ADAPTIVE CONTROL SYSTEM FOR SMART DYNAMIC CASTING

Defining Fabrication-Informed Design Tools and Process Parameters in Digital Fabrication Processes

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Abstract. This paper describes the process control system and the fabrication-informed design tool developed for Smart Dynamic Casting (SDC) - the innovative technique that merges the process of slipforming with robotic fabrication technologies to enable greater geometrical freedom in the production of architectural components made of concrete. The paper focuses on the process parameters that characterizes the production workflow and it outlines the system-specific geometry rationalization algorithm developed for the definition of feasible geometries. Furthermore, the paper introduces the first application of the SDC design tool within the architectural context of the DFAB HOUSE, a building project realized entirely by robotic and digital technologies.

Keywords. Digital fabrication; Smart Dynamic Casting; Control System; Design tool.

1. Introduction

The rapid development in computer-aided design and manufacturing (CAD/CAM) of the last decades has revitalized the design and fabrication of complex architectural structures. Several pioneering projects have focused on linking the design and production processes by exploiting digital fabrication techniques and applying them to architecture and construction. (Gerber and Pantazis 2016) (Willmann, et al. 2013). These processes are controlled through the implementation of computational tools that generally neglect the properties of the chosen material system (Picon 2010) and consequently, lead to architectural designs that are often difficult to fabricate and therefore costly to build (Howe 2013).

In regards to concrete construction, research institutions and building industries have been addressing the challenges of bridging the discipline of

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computational design to digital fabrication for the production of bespoke concrete structures (Martins and Sousa 2014). The major focus in recent years has been on Contour Crafting, a layer based concrete extrusion technique that combines layer deposition methods with the extrusion of cementitious materials (Khohnevis, D. and Yao 2006) (Lim, et al. 2012). The layer-by-layer process requires the bottom layer to be strong enough to carry the weight of the upper layers and, at the same time, to be soft enough to ensure the bonding between individual layers (Wangler, et al. 2016). In addition, the full integration of a reinforcement system with this technique is still at its early stages. For both of these reasons the construction of 3D-printed architectural structures still requires extensive manual post-processing to comply with the structural requirements of building norms (Lund-Nielsen 2017).

Smart Dynamic Casting (SDC) utilizes the well-known construction technique known as slipforming, traditionally applied for the fabrication of large scale on-site constructions of silos and high-rise buildings (R. G. Batterham 1980). By implementing an adaptive formwork system and a sophisticated approach to the use of admixtures in concrete processing, SDC enables the production of bespoke concrete elements (reinforced structural columns and façade mullions) that eliminates the need for labor-intensive and expensive non-standard formwork systems. In this process a formwork, considerably smaller than the structure produced, moves vertically while being filled with concrete at a velocity set to match the hydration rate of the concrete. The material inside the formwork is shaped by a dynamically controlled mechanical actuation system that enables the fabrication of vertical reinforced concrete elements with significant cross sectional change (Schraner, Sigrist and Brasey 2016). The potential of SDC in producing 1:1 architectural structures is demonstrated in its first architectural application: the production of interior façade mullions for the DFAB HOUSE (NCCR Digital Fabrication 2017) (Empa 2017). A project that highlights the potential of digital and robotic fabrication technologies and it links it to the exploration of new possibilities in architectures.

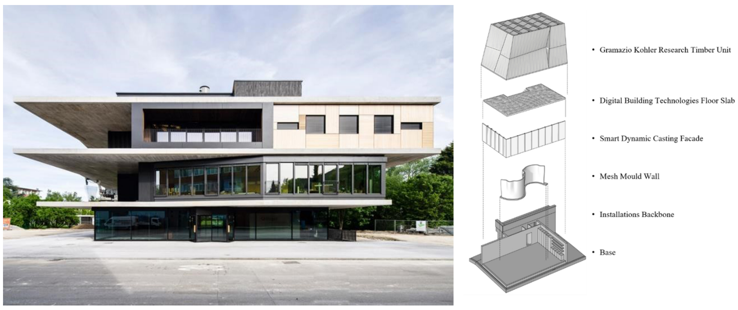

Figure 1. Left:NEST building at Empa; Right: DFAB HOUSE technologies description.

The paper introduces the SDC production setup and outlines the process parameters and their interdependence in the fabrication workflow. Furthermore, the paper links those parameters to the developed process control system, with detailed analysis of the functionalities of its modules.

