Physical input-driven offline robotic simulation through a feedback loop process

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This ongoing research describes a feedback loop procedure where physical inputs are used as the medium for offline robotic simulation. The purpose is to investigate the ability of industrial robots that are currently used in manufacturing processes to work in a flexible and productive manner whilst providing a continuous feedback loop between physical inputs and fabrication artifacts. In order to achieve this, a methodology is developed that involves the use of data acquisition devices to enable the transference of information from the physical to the digital environment and then to use this data as real-time parameters to control the robot's behaviour during fabrication. The aim is to achieve active involvement of robots in the manufacturing process to address complex construction issues and to ensure accuracy, a reduction in manufacturing defects and flexibility in the materials used. This investigation is accompanied by relevant experiments to exemplify the potential of control mechanisms to be used in prototyping case studies.

Keywords: *Physical input, Robotic simulation, Feedback loop, Manufacturing process, Material control*

INTRODUCTION

The continued development of strategies in digital fabrication that are used in the construction of complex morphologies and the need for accuracy and precision of the physical results obtained introduces the potential for new directions in manufacturing processes that move beyond the simple linear workflow between design and construction. Hence the need for effective control of physical prototypes during the construction process by computational mechanisms that allows the continuous evaluation of results according to physical changes via a feedback loop process is currently coming to the fore.

As described in Cybernetics (Wiener 1965), the term feedback refers to a process that occurs internally within a system where a part of the output is fed back to the input. Similarly, in architecture characteristics can occur during the construction process that could be fed back to the digital design to allow continuous control of the physical end product. Apart from the way morphological objectives are gained through robotic manufacturing techniques, physical characteristics, scale and materials play an important and influential role during this process and are often combined with other simulation strategies (Braumann and Brell-Cokcan 2012a).

In an initial interpretation of the above process, feedback logic can be calculated in relation to the physical characteristics and simulation of materials (Gramazio and Kohler 2008) resulting in a three-dimensional digital design, tool-path definition and execution by the robotic machine. Using this method, the construction of the ICD/ITKE Research Pavilion 2010 (Fleischmann et al 2012) exemplifies the development of a construction model where the behaviour of timber strips are simulated and then the robot is used to cut and fabricate the strips and their joints. Iterative feedback loops between design and manufacture can be created by developing parametric software and plug-ins that are capable of simulating and controlling the behaviour of robotic machines and offer real-time interaction with the physical manufacturing process (Braumann and Brell-Cokcan 2012b). This is strengthened by their ability to integrate design and simulation processes combined with additional input data from the physical world into a single digital environment. Analytically, physical input from sensors is incorporated into the program, processed and then robotic motion is simulated. In parallel with the digital simulation of the physical form, the actual robotic machine has the ability to perform the manufacturing process without any additional changes to the algorithm. The example of the Aggregate Structure (Dierichs et al 2012) follows similar logic. In this case, a modular system that is continuously controlled by a robotic machine is developed which involves the encoding of the physical information derived from the emptying of aggregate units and the controlling of the placement of the aggregate in a physical and a digital environment.

Within this frame, digital simulators can control the feedback behaviour of robotic machines and, therefore, can allow experimental investigation into the evolution of design proposals during construction development. Such robotic control could offer a number of additional advantages to the current manufacturing process including real time, open-ended construction that adapts to the designer's needs and to any unforeseen changes that may occur in the physical environment. Future applications could be designed for developing structures with the ability of providing feedback to allow refinement and readjustment of their morphology to suit any changes in the structure's surrounding environment. Another application could be for structures containing flexible material to continually report on its behaviour. The following chapter describes our proposed methodology.

INVESTIGATED METHODOLOGY

The logic of feedback loops in robotically-controlled construction can be interpreted in different ways, including feedback focusing on the design process and materials or construction based on the use of a robotic machine. This paper suggests the development of a cyclically iterative feedback loop process between four key aspects. These are: physical inputs, computer control, robotic machines and digital prototypes attempting to redefine the morphology of physical structures according to specific environmental influences during the construction pro-

