A Drone-Assisted 3D Printing by Crane Structures in Construction Industry

Fabio Parisi, Agostino Marcello Mangini, Member, IEEE, Maria Pia Fanti, Fellow, IEEE, Nicola Parisi

Abstract—Additive manufacturing is a disruptive technology that is starting to be analyzed and studied also in construction industry. There are different approaches in its usage, and most of them concern the development of specific technologies, that are not always the optimal path to follow if environmental and energy related aspects are considered. In this paper a different paradigm to apply in the additive manufacturing exploitation in the construction industry is given. Starting from well studied and settled technologies like tower crane and drones, a simple, effective and already possible alternative for the usage of 3d printing at the real scale of construction is presented. A preliminary model is studied, its feasibility is investigated and the promising results of this first study are presented. Finally, the baseline and path for future investigation for the real development of this approach are enlightened.

I. INTRODUCTION

Construction industry is historically characterized by delay in the adoption of new technologies and innovative production processes [9][25][12][20][15][21][10]. Also in robotic technologies and in additive manufacturing applications this delay can be noticed. There are numerous different studies that are dealing with the application of robotic technologies in the construction fields. Important approaches that are being investigated can be classified in [11][6]:

- additive manufacturing with different technologies as gantry, cable-driven parallel robot, plotter based robotic system;
- robotic assembly systems;
- robotic bricklaying;
- automated robotic assembly system;
- off-site automated prefabrication systems;
- drones and autonomous vehicles.

Technologies can be used both in on-site and off-site constructions, where methodologies are close to the prefabrication approaches.

Among robotic technologies applied to constructions, an important role is played by additive manufacturing. The technological aspects related the application of additive manufacturing in construction industry are manifold. In [3] a classification of technologies is presented basing both on the printer type and on used materials; [19] reviews additive manufacturing in construction by considering processes, applications and digital planning methods, while [26] focuses on robotic manipulator assisted 3d printing. The mentioned technologies suffer of limitations that preclude their usage in construction industries. These limitations are referred to several different factors, and among them, it’s possible to identify: i) economical factors, both for contractors and clients; ii) workforce challenges; iii) culture challenges; iv) industry-intrinsic challenges; v) R&D challenges [3][6]:

These limitations drive researchers to develop new fabrication strategies [26].

The main question that is attempted to be answered in this paper is: why should new technologies be researched for if the integration of existing ones could foster the application of the additive manufacturing to a real construction scale? The mean investigation in this paper is that the integration of the well settled tower crane technology with the strong modern UAV technologies can contribute significantly to the involvement of additive manufacturing in construction industry. Tower crane is a specific type of cranes used in different fields thanks to their great usefulness in moving heavy loads. As reported in [16], depending on their construction and mechanical features, they can be classified into many types, such as tower cranes [23], overhead cranes [18], boom cranes [8] and others. The specific common feature of the different configurations is that they have fewer independent actuators than the degrees of freedom of systems. Hence, cranes are a kind of typical underactuated systems [7]. Compared with fully-actuated systems, underactuated systems are superior in energy saving, cost reduction, weight reduction, and system flexibility; however, they are more difficult to control due to the lack of control inputs [16]. Hence, the studies of various underactuated systems have been deeply and broadly conducted because of its importance. In particular, the control problem of crane systems has become an hot topic in research [1][8][5][24].

In the on-site construction of high buildings or tall infrastructures, tower cranes are considered irreplaceable in terms of advantages compared with other crane systems; without tower cranes, modern buildings dimensions would be impossible to reach. A crucial research field is the automatic control of tower crane. In these works, towers crane are studied for the optimal application in standard construction processes, trying to improve safety and efficiency in operations during construction. High performing, automated and controlled tower cranes would solve the problem of the “automated construction site”. Since they are so important technologically developed, an idea is to try to use them as a support for additive manufacturing.

Obviously there are critical issues in their usage in 3d printing:
• the "pendulum" behavior: crane structures control literature focus on control performed on the motors, considering heavy loads for which they have been designed. These controls try to minimize the swing effect on heavy suspended masses, but this minimization is not suitable for additive manufacturing applications because values of swing assumed by the suspended masses;
• a human operator could work near the suspended mass to stabilize the swing, but safety issues are of great concern. Moreover, when the construction process overcomes the action range of the operators, there would be the need for temporary structure like scaffolding on which the operators should continue to perform this critical operation with safety issues.

