

# On the Improvements of a Cable-Driven Parallel Robot for Achieving Additive Manufacturing for Construction

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**Abstract.** Generalization of additive manufacturing has led to consider this technological solution for more and more challenging use cases. Porting this technology to construction industry is a major step to overcome. Most of the recent research deal with materials, construction and extrusion techniques. Positioning of the extruder or material handler is mostly carried out by standard anthropomorphic robots or large-scale gantries. Cable-driven parallel robots (CDPR) can be an efficient alternative to these positioning solutions, being capable of automated motions in six degrees of freedom and easily relocated.

The combination of the Cogiro CDPR (Tecnalía, LIRMM-CNRS, 2010) with the extruder and material of the Pylos project (IAAC, 2013), open the opportunity to a 3D printing machine with a workspace of  $13.6 \times 9.4 \times 3.3$  m. Two prints, with different patterns, have been achieved with the Pylos extruder mounted on Cogiro, drawing a wire of material of 11 m in width and 3 mm in height: the first spanning 3.5 m in length, the second, reaching a height of 0.86 m.

The motivation of this paper is to give an insight to the necessary technical implementations on a CDPR for dealing with additive manufacturing process relevant for construction, in particular acute modelling of the cable and its extension under load, and to showcase the experimental prints carried out by the authors.

## 1 Introduction

The recent developments in Additive Manufacturing (AM) have led to consider ever more various materials for printing parts. Cement and construction materials such as clay are some of them. With AM technology, based on CAD design, architects get the possibility of manufacturing quickly and with precision optimized complex geometries for parts, offering free shape design for serving specific purposes and refinement in material distribution. A clear potential have been identified by industries, contractors and architects to reduce the cost of customized fabrication, and therefore create a

change of paradigm from the twentieth century standardized architecture of mass production toward the contemporary digital architecture of mass customization and site specific adaptation [1].

The optimal material for printing strong parts with total freedom of design and with a proven printing process is yet to be found, and this is a subject of intensive research. Typically, printing is carried out through brick laying and joining with cement [2–4], fused deposit modelling [5–7] or inkjet-like process [8], with in some cases shaping tools [7]. Positioning of the printing process head is however a much less investigated area. Some of the processes focus on the printing of individual parts of smaller scale for architecture in a workshop, to be brought later on at a construction site, and therefore use anthropomorphic arms for moving the printing head [2–5, 9]. Alternatively, using gantry robots for carrying the head is fairly common practice [7, 8]. Another disclosed solution [6] has been to extend the dimensions of a linear delta robot design to reach a cylindrical workspace with a 6 m diameter and height.

These solutions are typically unfit for printing directly on-site, a mandatory option as printed parts get larger, up to printing a whole building in AM. Anthropomorphic robots require a strong base for operation, and have limited workspace of a couple of meters at maximum, which can however be extended using mobile robots [3, 4]; anthropomorphic architectures with longer reach could be used and can be automated, as they already have been for brick laying applications for example, but they require expensive sensors for compensating for their flexibility [2]. Gantry robots [6, 7] can be installed on site with however important impacts in terms of logistics and price for large-scale structures.

Use of more novel solutions such as cable-driven parallel robots (CDPR) for AM in construction have already been investigated [10, 11] but are yet to be proven in this specific field, which is the purpose of the experiment disclosed in this paper. CDPR offer the advantage of having its longest elements being cables, which can be reeled in for minimum storage space; its frame can be limited to a series of posts for the drawing points, more easily displaceable than the supporting beams and rails of a gantry robot. Such capability has been shown in foreseen applications for emergency deployable robots [12]; outdoor operation following autonomously detailed trajectories is a common operation for aerial cameras [13] and radio telescope receivers [14]. An example of 3D printing over a workspace spanning almost a meter has also been achieved [15].

AM for construction is a process that requires the printing machine to be able to follow trajectories with a tolerance of half the width of the material wire on horizontal directions, and one third of the thickness of the wire, for the print to be considered satisfactory for the current experiment, using clay as the manufacturing material. The objective is to print a part that is sufficiently close to its CAD design. It can be noted that imprecision within these limits can provide a texture to the material which can be appreciated in specific situations.

