cable robot and nonstandard fabrication is presented in Gramazio and Kohler (2017), where the automated deposition of silica sand was investigated. In (Sousa et al. 2016), a specialized deposition technique was developed, using a clay-based material process. The coupling between three-dimensional extrusion while moving the extrusion head through space was also investigated in Rajnoha (2016). Moreover, a large-scale printing process was demonstrated in Izard et al. (2017), using a cable robot to manipulate biodegradable material. (Tho and Nguyen 2021) presents the mechatronic design of a cable robot for concrete printing. However, holistic analyses are missing that investigate the dependencies between architectural design, material and mechatronic system design, where all factors impose both potentials and constraints. Furthermore, the application of cable robots for 3D-printing directly on an outdoor site and with continuous material flow has not been investigated yet.

# 3 Interdisciplinary approach

Research on cable robotic 3D-printing is based on specific components and strategies to explore and perform non-standard additive manufacturing processes. We have identified three general categories of research: 1) material and fabrication; 2) robotic control and mechanical system; and 3) computational design and system integration. The essential feature of this approach is therefore the combination of cable-driven robots and 3D-printing, and to introduce corresponding computational design processes so that account is taken of the system's overall capabilities and limitations regarding its aesthetic and functional performance. Important research parameters range from material behavior and particular extrusion techniques, to robotic control routines and mechanical design, and is completed by the exploration of advanced computational design logics and their integration into a unified design-and-fabrication workflow. This can be outlined as follows:

## 3.1 Material and fabrication

In the context of cable robotic 3D-printing, one important key is to develop a material system that is suitable to extrusion (in three-dimensional space) and is constructively lean. Thus, distinct material behavior and properties are required to allow for stable aggregations where, on the one hand, the material has to be soft enough to be pumped through a hose (of several meters length), and, on the other hand, to be stable enough during extrusion while taking the load of the next (horizontal) layer above. In addition, layer must bond and preserve structural stability. The speed of the robot is defined by the nozzle size and the behavior of the material under the pressure of an extrusion. The pump compresses the viscous material to transport it to the nozzle. As soon as the material is extruded the pressure is released and the

material expands. The robots speed has to be adjusted precisely to give the material enough time to expand. High performance concrete was chosen as a placeholder for viscous 3D-printing material as it offers unique plastic and rheological characteristics, and material properties such as pot life, the material's specific swelling factor and consistency can be precisely tuned towards the fabrication process by applying additives. A certified (general building authority approval DIBt Nr. Z-31.10-182) concrete mixture TUDALIT TF10 (see Table 1) has been chosen that is already in use on the construction site and already offers a soft plastic thixotropic consistency.

Together with an industrial partner the swelling factor was reduced under 0.06 Vol.-% to avoid cracks in 3D-printed objects while hardening. All components of the new material TUDALIT TF10 VP1 concrete are dried and mixed as powder and packed in 25 kg paper bags to provide manual handling and efficient usage for small and large 3D-printed objects. The high performance concrete needs to be hydrated with 15% water in a compulsory mixer for exactly 5 min. Quality and especially consistency can be controlled using a flow table test DIN EN 12,350–5. The material should be supplied and extruded rather continuously than in small batches to improve printing speed and allow efficient printing processes of large-scale objects. In turn, this requires the integration of a material mixing and feeding system. High performance concrete needs to be mixed for a defined time by a compulsory mixer. A screw pump (GmbH 2022a) was chosen to transport the mixed material through the hose to the nozzle as it allows a constant transport of the material in various speeds. All components of the material and mixture systems are already used on construction sites and could be easily customized to use them for 3D-printing. Overall, this encourages the development of advanced material processes where material can be precisely controlled and robotically accumulated where needed, enabling the implementation of 3D-printing on a tectonic scale (Salet et al. 2018). To

**Table 1** Material properties TUDALIT TF10 (GmbH 2022b)

| | | | |
|---|---|---|---|
| Grain size | | 0–1 | mm |
| Amount of water | max | 14 | % |
| Consumption (dry mortar) approx. | | 1.9 | kg/(m$^2$ * mm) |
| Fresh mortar raw density approx. | | 2150 | kg/m$^3$ |
| Processing time | +20° | 60 | min |
| Measure of extension DIN EN 13,395–1 | 24 h | 170–210 | mm |
| Swelling | 5 min | ≥0,1 | Vol.-% |
| Compressive strength | 1 d | ≥15 | N/mm$^2$ |
| | 7 d | ≥40 | N/mm$^2$ |
| | 28 d | ≥80 | N/mm$^2$ |
| Bending tensile strength | 1 d | ≥3 | N/mm$^2$ |
| | 7 d | ≥6 | N/mm$^2$ |
| | 28 d | ≥8 | N/mm$^2$ |
| E-module (static) | 28 d | ≥25,000 | N/mm$^2$ |

conclude, the focus is not only to precisely examine new material mixtures, but also their translation into novel fabrication processes, including a multitude of components and tools criteria.