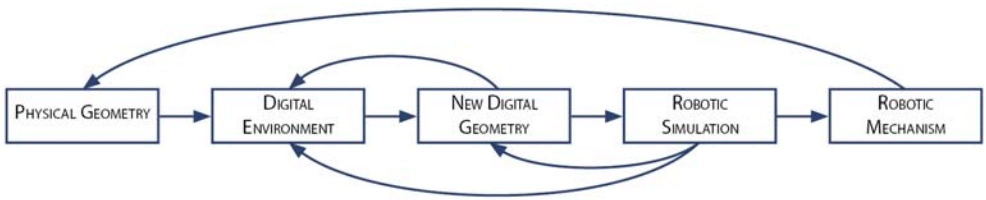


Figure 1
Flowchart of the feedback loop process

cess. Consequently, readjustment is achieved in accordance with the changes of the physical prototype and the designer's intervention. The efficient use of articulated robotic machines depends on repeated readjustment of material for optimising complex physical prototypes (Figure 1).

The behaviour of the physical structure is recorded by sensors and this information is then translated into data that can be input to the program. This data then activates an appropriate reaction of the robotic machine. Through this sequence of steps, the robot attempts to optimise the construction process and produce prototypes that are influenced by any changes that may have occurred in the physical environment resulting in reconfiguration of their initial appearance.

Analytically, using Microsoft Kinect (a depth map camera) or webcam devices, the initial physical form is recorded to a digital environment and, with the use of Firefly components [1] (a plug-in for Grasshopper [2]) (Payne 2013), it is converted into a list of points (xyz). Using the initial list and incorporating any decisions that may be made by the designer, the digital geometry is redefined as a new list of points. The new list is compared with the original list and new tool-paths for controlling the articulated robotic machine are created.

The changes that occur in the physical prototype are continuously recorded to capture the physical form's deformation and then to create a new list of points. Subsequently, the two lists are compared in relation to their distance and position. The proposed robotic control methodology is responsible for redefining the position of points and the robotic tool-paths in the digital environment. The process of readjustment and control of the robotic machine is achieved by the following basic rules (Figure 2):

1. If the number of points in the new list (List B) exceeds the number of points in the initial list (List A) then the extra points are removed via generated tool-paths.

2. If the number of points in the new list (List B) is less than the number of points in the initial list (List A) then the difference in the number of points is added to the system via generated tool-paths.

3. If the number of points in both lists (Lists A and B) is equal, tool-paths are created between the points in the new list (List B) and points in the initial list (List A) to redefine the physical geometry.

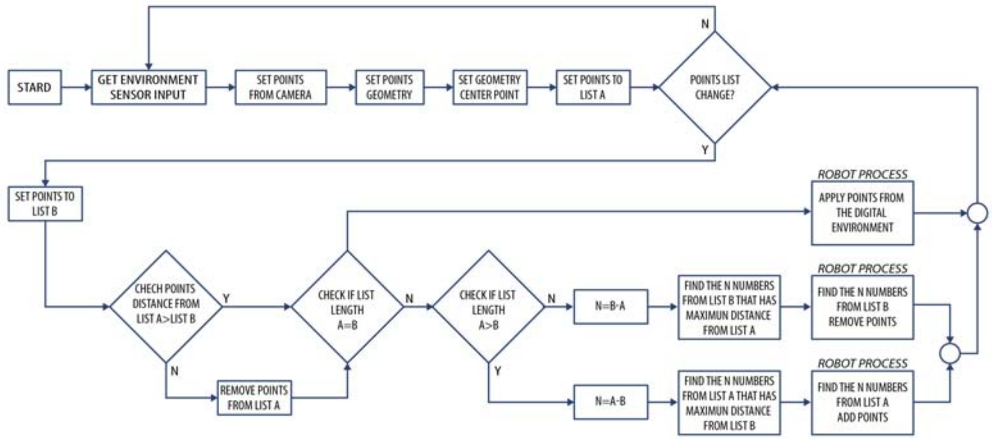


Figure 2
Flowchart of the proposed control methodology

4. If the distance between the points of the new list (List B) is larger than expected then the extra points are removed.

As the robotic machine is responsible for the removal, addition or reconfiguration of points via generated tool-paths, the continuous flow of information from the physical to the digital environment results in the dynamic redefinition of geometry in space.

EXPERIMENTAL CASE STUDY A:FEEDBACK CONTROL OF THE POSITIONS OF STRUCTURAL UNITS

In order to investigate the manufacturing process based on the idea of a feedback loop between the physical input, the digital environment and the robotic machine control, experiments based on the proposed methodology are developed using offline robotic simulation.

