Autonomous Big-Scale Additive Manufacturing Using Cable-Driven Robots

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Abstract –

Cable-driven parallel robots are a rather novel robotic system, with an advantage over traditional system in not occupying the ground level as it operates from the top down. This paper presents a possibility of additive construction similar to 3D printing at the scale of building parts or at house-size. This can be achieved by stacking elements as well as using a concrete-printing head. For this, a demonstrator is developed that is controlled by an architectural parametric tool that imports the design, checks the size/building limits/cable conflicts, creates paths, simulates the building process, and sends out the G-code to the robot. The goal is to use this robotic system on building sites as a flexible easy-to-use construction robot or for prefabrication purposes.

Keywords –

Additive Manufacturing; Cable Robot; Construction Robot; Simulation

1 Introduction

When thinking of robots fulfilling a function in a bounded area, we usually view them as ground–based machinery maneuvering around obstacles. Other classes of robots are the industrial arm robot, with various degrees of freedom, and the so-called 'delta' robots, often used on production lines for stapling, arranging, and packing. Because of their fixed requirements and rigid arms they cannot be easily placed in construction surroundings or used in the production of buildings. Over the last few years, a new class of 3D printing machines have been developed that can build complex and even large objects. However, these printing machines are not suitable for very large constructions, especially on-site and in challenging environments.

As an alternative to traditional robotic systems, we are researching cable-driven parallel robots in the context of building construction. These autonomous robotic systems move through space using ropes supported by an overlying and/or underlying construction. This gives the robot better access and operability for construction sites. They are light and cover a big operational area.

Similar to a giant 3D printer, this system can serve different needs in the building process. There are several construction scenarios, such as stacking elements on top of each other (similar to a brick wall) and layering fast-curing materials or two-component adhesive systems (traditional 3D printing). Since the robot is controlled by a minimum of six ropes, it also has six degrees of freedom, which provides additional functionality.

Positioning is achieved by changing the lengths of the ropes. This requires a winch system placed either at the cable ends (external) or inside the central moving unit (internal). In this work an external winch system is applied. The moving platform will have additional features that can be added to the robot, depending on the required function.

This paper describes the current research stage of this robotic system and its possibilities for autonomous building processes in big scale.

2 Related Work

Rope-suspended machines have been primarily used in film-making and television broadcasting. Their main effect is to access vantage points that are difficult or impossible to reach. The most popular commercial systems are "Spidercam" from CCSytems Inc. and a very similar "Skycam" from Outdoor Channel Holdings, Inc. (Figure 1).

In recent years, there has been considerable research effort at the Alto University in Helsinki, Finland, under the name of "Ceilbot" [1]. The main idea here is the development of a multifunctional robot acting from the ceiling. The work of one group [2] is showing the possibilities of a ceiling-mounted fire extinguisher robot operated on a rail-based system. Another group developed the concept of the Ceilbot Robot [3], a service robot system based on ropes.

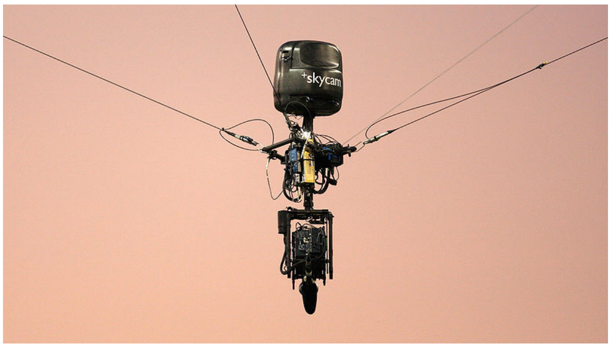

Figure 1. Hanging Skycam (wire-supported camera) skycam.com [4]

New technical possibilities for free-motion in space and stacking architectural modular elements are further developed by Gramazio and Kohler and Raffaello D'Andrea from the ETH Zürich. The idea of "Flight-Assembled Architecture" for building vertical structures uses a swarm of Quadrocopters that autonomously stack boxes. This system benefits from free upper space areas for maneuvers and new self-organized robotic swarm techniques. Short battery life of a single machine and low load capabilities are making this system not suitable for real construction scenarios.