## 3.2 Robotic control and mechanical system

To guide the printing head along the desired trajectory, an automated manipulator system is essential. Conventional serial industrial robots are widely used for manipulation tasks. Within this project, however, the flexible exchangeability of the manipulator system has been addressed. This allowed using the same CAD environment but employing a different robot system, featuring a parallel kinematic structure, while the extrusion and material system itself remains the same. While industrial robots are proven standard, the application of cable robots is still subject to research worldwide. However, for large-scale applications, the cable robot is superior to conventional robot arms in terms of workspace size, modularity and lightweight design. Cable robots use a simple and robust mechanical layout that only employs reliable and mature components already proven for applicability on construction sites (Gouttefarde and Bruckmann 2022). This includes the frame (as known from tower crane elements) and the motor-driven winches, which coil the cables. Those cables are attached to the printing head in a parallel topology and led by pulleys into the workspace (see Fig. 5). The steel frame provided for the described experiment is extremely stiff. However, for lightweight or even mobile systems, sensor based calibrations and local

pose measurements can be used to compensate imperfect geometries.

While the mechanical setup is minimalistic, the precise guidance of the printing head requires to accurately set both the computed tension and the correct cable length per cable, which is ensured by the control system. The values mentioned are measured by using force sensors and angular encoders, respectively, which are connected to the real-time control system using an EtherCAT data bus. The control system is based on a Beckhoff-PLC with a 2 kHz control frequency. A model-based cable length control approach is used to generate the set data for cable forces to obtain the desired end effector's pose. A disturbance observer to compensate for uncertainties completes the control algorithm.

As shown in Fig. 6, an augmented PD-Controller (APD), as presented in Hufnagel (2013), is used to control the end effector pose. This controller has proven itself for successful control of cable robots (Reichert et al. 2015a). The APD-controller adjusts the cable length $l$ and velocity $\dot{l}$ according to a desired pose $x_d$ and velocity $\dot{x}_d$. To calculate the desired cable length $l_d$ and velocity $\dot{l}_d$, the inverse kinematics of the robot, as derived e.g. in Reichert et al. (2015a), is used. The controller output $w_{pd} = A^T(K_P e + K_D \dot{e})$, with the diagonal gain matrices $K_P$ and $K_D$, is projected into the configuration space of the robot to eliminate antagonistic actuating forces. The robot's structure matrix $A^T$ is used for the projection. This prevents undesired tensioning of the cables (Reichert et al. 2015a). Based on the robot's inverse dynamic, see e.g. (Bruckmann et al. 2013; Reichert et al. 2014), the feed forward wrench $w_{ff}$ is calculated to follow the desired trajectory. Based on the total desired wrench $w$ and the structure

