Robotic Fabrication of Tensile Mesh Structures and Real Time Response

The Development and Simulation of a Custom-Made End Effector Tool

Odysseas Kontovourkis¹, George Tryfonos²
¹,² Department of Architecture, University of Cyprus
¹,² {kontovourkis.odysseas|at07tg2}@ucy.ac.cy

This paper presents an ongoing research, aiming to introduce a fabrication procedure for the development of tensile mesh systems. The purpose of this methodology is to be implemented in real time, based on a feedback loop logic cyclically iterated between robotic machine control and elastic material behaviour. Our purpose is to extend the capacity of robotically driven mechanisms to the fabrication of complex tensile structures and at the same time, reduce the defects that might occur due to the deformation of the elastic material.

In this paper, emphasis is given to the development of a custom-made end effector tool, which is responsible to add elastic threads and create connections in the form of nodes. Based on additive fabrication logic, this process suggests the real time development of physical prototypes through the increasing smoothness of mesh structures.

Keywords: Robotic fabrication, Tensile mesh structures, Real time response, End effector tool

INTRODUCTION

The continued development of digital fabrication strategies used in the construction of complex morphologies and the need for accuracy and precision in regard to the physical results obtained, open new directions in this area that go beyond the simple linear workflow from design to construction. Hence, the need for the effective control of physical prototypes during construction through computational mechanisms, which allow continuous evaluation of results according to physical changes within a feedback loop process, is currently coming to the fore.

In addition, the experimentation and use of various materials during the construction of complex forms is possible, thanks to the computational investigation of morphologies and the parallel simulation or implementation of the construction process, as well as the use of external data acquisition devises, i.e. vision systems and control devices, i.e. Arduino microcontrollers (Braumann and Brell-Cokcan, 2012a). This new logic requires the combination of different manufacturing methods like cutting, welding, forming and milling (Iwamoto, 2009). Currently, the development of robotically driven fabrication methods, which are able to handle complex morphologies and materials, requires the use of more
sophisticated applications than simple industrial end effector tools, such as hot wire and gripper (Braumann and Brell-Cokcan, 2012b).

Related works in this direction can be found, for instance, in the project 'Aggregate Structure', where a continuous control system between robotic machine and physical information processing is developed that uses a magazine emitter-head for pouring spiny plants (Dierichs et al., 2012). In parallel, the need for material control during the prototype development process leads to the design of custom-made end effector tools. In this direction, the example of 'Magnetic Architecture' demonstrates an end effector that is able to control the force and distance of magnetic field creating structures of iron filings (Durbor and Diaz, 2012). The capacity of robotic arms to allow the adjustment of different end effectors at their end, as well as the efficient control of their behaviour, enables the introduction of new fabrication approaches and materials for the development of complex systems in different scales.

METHODOLOGICAL FRAMEWORK OF THE END EFFECTOR TOOL DEVELOPMENT

This ongoing work follows previous investigation done by authors in regard to a suggested holistic fabrication process implemented in real time (Kontovourkis and Tryfonos, 2014). Using an offline simulation process (Biggs and MacDonald, 2003), the aim was to develop a fabrication methodology using feedback loop logic for the construction of tensile structures, that combined robotic machine control and elastic material deformation (Kontovourkis and Tryfonos, 2014). Specifically, the suggested procedure involved the gradual addition of elastic threads used as the proposed material, creating an overall mesh geometry consisting of nodes and lines. This resulted in the deformation and alternation of the overall structural system in real time and hence in the repositioning of the nodes within the system. The proposed scenario involved capturing the nodes position using camera devices and transferring the input information into the digital environment. Then, the next movement step of the robotic arm was calculated, controlling the additive behaviour of the machine. This was also influenced by the number of repetitions undertaken during material addition, influencing the overall shape or the smoothness level that was specified and controlled by the architect-user. Through the suggested real time manufacturing process, the possibility for developing complex morphologies that were adapted according to the decisions taken by architects was examined, in order to optimize the respective construction outcomes [Figure 1].