In this paper, the contribution of cranes technologies to the additive manufacturing approach is studied by substituting the suspended mass with an extruder able to deposit viscous material layer by layer, like in standard 3D printing techniques. The swing issue that can compromise the results of such operation is corrected with a direct control on the extruder performed by a drone. A drone is suitable for this application because of its role: it has only to direct and lead the suspended load, accompanying it in the movements, and not to carry and precisely locate any heavy load that influences its stability and its performance. To the best of our knowledge, there is not yet an attempt in literature to investigate in such a research direction.

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II. PROBLEM STATEMENT

A. Problem Description

The study aims at investigating the possibility to use automated towers crane integrated with a drone to perform additive manufacturing at the construction full scale.

A simplified crane structure is considered to preliminarily investigate the feasibility; in the specific, an overhead crane structure is studied considering a simple dynamical model. The considered machine shown in Fig. 1 is composed by two rails on which a girder can moves. On the girder, a trolley to which a mass is suspended can moves parallel to girder and parallel to rails together with the girder itself.

In the present study, the suspended mass is represented by an extruder for viscous materials (such as concrete or clay). This extruder has to follow a predetermined trajectory that describes the object to 3D print; the extruder deposits material over other material to create the object layer by layer. Like in other literature studies regarding crane structures, the main problem of the proposed application is that the
swing behavior of the extruder does not allow precisely following the shape of the object to create. The extruder swing behavior is controlled by a drone that can sense the load state and can act to compensate the swing. This allows a better performance in comparison with not controlled task performed by the same machine, with no need to implement a control directly on the machine actuators. In particular, a semi-circular trajectory is chosen with radius \( r = 2m \) (Fig. 2). The trolley is the only actuated element of the system, and it is programmed to follow the circular trajectory. By following the trajectory, a construction element such as a semi-circular trajectory is chosen with radius \( r = 2m \) (Fig. 2). The overhead crane dynamic model is obtained by the cable length changes when the \( i \)-th layer changes. Therefore, \( \theta \) and \( \phi \) are coordinates and angles as in Fig. 2.

Next, the Lagrange function is defined as:

\[
L(t) = T(t) - P(t) = T_i(t) + T_p(t) - U_p(t). \tag{4}
\]

Finally, using Lagrange modeling technique, the dynamic model of overhead crane systems can be calculated by the following equations:

\[
d\left( \frac{\partial L}{\partial \dot{q}} \right) - \left( \frac{\partial L}{\partial q} \right) = F(t) \tag{5}
\]

where \( L \) is the Lagrangian function of equation (4), \( q = [\theta, x, \phi, y]^T \) is the vector of physical degrees of freedom. In particular, \( \theta \) and \( \phi \) are the angles that the extruder creates with the vertical when subjected to swing respectively along \( x \) and \( y \) axes, \( x(t) \) and \( y(t) \) are the movements in \( x \) and \( y \) axes directions of the trolley (see Fig. 2). Moreover, \( F = [-b\dot{\theta}, F_x, -b\dot{\phi}, F_y]^T \) is the vector of forces: \( F_x \) and \( F_y \) are the forces acting in \( x \) and \( y \) axes directions of the trolley, \( b \) is the viscous rotational friction of the extruder during the swing (Fig. 2).

Now, applying (5) taking into account (4), it holds:

\[
M\ddot{x} - lm \sin(\theta)\ddot{\theta} + m\ddot{x} = F_x \tag{6}
\]

\[
glm \sin(\theta) \cos(\phi) - l^2 m \sin(\theta) \cos(\theta) \ddot{\theta}^2 + l^2 m \cos^2(\theta) \ddot{\theta} + lm \cos(\theta) \ddot{x} = -b\ddot{\theta} \tag{7}
\]

\[
M\ddot{y} - lm \sin(\phi)\ddot{\phi} + m\ddot{y} = F_y \tag{8}
\]

\[
glm \sin(\phi) \cos(\theta) - l^2 m \sin(\phi) \cos(\phi) \ddot{\phi}^2 + l^2 m \cos^2(\phi) \ddot{\phi} + lm \cos(\phi) \ddot{y} = -b\ddot{\phi} \tag{9}
\]

where \( M \) is the mass of the trolley, \( m \) is the mass of the extruder and the length of the cable \( l \) changes every time the extruder finishes one layer of the printing task.