**Fig. 5** Main components of the cable robotic 3D printer
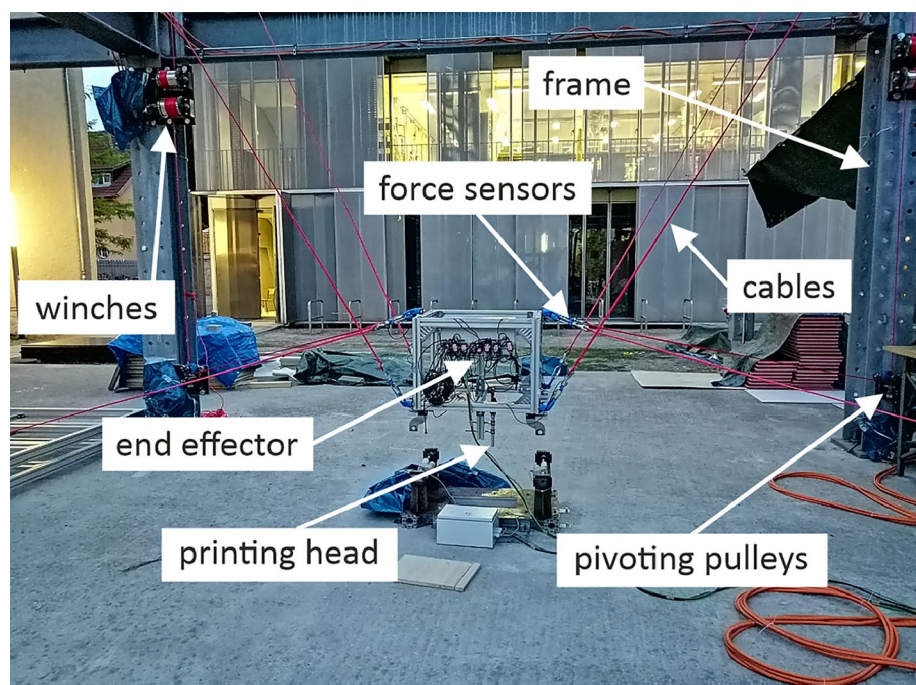
**Fig. 6** Structure of the augmented PD-Controller, here with disturbance observer
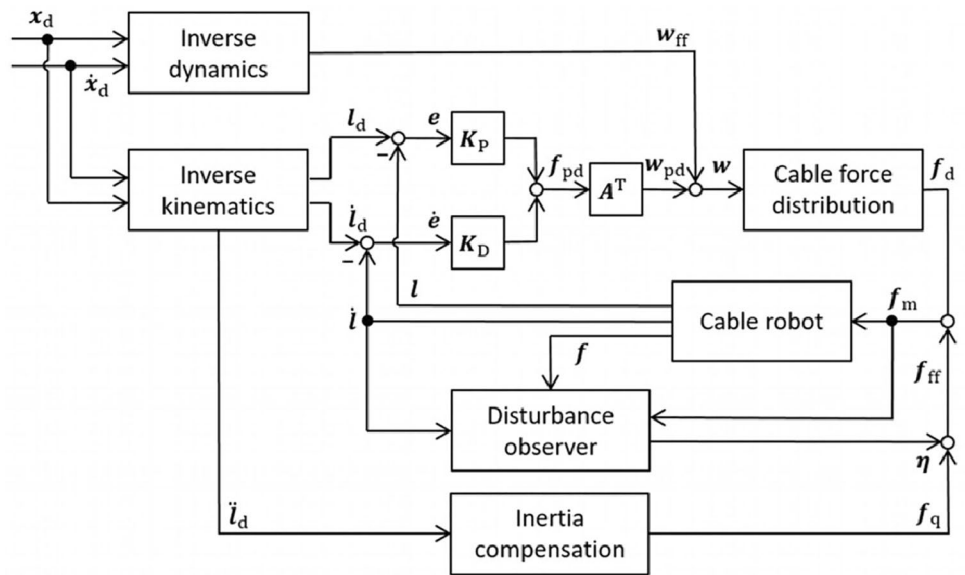
matrix $A^{\mathrm{T}}$, the cable force calculation is carried out, using an active set algorithm as shown in Gouttefarde et al. (2015). The calculated desired cable forces $f_{\mathrm{d}}$ are corrected by the value $f_{\mathrm{ff}} = J\ddot{q}_{\mathrm{d}}$, based on a feed forward compensation of the motor inertia matrix $J$ with desired joint acceleration $\ddot{q}_{\mathrm{d}}$. The resulting forces $f_{\mathrm{m}}$ are fed into the system. The controller structure as presented here is a simplified version of the structure described in Reichert et al. (2015b). Based on the force and encoder measurement, the actual cable lengths $l$, velocities $\dot{l}$ and forces $f$ are fed back into the controller loop. In an extended version of the controller, a nonlinear observer, as described in Luca and Mattone (2003), based on generalized momenta as measurement has been included. The idea is to reconstruct the disturbances $\eta$ acting on the system and to treat them as system errors in the form of frictional forces (Reichert et al. 2012).

In addition to the robot control, the system integrates the cable robot into the computational design workflow by also offering a G-code capable interface which derives $x_{\mathrm{d}}$ and $\dot{x}_{\mathrm{d}}$ from the provided G-code. G-Code is a standardized format applied in CNC-machines, typically derived from CAD data. This format allows the exchange of the specific control system as well as exchanging the robot itself, as long as the involved robotic systems have the same data interface.