In order to achieve the suggested fabrication process, a number of necessary steps are taken into consideration: a. Investigation towards the correlation of material behaviour in physical and in digital level as well as the simulation of the overall structural deformation, b. Research on the adaptive control of robotic arm behaviour and generation of fabrication

Figure 1
Simulation steps of robotic handling during tensile mesh structure development
tool paths, and c. Development and simulation of the end effector tool.

In this paper, attention is given to the third part of research that is the development and simulation of the end effector tool, which is considered to be a fundamental element of the overall fabrication process since it is responsible for the elastic material handling and hence the results of construction. Specifically, through the continuous addition of elastic threads, the welding and finally the nodes creation, the construction of tensile mesh and the geometrical smoothness of structure can be achieved.

Within this framework, an initial investigation into the production of physical prototypes using conventional methods of fabrication is introduced. The process of adding elastic threads based on specific geometric rules results in the formation of mesh systems consisting of edges and nodes. As part of the welding procedure, the bonding of threads is achieved by the use of a hot-melt adhesive. Based on the observations derived from the experiments and the elastic threads control requirements, a multipurpose end effector that involves three operations is proposed [Figure 2]:

1. Length control and elastic thread feed
2. Supply and hot-melt adhesive
3. Holding and creation of nodes

**DESIGN AND CONTROL OF THE END EFFECTOR**

The proposed end effector tool consists of three actuators that control its mechanical and movable parts. Each of them is responsible for an operational procedure that has been mentioned in the previous section. Through synchronization and calibration of operational steps the overall handling process is achieved. The design of the end effector tool is influenced by the size of actuators, the scale of material handling, the welding of silicone elastic threads, the base of mounting on the robotic arm (axis J6), the size occupied by the movable parts and finally, the scale of the overall mesh structure [Figure 3].

**Length control and elastic thread feed**

The purpose of the process of length control and elastic thread feed is the accurate control of the thread's movement from the bobbin part until the welding spot. The length control of elastic thread is an important part in the development of physical model since it defines the extension that causes the local thread deformation.

Thus, for this operation, a bipolar stepper motor (1.8 degrees steps) is introduced. At the end of motor a 3D printed pulley 15T is placed, in which its rotation is transferred to a similar type of pulley that is connected with the PLA roller. The full circumference (360 degrees) of the stepper motor is equal to the complete rotation of rollers. Their rotation corresponds to the length of thread necessary to be fed depending on different cases. The material bobbin is mounted to the back and upper part of the end effector for easy access by the architect-user. Thus, the
rollers pull and unwind the elastic thread from the bobbin and feed the PLA cylindrical tube, which in turn transfer the thread to the welding spot [Figure 4].

**Supply and hot-melt adhesive**

For the welding of threads and the creation of expected nodes, the hot-melt silicone adhesive technology is applied. Due to the same type of silicone material used, both for elastic threads and for hot-melt glue stick, this technology is considered ideal for the creation of nodes/connections. The expected future development of the research as regards the recording of nodes via a vision system requires the use of hot-melt adhesive tube in black color. In a future stage, through image processing, the physical nodes will be tracked and transferred to a digital environment in the form of information points.

The supply of hot-melt glue stick (11mm) is achieved via the use of a continuous rotation motor (360 degrees servo motor). The rotation of servo motor and its connections with the 3D printed pulley T15 causes the transfer of motion via belt to the 3D printed pulley T30. The increase of pulley's size allows the reduction of rollers' rotation relative to the rotation of the servo as well as the increase of the rotational torque generated by the rollers. For the better control of the supply of hot-melt glue stick, the rollers are connected to an additional pulley that transfers the rotational movement via the 3D printed pulley T15 in rollers (this appears on the back side of the end effector). In order to maintain the correct direction of movement for the hot-melt glue stick, a PLA tube is designed that allows the material to move into and feed the melting apparatus. In this way, the rotation of four rollers pushes the material into the machine for melting purposes. This converts the solid material into liquid, which is poured in the hemisphere in the hot end of the end effector tool for welding the elastic thread material and for creating nodes [Figure 5].