Since this study is concentrated on the use of physical inputs as the driving force to accelerate robotic behaviour for material control, the initial investigation focuses on the mechanisms for physical information recording and computer processing. This is achieved by simulating the behavior of the robotic machine and, hence, the readjustment of the digital form. The experimental results aim to evaluate the proposed control methodology of a feedback loop based on the four basic rules mentioned above.

Physical data and digital processing

The first study focuses on the identification and translation of physical information into digital input data as well as on the control and reaction of the robotic machine according to any changes that have occurred in the physical environment. By using a Kinect camera, the movement of black acrylic rectangular units on a white background is observed. Their two-dimensional centre position is recorded into a digital environment by using Grasshopper/Rhino [3] software and the 'edge detection' component in Firefly. Then for the motion control of the robotic machine, tool-paths in the form of a 'pick and place' procedure are created, which aim to restore the initial state of the physical environment (Figure 3).

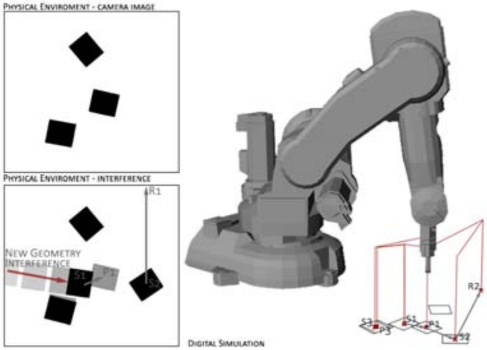


Figure 3
Robotic response: physical interference, generated tool-paths and robotic behaviour simulation

Analytically, the initial physical geometry is changed due to external factors that cause the increasing, decreasing and repositioning of the acrylic units. In a continuous procedure, the new positions of the units' centre points are recorded and compared with the initial list (List A). Thus, by using the first three rules (1st, 2nd and 3rd rules) described in the previous chapter, the methodology is responsible through simulation to restore the new list of points, repositioning the units in their correct position.

Digital control of prototype through robotic simulation

The first study described in the previous paragraphs recognises the ability of algorithms to respond in real time to any changes that may have occurred in the physical environment to continuously restore the position of the units. This second study aims to clarify the relationship between digital control of the geometry and the construction of a prototype using a robotic machine's behaviour simulation. Thus, in order to simulate the construction of a three-dimensional geometry, the robotic simulation program HAL [4] (a plug-in for Grasshopper) is used to generate a real time robotic motion (Schwartz 2012). By using a parallel gripper as the end-effector, the

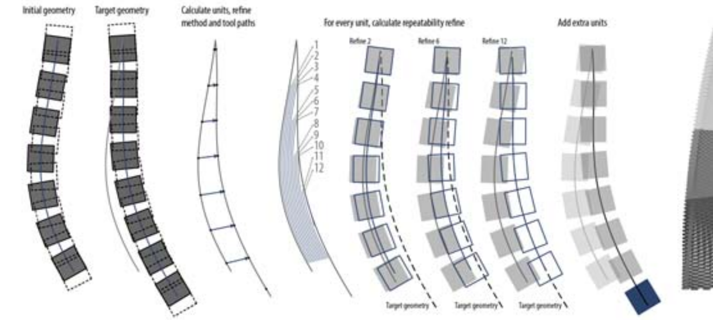


Figure 4
Process of prototype construction and units repositioning

robotic machine assembles and adjusts acrylic structural units (dimensions 4cm x 4cm x 1cm) within the overall structure and these are influenced by external changes that have occurred in the physical environment.

Subsequently, the desired geometry is defined by a curve system that generates a surface. Through the separation of the existing surface and the introduction of digital points in Rhino by the designer and taking into account any static factors, the existing surface is defined. This results in the creation of initial units handled by the robot.

During the construction process of the units, the user can redesign the surface by deforming the curves or by influencing the manufacturing process via the addition of new units. Thus, the proposed control methodology uses the 1st, 2nd and 3rd rules to adjust the position of the units according to the desired geometry. Because the changes of curves directly effect the number and position of the units, the robotic control behaviour includes local movement of existing units within a desired position, the addition of new units or the removal of unnecessary ones (Figure 4).

In the first study, the ability of the robotic machine to react in real time to control the geometry of design based on decisions effecting the manufacturing process is observed. The relationship that is developed between the designer and the robotic procedure can be considered as dynamic when the robotic machine's actions are simultaneously based on the decisions taken by the designer. While in previous cases the complexity, precision and the need for structural stability justifies the use of a robotic machine, the relationship that is developed between sensor devices (Kinect or webcam) and materials appeared to be supportive of the construction process.

