

COOPERATION SIMULATION OF TWO 6-AXIS ROBOTS IN AN ADDITIVE CONCRETE CONSTRUCTION APPLICATION

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Abstract- The aim of this work is to develop a 3D printing system for concrete by the cooperation of two ABB robots with six degrees of freedom (6-DOF). A diversified study was conducted not only to master the 3D printing process by robotic cooperation but also to design the necessary mechanical tooling well adapted to the ABB robots. This study resulted in a prototype justified by calculations and construction simulations on RobotStudio. In the framework of this simulation, we are investigating the possibility of planning the by process taking into account the rheological and mechanical properties of fresh concrete, as well as the design requirements. Finally, to draw conclusions on the validity of 3D printing construction.

Keywords: ABB Robots, Perform Construction, 3D Printing Construction, 6-DOF, RobotStudio.

1. INTRODUCTION

Lately many researchers are focused on additive manufacturing technology, which has the potential to totally change construction methods using advanced construction-based technologies using concrete and cementitious mortars [1]. In this guideline, the mixing material is precisely distributed to predetermined locations through a printing nozzle that moves in 3D space in a prescribed path, robots work together to build the designed structure layer by layer [2, 3].

The mastery of 3D printing of concrete requires several steps that must be validated successfully. The first one concerns the material: it is necessary to formulate concrete with a certain number of characteristics in accordance with the process, the environment of implementation, and its future use. The second step can be carried out in parallel to the first one. It consists in developing an experimental device to simulate the 3D printing process in the laboratory [4, 5].

For this, it is envisaged to add a digitally controlled ABB robot to the system. This system will be inspired by the 3D printers used for plastics but have very different characteristics. The system developed will be original and will not aim to manufacture houses but to study the "Printability" of materials of civil engineering.

2. IMPLEMENTATION OF 3D PRINTING OF CONCRETE

In this chapter, we will focus on the work on the RobotStudio station in order to set up the different configurations necessary for printing, namely [13].

- The definition of the tool the extruder
- Connection of the motor reducer to the controller
- Definition of a printing strategy and configuration of the "Rapid" program.

2.1. Description of the Robots

The IRB 120 industrial robot, manufactured by ABB, is an articulated robot arm and currently the smallest ABB robot arm produced. The IRB 120 is a six degree of freedom robot with. Having six degrees of freedom allows the IRB120 to have a full range of motion in all directions. The robot is attached to a table to fix it [6].

The second part of the robot is the controller, figure 1. This contains the signal distribution power, and a programmable. This controller is programmed by the user to execute the robot by logical operations. The controller interprets the user's program and works out the best path to move the robot. It then sends signals to the robot to set the motors to the right position at the right speed. The controller is connected to the computer via Ethernet. It is possible that it is directly from the controller to the computer.



Figure 1. ABB Controller robot

2.2. Definition of the Extruder Tool

Before importing the extruder to the RobotStudio station, we have to measure the distances between the nozzle (end effector) and the fastener in order to define; Figure 2 shows the distances to be measured.

The next step is to import the extruder file to RobotStudio and modify its origin as shown in Figure 3. Once the tool is created, we can connect it to the robot paying attention to the position of TCP Figure 4.

