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A "low-cost" subtractive method for freshly finished 3D concrete printed structures

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Abstract

Until now, construction is an area where most activities are artisanal. Concrete is linked to the masonry trade where few machines are used. Moreover, this material is mainly used for building construction, but it can be used for other applications like urban furniture for example where a mold is necessary to pour and maintain the concrete until it is dry. This method can be expensive for unique part because of the implementation time. Moreover, the part geometry is limited by the mold shape. For a few years, the additive manufacturing is used with the concrete material, mainly to build house walls but without finishing step to have smooth or assembling surfaces. So, it is composed by the layers of concrete and it is difficult to assembly two parts for example because of the shape but also dimensional accuracy. For these reasons, in the frame of the HINDCON project, a low-cost subtractive task has been introduced, to perform post-printing machining with respect of geometrical constraints.

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Keywords: Concrete construction; Subtractive process; Sensor; Robot toolpath generation

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1. Introduction

If many projects [1][2][3] deal with additive concrete manufacturing, none of them includes subtractive operation just after printing. While subtractive technologies could allow post-processing, removing of supporting material, surface polishing, errors reparation, holes and cavities, etc., these operations are usually used to build molds to get specific shapes by molding concrete [4]. Thus, having the possibility to do subtractive action on printed 3D concrete structure can help in getting functional part adapted to final use of product (flat surfaces, sharp corners, etc.).

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In HINDCON project, our ambition was to realize low cost machining operation for getting flat surfaces and corners (allowing assembling, polishing, drilling, engraving, etc.), with low cost and standard construction tools.

The main constraints came from the printer architecture, made of cable robot and 6 Dof arm, and the size of elements to be printed. Thus, the ability to do machining was challenged by accuracy of printing (exact positioning of printed part) and the elasticity of cable robot ropes leading to flexibility in presence of efforts on the end effector during subtractive task.

In this paper we present the approach adopted in HINDCON project to face these constraints that are precise localization and flexibility while machining freshly printed structure.

2. HINDCON context

2.1. Project description

The HINDCON European project is composed by twelve partners working in different areas: architecture, construction, material, hardware or software development, life cycle assessment. HINDCON means Hybrid INDustrial CONstruction and the purpose is a 3D printing “all-in-one” machine for large scale advanced manufacturing and building process. HINDCON Project aimed to adapt manufacturing technologies to the construction sector, advancing towards industrialization and overcoming the limitations of actual approach for introducing Additive and Subtractive Manufacturing in construction activities.

Four main areas of development were studied:

- Additive material development: the use of cementitious materials including mass materials with alternatives in concrete and additive, reinforced with composites.
- Additive, Subtractive Manufacturing and Robotics technologies: the “all-in-one” machine integrates Additive Manufacturing concrete extruder and Subtractive Manufacturing tool kit.
- Software Development: a software layer placed on the top of the integrated HINDCON solution.
- Manufacturing and Construction Processes: embrace true process-based design strategies for architecture and civil engineering.

2.2. Global robotic cell

The global robotic cell (Fig. 1. Global robotic cell) is composed by a cable robot developed by Fraunhofer IPA to move without collision the additive and the subtractive systems fixed on a mobile platform [5]. This mobile platform can move a maximum of 300kg. This constraint must be into account during the additive and subtractive tools conception. The additive tool is an extruder developed by Fundación CIM (CIM UCP) that prints concrete material developed by Lafarge Holcim. The subtractive tool composed by an arm manipulator and finishing tools and control is developed by ESTIA. This article presents mostly this work on low cost subtractive operation on freshly printed structures. First, the additive tool is mounted on the mobile platform to print the part. Then, it is removed to be replaced by the subtractive tool to obtain the final surface.

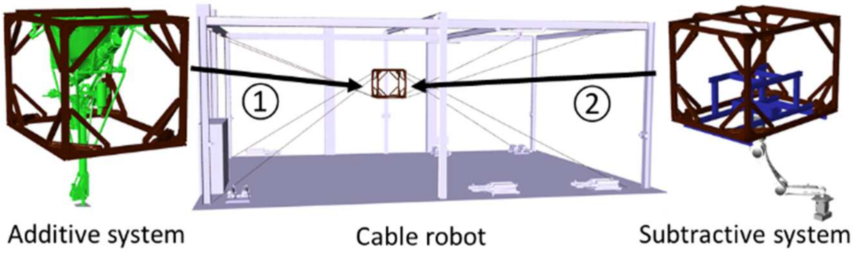

Fig. 1. Global robotic cell

3. Subtractive method and tool system design

3.1. Concrete material behavior

Design of experiments have been conducted to know the correct drying time of the concrete to start the subtractive process.