This paper will first focus on the enhancements on the Cogiro CDPR [16] that have been required to achieve properly AM. The integration of the Pylos extruder [17] using clay on Cogiro is then discussed. A sample of the test prints is finally disclosed, with a discussion on the facts witnessed during this printing experiment.

## 2 Enhancement of Vertical Precision of Cogiro

Cogiro is a CDPR owned by TecNALIA and CNRS-LIRMM [18]. Its original point of design resides in the way the cables are connected to the frame, called the configuration of the CDPR, which makes it a very stable design [16]. With a footprint of  $15 \times 11$  m, 6 m high, it is capable of holding a load up to 500 kg over more than 80% of the footprint. Several demonstrations of industrial scenarios have already been run using Cogiro [18, 19] picturing the versatility of a CDPR.

Cogiro winches are capable of pulling the 4 mm diameter cables at up to 4150 N, or 1/3 of their calculated break strength. These cables are non-rotating cables manufactured in steel. They show a weight per length of 68.5 g/m and an EA factor (calculated as per ISO 12076) of 860 kN.

Advances in the control of the robot have allowed to reach repeatability in the millimeter range and precision in the low centimeter range [20], depending on the position. Most of the precision loss is today to be accounted on mostly the vertical direction at the center of the workspace, and progressively horizontal directions as the platform is brought closer to the sides. Yet higher positions will however show higher error in precision because of the geometry and the forces in the cables. This imprecision will therefore mostly bring an error on the height of the part to be printed. The position of the platform being reconstructed in the control scheme exclusively through the use of the angular position of the winches. It therefore appears that this imprecision would be due to error in the models, being geometric or due to the stiffness of the structural elements as the cables or the structure. Similar approaches in other CDPR [21] suggest that the modelling of the drawing points and the yield of the cables under stress would be the main factors of this imprecision.

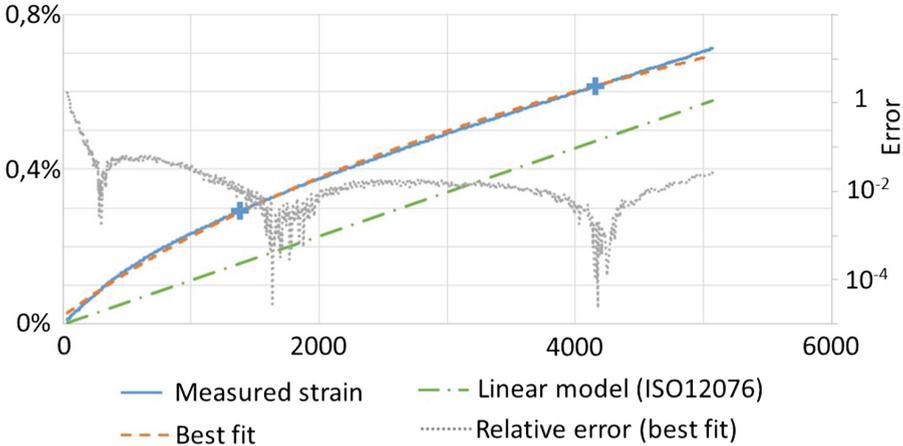
Calibration of the robot is carried out using a laser tracker capable of very high resolution (10  $\mu$ m) over a large span (50 m). A global frame is reconstructed each time the laser tracker is powered on, using elements fixed to the floor. The positions of the fixing points at the platform are measured at the same time as a series of fixed elements on the platform to reconstruct a platform frame. The points measured for the drawing points, coined as reference points, are the intersection of the axis of rotation of the pulley with the plane normal to this axis passing through the center of the pulley, measured using features of the parts holding the pulleys. Finally, the position of the platform in the homing position of the CDPR is measured using the laser tracker as well, allowing for linking drums positions with cables lengths.

### 2.1 Basic Implementation

In this first implementation, taken as the basis for this study, cables are considered inextensible and massless. The length of the cables are computed being the straight distance between the fixing points with the desired position and the reference points for the pulleys. The desired length of each cable over the wished trajectory is then fed to the control scheme that computes the input for each winch.