This research seeks for a dynamic relationship between digital results, manufacturing processes and physical prototypes within a continuous feedback loop procedure. In this case, each modification of a prototype's physical condition made by the designer or the robotic machine requires physical data recording.

EXPERIMENTAL CASE STUDY B: FEEDBACK CONTROL OF ELASTIC MATERIAL SYSTEMS

Based on the results derived from previous experiments and by using similar control methodology, this third study aims to clarify the relationship between the material's composition and the construction capacity of complex forms.

Taking into consideration the four key aspects mentioned in the 'Investigated Methodology' chapter and in order to avoid any failures of the robotic machine during the fabrication process, this paper continues by introducing a comprehensive study dealing with the offline robotic simulation process (Biggs and MacDonald 2003) of the proposed control methodology.

Specifically, this experimental investigation uses silicone elastic threads as the material. The current study intends to define a manufacturing process that can be considered as a form-finding procedure applied in the physical environment for creating tensile mesh structures in real time. Through the additive manufacturing process, the designer is able to control the increasing smoothness (levels of smoothness are explained in each study) of the overall structure (Pottmann et al 2007). In order to achieve this, the control methodology is concentrated on the 2nd, 3rd and 4th rules (see 'Investigated Methodology').

This experiment introduces an end-effector that controls the local addition of silicone elastic threads into the tensile mesh system. In order to achieve this, the investigation is concentrated on the development of a multifunctional end-effector tool (Braumann and Brell-Cokcan 2012c) with material handling and local welding abilities. All welds that are created are recognised and continuously recorded by the image recording device. The positions of the welds are then translated into nodes within the overall tensile structure and are converted into input data for the proposed algorithm (a detailed description of end-effector functionality will be given in a future work).

The increasing smoothness of the prototype is examined through two main mesh typologies, i.e. triangular mesh and square mesh (Pottmann et al 2007). The first typology aims for the overall mesh structure development through triangulation and the second typology through polygons. The generated mesh structures consist of nodes derived from the physical world (in this case points are used as input data) and handled in the Rhino digital environment. To record the refinement of the existing mesh structure, the designer is able to define different levels of smoothness that specify the repeatability of additional material (Figure 5) with the use of Grasshopper (a plug-in for Rhino).

Triangle mesh prototype

The study of triangle mesh typology begins by introducing three points that are increasing sequentially with at least one common edge that creates a number of initial triangulations in the Rhino environment. Then for each triangulation a mesh configuration is predefined, initially by dividing individual edges into eight points that are connected to the opposite edges, creating lines that are sorted according to their length. In this way, a list of seven lines for each pair of edges is created that defines the robotic tool-paths. In turn, the generated lines are