**Holding and creation of nodes**

An important feature in the process of creating nodes and controlling the threads' length is the technique for approximation positioning and holding. The retentation of elastic thread is found to be necessary in order to reduce failures caused by the pretention of
the filament as well as the elevated temperature due to the hot-melt adhesive process.

To control the holding procedure and cut the elastic thread, a linear actuator is used. The design and printing of a 3D prefabricated gripper in front of the end effector tool manages to control the approximation of thread in the predetermined level and to hold the material. In order to achieve this, the gripper tool includes a hemispherical shape as well as a blade for threads cutting. When closing the linear actuator, the projection moves linearly in the vertical plane of the melter device, in which it holds the thread, for nodes creation. In parallel, the linear actuator is able to bring additional strength causing the cutting of thread. With the opening of linear actuator, the node is released, activating the elastic behaviour of thread. Finally, the end effector tool is withdrawn from the welding spot [Figure 6].

FACTORATION OF THE END EFFECTOR
For physical development purposes, the mechanical parts that make up the end effector are fabricated on a 1:1 scale and their motion is optimized through trial-and-error testing [Figure 7], aiming at the final-
self-weight distribution of the end effector, the stepper motor that is responsible for the length control and material feed process is placed close to the end of the robotic machine. Then, the mechanical and actuator case is adapted and screwed into the bottom of the electronics and material case. At this part of the end effector, rotary actuators and mechanical details (pulleys, belts and rollers) that are responsible for the supply and hot-melt adhesive operations, can be found. Also, this section incorporates the linear actuator that is responsible for the holding and nodes creation process. Finally, the melding and adhesive components are added and screwed in front of the mechanical and actuators case. This component consists of two parts. The first part represents the case for the melter that is used for supply and hot-melt adhesive process. In the front area, the cooperation with the linear actuator achieves the accomplishment of the holding and nodes creation process. The second part is connected to the first part and it bears all mechanical details, i.e. pulleys, rollers and PLA tube for the length control and elastic thread feed process [Figure 8].

The three main parts are connected together, so as to control and synchronize the whole procedure. In addition, the separation of parts enables to redesign the parts in order to optimize the motion behaviour and improve the mechanical details.

**PROGRAMMING AND CONTROL**

To program the mechanical parts, the Arduino board that is linked to Grasshopper (plug-in for Rhino) via Firefly (plug-in for Grasshopper) (Payne and Johnson, 2013) is used. Three programming tasks responsible for the control of the end effector are distinguished:
a. Creation of the start node, b. Length control of elastic thread, and c. Creation of the end node. The three tasks are responsible to control the information from the digital model activating the respective movement of actuators. Initially, to develop the control algorithms the actuators are connected to the Arduino board. Because the stepper motor needs to receive data in pulses, an Easy stepper driver board that is connected to the Arduino board is used. The stepper driver is responsible to control the data from the Grasshopper to the stepper motor, controlling in parallel, the direction and angle of rotations. The control of linear actuator and servo motor is achieved by the use of a simple 3pin wiring. With the use of numerical values 0-180 degrees, which are designated in Grasshopper and transferred to the Firefly writer, the lengthening of the linear actuator, as well as the speed and direction of rotation of the servo motor are defined [Figure 9].

Initially, actuators are calibrated in relation to the rollers of operations. For the length control and elastic thread feeding procedure, a full rotation (360 degrees) of stepper motor equal to the perimeter of roller (55,2mm) is introduced, that achieves respective thread feed. The supply and hot-melt adhesive procedure is calibrated by the time of rotation of servo motor. Specifically, a time interval of 5sec is required for pushing the expected glue stick and for creating the node. To activate the servo motor and stabilize its speed, a numerical value 80 is defined in Firefly, while to deactivate the motor, the numerical value 89 is used. Finally, to control the linear actuator in the holding and creation of nodes procedure, a numerical value of 40 and to open and release nodes, a value of 55 is defined.