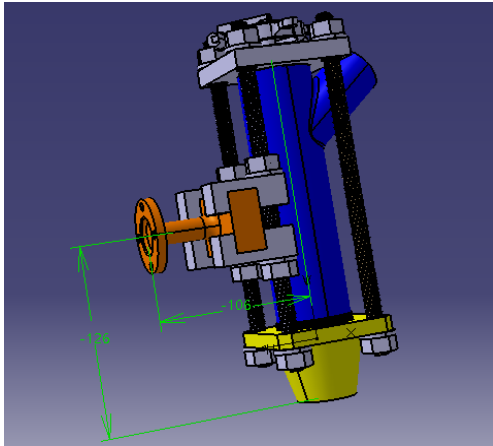


Figure 2. Printing head

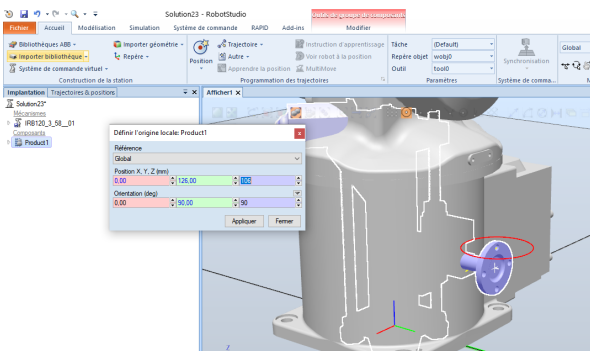


Figure 3. Setting up the tool on RobotStudio

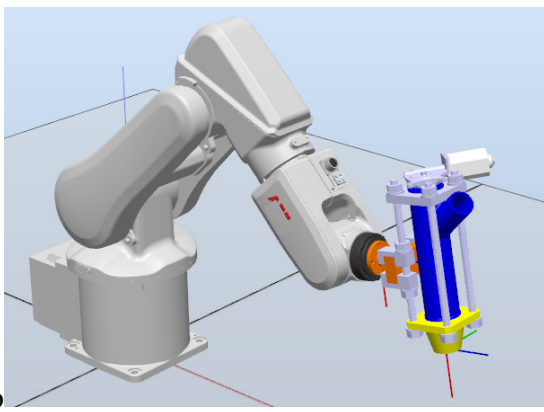


Figure 4. Visualization of the robot and extruder assembly

2.3. Connection of the Motor Reducer to the Controller

In order to set up a printing process, we need to establish a connection with the motor reducer. To do this, we need to declare the output of the robot controller, remembering that our controller has several 24 V outputs.

The configuration of the output is done by communicating with the controller using the "FlexPendant" tool (Figure 5). The "FlexPendant" connects to the controller and consists of a touch screen interface, some buttons, and a joystick. It provides one of the ways the user can interact with the robot. Using the "FlexPendant" it is possible to move the robot through Cartesian space, or each axis individually. It is possible to start, stop, pause, and resume programs via FlexPendant. also provides feedback to the user. When running a program, it is possible to display the current XYZ position of the end effector, as well as the quaternions or common angles for each axis.



Figure 5. The IRC5 FlexPendant (ABB, 2004)

We list after the steps to declare the output variable:

- Open the "FlexPendant" tool and click on the configuration control panel as shown in Figure 6.

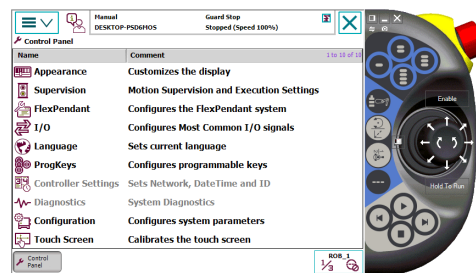


Figure 6. FlexPendant control panel menu

- Then create a digital output under the name "motored" or modify an existing one.

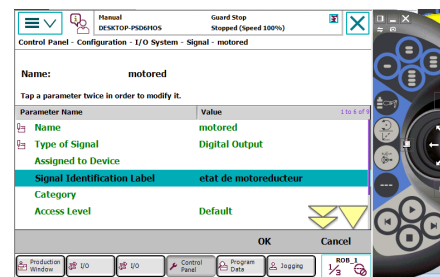


Figure 7. Motored output setting

- A restart is necessary after this modification
- The gear motor is connected to the output in question and a return to manual mode is required for the configuration of the equipment
- The output can then be simulated, i.e. the gear motor power supply output can be simulated:

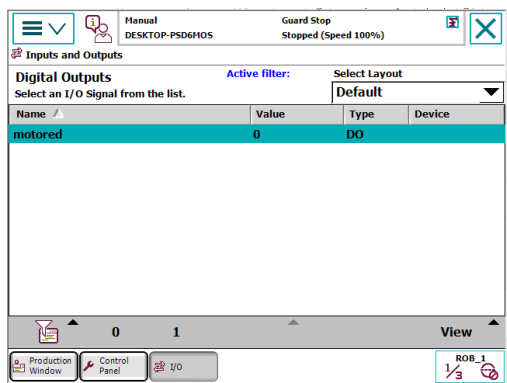


Figure 8. Visualization and simulation of the "motored" output

3. CONFIGURATION OF A PRINTING STRATEGY AND DEVELOPMENT OF THE "RAPID" PROGRAM

3.1. Configuration of a Printing Strategy

A better printing of concrete is not achieved without coordinating the properties of the printed material with those of the robot. In this respect we want to establish in this paragraph an effective strategy for successful printing by overcoming the printing problems mentioned in the first chapter. We recall the parameters of the printing previously mentioned in the Table 1 [5, 7, 13, 14].