If the drying time is less than two hours, the concrete returns to liquid phase because of vibration caused by the cutting tool. Otherwise, if the duration is more than six hours, the concrete becomes too hard, the subtractive process works but the cutting tool is faster damaged. Consequently, in our low-cost approach, the subtractive process must be run between two and six hours after the part printing.

3.2. Hardware architecture

The maximal payload of the cable robot is of 300kg. The following equipment must be considered: machine, controller, power supply, etc. The subtractive tool must mill a 3D part and needs accessibility to work on the whole surface. Collision must be avoided between the cables, the subtractive tool, and the part. So, the 6 Dof arm manipulator is chosen to pilot the machining tool.

3.2.1. Manipulator arm

Because of its mass and accessibility, the arm manipulator is KUKA KR10 R1100 Agilus and the controller is the compact KRC4. This robot is mounted on the mobile platform thanks to an interface. So, the total weight is around 150kg.

3.2.2. Subtractive effector

Two different tools are used to make the polishing task and the milling/engraving task. For the polishing task, the BAIER BFF222 Orbital Sander with Diamond Tray Sets Left / Right is chosen. The reverse rotation of the two discs allows to limit vibration and avoid lateral forces. For milling and engraving task, a drilling machine with passive compliance is used. The system is an assembly of two aluminum sheets with linear bearing to ensure compliance during the process. Moreover, a vacuum cleaner is added on the subtractive tool to remove the dust of concrete.

3.3. Software architecture

3.3.1. Sensor-based control

The maximal arm payload is of 10kg. Because the effector mass is of 7kg, the applied force must be low to not damage the robot and the cutting tool. Consequently, to take into account the surface irregularity, a sensor system returns the force measured between the tool and the part during the subtractive process. The force system (Fig. 2. Force sensors system) is an assembly of four force sensors between two aluminum discs. It allows having uniform distribution of effort and the possibility of controlling the orientation (torque) of the tool. This system, mounted between the robot and the cutting tool, is used for controlling subtractive tasks process, dealing with process itself but also cable robot platform flexibility.

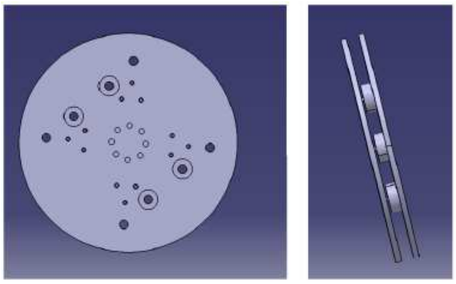

Fig. 2. Force sensors system

3.3.2. RSI communication

Because of the industrial context, the intern position loop control is not accessible due to the constructor warranty. So, an intermediate system, the Robot Sensor Interface module is implemented between the robot controller and the sensor system to make an overlay of the intern position loop control [6]. It allows to exchange data between the robot and an external computer thanks to XML frame. To do that, a client-server communication (Fig. 3. Sensor based control architecture) is implemented: the robot client communicates with the sensor client thanks to the application server via the TCP communication. The robot sends its cartesian position to the external computer every 4ms. In the meantime, the force sensor system sends the measurements to the external computer. Then, the data is processed, and the delta of position is sent to the robot via the XML frame. The same architecture is used to interface Optitrack system and to synchronize both information regarding the task control and data logging.