For the robotic control, the HAL (plug-in for Grasshopper) (Schwartz, 2012) is introduced. Specifically, the actuation of the end effector tool is synchronized to the control of robotic arm movement. By using feedback loop logic between robotic machine and the HAL software, the algorithm is responsible to control and determine the order of elastic threads' addition. Each thread is added by using the three tasks described above.

The task programming occurs by calculating the time duration depending on the position of the robotic machine. Initially, the algorithm for controlling the start node creation activates the opening of the linear actuator. Subsequently, the activation of the stepper motor manages to feed the welding spot with 20mm length of thread. Then, the linear actuator slightly closes in order to hold the threads. Parallel to the complete closure of the linear actuator, the servo motor is activated to feed the hot-melt glue stick. This is liquefied using the melter and the threads are adhesive for node creation. Finally, by opening the linear actuator, the robotic machine withdraws and continues its movement.

Parallel to the relocation of the robotic arm from the start node, the task for controlling the length of thread is activated. This procedure aims to supply, in each case, the required length of elastic silicon thread. The suggested algorithm checks the result of tensile structure simulation and sets the re-
required length of thread in order to achieve the desirable pretension and deformation of the mesh structure. The defined length is translated into an angle used for stepper motor rotation that causes the release of expected material. The time of rotation is calculated and compared to the time needed by the robotic arm to move from the start node to the end node. If the time needed for length thread wrapping is longer than the time needed for the robotic arm movement, the robot waits to execute the task for a respective time and then continues the end node creation procedure.

Finally, when the robotic machine reaches the point, the end node creation task is activated. The linear actuator closes and holds the thread. At the same time, it cuts the thread from the bobbin and simultaneously the servo motor for the hot-melt glue stick procedure is activated producing the node. Then, the control algorithm specifies new coordinates in which the silicon elastic thread addition procedure will occur.
DISCUSSION ON THE END EFFECTOR POTENTIALITIES

The use of mechanical parts and actuators as well as their programming control enables the development of a custom-made end effector tool with specific fabrication abilities defined according to the construction task under investigation. Also, the recent advancement in the area of real time control and simulation (Braumann and Brell-Cokcan, 2012c) enables the robotic machine and elastic structure behaviour simulation, as well as the activation of the end effector tool. At the same time, the architect-user is able to make decisions in regard to the final construction result, thus defining the smoothness level of tensile mesh structure.

The end effector tool is an important part of the suggested robotic manufacturing process. In this automated procedure, three operational steps are applied, which can be evaluated according to the quality of the result achieved due to the required highly accurate process of threads installation and nodes creation. Therefore, the results of construction directly relate to the decisions taken at the digital design level as well as at the level of programming and control. The future use of vision-based systems is expected to achieve the proper calibration of the design and construction results, in which the accurate placement of the filaments during the physical construction will inform the digital model and vice versa.

By synchronizing the physical with the digital prototype, this research aims at handling complex silicon elastic mesh structures. The possibility for the direct relation between the architect-user and the digital environment is extended to allow a simultaneous relation with the manufacturing process, whose results are affected by design decisions.

CONCLUSIONS

In this ongoing research, the design and development of an end effector tool is presented, which is able to add material of elastic threads on a mesh system, aiming at the gradual smoothness and the overall construction of tensile structures. This becomes necessary when the objectives involve the construction of complex morphologies and the introduction of materials with elastic behaviour.

Further research will concentrate on the physical performance of the proposed end effector mechanism. This will be achieved by testing the tool in a series of experiments on a one-to-one scale. The results of actual scale testing will direct the next steps of this ongoing research work, aiming at a comprehensive development of a real time manufacturing process.

Additional directions of investigation will include the transfer of structures' physical behaviour to the digital environment in order to compute the robotic movement in a continuous iterative process. Such feedback loop mechanisms will enable accuracy during the manufacturing process and at the same time, they will open new directions of research in the area of digital fabrication.

REFERENCES