Table 1. Printing characteristics

Nozzle section S	20mm × 30 mm
Extruder output Q_{max}	3L /min
Speed of concrete or clay exit V_{sortie}	83 mm/s
Construction volume	800×600×400 mm
the printed layer shrinkage's	2±0.85 mm

In order to obtain a correct printing, we must follow some steps described by the flowchart representing the process of obtaining the correct concrete (or clay) layer.

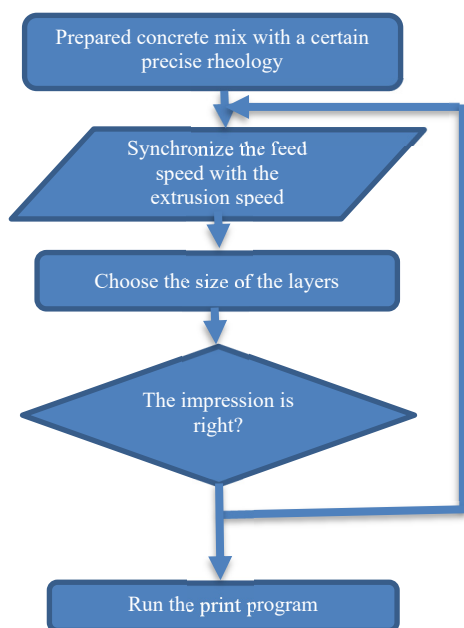


Figure 9. The correct printing logogram

In order to synchronize the feed speed of the robot noted V_{Head} with the material output speed noted V_{Output}

we must calculate the ratio of $\frac{V_{Output}}{V_{Head}}$.

This ratio determines the amount of material that is extruded during nozzle displacement. Thus, reported in % with 100% representing the case where $V_{Head} = V_{Output}$. A very high displacement speed (V_{Head}) will make the wefts unstable and discontinuous.

Using $V_{Output} = \frac{Q}{S}$, when Q is the beginning of output

3L/min and S the section is variable since the nozzle is mounted by a thread, the latter allows to change the shape of the nozzle is therefore consequently to adjust the speed V_{Head} . The following table gives the head speed to have a filling ratio of 100%.

Table 2. Nozzle dimensions [6]

	Circular section in mm		Rectangular section in mm ²	
	φ20	φ30	20×30	20×40
V_{sortie} in mm/s	100	44	833	416

Note: The ABB robot cannot do the whole range of speeds, so it is necessary to choose sections that coincide with the speeds that can be executed by the robot.

4. THE ROOM CONSTRUCTION ROOM WITH A CONCRETE WALL INCORPORATING A LINTEL

4.1. Procedure for the Concrete Construction for Wall Integrating a Lintel

We are interested in a model of a printed wall, whose dimensions are presented in the next Figure 5. The wall would be constructed by laying down layers of 10 mm × 30 mm, by a print head moving at a velocity of $V = 1000$ mm/min. The building was separated into four sections: the left wall, the right wall, the lintel and the top wall [6].

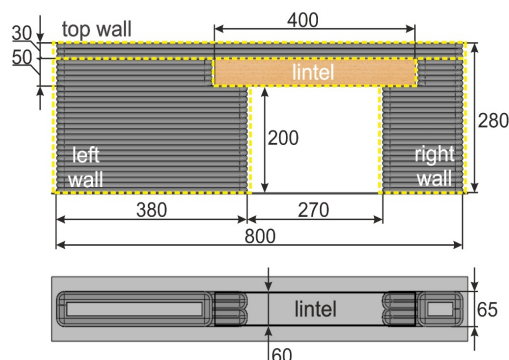


Figure 10. Wall dimensions [6]

The construction activity was organized in five stages, the preliminary stage including all preparatory activities, then four production stages:

- Step 0: implementation of all process elements, i.e., lintel deposition, print head and "Rapid" process program;
- Step 1: preparing 25 L of concrete mixture, approximate time: 15-20 min;
- Step 3: pick up the lintel from the depot and put it on the door opening, suggested time: 4-7 min;
- Step 4: put new layers of concrete on the lintel, construct the top wall.

4.2. Concrete Mixing

One of the obstacles to the implementation of 3D printing in the construction field thus concerns the lack of specifications for the printed materials, as discussed by [8]. Some examples of materials tested in 3D printing, their compositions, rheological and mechanical properties, and the machines used for their printing are presented in the table 3. This table shows that most of the mixtures are made with Portland cement. Other components such as fly ash, silica fume, gas pedals, retarders or other additives are used to regulate the rheological behavior and setting of the materials to be printed [15-17], [20].