2. Fabrication Setup

The SDC fabrication setup relies on a control system to synchronize all major fabrication procedures. It centralizes all main operations to enable a stable production while providing continuous feedback on the properties of the concrete during the fabrication process. The schematic representation in Figure 2 shows the procedural workflow of the SDC production.

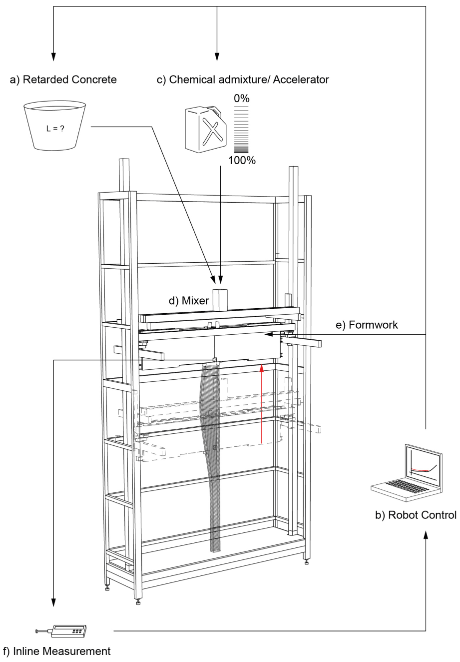

Figure 2. Diagrammatic representation of SDC fabrication setup.

Prior to initiating the fabrication procedure, a large batch of concrete is prepared and retarded to delay the hydration process (a). A custom software system (b) controls the pumping of small batches of concrete and accelerators (c) into a mixer (d) placed right above the formwork (e). In the mixer the material transforms gradually into a self-compacting concrete - that flows into the formwork in specific time intervals. The intervals are defined by the software that synchronizes the vertical movement of the formwork with the pumping rate. By doing this, the height of concrete inside the formwork is kept constant to ensure a continuous casting process. An inline feedback system (f) has been developed to monitor the material properties at the formwork exit point and to adjust accordingly, the vertical speed and pumping rate (E. Lloret-Fritschi, L. Reiter, et al. 2017).

In this setup, the formwork is built up following the concept of 'global shaping'

(Lloret-Fritschi, Reiter, et al. 2017) in which the material is shaped along the entire height of the formwork by the means of multiple actuators that are spaced vertically at defined distances (see Figure 6). The range of movement of the actuators along with the shapability of the material determine the main design constraints integrated in the digital design tool presented in this paper.

Analysis on previous prototypes revealed that the weight load of the concrete at the formwork exit point is greater when the cross-sectional area is continuously increased (E. Lloret-Fritschi, L. Reiter, et al. 2017). Thus, the design tool must provide geometrical solutions that are developed within the constraints provided by the formwork setup and the material properties.

3. Fabrication Parameters and Process Control

The SDC fabrication process control system ensures that the slipping procedure is executed in a time range in which the material fulfill the following conditions. The retarded material must be self-compacting when pumped into the formwork, it should be shapable while inside the formwork and, moreover, it should reach enough strength at the formwork exit to sustain its own weight and the weight of the material inside the formwork. The synchronization of those properties is a fundamental operation of the SDC process and three main fabrication parameters have been identified to define the fabrication control system. Those parameters are exemplified in Figure 3 and are defined as follows: the rate at which the concrete is pumped inside the formwork (P), the vertical speed with which the formwork is moved upwards (V) and the horizontal positioning (H) of the shaping actuators along the fabrication paths (Figure 3).

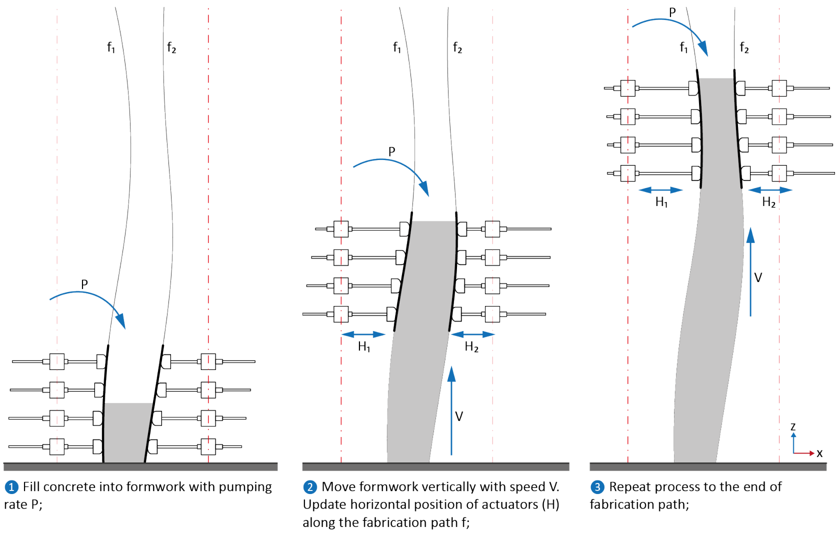

Figure 3. Diagrammatic representation of the fabrication parameters defined for the SDC control system.