## 3.3 Computational design

The conceptual decision for the computational design was to create a spatial and yet transparent volume. This in the sense of variation in the digital age and thus as a parametric design (Reas and McWilliams 2010). To realize this, an algorithmic approach was used for the computational generation of a façade system, which relies on McNeel's CAD environment
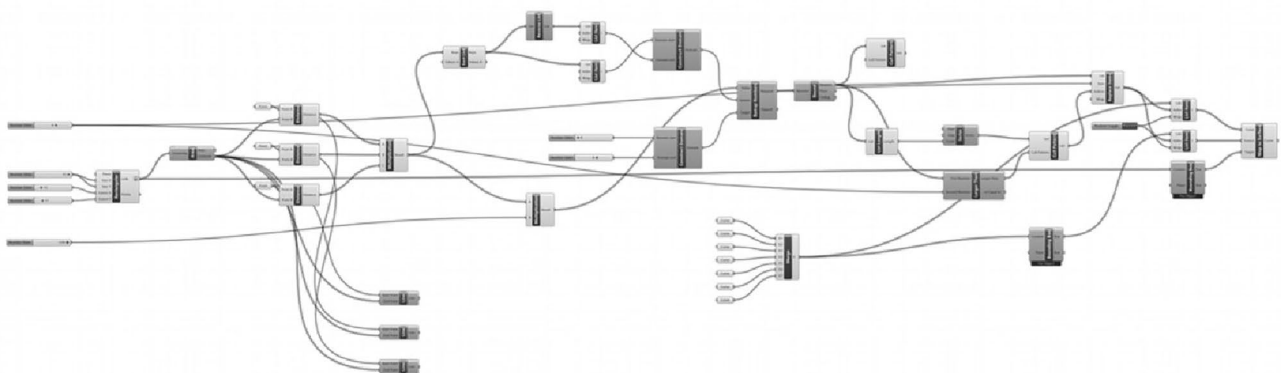


**Fig. 7** Grasshopper-Algorithm for parameterization

Rhinoceros and Grasshopper (McNeel and Associates 2022) as programming interface (see Fig. 7).

Basically, different panel types form a panel family whereby the outer frame sizes of each of the rectangular panels always remain identical during parameterization in order to allow for later assembly on a standardized substructure after robotic fabrication. While the panel design in Rhino was created using NURBS geometry, it also allowed the extrusion paths to be extracted directly, namely the curves to define the robot's path when placing the layers of material horizontally (see Fig. 8). For example, the radius within these NURBS geometries was determined using the manufacturing parameters. In particular, this sizing of the radius was dependent on the size of the nozzles (diameter) used in the robot-assisted manufacturing system and on the properties of the material system.
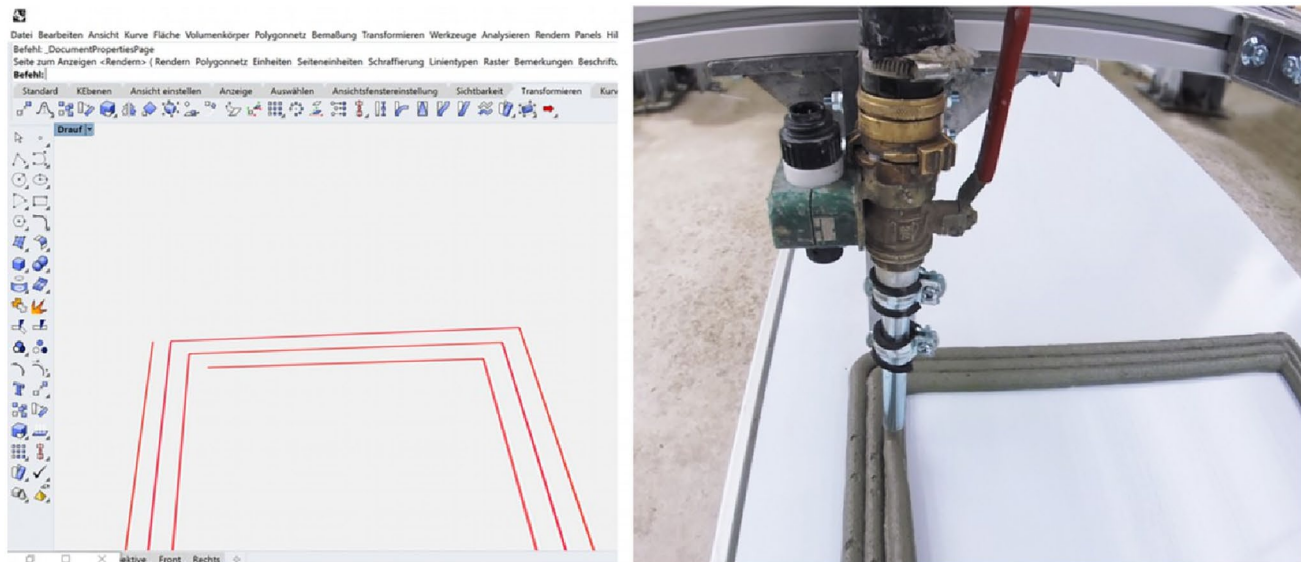