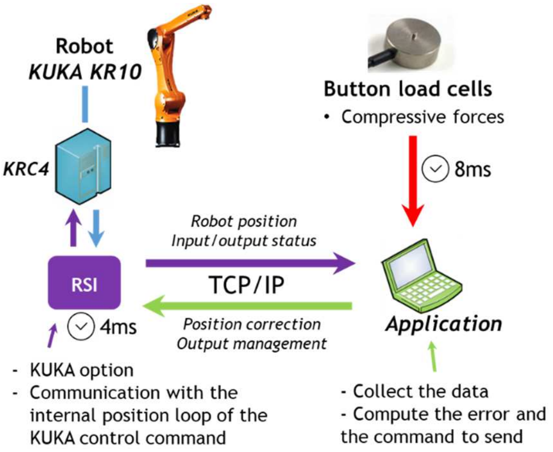

Fig. 3. Sensor based control architecture

3.3.3. Milling strategy

The cable robot moves the arm manipulator to a strategic place and stays static during the subtractive process. This consists in programming a sweeping toolpath for the robot to smooth the surface (Fig. 4.). The trajectory is programmed on the theoretical surface, so the final surface, and the force is measured between the cutting tool and the part. If the applied force is more than 1kg during the milling process, the robot adapts the pressure and repeats the sweeping trajectory until have measured force less than 1kg. When the forces are almost zero, the surface is smooth, and the theoretical surface is reached.

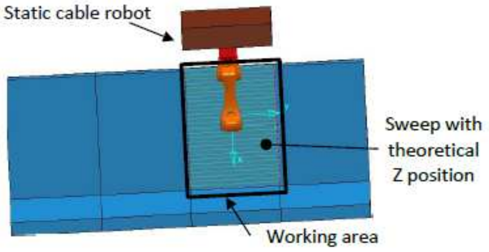

Fig. 4. Milling strategy

3.3.4. Localization of printed parts

If flexibility of cable structure is “solved” regarding the process execution thanks to force control, the control must be coupled with dimensional control for ending operation. Here the localization of printed part and robot must be known so that the targeted final surface can be monitored in parallel of the force control process.

For this purpose, we used an Optitrack system observing the scene (Fig. 5.) and delivering robot localization (position/orientation). While printing, the system is used to record the position/orientation followed by printer and to monitor the possible vibration. This information is then used to know the real positioning of printed part when starting subtractive operation. Thanks to this information it is also possible to validate that theoretical surface is reached.

Fig. 5. Working scene with Optitrack system (red circles)

4. Automated toolpath generation

4.1. Programming software

For cable robot and the arm manipulator programming, the software Rhino - Grasshopper - HAL Robotics is used (Fig. 6.). Rhino allows to visualize parts, robot, environment, and trajectory. Grasshopper is a graphical algorithm editor tightly integrated with Rhino’s 3D modelling tools allowing to make parametric design, toolpath creation thanks to geometrical tools. These tools are mainly used for architectural projects [7] because of their parametrical options. HAL Robotics [8] is also used, it is an additional robotic plugin allowing to consider the robot and its controller, compute the simulation, detect collision, and generate program for the robot in the appropriate language. Thanks to the parametric possibilities, when the development is finished, the part or the toolpath can be modified, and the robot program is instantly updated.

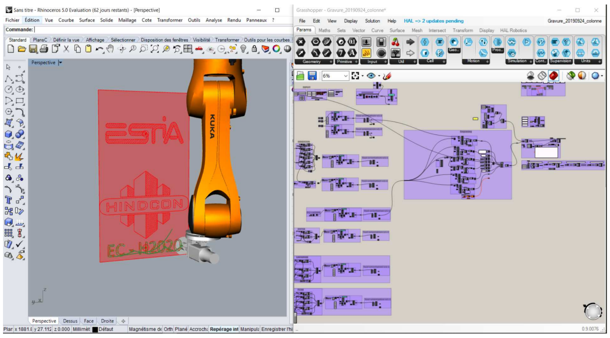

Fig. 6. Software environment

4.2. Architecture

The subtractive algorithm (Fig. 7.) has got:

- Inputs: the milling constraints to consider like the cutting tools and the Z-axis orientation, and the part geometry.
- Output: the KRL program for the KUKA robot.

It is composed by three important steps. First, depends on the finishing type, the toolpath is computed with different algorithm (sweeping toolpath for polishing and milling, pattern for engraving) taking into account the milling constraints and the part geometry. Then, the parameters of the simulation are configured: robot and cutting tool importation, collision detection. Finally, the KRL program is generated after the post-processor parametrization and the validation of the simulation.