There are a few recent examples of robots with a linear top-to-bottom motion system, such as Aaron Fan's "Pythagoras" and "Kritzler" from Alexander Weber, which works along two axes. In the "Makers & Spectators" exhibition, Niels Völkers, an artist and communication designer, developed a very similar system out of LEGO Mindstorms parts that unifies the hanging robot together with the drive mechanism.

The longest working cable-driven robot is RoboCrane from NIST, with a working age of 16 years. It is based on an inverse Steward Platform, where cables under tension replace the linear actuators. Six cables give the platform six degrees of freedom.

In 2014, Thomas Monroy and Taole Chen developed a "Sky Printer" [5], which is a hanging device suspended by three ropes that 3D-prints forms out of fast-curing material. This system is interesting for its simple construction and setup, but is missing precise positioning due to jiggling.

Fraunhofer has been developing an 8-cable-driven system "IPAnema Robot" series, with cables coming from each space corner [6]. The project group, under Dr Andreas Pott, has published numerous articles regarding this system and has made significant contributions for further development.

Parallel to Fraunhofer, a group around Tecnalia Institute is working on CoGiro an 8-cable-driven robot, with cables located only in four corners [7]. Demonstrations of movement and precision are proven to be very reliable. As this system can also carry weights and leaves the lower workspace area free of cables, it is suitable for construction purposes.

1. Autonomous Building Robot

Cable-driven hanging robots can be used for various purposes in a defined space. The focus of this work is to develop a 6-DOF moving unit that can be used for building applications. By permitting flexible movement in the upper areas of a construction site, a cable-driven robot can stack building elements in a particular order or 3D-printing large-sized objects. Such an autonomous building system that is also mobile can be installed in dynamic environments with moving and intersecting additional actors and is the higher goal of further research. In addition, several other applications as end-effectors will be the subject of upcoming research.

3 Eight Cables - Description

The main difficulty faced in the development of rope-supported systems is the precise positioning of the hanging device (end-effector). This is mainly because the device hangs on three or four ropes in one level. As the angles between the hanging object and the ropes were not adjustable, a deviation from the null position increased towards the border of workspace (see Figure 2).

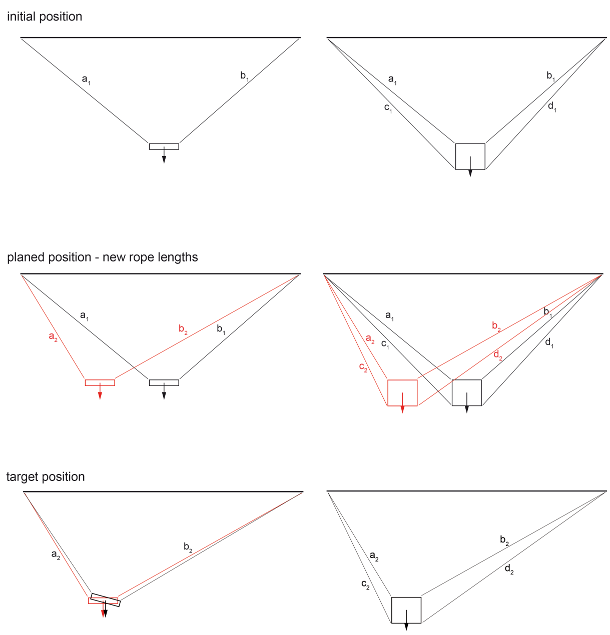

Figure 2. One- and two-level wire systems and deviations from the target position.

By adding an additional level of ropes to the system, a much more stable, rigid, and wider workspace range is achieved [8]. Furthermore, this increases the operational degrees of freedom (from 3-DOF to 6-DOF). This development, therefore, is extremely useful for robotic building and stacking purposes where simple rotation operations can be handled without additional motors.

A better and more precise transition of an end-effector can be reached by setting a gimbal-system to the hanging object that points the end-effector to the desired direction; however, even this system cannot avoid shaking and unstable movements. Further development will combine a gimbal system with a two-level wire-system.