## 2.2 Stretching Cables

In order to qualify the extension of the cables under various tensile forces, a stress test in accordance to norm ISO12076 has been carried out using a stretch test bench over a cable length of 600 mm for a force spanning from 0 to 5000 N (Fig. 1).



**Fig. 1.** Strain  $\epsilon$  (%) vs Tensile force (N)  $F$  measured in the cable used in Cogiro. Crosses show the measure points for determination of the Young's modulus as per ISO12076.

It appears the number of 860 kN for EA factor is misleading, as this is in fact a measurement of the slope between two single points, one at 10% of the break strength, and another at 30% of the break strength as per ISO12076. In reality the cable shows a faster extension at lower forces (EA factor 339 kN) followed by a stiffer behavior at higher forces. Best fit between strain  $\epsilon$  and tensile force  $F$  has been found to be an offset squared logarithmic curve with the shape of  $\epsilon = a \cdot (\ln^2(F - F_0)) + b$ .

In addition to the basic implementation, at each point of the trajectory, a set of forces in the cables are computed using the inverse of the Jacobian of the system for balancing the expected weight on the platform. This requires the user to enter by hand the weight in the control interface. Each force is converted into a stretch, which is added to the target length for the control at each position.

## 2.3 Swiveling Pulleys

Another aspect taken into account is the model of the pulleys. Details of the model implementation has been developed in [20]. With this model, the length taken into account is the length over the circle of the pulley added to the length of the straight massless inextensible cable tangent to the pulley to the fixing point.

### 2.4 Test and Results

The test carried out for qualifying the improvement in accuracy is the measurement of the vertical position of the platform for various targets in position. These measures have been made at the center of the workspace, which is also the homing position of the CDPR. Platform actual position is measured every 0.1 m from Z = 1.27 m to Z = 3.57 m. Platform payload has been measured at 142 kg. The center of gravity of the platform is expected to be at the center of the cube.

Figure 2 shows the impact on the precision that the extension of the cable on one hand and the approximations in the cable model on the other had on the precision of the machine. From an original error of 0.25 m (at a very high position, where the cables are almost horizontal), the consideration of the real path of the cables and the extension in the cable, calculating the force in the cables, reduces the error to a few millimeters (max 6 mm, mean error 2.5 mm) in the measured conditions.

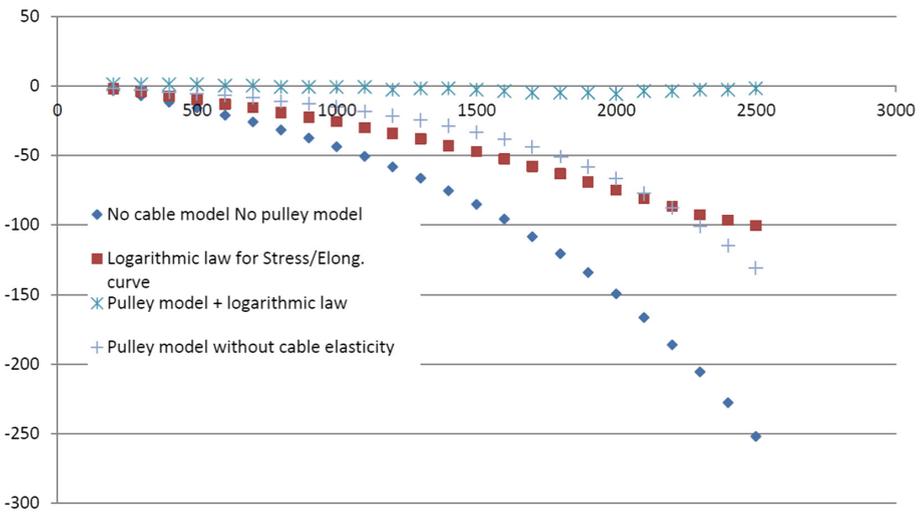


Fig. 2. Error measures in Z, in mm, versus desired height, in mm. Desired height is expressed in relative to the homing position, situated at Z = 1.07 m.