The interactions of those parameters have been regulated within the control system specifically designed for the SDC fabrication process, defined here as 'Process Control System' (PCS). The following paragraph will introduce the procedural logic of the PCS and it will describe the characteristics of the modules that constitutes it.

3.1. PROCESS CONTROL SYSTEM (PCS)

The PCS is characterized by three consequential modules and its workflow is represented in the flowchart in Figure 4. The first is the 'Input Parameters Analysis' (IPA) module, in which the input variables are defined and evaluated. The IPA is then followed by the 'Sync Module' (SM) which configures and initiates the actuation and pumping operations and synchronizes all the process parameters before initiating the fabrication procedure. And finally, the 'Fabrication Processing Module' (FPM) that is designed to provide control and feedback during the fabrication process.

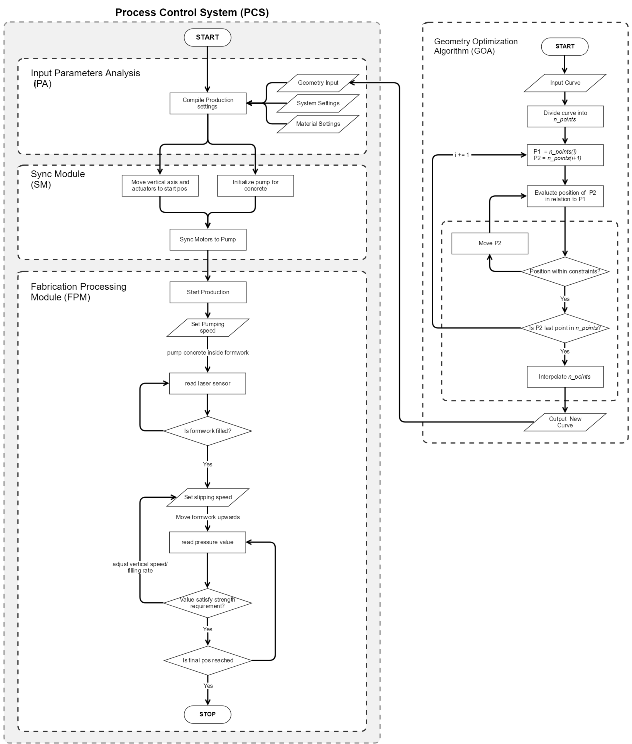

Figure 4. Flowchart diagram representing the SDC Process Control System.

3.1.1. Input Parameters Analysis (IPA)

The IPA module requires three main user-defined parameters that are specified as *Geometry Input*, *System Settings* and *Material Settings*. The *Geometry Input* expects a curve geometry that is used as fabrication path for the shaping process. In order to rationalize the input curve into a feasible SDC fabrication path, a sub-process has been developed to optimize the input geometry to fit with the fabrication constraints of the system. The process is referred as 'Geometry Optimization Algorithm' (GOA) and it procedural operations are described in details in paragraph 4. In the *System Settings*, the program collects information on the pumps' flowrates and the formwork parameters. The pumps' flowrates refers to the settings of the swing and peristaltic pumps, respectively used for precisely dosing the amounts of concrete and accelerator that are systematically pumped through the equipment. The formwork parameters are used to calculate the amount of concrete pumped inside the formwork. The depth and height of the formwork are fixed parameters, whereas the length value is variable and dependent on the geometry to execute. The *Material Settings* of the IPA module refers to the total mass of concrete and accelerator used in the fabrication process and they are used to calculate the volume of each respective component for every pump cycle.

3.1.2. Sync Module (SM)

The SM executes the synchronization routine needed to proceed into the fabrication operations. The module requires two main procedures. The first drives the vertical axis and the horizontal actuators to the start position. The second initializes the mixing of small amounts of concrete and accelerator to provide a homogenous material for the casting process.