4 Research Stage

For testing purposes, a machine was designed that has fixed box side dimensions of 2m. With fixed cable positioning at the top corners of the system, the robot belongs to the Suspended Wire Robot type that needs external forces as the gravity of the carrying object to keep the tension of the cables. T. Bruckmann at el. are distinguishing this kind of cable robots from the Fully-tensed Wire Robot type that is having cables from each corner of the system and so more stability and less vibration [9]. Because collisions with the cables are minimized together with the option of building more complex and space-filling forms, Suspended Wire Robot type is chosen for the robot prototype that will be described in the next chapters.

4.1 Robot Design

The whole robotic hardware system consists of:

- frame 2000 x 2000 x 2000 mm with two winches in each lower corners,
- wires connecting the winches and the moving platform,
- moving platform with added end-effector that can be changed in dependency of the function,
- motor controllers that are rotating the winches,
- computer for sending commands to the controllers and to the end-effectors.

The software parts are:

- cam-software for making brick walls out of simple surfaces, calculating trajectories, controlling collision free positions, and exporting positions and actions for the controlling-software,
- Robot Control software that is transforming positions and actions into g-code and sending it to the controllers of the robot,
- Motor-software, interpreting the g-code and calculating the motor motion.

Measuring the rope length precisely is the most difficult task in the robot design. The winch is separated from the deflection pulley over whole height of the robot. Deflection pulleys are placed on top and the winches are placed on bottom corners. This distance minimized the length differences through rope movement along the winch axes. Motor controllers, that are usually used for controlling 3D-printers, are installed for moving the winch motors. The benefit is the build-in function of processing the G-code that enables a smooth and coordinated movements of the motors. Due to the large number of motors, two controllers are necessary for the control of each of the four motors. To coordinate the movement of each motor connected to the different controller a feed rate is calculated prior of sending the G-code. This is necessary to get a balanced interaction of the motors especially when some motors have much less movement then others and they have to adapt the feed rate in order to stop moving at the same time.

Figure 3 is showing the processing steps from manually drawing a 3D-wall to the stage of stacking the bricks.

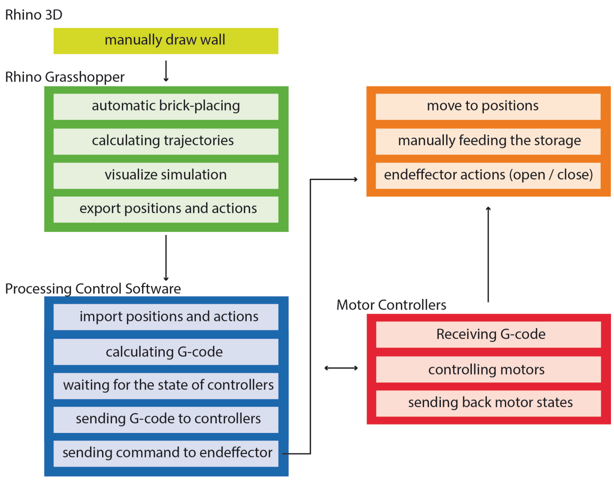

Figure 3. Chart showing the process with the different software clusters

The Robot Control Software divides between controlling motors for moving the winches and the motors for moving the end-effector. This is necessary because the end-effector is controlled through a wifi-connection and a battery-energy supply. A wired connection would make the prototype setup technically more complicated. For further development, a wired connection will give more possibilities with stronger end-effectors and better controlling options.

4.2 Trajectories Planing

The movement of the robot along a predefined path, called trajectories, is done by a software that is commonly used by architects and engineers called Rhinoceros by Robert McNeel & Associates. The parametric tool Grasshopper, a plug-in of Rhinoceros, is planning the position of the bricks, collision checking, and automatically delivers the trajectories. They are defined as a sequence of locations and rotation information of each position in relation to a reference point. These positions are combined with action commands (Fig. 4) and sent out to a file that has been read by the Robot Control Software. The visual control of the trajectories in form of a continuous poly-line can help in tracking errors.