**Fig. 8** Marked in red: Selection of a final panel geometry (left); extrusion process based on the computational generated panel geometry (right)
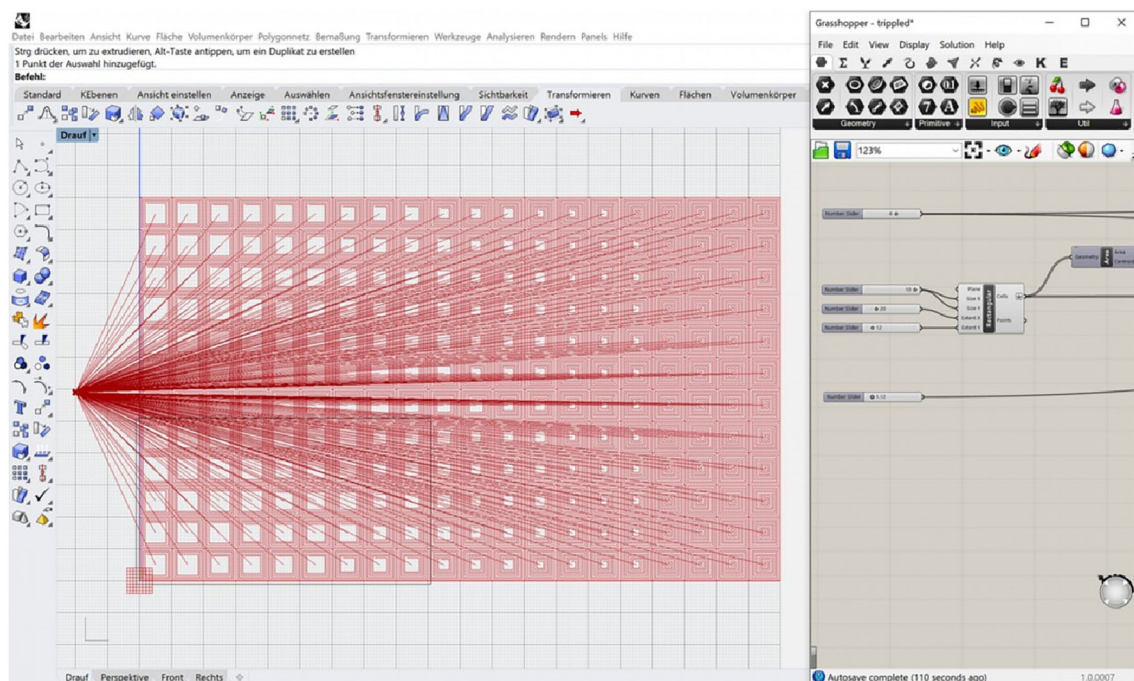


**Fig. 9** The distances to the attractor (red lines) define the form of each panel

Using a Grasshopper algorithm, the number of panels on a defined surface in X and Y direction can be determined. Once a selection has been made, it is possible to determine different panel types on this plane by means of so-called attractors. The reference for the determination of the respective panel type is the distance from the center of each panel to the respective attractor point (see Fig. 9).

It is possible to use several attractors to achieve a morphological appearance on the entire surface due to the various panel types. The generated attractor points can be moved freely on the surface at any time to vary the visual appearance of the entire surface. The attractor points can be located within the area arranged on a surface, but also outside this area.

## 4 The Bauhaus experiment

For the Bauhaus Centenary, the installation Robotic Printed Morphologies (RPM) was developed as a collaboration between Bauhaus-University Weimar, University of Applied Sciences Dortmund, and University of Duisburg-Essen (Willmann and Braun 2019). It takes a new approach to automated construction of architecture and provides a first experimental setup for the research into cable robotic 3D-printing. The project was exhibited in July 2019 and included a non-standard 3D-printed façade system, featuring particular aesthetic, functional and programmatic



**Fig. 10** Cable based 3D-printer mounted in an existing steel structure

characteristics. For the first time concrete façade elements were realized by a cable robotic system (see Fig. 10).