4.3. The printed wall structure design

According to EN 14374:2004, with a moisture content of 11% to 1% [17, 18]. The lintel was planned as an LVL beam of $a = b = 60$ mm in width $h = 50$ mm in height and $L = 400$ mm in length with transversal plating [18, 19]. Table 1 below lists the different parameters of the lintel beam.

Table 3. The different parameters of the lintel beam [6]

Parameter	Unit	Value
Weight per unit volume	kN/m ³	5.1
Modulus of elasticity	kN/cm ²	1000
Inertia moment	cm ⁴	62

The calculated deformations will allow us to determine the stress distribution under the lintel. We then present in the Figure below, the schematic loading, containing the own weight of the lintel and the weight of the fresh concrete deposited on top of the lintel. While the weight of the beam is estimated at $G_L = 0.612$ kg, and the weight of the fresh concrete deposited on top at $G_C = 2.592$ kg, we can therefore schematize the loading of the lintel by the diagram in Figure 11.

$$U_{fin} = \frac{5}{384} \cdot \frac{(G_C + G_L) \cdot g \cdot L^3}{E_0 \cdot I_Z} \left(1 + 19.2 \left(\frac{h}{L}\right)^2\right) \quad (1)$$

where,

- U_{fin} : lintel deflection,
- G_L : weight of the beam,
- G_C : the concrete weight deposited on the beam,
- E_0 : average modulus of elasticity,
- L : width of the lintel,
- h : height of the lintel,
- I_Z : squared moment.

The deflection was computed by assuming a span/Height report of L/h of 20. For the selected loading and lintel design, the lintel deflection, determined with Equation (1), was 0.005 mm. This value was calculated due to the high stiffness of the lintel beam.

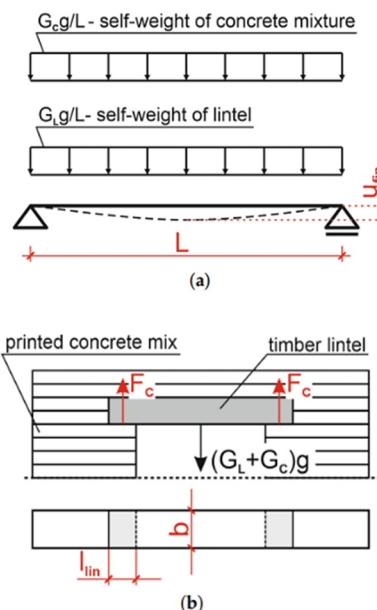


Figure 11. Wall loading scheme [6]

The constraint level at the lintel support point σ_c was obtained using the next Equation (2) [6]:

$$\sigma_c = \frac{F_c}{A_c} = \frac{(G_C + G_L) \cdot g}{2 \cdot b \cdot l_{lin}} \quad (2)$$

where,

- σ_c : Stress at lintel support
- F_c : Reaction effort at the lintel support
- $g = 9.81$ m/s² is the gravitational acceleration.
- A_c : Support area
- b : width of the lintel
- l_{lin} : Side end bearing length

The calculated stress must not exceed the maximum allowable stress supported by the material already deposited. The letters σ_c and σ_{max} depends on the age of the concrete, i.e. time t .

$$\sigma_c \leq \sigma_{max}(t) \quad (3)$$

$$\frac{F_C(t)}{b \cdot l_{lin}} \leq \sigma_{max}(t) \quad (4)$$

Since the width of the lintel designated by b is constant, Equation (4) can be arranged to calculate the length l_{lin} :

$$l_{lin} \geq \frac{F_C(t)}{b \cdot \sigma_{max}(t)} \quad (5)$$

In the next step, the allowable stress level σ_{max} in the fresh concrete is determined as a function of time t . The mechanical properties of concrete mixtures were determined using a test device. Place a new concrete sample of 35 mm high and 60 mm diameter between two parallel faces and gradually apply a load of 150 g to the top face. The displacement of the load board is measured with an inductive LVDT sensor. These measurements are used to determine the deformation of the sample. Figure 12a shows a view of the specimen during loading and Figure 12b shows the specimen after failure.