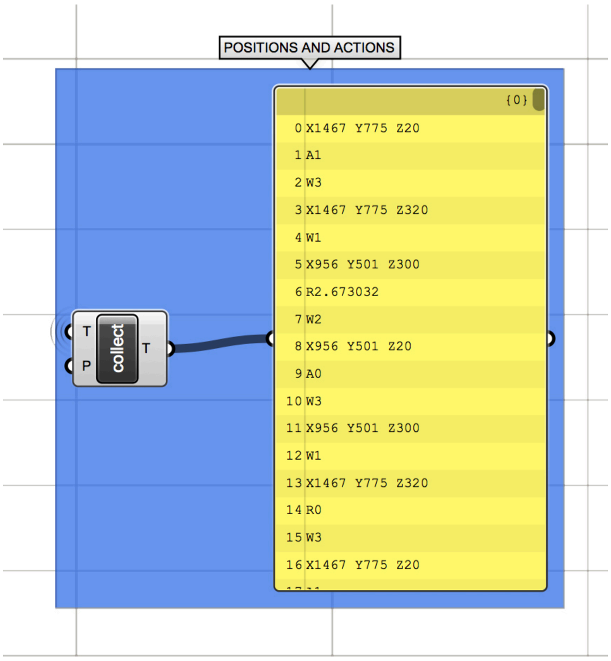

Figure 4. List of positions, wait, and action commands from Grasshopper/Rhinoceros that is then exported to Robot Control Software

4.3 Simulation

For the purpose of getting the position of the bricks in the wall a virtual parametric model is realized within the Grasshopper in Rhinoceros. All non moving objects are built as fixed 3D-objects (Fig. 5) and objects that are moving are part of the parametric Grasshopper model. A surface is defining the main brick positions and the parametric model is placing bricks along the surface automatically with incorporated balance testing. This helps to build up a wide range of testing arrangements.

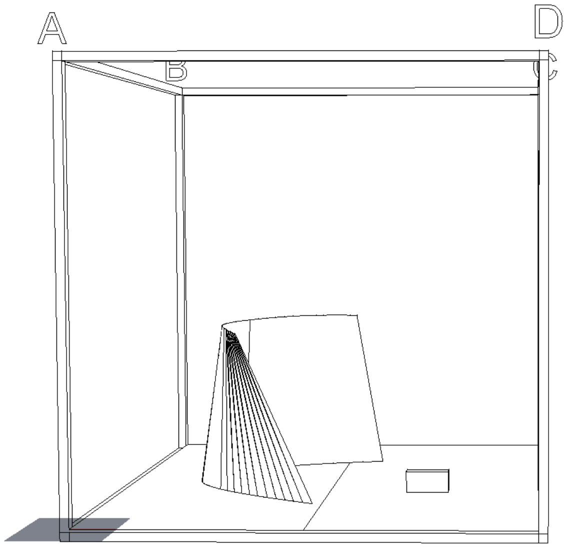

Figure 5. Frame of the robot with the initial feeding position and the wall surface. Bricks are positioned along this surface.

An animation of the brick building is showing all movements with possible verification of the sequence (Fig. 7). Improvement to this system will be the automatic calculation of the optimized brick feeding position as well as moving feeding position vertically. Another improvement will incorporate positions that are not reachable by the robot mostly on the edges of the frames as well as critical height positions.

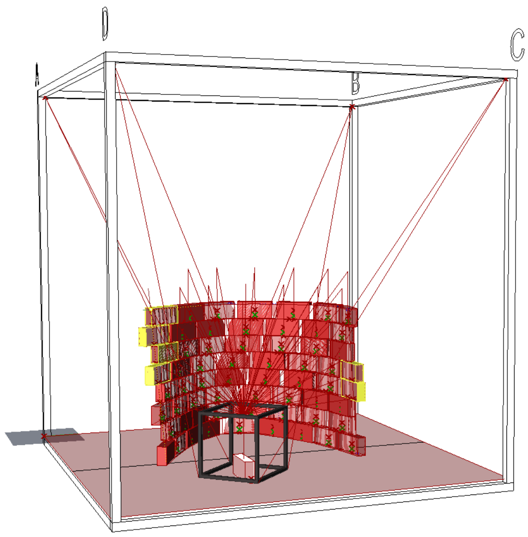

Figure 6. Parametric model with visualization of the trajectories. Yellow marked bricks will not be

placed due to their unstable position.

Similar to any CAM-Software this step is processing the positions to the Robot Control Software.