Mounted within an existing steel structure, the outdoor installation used a cable robotic system to extrude concrete with a screw pump (see Sect. 3) for the realization of discrete panel façade, thus creating a shell around the steel structure. The resulting build space of the cable-driven 3D printer was approx. 35 m$^3$.

Although the system was capable of printing large-scale concrete objects, at the short time of exhibition, the production of relatively small facade elements was initially chosen to simplify material handling and to reduce scrap: the geometry of the 3D-printed panels featured varying rectangular spirals within a standardized panel size of 590 mm × 590 mm × 32 mm, such that it could manually assembled on a rectangular aluminum support structure. As a result, the arrangement of the façade panels formed a global pixel pattern, associating with the surrounding context, that fills the open steel structure and forms a spatial volume. In this regard, an algorithmic approach was used for computationally designing a (panelized) façade system, drawing on McNeel's Rhinoceros CAD-environment, and Grasshopper as programming interface.

In total, 3 surfaces of the open steel structure were designed using the principle of parametric panels, and thus using the Grasshopper algorithm (described in Sect. 3: Computational Design). In the first step, the surface sizes for the facades were measured from the open steel construction and transferred to the CAD environment (McNeel's Rhinoceros). These simulated surfaces were then completely filled with the parametric panels. The two identical large areas were each equipped with a total of 45 panels (9 panels per horizontal row with 5 rows), and the smaller side area with a total of 25 panels (5 panels per horizontal row with 5 rows). This results in a total number of 115 panels.

This was followed by the parameterization of the individual panel geometry, such as individual instantiation and definition of the attributes of the geometry (e.g. including the number of rows of material; determination of the radii of the corners; determination of the distances between the panels within the area). This parameterization was carried out on different local areas of the facade surfaces, creating individual panel variations and thus curvature topologies. This was done using the attractors described above. Using the example of the lower large area starting at ground level, a total of two attractors were used to develop the individual design (see Fig. 11).

The three surfaces of the open steel construction were designed in relation to each other and merge visually morphologically into each other. They react to each other, so to speak, to create a uniform, global overall appearance in the architectural context of the experimental building (see Fig. 12). With this method it was possible to generate a large
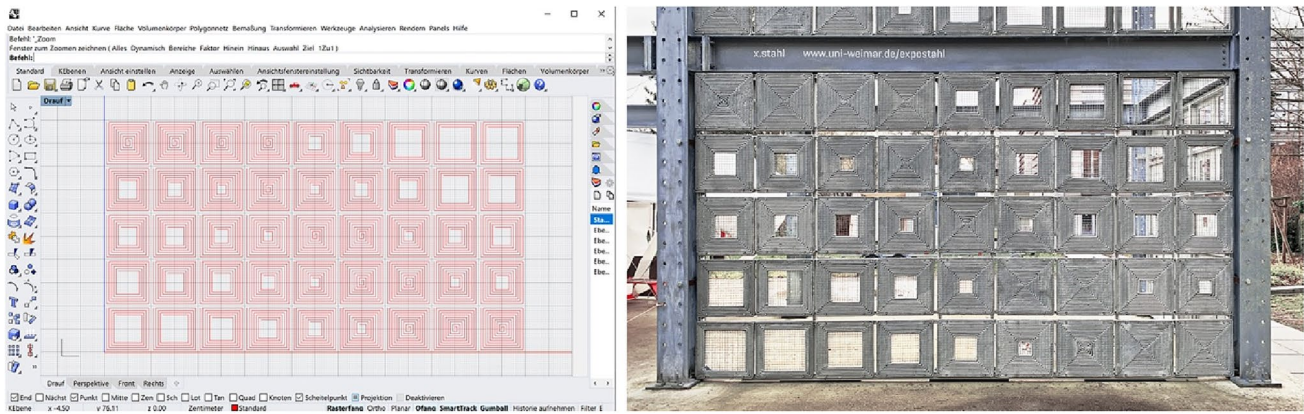
**Fig. 11** Computationally generated façade design (left); the robotic fabricated final façade design (right)