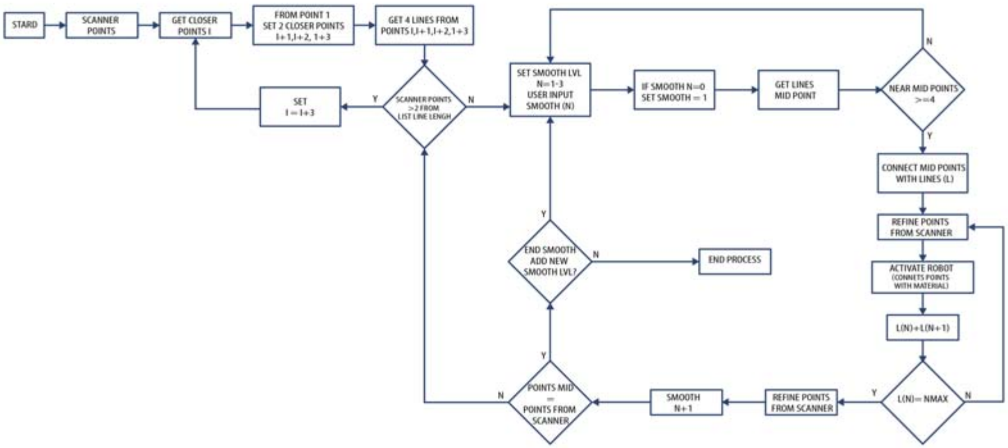


Figure 5
Comprehensive flowchart of the proposed smoothness control methodology

Figure 6
Evolutionary development of triangular mesh smoothness procedure

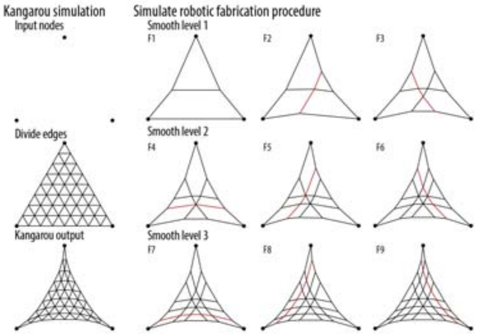
divided into between two and eight points, depending on their position in the sorted list, creating points of intersection. Those points are defined as the desired nodes for the robotic welding process. The designer then specifies the level of smoothness and the robotic system can begin the fabrication procedure.

After the initial mesh configuration is specified, the real time robotic control that involves material behaviour simulation is then developed. Using Kangaroo (a plug-in for Grasshopper) (Piker 2013) and applying the 'spring behaviour' (Fleischmann and Ahlquist 2009; Kontovourkis et al 2013), the simulation of silicone elastic threads forming the mesh typology is achieved by determining, in parallel, material deformation and robotic behaviour.

Analytically, the length of the thread is controlled during the construction process by first calculating the distance between predetermined nodes under 'spring behaviour' control. This is reached using the simple equation: Spring Length = 0.7 x Start Length. Then, to add elastic threads that connect the nodes, their length in the overall system under tension is checked. If their simulated length is less than the desired digital length then the specific thread connections are excluded from the construction process (usually this is observed in connections close to the naked edges). This results in the formation of four-sided polygonal patterns near the naked edges.

By taking into consideration the results derived from the physics-based simulation, the robotic toolpaths are defined as follows: sorted line 5 for all edges resulting in smoothness level 1, sorted line 5 and 6 for all edges resulting in smoothness level 2 and sorted line 5, 6, and 7 for all edges resulting in smoothness level 3.

In the case of online fabrication, the generated physical nodes are recorded through the camera sensor and their position in space is compared with the results derived from the digital environment. In order to find consistency between triangular units, the distance between nodes in the physical output is correlated with the expected distance of the nodes. By following the rules of a control algorithm, the fabrication procedure continues until the desired smoothness of the mesh structure is achieved (Figure 6).



The process of smoothness is characterised as continually additive, where the designer is able to add new points to define the overall mesh system. Through the camera sensor, these points can be taken into account and used in other triangulated mesh systems. The new triangulations effect the existing system, triggering a new smoothness procedure that is continuously repeated until the required smoothness is achieved (Figure 7).

The outcome of the smoothness procedure can be characterised as the result of a feedback loop between the material, the manufacturing process and design decision making. In every step of the cyclical iteration process, the robotic machine is effected by the target configuration and desired smoothness. By adding nodes and material, the smoothness of the overall system is increased and, in parallel, the initial geometry is redefined, optimising the dynamic behaviour of the elastic material.

Polygon mesh prototype

The study of quad mesh typology is based on the evolutional development of the triangle mesh using a similar process to find correlations and discuss results.

The quad mesh is defined by four points in the Rhino digital environment. For the sequential development of basic quadrilaterals, the designer defines two additional points that are connected to the two

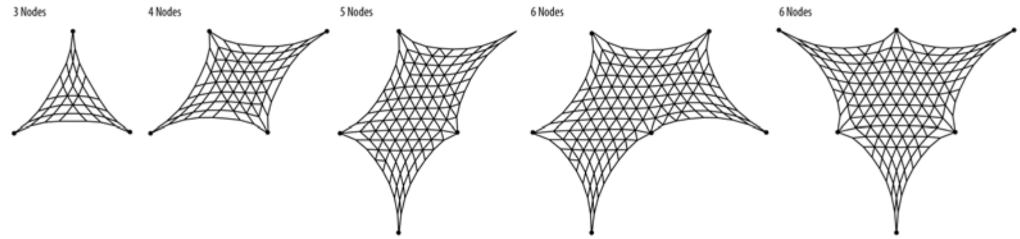


Figure 7
Results of the triangular mesh typology

points of the nearest naked edge of the existing system. Each edge of the quadrangle is divided into three points (start, midpoint and end). The middle of each edge is successively joined with each other for the creation of a new quadrilateral. The new edges define the tool-path that directs the action of the end-effector. Joint marks are defined at the start and end point of each tool-path.