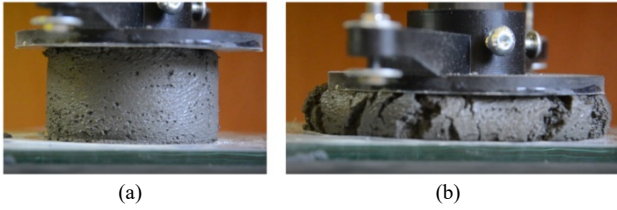


Figure 12. (a) Mortar sample during testing and (b) Mortar sample after testing [6]

Considering the relations (5), it is possible to calculate the minimum lintel rolling length l_{lin} . It can be seen that the reaction force of the lintel F_C grows linearly. The minimum length of the lintel end was calculated with Equation (6) assuming the worst-case combination, including dead loads as well as the weight of the GL lintel was taken as dead load, with a safety factor of 1.35 [11] [12].

$$l_{lin} \geq \frac{1.35G_L + 1.5G_C(t)}{b \cdot \sigma_{max}(t)} \cdot 1.35 \quad (6)$$

From the above numerical values, we can calculate numerically the minimum length of the end bearing must exceed the value of 6.3 cm, in this case, a value of 6.5 cm was finally taken for the l_{lin} .

5. DEVELOPMENT OF THE "RAPID" PROGRAM AND VISUALIZATION ON ROBOTSTUDIO

RobotStudio is an application created by ABB to program their robots. Through RobotStudio, it is possible to simulate the robot program before executing it. This allows to avoid potentially dangerous situations not only for the robot but also for the user, so it allows to rectify errors before applying the program to the robot [7].

5.1. Programming with the Rapid Language

The Rapid language includes several commands for moving the robot. All of these commands have location, speed, area, and tool parameters. Other parameters contain either common angles or position and orientation data for the robot. Once the trajectory is realized we can synchronize the station with Rapid in order to establish the program below and add some commands to make the cube build layer by layer.

5.2. Communication and Transfer to the Controller of Both Robots

Once the simulation on Rapid is running smoothly, we can create a transfer for this reason, RobotStudio provides mechanisms to facilitate communication to and from the robot controller (Figure 13).

We can configure the communication after we transfer the data as shown in the Figure 14.

After this transfer we can execute the program on the real robot in order to test the constructability of concrete or clay if everything works as expected we keep the printing parameters otherwise, we proceed to a new adjustment of the rheology of printable material.

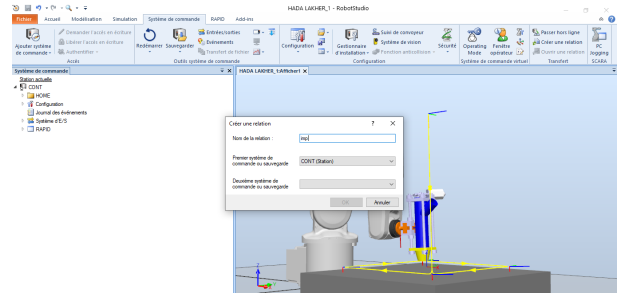


Figure 13. Creating a relationship from Rapid to the controller

5.3. "Rapid" Program Elaboration

The synchronization of the two robots is essential in this industrial application, i.e. the printing of the concrete and the deposit of the lintel. This coordination between the two roots is made possible by the RobotStudio station.

5.4. Second Program of the Lintel Manipulator Robot

The robot manipulator must place the lintel on the two freshly painted walls for this we have designed a tool "lintel pose" Figure 14.

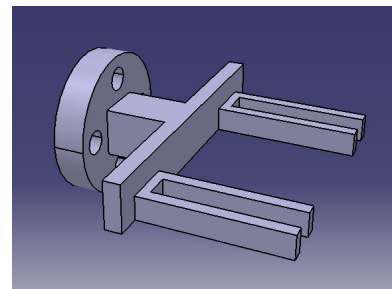


Figure 14. Lintel deposit tool

In order to succeed in the simulation, we have to configure the control system inputs/outputs in such a way that we add three actions Position_STRIP and Attach_STRIP and Detach_STRIP as in Figure 15.

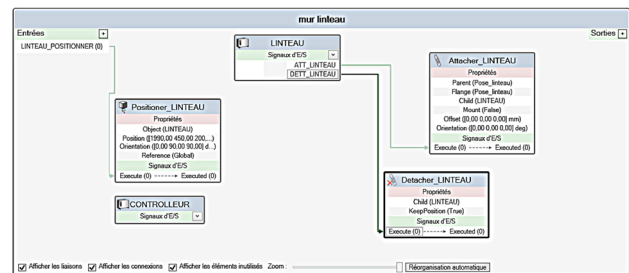


Figure 15. Control system inputs/outputs

The addition of these three inputs/outputs allows us to insert "Rapid" instructions such as "PulseDO ATT_LINTEAU" and "PulseDO DETT_LINTEAU" which are essential for the lintel deposit on the wall.