C. Linear System Model

The described model is a non linear, time-dependent and four order system. The following assumptions are made to study the system with the aim of preliminary investigating the feasibility of the drone-based control of the extruder swing:

- the drone is modeled as an external contribution acting on the extruder. Moreover, it is supposed that the drone can sense and measure all the system variables;
- the variables \( x(t) \) and \( y(t) \) are not system degrees of freedom since they are fixed on the basis of the imposed trajectory. Consequently, \( \ddot{x} \) and \( \ddot{y} \) satisfy equations (6) and (8) and can be omitted in the model;
- the system inputs are the accelerations of the trolley with respect to the two directions \( x \) and \( y \);
- the cable length \( l(i) \) changes when the \( (i-1) \)-th layer is completed and it depends on layers thickness.

These assumptions allow expressing the system only in terms of the two angles \( \theta \) and \( \phi \) as state variables:

\[
\dot{\theta} = \frac{b\ddot{\theta}}{l(i)^2 m} - \frac{g \sin(\theta) \cos(\phi)}{l(i)} + \frac{\cos(\theta)}{l(i)} \ddot{x} \tag{10}
\]

\[
\dot{\phi} = \frac{b\ddot{\phi}}{l(i)^2 m} - \frac{g \sin(\phi) \cos(\theta)}{l(i)} + \frac{\cos(\phi)}{l(i)} \ddot{y} \tag{11}
\]

Now we define the state vector \( x = [x_1, x_2, x_3, x_4]^T = [\theta, \phi, \phi, \phi]^T \). Moreover, the input of the system is vector \( u = [\ddot{x}, \ddot{y}, d_1, d_2]^T \), where the inputs \( d_1 \) and \( d_2 \) are the external forces applied by the drone on the extruder state components \( x_1 \) and \( x_3 \), respectively. Then, taking into account equations (12)-(15), the system model is the following:
\[
\dot{x}_1 = x_2 \\
\dot{x}_2 = \frac{b}{l(i)^2} x_2 + \frac{\cos(x_1)}{l(i)} x_2 - \frac{g}{l(i)} \sin(x_1) \cos(x_3) - d_1 \\
\dot{x}_3 = x_4 \\
\dot{x}_4 = \frac{b}{l^2} x_4 + \frac{\cos(x_3)}{l(i)} y - \frac{g}{l(i)} \sin(x_3) \cos(x_1) - d_2 
\]

The state \(x_0 = [0, 0, 0, 0]^T\) is the equilibrium point of the system and it is a desired work point to make the system work as needed to depose material by minimizing form defects. The system model is linearized around the point \(x_0\) and the linear system model during the \(i\)-th layer is the following:

\[
\dot{x} = Ax + Bu
\]

where

\[
A = \begin{bmatrix}
0 & 1 & 0 & 0 \\
-\frac{g}{l(i)} & \frac{b}{l^2} & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & -\frac{g}{l(i)} & \frac{b}{l^2}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 & 0 & 0 & 0 \\
1/l(i) & 0 & -1 & 0 \\
0 & 0 & 0 & 0 \\
0 & 1/l(i) & 0 & -1
\end{bmatrix}
\]

Since the system is controllable, the inputs of the system are controlled by the drone by the following static state feedback:

\[
u(t) = r(t) - Kx(t)
\]

where \(K\) is the state feedback matrix, and the \(r(t) = [\dot{x}, \dot{y}, 0, 0]^T\) is the reference input.

### III. Simulation Studies

In this section some simulations are performed in order to show the system behavior under the proposed control.

#### A. Set-up of the simulation

The system has to build a semi-circular object with radius \(r = 2m\) and with global height \(h_{wall} = 0.5m\). Each layer is \(l_{lay} = 0.02m\) thick so that during each layer deposition the cable changes its length and the length of the cable during the \(i\)-th layer is \(l(i) = l_{in} - i \cdot l_{lay}\) where \(l_{in} = 7m\) is the initial cable length.

As specified in Section II, the trolley movements are considered the inputs of the system. Its trajectory is imposed to be circular so that a motion with constant angular speed \(\omega = \pi/10\text{rad}\) produces varying values of \(\dot{x}\) and \(\dot{y}\) (Fig. 2). For each layer the state feedback matrix is determined to obtain the following eigenvalues that provide a two dominant poles with good settling time \((t_s \cong 0.6 \text{sec.})\) and very limited overshoot:

\[
\lambda_1 = -20, \lambda_2 = -30, \lambda_{3,4} = -5 \pm 2j.
\]

The computed final values of the state variables \(x\) for layer \(i\) are the initial conditions of the state variables for layer \((i + 1)\).