**Fig. 12** The façade system in its architectural context
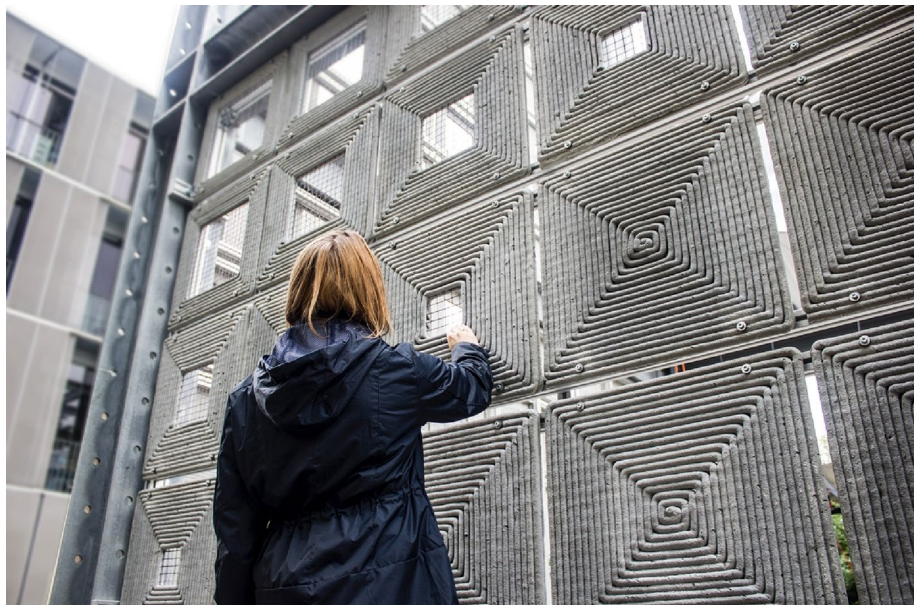


number of individual arrangements of the façade panel types on the selected surfaces, to extract corresponding production data and to optimize their geometry (locally and globally) and to assign specific attributes (e.g. structural fixing) to them.

The façade system was additionally adapted to structural and programmatic parameters, for instance, the introduction of a particular material extrusion tolerance factor of 2 mm to ensure a robust assembly and the incorporation of weight and wind load constraints. The design was then iteratively tested by fabricating and assembling a series of test panels, and then, in turn, optimizing the computational model accordingly. As a next step, the (refined) design of the façade panels was translated into extrusion paths to guide the robotic end-effector, and to continuously aggregate the material according to the initial blueprint. The extrusion paths were then be translated into specific G-code for operating

the cable robotic system on site or machine code for an industrial robot for pre-production purposes using McNeel's Grasshopper interface. Noteworthy, the choice of software tools with adaptable output interfaces also allowed to alternatively employ conventional industrial robots for testing and pre-fabrication purposes within the project, demonstrating the importance of open interfaces and tool exchangeability in digital fabrication toolchains and workflows (as described above). In addition to the open interfaces, the importance of intuitive user input for the cable robot in the event of changing external influences must be emphasized. A new graphical user interface, optimized for a touch panel IPC, was developed to ensure controlling the system during the entire process. The cable robot in general consists of a frame, power trains with electric motors and cable drums, the end-effector, pivotable deflection pulleys, cables and a control system. Moreover, a device was installed for resting

the end-effector and referencing the robot. A section of the large-scale steel structure in Weimar was planned to be used as a frame for the cable robot. Nevertheless, before the Bauhaus Centenary, the original frame with a size 3 m × 5.5 m × 5 m was replicated in a controlled environment under prototyping conditions within a supporting frame to allow function tests for the digital fabrication toolchain. Aluminum strut profiles were used to realize the frame. All components have been designed to withstand at least 2.5 kN per cable. The cable robot consists of eight actuated cables, each equipped with a force sensor. The used cables are braided cords with a diameter of 6 mm. The individual fibers are made of the high-performance material Dyneema, which is one of the strongest plastic fibers known (Reas and McWilliams 2010) (minimum breaking load for a diameter of 6 mm is 35 kN). All cables, which were led from the powertrain over the pivoting deflection pulleys, were connected with the end-effector. In order to realize a compact and cost-effective system, two powertrains of modular design were arranged between each upper and lower pivotable deflection pulleys. All components have been designed for easy attachment to the frame, so that the system can be quickly reconfigured on a construction site in the future. The façade modules were printed on a fabrication table designed to slide over the home position via a rail system to perform the printing process in the center of the robot's workspace. Thus, the robot could be optimally used with regard to the forces to be applied and the printing result could be taken out of the working area.