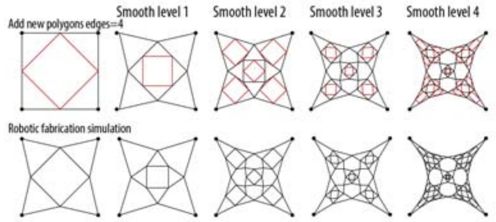


Figure 8
Evolutionary development of polygonal mesh smoothness procedure using four edges

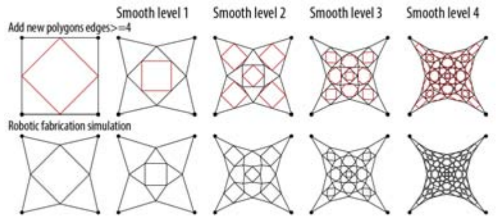


Figure 9
Alternative polygonal mesh smoothness procedure with minimum four edges

In this case, the simulation of the robotic fabrication procedure is directly combined with Kangaroo simulation observing results in real time. Elastic material simulation is controlled by tension behaviour using 'spring force' with the length calculated by using the simple equation: Spring Length = 0.7 x Start Length. The system's level of smoothness is determined by the designer by repeating the process with each addition of new material. Each iterated step is defined as the action of the algorithm to measure and react to changes in the existing system and to create new quadrilaterals to update the existing ones. In this case, the maximum repetition degree to be controlled in the Grasshopper environment is limited by the scale of the prototype (the initial distance between nodes) compared to the scale of the end-effector tool (this also influences the size of any added nodes). The iterative results of simulation are shown in Figure 8.
The following observations are made using the generated results:

- The triangles within the quadrilaterals are the result of the intervention of the algorithm. This is due to the addition of the material that allows deformation of triangulations into quadrilaterals.
- The fabrication procedure creates large polygons in the middle of the geometry that could cause instability of the three-dimensional system.

As a result, the quadrilateral forming procedure is altered in a process for a multifaceted formation. The algorithmic control can be applied to create more than four nodes. For the new polygon formation, the robotic machine adds the new material to the system and defines the new nodes. The deformation of the system is caused by the new material influencing the division of subordinate threads at their midpoint position. Using the camera sensor, the new nodes and the repositioning of the existing nodes are

Figure 10
Results of the polygonal mesh typology

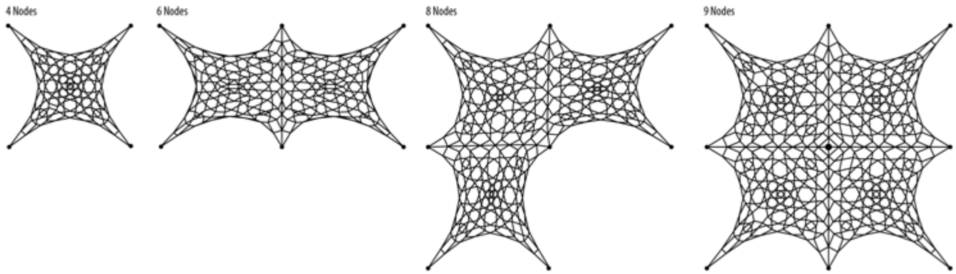
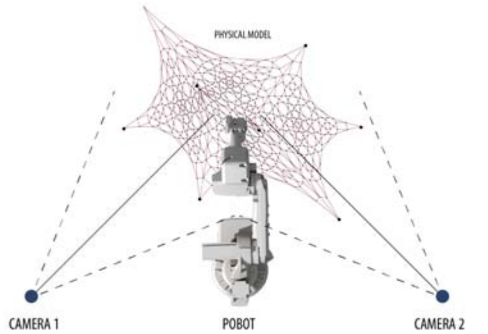


Figure 11
Installation of robotic machine and camera devices for the fabrication process



recorded. By transferring the information into the digital environment, the geometry is redefined and the algorithm recognises the new polygons. Then, from the midpoint of the edge of each polygon a new polygon is formed internally and its points are recognised as new nodes. The lines of the polygons are converted into robotic tool-paths, which are used by the robotic machine to add the elastic material. The process between the physical manufacturing and the digital feedback loop is repeated until the required level of smoothness is achieved (Figure 9).