#### B. Simulation Results

The motion equations, both the controlled and non-controlled ones, are simulated and the results of the simulations are shown in this section. The system is modeled in Python environment and solved with standard numerical integration tool.

In Fig. 3 a graphical results of the simulated system both in non-controlled and controlled situation is shown; both systems start with initial condition different from zero, and in both cases the trolley of the overhead crane structure follows.
Fig. 4. Trajectories on the first layer

The pre-determined circular trajectory with angular speed $\omega$. The trajectories followed by the extruder are represented. As expected, this graphical result shows that the controlled system performs better than the non-controlled in additive manufacturing applications, because of the evident deviation from the desired form.

To better notice this behavior, Fig. 4 shows the first layer of material deposition and a visual comparison between the desired trajectory that is the one followed by the trolley (in black), the controlled trajectory (in blue) and the non-controlled trajectory of the free extruder (in red). If the desired form to obtain with an additive manufacturing technology is the black, it’s clear that the non-controlled approach it’s absolutely unsuitable, in comparison with the controlled one.

Fig. 5 shows numerically how much worst the non-controlled approach is in comparison with the controlled one. The red curve represents the mean squared error of the red trajectory of Fig. 4, that reaches about $mse = 0.30m$ in the worst case. The blue curve instead represent the mean squared error of the blue trajectory of Fig. 4.

IV. DISCUSSION AND FUTURE WORKS

This work is a preliminary study to investigate the feasibility of the proposed approach: an extruder controlled by a drone that can deposite viscous material, layer after layer, to create elements at full construction scale by additive manufacturing methodology.

The feasibility of tower cranes usage instead of overhead cranes should be investigated by studying the dynamical behavior of the tower cranes considering also its deformation: in comparison with overhead structure, tower cranes are much more influenced by slenderness, in particular when subjected to moving heavy loads far for the tower or vertical column. The dynamical characterization of such structures is analyzed [22][14][13].

The study of the drone as a sub-system need to be performed and in the following the main aspects to be investigated are enlightened.

- Proper dimension and load capability: one of the most important aspects of the presented approach is that the drone act only as a “support” on the extruder, so that it’s load capability is only partially exploited; the suspension cable has this function. Nevertheless, the drone has to work in opposition to swing behavior of the extruder so that must actively act applying balancing forcing. Depending on the mass of the extruder (that is not constant during the process), the drone need to be properly sized. The development of strategies to enhance drone lifting capacity is one the most active topic in drone-related research field [4][17][2]. This is important because this preliminary study does not need a specific investigation in this direction, but can exploit the results from other active researches.

- Drone as sub-system: in this work the drone is supposed to be able to measure in every time instants the state of the extruder. This capability is at the base of the proposed approach. A specific drone control need to be designed taking in count these requirements.

- Drone and tower crane as a unified system: in this study the two systems are considered separately. To further investigate the presented approach, the two systems need to be studied in their integration, so that real performance of each of them could influence performance and capabilities of the whole system to its effective usage in construction additive manufacturing. The main objective is to act on system features that influence the drone force magnitude in compensating the swing effect. In particular, a specific control of the tower crane can be further investigated to find the optimal position that reduces the load for the drone.

- Comparisons of the presented method with compensation schemes in conventional additive manufacturing will be analyzed and possibly performed in the construction industry.

V. CONCLUSION

This research aims at introducing a new paradigm to exploit additive manufacturing in construction industry by
integrating already existing and well developed technologies such as crane structures and drones. The work does not focus on strictly on the control issue, neither on the comparison with already existing control strategies for crane structures present in literature, but aims at offering a new vision and a path to a possible alternative in usage of additive manufacturing in construction industry. In particular, a suspended extruder capable of depositing viscous material is considered actuated by an overhead crane and controlled by a drone. The extruder has to follow a trajectory to 3d print a construction element, while the drone has to minimize the swing effect due to the suspension of the moving mass.

After the problem statement, a simplified dynamical model is derived using the Lagrangian modeling method. Then a linear control is determined, and both the controlled and non-controlled behavior are represented: the unsuitable non-controlled performance is compared with the simplified proposed one.

Future works will focus on the study of the entire system characterized as the integration of the crane together with the drone. Requirements and performance for a real case scenario will be investigated.

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