Ultimately, this allowed to apply a specialized concrete mixture of Pagel TF10 VP1 (using 14% water) and to automatically manufacture 115 façade modules using a specialized end-effector and a continuously working screw-driven extrusion system that works both on an industrial robot as well as on the cable-driven system. The individual modules were horizontally extruded using a 18 mm cylindrical steel nozzle and inserting an additional carbon reinforcement mesh (SGrid40) to stabilize the buildup and to preserve overall structural integrity. A particular challenge were the changing climate conditions and thus the material's rheological behavior during the (outdoor) production process. Against this background, the combination of strong computational and material orientation and robotic logics has become an essential concept of this experiment. Despite the complexity of the task, we purposely chose to examine in depth the specific dynamic characteristics of this combination, in order to unlock a new and interdisciplinary research direction for design and architecture, material research and robotics. Even though the experiment has not proven fully automated operationability, it has successfully demonstrated a new approach in robotic construction and provided a specific computational design and fabrication method that can be transferred to cable-driven robotic systems, and 3D-printing specifically.

# 5 Conclusion & outlook

This paper documents the project on the use of new automated construction processes in architecture with the use of cable-driven robots for large scale additive 3D-printing manufacturing. In sum, the vision of cable robotic 3D-printing creates a new level of robotic use in construction while radically extending the traditional spectrum of additive manufacturing towards large-scale applications. When exploring the link between computational design and robotic fabrication the differing characteristics of material systems and automated manufacturing are a prominent issue. Three principal factors determine the integration of design and robotics: 1) tolerances and other unmodeled material effects influencing the design and manufacturing process; 2) the need for interfaces that provide a seamless digital information chain and allow the use of different robotic manipulators; and 3) knowledge of different research methodologies and disciplines (such as, computational design and architecture, mechanical and electrical engineering, material science and automation engineering) to guide the research process and determine how comprehensively the research can be undertaken. In the first experimental setup a material with a soft plastic thixotropic consistency suitable for 3D-printing was chosen that was already in use on construction sites and could be customized for the specific use in additive manufacturing of architecture. A computational design workflow was developed, which translates design information into specific buildup logics and extrusion trajectories for different robotic manipulators. In the Bauhaus Experiment this workflow was proven by developing a 3D-printed façade system using high performance carbon reinforced concrete system, a screw pump and standardized industrial robots as well as a cable-driven robotic manipulator, which was exhibited in action. As demonstrated, a cable robotic 3D-printing also enhances robotic use directly on the construction site, where an automated fabrication system can be easily transported and installed, being able to specifically react to different design, material and contextual constraints. The flexibility and the mobility of such a system greatly enhances the possibilities for sustainable on-site fabrication processes (Helm et al. 2014) and rejuvenates the concept of on-site fabrication being transportable, adaptable and integrable in the overall building process. Most of all, cable robotic 3D-printing pursues a shift in computation where design decisions orchestrate not only non-standard forms but also their manufacturing, including, for example, processes like material supply and deposition, or the integration of specific constructive and functional criteria, which is essential to leveraging new architectural potentials. Thus, cable robotic 3D-printing

fosters information penetration across the whole process of making, from the mixture of material to extrusion processes directly on site, opening up new ways of thinking about design, information and materialization. On that scope, it is a vision of process, not just a product: in contrast to conventional manual construction, the production process must be considered in detail beginning with the architectural design process, and both product and process must be reflected in digital representations for effective workflows. Similar observations have been made in the automation of other construction processes (Brosque et al. 2021). However, the system requirements of this approach are task-dependent and thus, as of today, no consensus on the "fundamentals" of cable robotic 3D-printing has been characterized. As identified in this paper, the amount of available research on this topic is not abundant, and only a few experiments have been conducted in the field of design and architecture. And yet this approach is captivating: cable robotic 3D-printing not only creates a new vision for construction robotics, but also emphasizes new possibilities for the perception and understanding of it.

As a next step of this research, it is planned to print larger parts and multiple layers. Thus, three dimensional objects shall be created which goes beyond printing façade elements. Here, the remarkably large workspace of cable robots can be utilized adequately. In this context, also the printing tool will be optimized to enable the usage of different printing heads and to include an automated start/stop function of the material flow. Hence, different printing heads can be used to create complex and appealing 3D-geometries.

## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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