Presentation of a concrete additive manufacturing extruder with online rheology modification capabilities

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Abstract: To date, Additive Manufacturing (AM), a driving technology for the Industry 4.0 paradigm, is a growing technology field but has not reached relevant impact in the construction sector. The reason exposed in this article is the fact that current capabilities in terms of control of the setting reaction of concrete in real time are limited. Experimentation with a state-of-the-art concrete AM print-head has evidenced that the full stabilization of concrete’s chemical reactions is complex and involves phenomena that are not yet fully understood. Addressing this problem and the development of a fully automatic closed loop control would allow a great step forward in the capabilities of concrete additive manufacturing. So, as a first step, valuable information from thermal and pressure sensors were collected along the printing process, and their variations associated with the control of actuators (mixers and pumps) have been noted. A path for full real-time automatic control can be foreseen, and will guide future research and developments.

Keywords: Additive manufacturing, Material Extrusion, Concrete, Construction.

1. Introduction

1.1. Advantages of Additive Manufacturing in construction

Additive manufacturing (AM) is growing in the construction sector, and this is due to several factors: new advances in regulation, such as the new European Green Deal [1] or the mandatory use of Building Information Modeling [2], a growing concern about environmental impact, economic considerations and finally, the need for a transition to digital. This tendency for AM has been going on for several years now, for instance Contour Crafting [3] which pioneered the sector, Eindhoven University[4] made great advances in characterizing the materials, Apis Cor [5], COBOD [6] or Winsun (now Yingchuang) [6] completed the first large scale implementations. These applications that are starting to emerge, consist in fabricating house walls and other architectural elements (see figure 1) through AM.

Does this mean that the technological goals of Concrete AM such as reduction of the environmental impact and of the well-being of the workers are achieved? No, even if some advantages can be found in terms of costs or freedom of design, the technology is still far from maturity and the fulfilment of all its promises.

Figure 2 opposes house built COBOD company with state-of-the-art concrete AM technique (left), and the topology optimization of an aeronautical [7] part (right) that is only buildable through additive manufacturing. Concrete AM does not yet allow such dramatic changes in the geometry of buildings and other concrete elements.
Figure 1. HINDCON EU project allowed 3D-printing an architectural element with complex geometry [9].

(a) (b)

Figure 2. (a) House additively built by COBOD in Belgium (2020) compared to (b) an automotive part topologically optimized [7].

There is still a technological leap to be carried out by concrete AM in order to have technological maturity therefore revolutionizing the construction sector in the same way AM has changed aeronautical or automotive sectors.

1.2. The working principle of concrete AM

AM consists of adding successive layers of material each with a different desired shape in order to create a solid with less geometrical constraints than using traditional methods.

According to ASTM 52900, Material Extrusion (MEX) is one of the seven categories of the AM technologies. Within it, Fused Filament Fabrication is based on depositing melted thermoplastic that quickly solidifies allowing the following layer to be deposited. The other technology within MEX is Direct Ink Writing (DIW), also known as Robocasting, that consists in depositing inks or pastes with a shear thinning behavior. Concrete AM is closely related to the latter.

In order for AM to be possible, there must be some kind of change of state in the supplied material: at first, it has to flow to be deposited, and afterwards has to “consolidate” to withstand the weight of the material of the subsequent layers with minimal deformation.

In thermoplastics this change of state is a change from liquid (when melted in the nozzle) to solid once deposited. The simplicity of this mechanism compared with metallic materials is due to their low
energy of fusion, 10 times less than aluminum, and their low thermal conductivity, 1500 times lower than aluminum.

Opposite to these materials, for concrete, the transition from liquid to solid is not a thermal solidification but a chemical reaction called setting. Cement is mixed with an aggregate (small rocks) and water. The water creates a chemical reaction between cement and water, a process called hydration, which changes its physical properties.

There are many factors that can affect the way concrete sets, including temperature. Hot conditions can speed up the chemical reactions taking place inside concrete, reducing the time it takes to set. Moisture also affects the setting process. Without the required levels of moisture during setting, concrete can have reduced durability and strength.

1.3. Online rheology modification

Standard concrete setting is a long process that lasts for hours. This gradual transformation from liquid to solid makes it difficult to define a maturity point where, after the material is deposited, it is promptly solid enough to withstand the weight of the next upper layer.