### 3 Combining Cogiro and Pylos

Pylos [17] is the result of a research action at IAAC on AM processes of large scale, using material with low ecological impact, 100% natural and biodegradable, for architecture. The material is a soil based mixture with natural additive specially tailored for AM process with an improved tensile strength and viscosity compared to the traditional soil used in construction. The extruder developed in order to test this material is composed of a canister with 15L of capacity for the material, compressed by a pneumatic cylinder. The extruder measures  $0.3 \times 0.3 \times 2$  m, weighing between 65 kg empty and 85 kg full. It prints with a wire between 1 and 7 mm in thickness and 6 to 30 mm in width, at a speed between 0.05 and 1 m/s.

### 3.1 Mounting Pylos on Cogiro

The whole platform together with the extruder filled with clay weighs between 157 kg empty and 169 kg filled up. It features the standard cubic platform of Cogiro with the Pylos extruder mounted on it by the means of a connecting plate (Fig. 3). The extruder is controlled by an output of the controller of the CDPR through the switching on and off of a pneumatic valve.

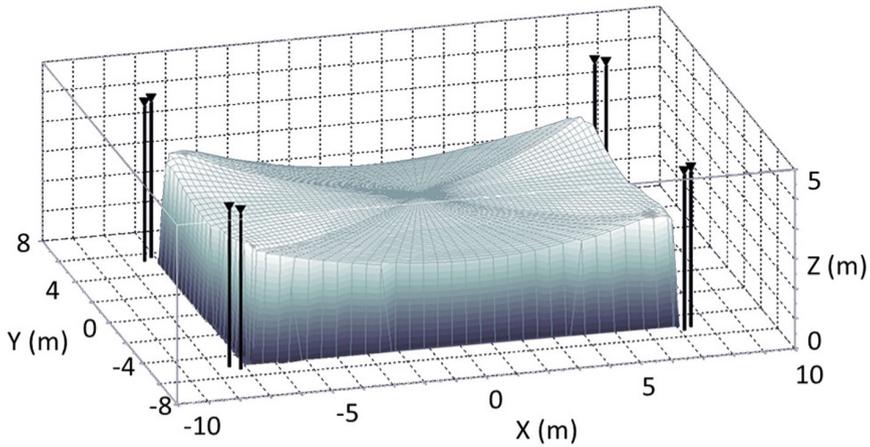


**Fig. 3.** Assembly of Pylos extruder on Cogiro.

The original design of the Pylos extruder has been modified for its use on the CDPR. Originally, the material chamber was filled directly into the extruder. For this operation the extruder is placed upside down and the nozzle removed. This operation is not possible with a CDPR because of cable collisions. It is also unpractical for large volume prints such as envisioned for such a large machine, with down time between two prints being too important for an efficient printing.

For these reasons a system of canisters has been developed, through which the piston pushes the material. It offers the advantage for the team to be able to prepare the material in masked time, when the printing is being processed. This reduces the amount of clay that can be printed in a go from 20 kg in the original design to 12 kg.

With this payload, Cogiro is capable of moving the tip of the extruder with the platform in upright position inside a rectangle measuring  $13.5 \times 9.4$  m, and up to 3.36 m above the floor. Figure 4 shows the volume within which the wrench due to the weight of the platform and extruder at the center of the cube, added to half of the weight of deployed cable at each fixing point, accordingly to the simplified cable model proposed by Irvine, can be balanced by the cables by taking into account their limitations. Coordinates show the position of the tip of the extruder. For balancing this wrench, when the tip is inside the pictured volume, there exist a set of forces in the cables, expressed along force lines set by fixing points at the platform and drawing points at the frame, which are all lower than 4150 N (1/3 of break strength of the cable) and higher than  $20 \times$  the weight of the deployed cable.



**Fig. 4.** Wrench-closure workspace of Cogiro with Pylos extruder mounted. Black triangles indicate the drawing points.

### 3.2 Trajectory Control of the CDPR

In order for Cogiro to follow precisely the trajectories, a G-Code postprocessor module has been integrated, based on CNC modules on the B&R software and hardware of the CDPR, running on Automation Studio 4.