The feedback loop procedure between the physical and the digital information and the designer/robotic machine interaction leads to an evolutionary process of adding new material to an existing mesh system. The main purpose of this procedure is to investigate and adjust the levels of smoothness of structural systems. By using an iterative robotically driven procedure, the existing physical prototype is strengthened by the addition of new material and adapting the intervention of the robotic machine. The redefinition of the nodes leads to a dynamic deformation of form and these results are influenced by the relationship between designer, robotic machine, digital control and material behaviour (Figure 10).

Discussion on triangle and polygon mesh prototype typologies

The experimental simulation of the two mesh typologies based on the methodology and algorithmic procedure described below leads to the versatility of material and the generation of different outcomes (Figure 11).

The results obtained from the production of the triangle mesh are adapted to the characteristics of the selected material. Depending on the basic triangulations, the new mesh system can generate triangular or square patterns. The calculation of the added material is predetermined by the initial nodes and is redefined in the physical environment. The equilibrium of the system based on the tension forces applied due to the elasticity of the elements causes the continuous deformation of the structure until it reaches the desired shape.

In the case of a polygon mesh, the addition of material to the basic quadrilateral shapes happens gradually in a bidirectional manner combined with the physical environment that transforms the existing prototype into a new multifaceted product. In this case, the recording procedure of the camera sensor is an indispensable part of the evolutionary development and smoothness of the prototype. The procedure of adding material to the mesh combined

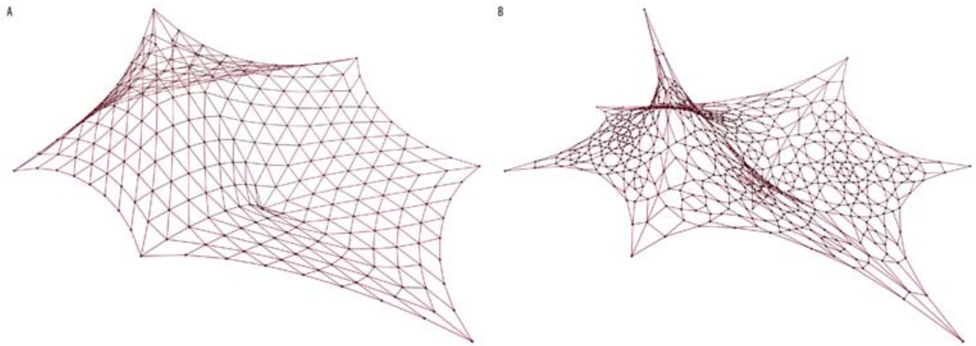


Figure 12
Generated elastic mesh prototypes with eight initial points using the proposed control methodology: A. Possible triangular mesh result, and B. Possible polygonal mesh result

with the application of tensile forces causes the redefinition of nodes in the digital environment. The reformation of digital geometry is the result of the behaviour of the physical prototype in every level of smoothness (Figure 12).

CONCLUSION

In this ongoing experimental study, an attempt to establish a cyclically iterative feedback loop process between design and robotic machine control driven by physical input data is demonstrated. Through the application of data acquisition devices and parametric plug-ins, the assembly and redefinition of structural elements and the addition of elastic material that creates tensile mesh structures in digital space is investigated. By simulating the real-time dynamic relationship between proposed designs, manufacturing processes and the physical behaviour of added materials, the capability of a robotic machine to adjust digital geometries in space precisely and to react to any changes that may occur in the physical environment is examined.

This paper argues that the application of feedback loop logic involving physical data collection and robotic machine control might open up new directions in digital fabrication research. This technological shift towards an adaptive construction process that is influenced by design decisions and flexible material behaviour in real time can allow new investigations to respond to new manufacturing demands. Potential applications of such technology could be found in the fabrication procedures of complex structures that continuously readjust, redefine and refine their morphology in the physical environment and allow structural accuracy and a reduction of manufacturing defects via the cyclical iterated feedback loop logic.

Future development in regard to the proposed control methodology aims to examine and investigate further a number of case studies in order to reduce the amount of defects that occur during design and fabrication based on digital and physical mechanisms. In addition, different aspects of the proposed process including the functionality of the end-effector, control of the robotic machine and the elastic behavior of material will be investigated and developed further. Finally, the application and testing of proposed methodology in physical conditions using an actual robotic machine is important for validating the current hypothesis.

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