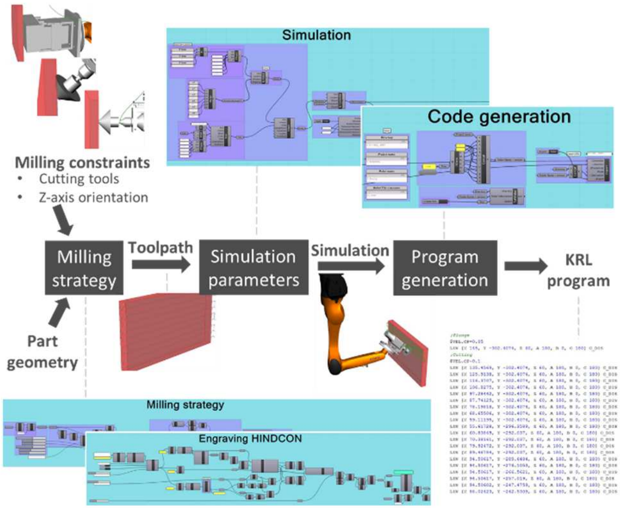

Fig. 7. Subtractive toolpath generation

5. RESULTS

5.1. Polishing

If the polishing programming is very simplified thanks to the force control strategy, the result is perfect with planarity and regularity of the obtained surface (Fig. 8.). But this way to work (dry concrete) is classical and the time to get perfect flat surface is around 15mn for 1m² starting with surface irregularities of 0.5cm.

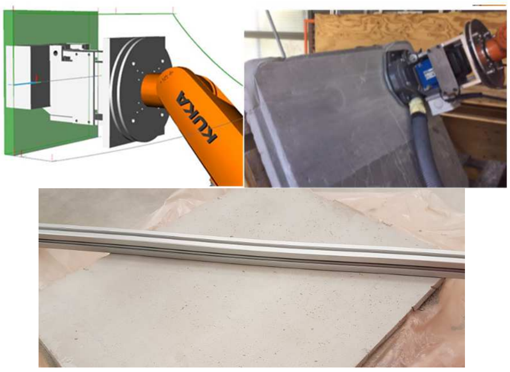

Fig. 8. Polishing result

The results obtained in next sections were impressive and promising because they were obtained using cheap cutting tool and only 3 were used, 2 for milling, the other one for engraving.

5.2. Milling

Following the polishing trials to get a flat surface, we started working on milling in order to be able to get more complex type of surface and to access any part of the printed structure. The objective of milling was to get a flat surface in much more quick way but with similar results in terms of planarity, and also to have the possibility to create sharp corners (for assembling parts). Here we had the constraint to work between 2 and 6 hours after printing. The toolpath was just a tool round trip on the surface with small recovery of path.

Here the result was just impressive compared to classical hard concrete polishing process, in less than 5min, 1 m² can become perfectly flat and ready to be engraved (Fig. 9.). Also, the corners obtained after flattening 2 surfaces were just perfect.

Fig. 9. Milling result

Test was made with two types of tool, one was a basic and cheap quick steel tool, and the second one was reinforced with carbide. Because of the speed the one without carbide gave good results but after 3m² started to be slightly damaged. The one with carbide was not different in terms of results, however, thanks to the freshly printed concrete was never damaged during all our trials (several m² of milling concrete) and even after project closure is still ready to work. Same milling tool was used to create big hole, also with a successful result.

5.3. Engraving

Next operation to be tested was engraving. We made two different types of engravement, one on raw printed surface and the other one on flat surface after milling operation. The tool use was a cheap quick steel tool (15€) and was for all engravement we made. The pictures show the results obtained for writing on surface but also for engraving pictures (Fig. 10.). Different depth can be obtained to create different type of writing appearance.

Fig. 10. Engraving result

6. Conclusion & Future works

In this paper we have presented a low-cost subtractive method for finishing 3d on freshly printed concrete structures. The results shown are very promising as it opens a way for low cost machining of concrete but not only, it also allows to envisage new applications for printed concrete structure. We are not talking here about mass production, where the use of molds would be probably less costly, but about specific on-site operation for customized application for which additive manufacturing already shown clear advantages [9].

Indeed, having the possibility to do machining in a low-cost way and just after printing makes it possible to envisage on site printing/finishing/assembling parts with more complex shapes like could be structural parts but also urban furniture or artistic work.

Next step is to define more scientifically the perfect time slot for doing machining. For now, we are working on the integration of sensors to monitor the material evolution through humidity and temperature parameters in order to optimize the scheduling of printing/machining operations. And this will open the door to interactive 3D printing, with correction of printing defects, redefinition of shape during printing process, etc.

Acknowledgements

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