Trajectories are designed using Rhinoceros 3D and Grasshopper 3D, using a custom script crafted by IAAC. This script computes the optimal path of the CDPR much like a CAM software. The output of the script is a G-Code file with the position and feed instructions for following the desired trajectory with a deviation of less than 2 mm. Each canister is able to print 100 m of wire; one file is calculated to correspond to one canister, and featured with a homing movement at the beginning and the end of the file, for approaching the printing position at first, and for going back to home position at last.

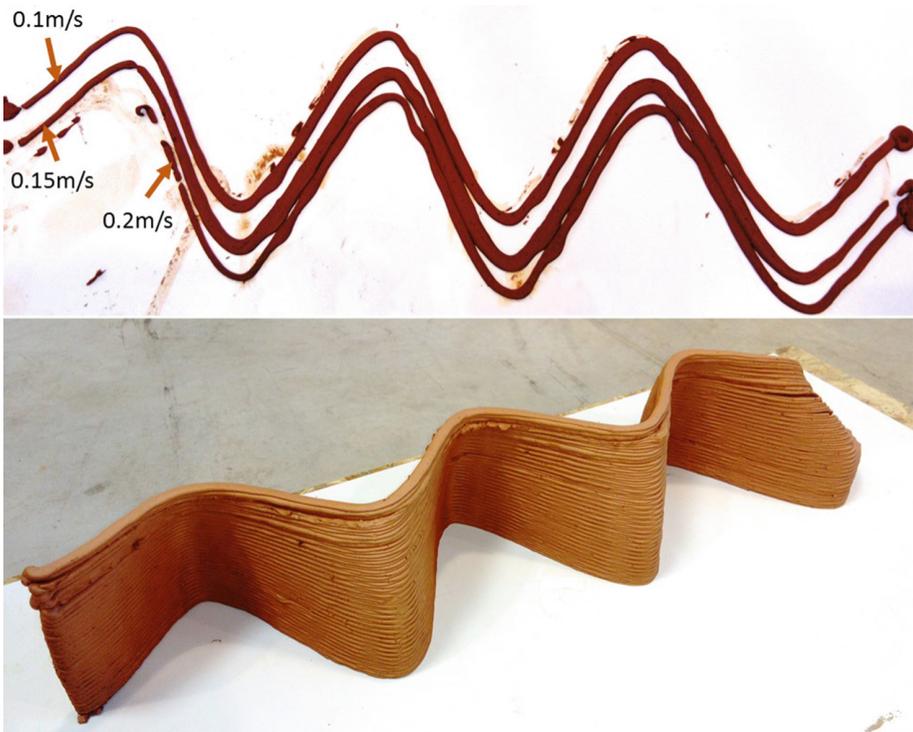
The G-Code postprocessor is a specific module integrated into the B&R Automation Studio suite enabling up to 5 axis of synchronous movement composed of lines, which are connected by circular portions to manage a continuous trajectory. Once a trajectory file is processed, it provides a timed output providing the position target that the CDPR should follow in order to follow the trajectory. This output is linked to the position target of the control of Cogiro until the end of the trajectory is reached. The G-Code also controls the output for controlling the starting and stopping of the extruder, so that the printing process starts and stops adequately.

Curvature has also proven to be a very important feature of the trajectory for printing with a CDPR. Preliminary tests on Cogiro with a print wire of  $11 \times 3$  mm have proven that at the desired printing speed (0.15 m/s) the local radius of curvature should not be lower than 25 mm. Undesired vibrations exceeding the tolerances (5 mm horizontal, 1 mm vertical) show up when this limit is not respected. When a smaller radius is required, the printing speed is brought lower in order to limit the acceleration

from the trajectory. In addition, at the end of each layer, the robot has been programmed to make a start and stop at both the finishing point of the current layer and the starting point of the coming layer.