The synchronization operation consists in linking the user-defined speed parameter to the coordinates of the vertical axis and, consequentially, to the position in time of the actuators along the fabrication path. The diagram in Figure 5a, depicts the setup configuration at the start position, prior initiating the fabrication process. In this state, the time value t is equal to zero since it refers to the production time. After providing the driving speed and initiating the fabrication process, the position of each actuator is linked with the vertical coordinate of the formwork, by extracting their correlated horizontal values on the fabrication path. The position of the actuators along the fabrication path is updated once a second and Figure 5b depicts their configuration after 60 minutes of production with a constant vertical speed of 12mm/minute.

In addition to the actuation control, the vertical speed is also used to synchronize the rate with which the concrete is pumped inside the formwork. By reading the position of the actuators, the system constantly calculates the volume of concrete needed inside the formwork and adjust the intervals between the filling cycles to match with the provided vertical and filling speed. It increases the length of those intervals for smaller cross-sections and, on the contrary, it reduces them to fill concrete in larger cross-sections.

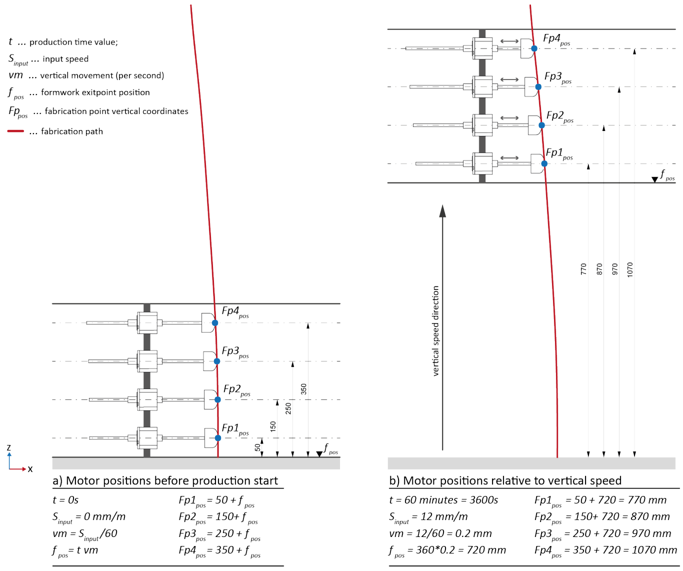

Figure 5. The diagram show the synchronization of the horizontal actuators along the fabrication path. On the left, their positions at the start; On the right, their position on the fabrication path after one hour of production time.

3.1.3. Fabrication Processing Module (FPM)

After finalizing the synchronization procedure, the real time fabrication control is executed through the 'Fabrication Processing Module' (FPM). While the formwork is at its start position, accelerated concrete is pumped into the formwork in specified intervals, which are defined by the hydration rate of the concrete. A laser sensor above the formwork monitors the height of the material inside the formwork and, when the maximum height is reached the process starts at a speed defined by the user. After starting the slipping procedure, the FPM evaluates the vertical speed and pumping rate at every second in order to generate appropriate filling cycles that fulfill the requirements provided. Additionally, the inline feedback system evaluates the hydrostatic pressure inside the formwork during the fabrication process and provides data that can be used by the FPM to adjust the production parameters while running (Lloret-Fritschi, Reiter, et al. 2017) .

4. Geometry Optimization Algorithm (GOA)

The GOA is a sub-process of the above mentioned IPA (paragraph 3.1.1) and it is designed to evaluate the geometrical suitability of an input curve in respect to the constraints of the fabrication setup. The range of feasible geometries for the SDC process is highly dependent on the limitations given by the flexible formwork and the properties of the processed material. Although the full scale experiments allowed to define the specific geometrical constraints provided by the material system, this section will only focus on the analysis of the constraints of the formwork system. The 'global shaping' operation is executed by 4 actuators, placed vertically at a distance d of 100 mm and a flexible metal strip to which the actuator are connected to.

The geometries supported by the formwork system have been validated through a set of experiments that allowed to evaluate the maximum bending properties of the flexible strip attached to the actuators. This was done by moving each actuator individually and defining the minimum and maximum values for the movement range. The outcome of this analysis led to the definition of a horizontal displacement (Δx), which refers to the range of motion each actuators can execute while connected to the shaping strip (Figure 6).