In order to have a workable concrete its primary properties must be modified enough for the usage of chemical additives. First in the process the material must be sufficiently fluid, to be pumped and deposited, this requires an additive of the plasticizers family. But on the other hand, once the material is deposited, it must gain mechanical properties as quickly as possible, this gain in mechanical properties is done by two “mechanisms”: rise of viscosity and accelerated setting reaction:

- Rise of viscosity: the concrete mortar is not a Newtonian fluid and its viscosity will depend on addition to the temperature and also on the state of agitation to which it is subjected, it is therefore considered a pseudoplastic fluid. This behavior, which can be enhanced with calcium nitrate (Ca(NO3)2) based additives, will give to the concrete once deposited a very high viscosity, i.e., enough consistency until the second mechanism occurs.
- Accelerated setting reaction: setting can be accelerated to boost the early setting times and increase concrete strengths at an early stage. However, as it is shown in figure 3, this reaction is still highly dependent on the temperature [8] that will influence both the strength evolution and the final strength.

![Figure 3](image)

**Figure 3.** Effect of accelerators and temperature on concrete setting time [8].

Figure 3 Illustrates the effect of temperature and the amount of additive has in the setting time of concrete. It is shown that for a given concrete, setting time is decreased both by the concentration of accelerator and by the temperature.

2. Experimental procedure

The experimental part presented in this section has been developed in the framework of the H2020 HINDCON project [9] that has the specificity to require an independent printhead with the only exception of current, compressed air and LAN ethernet connection. The AM part of the project consisted in displacing the concrete additive manufacturing print-head using a cable robot developed by Fraunhofer IPA.
2.1. The concrete additive manufacturing extrusion head

Due to the requisites of the project the process is not continuous but volumetrically limited to batches of 100 l of concrete.

The basic process is the following:

- First a batch of concrete is prepared, and the plasticizing agent is added to it.
- This concrete is filled in the primary tank, the auxiliary tank is also filled with the accelerating agents.
- The print sequence begins, the printhead carried by the robot is displaced following a pre-established path.
- Once the print is over, the tanks are purged and the system is cleaned.

![Scheme of the additive concrete printhead.](image)

The scheme on figure 4 above presents the main components of the additive concrete print-head with 3 main components:

- The primary circuit, composed of the primary tank and pump, is in charge of giving pressure to the main circuit. The pump, volumetric and servo controlled, is in charge of dosing the amount of mortar going to be extruded. The actuation variable is called VM1.
- The auxiliary circuit, composed of the auxiliary tank and pump, is in charge of dosing the amount of accelerating additive added to the mortar in order to modify its properties (as described in section 1.3) just before deposition. In order to have an accurate dosing of the additive this pump is also volumetric. The actuation variable is called VM2.
- The mixer mixes mortar and additives and has the side effect of modifying the rheology of the material due to the shear stress induced by the rotation of the blades of the mixer. The actuation variable is called VM3.

In order to get data from the state of the system, four sensors are installed:

- A pressure sensor placed directly at the output of the primary pump is the point with the highest pressure in the circuit. The sensing variable is called PRE[0]
- A pressure sensor at the output of the auxiliary pump. The sensing variable is called PRE[1]
- Temperature sensor at the input of the mixing chamber. The sensing variable is TEMP [0]
- Temperature sensor at the output of the mixing chamber. The sensing variable is TEMP [1]
To end this description, a safety ball valve is installed at the output of the primary pump to relieve the pressure in the circuit in case of clogging.

2.2. Print-head control and external factors
Due to the uncertainties in the behaviour of the concrete setting reaction and the high pressures at stake, the system is manually controlled by an operator who also controls the robotic positioning system.

As described in the latter section, there are 3 actuation variables and 4 sensing variables.

**Table 1. List of control variables.**

| Variable | Description                     | Exchange units | Memory usage |
|----------|---------------------------------|----------------|--------------|
| VM1      | Primary pump speed              | RPM            | 2 bytes      |
| VM2      | Mixing speed                    | RPM            | 2 bytes      |
| VM3      | Auxiliary Additive flow         | mL/min         | 2 bytes      |
| PRE[0]   | Pressure sensor primary circuit | Bar            | 2 bytes      |
| PRE[1]   | Pressure sensor auxiliary circuit| Bar            | 2 bytes      |
| TEMP[0]  | Temperature at mixer input      | ºC             | 2 bytes      |
| TEMP[1]  | Temperature at mixer output     | ºC             | 2 bytes      |

During different working cases, the expected results in terms of control are the following:

- When VM1 is ON at any speed, the PRE[0] is low and increases slightly with VM1. TEMP[0] and TEMP[1] are equals and indicate the room temperature.
- When VM1, 2, 3 are ON with the theoretical ratios stated by the concrete’s manufacturer. PRE[0], and PRE[1] rise proportionally and reach a step. This is due to the increase in viscosity due to the adding of additives. Simultaneously TEMP[0] and TEMP[1] start rising due to the increase of temperature caused by the increase of pressure in the circuit, TEMP[1] diverging and rising quicker than TEMP[0]. This is due to the exothermic setting reaction of the concrete. This is the nominal case.
- In the nominal case, when VM3 is reduced, with all remaining parameters equal, then PRE[0] and PRE[1] decrease and TEMP[0] and TEMP[1] decrease with their respective differences also decreasing.
- In the nominal case, when VM3 is increased, with all remaining parameters equal, then PRE[0] and PRE[1] increase and TEMP[0] and TEMP[1] increase with their respective differences also increasing.
- In the nominal case, an action on VM2, should only have a limited effect on the PRE[0] and PRE[1] because a better mixing should improve the reaction but reduce the viscosity due to the pseudo plastic behaviour of the material.
- A sudden increase of PRE[0] without action from the operator indicates a clog in the primary circuit.
- A sudden increase of PRE[1] without action from the operator indicates a clog in the auxiliary circuit and should be followed by a drop of PRE[0].

The correct value of the different parameters VM1, 2, 3 can be fixed theoretically by the material manufacturer, but have to be adapted to the specificity of the mixer and the room temperature.

The system was installed in an industrial hangar with no insulation, the temperature will vary depending on the day and also during the printing process itself. Once this is taken into account, the lecture of the sensors is expected to be stable.

3. Results and conclusion

3.1. Operational control of the print head
During the experimental part of HINDCON project, a series of 35 printings where effectuated, numerous events happened and the full study of all cases would be too long to explain in this article, so
the focus will be placed to the print named as PRINT 19, which it can be considered a "standard" print case.

The chart below on figure 5 shows PRINT 19 of the test series. In this chart the actuation variable can be differentiated from sensor data due to the presence of interferences in the sensor data. VM1,2,3 are pictured in yellow, blue and green respectively. TEMP[0] and TEMP[1] are shown in grey and red respectively, PRE[0] and PRE[1] in Green and blue.

We can observe that several cases were expected (see section 2.2) but other cases diverge from the expectations.

- Case 1. As expected, without an accelerant or Viscosity modification agent (VMA) the pumping pressure is below the sensor's threshold. With case 2 differences begin to happen. When VM1, 2, 3 are ON, PRE[0], and PRE[1] rise proportionally. Simultaneously TEMP[0] and TEMP[1] start rising and diverging with TEMP[1] rising quicker than TEMP[0]. But, unlike what was expected, oscillations in pressure can be observed. Additionally, once the temperature rise (TEMP[0][1]) has reached its step, the pressures (PRE[0][1]) start falling, at a pace that seems constant (≈0.1 bar/min) in the different prints of the test series.
- Once the pressure fall has reached a level, the pressure is less reactive to control actions (cases 3, 4, 5). However, a clog caused by a flow stop at the end of the print (case 6) is clearly noticeable.

![Figure 5. Actuator and sensor history chart during Print 19.](image)

### 3.2. Discussion

It has been demonstrated that this system is nonlinear, and the first obvious explanation to this behavior would be that data from the actuators do not reflect reality. But both pumps are volumetric and the mixer is servo controlled so there is no reason to think that the output of the actuators is different from the inputs. Additionally, this behaviour is perfectly repeatable in every print (see figure 6 below).

![Figure 6. Actuator and sensor history chart during Print 1.](image)

The falling rate seems fairly constant for one material (Lafarge’s Ductal® 3DP the most used ≈0.1 bar/min), but higher for a C60 mortar with bigger aggregates. Therefore, this fall in pressure may be the consequence of the sedimentation of aggregates in the tank during the preparation phase. Although this phenomenon is not yet fully understood.
4. Conclusions
All these tests have been carried out at a constant extrusion (primary) flow, under constant supervision, during a relatively short time (all inferior to 45min). These conditions are standards for State of the art concrete 3D printers, the bigger constructions made up to this day require pauses in the printing process. As long as a human will be in charge, the control of the concrete print-head will need to be for short periods of time and with constant flow. The constant flow condition is a great limit for the freedom of the 3D printer because it inhibits the possibility of “travelling”. Allowing this change of flow will allow the machine more time to reach its final linear speed, allowing it to achieve great final speeds, greatly improving the resolution of the process.

Clearly in order to give concrete AM its full potential the control of the concrete additive print head needs to be fully solved. Automatically controlling the above mentioned parameter will allow the concrete printer to behave similarly to a standard desktop 3D printer and print sequentially several coplanar closed patterns, which is impossible in the current state of the art. Virtually allowing the same degree of shape freedom as current FFF printers.

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