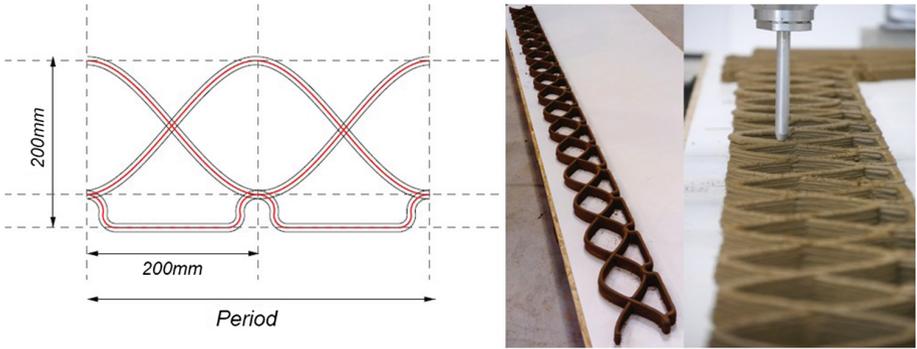
## 4 Test Prints

Several test prints have been achieved with Pylos and Cogiro. First tests involved the qualification of the best printing speed for the process, and the achievement of a 0.25 m high and 1 m long print with a sinusoidal shape (Fig. 5).



**Fig. 5.** Test prints with clay material.

The first demonstrating print for showing the CDPR capabilities for 3D printing is 0.2 m wide and 3.5 m long, in an overall straight line (Fig. 6). It features a special pattern that allows it to deal with the material shrinking under the process of drying, and improvements in the material composition for improving material strength. The pattern was repetitive which makes it more practical for the designer to design long structures. The coordinates for the center of the print were ( $X = 0$ ,  $Y = 2.2$  m,  $Z = 0$ ). The print showed a steady height over its full length.



**Fig. 6.** Long wall print.

The pattern used for this first print led to further improvements in the pattern design, optimizing the crossing of the lines and the dimensions of free lengths of wall. Parametric design has also been implemented for a shape of the wall changing with the height, showing the full potential of the 3D printing process. The second printed piece targeted a 1.5 m height and consisted of two periods of 0.338 m long by 0.415 m wide



**Fig. 7.** Cogiro, Pylos and the high print being processed.

each, which could be extended endlessly (Fig. 7). All prints have been carried out at coordinates ( $X = 0$ ,  $Y = 2.2$ ,  $Z = 0$ ).

As the part was getting printed, it appeared that the unloading of the clay from the CDPR was generating a steady vertical shift of about +5 mm. This made every stack of layers printed by a single canister 5 mm thicker than it should be. In order to compensate for that effect, after each canister the actual height of the print was measured and the Z positions in the G-Code file were offset such that the first layer of the new canister prints right on top of the last printed layer. Alternatively, other solutions were to modify the weight input of the control of the CDPR in function of time for the control to compensate for the weight loss; or use adaptive control [22] in order to compensate automatically such changes in the model.

At higher levels of print, the quality of the level of the layers had also degraded. The layers were showing oscillations on Z of  $\pm 1$  mm; they did not show any dilatation on the width however, because the oscillations were very repeatable from one layer to the next. This shows that the control of the CDPR needed finer tuning to achieve the wanted precision of  $\pm 1$  mm.

## 5 Discussion on the Results

Both prints are considered good results, and the test campaign discussed proved fruitful in experience. One of the main outcomes of the demonstration is to show that the Cogiro CDPR is capable of trajectories with millimeter precision, despite its workspace spanning meters long. It has been capable of drawing a material wire measuring 11 mm in width by 3 mm in height over long trajectories without substantial modifications on the height of the wire. This has been achieved only using the encoders of the motors for reconstructing the position of the extruder.

The need of acute control design for achieving such a precision has also been pointed out. Natural stiffness of the CDPRs played a role too: it clearly appears as the first source of errors for the estimation of the pose of the platform, and had an incidence on the print itself because of the unloading of the printing material. At this level of precision, a lot of detail is required on the models and parameters.

Future steps foresee the development of a continuous flow extruder, allowing to suppress down time from extruder loading, and print large scale elements of the size of a small building. The use of concrete as building material, requiring pumping of the material to the platform, will be investigated as well. Further research is also required on how to achieve high levels of precision with a CDPR in outdoor conditions, towards the application of on-site robotics for the construction industry.

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