4.4 Prototype

Machine controlling is realized by the free available programming tool Processing [10] that has good scope for visualizing information and server communication to the two controller boards of the robot over a serial interface. All incoming positions are translated to rope lengths and to winch positions as G-commands. Sending this commands with the positions is moving the winches. The machine waits for the feedback of the motors, to get their actual position and is sending new commands only when these new positions are reached.

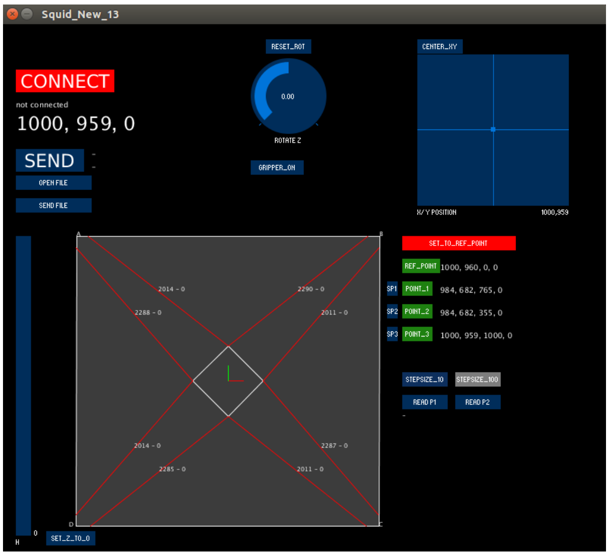

Figure 7. Robot Control Software that controls the machine. It loads the positions from a separate file made by the previous simulation.

A simple gripper is getting a separate non G-Code command, as it is not connected to the controllers. A wireless wi-fi connection and its own battery are activating the end-effector. However, more complex end-effectors may need a wire connection that can be provided from top-middle of the frame.

For this testing prototype styrofoam blocks were used to see the capabilities of brick stacking. Moving real bricks will need stronger motors and eventually a bigger frame.

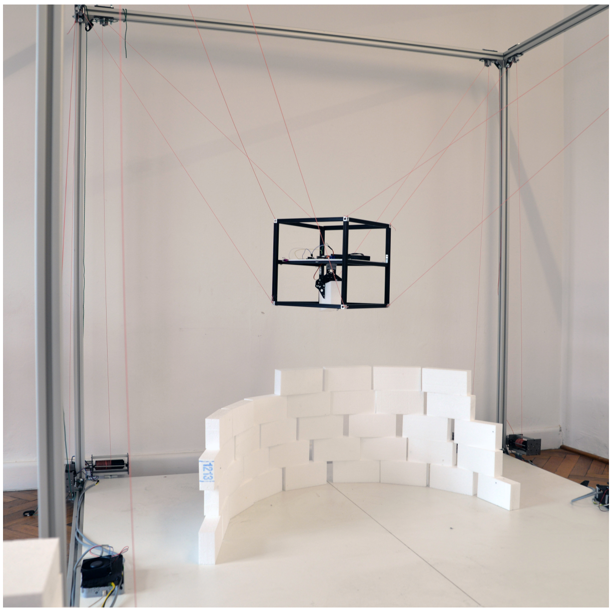

Figure 8. Robot in action stacking the bricks

5 Summary and Conclusion

This paper shows a step in additive manufacturing for buildings in a larger scale. This will lead to scaling the robot in space and force towards further development of automatized construction of building walls. Using cable-driven robots for additive fabrication in real construction sites is still not possible, but the presented prototype is showing that there is a future for applications on building construction sites. For the model-simulation an industrial standard is chosen that is near architectural production. The Suspended Wire Robot was chosen due to better collision properties between wires and the constructed object. Next to adding bricks in layers, there are several other possible usage scenarios for cable-driven robots:

- addition to and in combination with normal cranes on construction sites for precise moving elements,
- addition of scanning devices for complex 3D-scanning,
- addition of 3D-printing devices for the production of huge scale 3D-printed objects.

Next steps will be the development of non-linear motor controls, especially for the robot as a mobile version with variable corners. Subsequently, self referencing features will help as well as an optical object recognition system for a better feeding process. A vertically adjustable feeding station will help to build higher objects. Furthermore, the optimization of the data transfer from the simulation software to the robot control software will simplify the overall testing.

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