6. SIMULATION RESULT

The designed wall will be built through coordination between two robots as described in the above procedure. Figure 16 shows the respective steps in the simulation process of the wall construction.

The steps include the preparing and setting up of all the equipment needed for the work, setting up the lintel and defining the location of the lintel in the reference system, identifying the location of the printing area, and finally running the "Rapid" program.

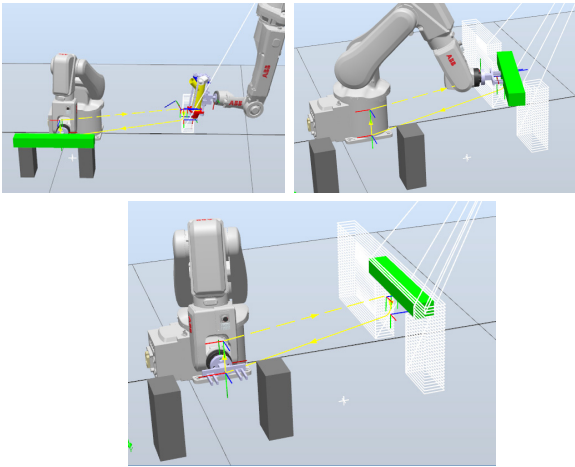


Figure 16. The steps of the concrete wall printing simulation

6.1. Generalization of the Program of Construction of a Small House

As soon as the wall is completed, the construction of a small chamber can be carried out in the same way. Except the handling of the roof requires the addition of signals related to the deposit of the roof on the chamber. It is of dimensions 600x800x300 mm as shown in the Figure 17.

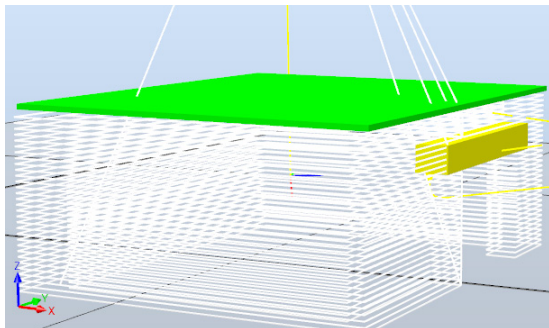


Figure 17. Small house designed in RobotStudio

In order to succeed in the simulation, we must add configuration signals of the "Toit" in order to define the position of the Roof in the reference system, Figure 18 shows the input-output diagram of the control system.

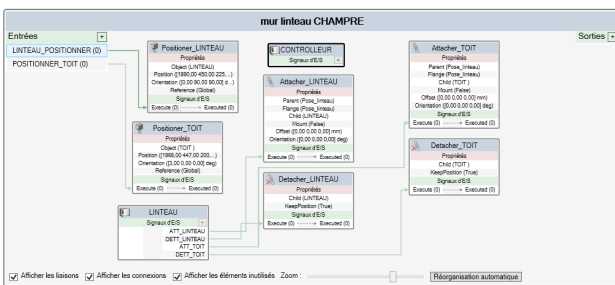


Figure 18. Control system inputs/outputs

After defining the location, the robot can be controlled by the program "Rapid" below for the placement of lintel and roof during printing.

7. CONCLUSION

The results of this simulation confirm the possibility of automating the construction process of the wall incorporating a lintel, all in this additive manufacturing technology. To succeed this printing process, we recommend the following:

- The reduction of the total investment costs can be done by increasing the number of tasks in the additive manufacturing process.
- The settling time of the collector must not exceed a threshold in order to reduce the impact of the delay on the rheological properties the mixture.
- The pumping installation can have an improvement that it will allow him to determine the rheological properties in real time.
- A monitoring system is an effective solution to control the speed and temperature [20] of pumping and printing in order to produce a trajectory to the desired dimensions.

Of course, the simulation of this process is not sufficient to judge its validity because in reality several problems suggest due to the age of the mortar and its rheological behavior. Nevertheless, this pre-study can be used as a basis to start larger research programs. It will allow to obtain interesting results at the laboratory scale, to judge the relevance of such a process and finally to attract potentially interested industrial actors to launch a realization program.

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BIOGRAPHIES



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