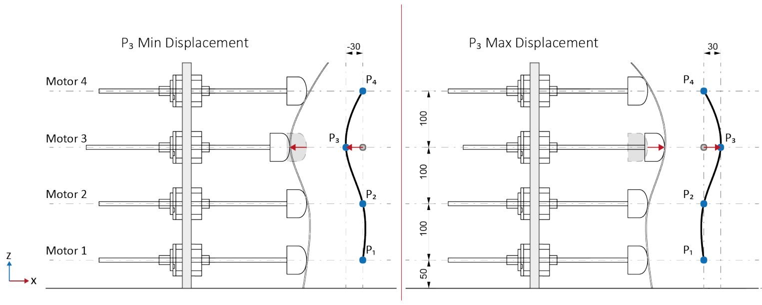

Figure 6. Diagram showing the horizontal displacement relative to actuator 3.

The horizontal displacement is later used in the geometry optimization process for the evaluation of the input geometry. The geometry is user-defined and it is represented as a two-dimensional curve. The initial phase of the GOA focuses on constraining the input curve geometry to a perpendicular YZ plane and matches its direction to the direction of the slipping process (Figure 7).

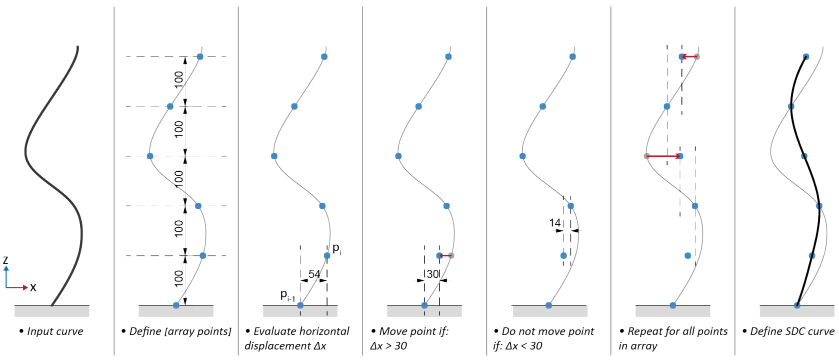

Figure 7. Diagram showing the optimization operations executed within the 'Geometry Optimization Algorithm'.

The curve is then divided in n number of points that are vertically spaced with a distance equal to d, the distance between each actuators. They are compiled into an array and sorted by their vertical position. The iterative operation of the algorithm is based on the analysis of the horizontal displacement value ($\Delta_i x$) of each of the points, retrieved by subtracting the coordinate of a point along the horizontal x axis ($p_i x$) and the x coordinate value of the point that precedes it in the array ($p_{i-1} x$). The displacement parameter of each point is expressed as follow:

$$\Delta_i x = p_i x - p_{i-1} x \quad (1)$$

The initial empirical analysis of the physical properties of the shaping metal strip and its effect on the range of movement of the actuators, enabled to define a fixed horizontal displacement equal to a maximum of 30 mm in each direction (Figure 7). Therefore the horizontal displacement of each point ($\Delta_i x$) must fulfill the follow condition:

$$-30mm < {}_i x < 30mm \quad (2)$$

The algorithm computes the horizontal displacement for each of the points in the array and it evaluates it against the above mentioned condition. If the condition is not fulfilled, the point and its displacement value are used as parameters for the successive phase of the algorithm. In this next step, the algorithm intervenes on the position of the given point in order to optimize its displacement value to fit within the given range. The direction of the movement vector is identified with the displacement value and its amplitude calculate as shown in Figure 7. Once all the points in the array are analyzed and the appropriate modifications are applied, the points are interpolated to generate the optimized curve geometry that is used as fabrication path for the shaping process.

The first applications of the design tool focused on understanding the geometrical limitations indicated by the physical prototypes. These observations led to a series of revisions of the design tool in order to provide geometrical solutions that are more tailored to the fabrication system.

5. Conclusions and Outlook

The geometry optimization algorithm and production processing logic presented in this paper, illustrates the advances of the SDC technology towards the development of an adaptive fabrication control system. The observed set of constrains (provided by the material and formwork system) informed the implementation of a specific design framework which allows for the fabrication of geometries that reflects the characteristics of the fabrication process.

The evaluation operations (geometry optimization, sensor reading) have not been implemented in the fabrication program and are still executed externally by the process control system. Thus, strategies to integrate those functionalities within the SDC computational tools are part of ongoing research and they are developed with the aim of achieving a fully adaptive process. By embedding a system-specific feedback process, the control system would provide an automated interaction between the process and its production parameters. A further topic of research is to define machine learning algorithms to provide prediction on material behavior during the fabrication procedure and provide unsupervised control of the fabrication process.

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