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Design, Development and Experimental Assessment of a Robotic End-effector for Non-standard Concrete Applications

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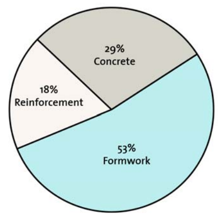
Abstract— **Despite the recent advances in, and the adoption of robotic technologies in the construction industry, the architectural processes which demand a high degree of geometric freedom still remain largely labour intensive and manual. This is due to the inherent difficulties in robotizing the current implementation of such processes coupled with the lack of alternate robotic technologies. A specific example, which is also the focus of this paper, is that of building a steel reinforced concrete structure, with varying curvature or cross-section. This process still remains rather manual and requires extensive support of customized form-work. In this paper, first we describe an alternate novel robotic fabrication process for building steel wire meshes which act as both reinforcement and formwork. The robotization of such a process is discussed with the use of a previously developed mobile robotic system. Based on the specifications derived from the process, design of a novel custom designed robotic end-effector, enabling this process, is detailed. Automation of the full robotic system comprising the mobile robotic system and the robotic end-effector is discussed from simulation to control. Through experimental evaluation of the robotic system, we demonstrate the ability to fully automate the construction of non-standard steel reinforced steel meshes of varying curvature and cell sizes.**

I. Introduction

In recent years research in robotic fabrication in architecture is experiencing a revival [1]. After the first attempts in robotization of the construction site in the 1980s in Japan [2] have faded, recently a new line of inquiry is emerging. Compared to those early attempts which focused primarily on automation and the replacement of human labour, the current endeavours predominantly focus on the potential that robotics may offer for architectural design [3]. While a large variety of creative, small-scale demonstrators with diverse materials have highlighted the potential of robotic fabrication as a design driver [4], [5], [6], recently there is also a considerable interest in developing robotic fabrication processes for solid loadbearing constructions on a 1:1 scale. As such, concrete, the globally most used construction material, is the focus of several investigations into robotically fabricated, geometrically complex, non-standard loadbearing constructions [7].

Traditional concrete processes require the extensive use of external formwork and support structures and hence still remain labour intensive. As such, there is a great potential in the elimination of the external formwork which, even for simple geometries, exceeds over 50% (Fig. 1) of the final cost of the structure [8]. Concrete 3d (three dimensional) printing techniques have been developed, which aim to eliminate the need of formwork completely [9], [10]. In this process, a cementitious paste is extruded, layer by layer, which builds up into a 3d shape. However, due to characteristic hydration process of concrete, layers of different age do not sufficiently bond with each other, forming so-called cold joints. Also, the integration of structural reinforcement, a necessity of every load bearing concrete construction, has not been solved sufficiently. In response to the above mentioned limitations of concrete 3d printing, we introduced an alternate construction technique, in our previous work [11], which we call "*Mesh Mould*". Rather than eliminating the formwork completely, the Mesh Mould process is based on the concept of unifying formwork and reinforcement into one robotically fabricated material system. This is achieved by transforming the material used for reinforcement, into a 3d mesh structure, so that it can act as formwork as well (Fig. 2). Firstly, this concept solves the issue of integrating reinforcement and secondly, by pouring all of the concrete at once the material can hydrate isotropically and the formation of cold joints is avoided.
In this previous work, we developed a fabrication process that was based on the spatial extrusion of polymers which allowed us to examine the rheological behaviour of concrete within the mesh, and the mesh ability to hold and shape the concrete in a desired shape. However, the polymer material



(a)

(b)

Fig. 1: (a) A pie chart showing the contributions of reinforcement, external formwork and concrete towards the cost of building solid load bearing constructions. Reprinted from [8]. (b) An example where extensive wooden formwork has been laid out for simple geometries. This formwork is generally lost after the construction is over and leads to wastage of resources. Reprinted from this website[1].

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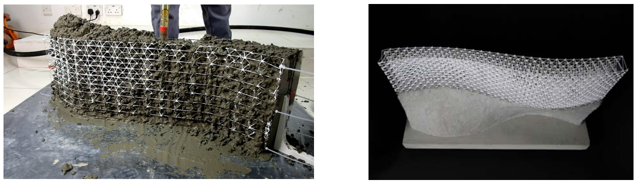


(a) (b)

Fig. 2: (a) A polymer 3d mesh is being filled with concrete using a vibrator which causes concrete to protrude out of the mesh. The polymer mesh holds the concrete into desired shape and does not need external formwork. Reprinted from [11]. (b) Half filled polymer 3d mesh, surface of which has been trowelled after filling. Reprinted from [11].

does not provide sufficient tensile strength in order to be considered as reinforcement for load bearing applications in the construction industry.

This paper addresses this material challenge by proposing a novel robotic fabrication process to combine reinforcement and formwork using steel wires instead of polymers (Fig. 3). This process, which we call "*Mesh Mould Metal*" (MMM), allows for autonomously fabricating 3d steel wire meshes with great flexibility to vary the local or global curvature of the mesh and the cell sizes. The requirements coming from the processing of steel wires were used for the definition of the above robotic fabrication process and for the mechatronic design of the robotic end-effector. Currently, in the steel reinforcement industry, the fabrication of metal meshes, so called welded wire fabrics, are restricted to planar geometries with equal cell sizes [12] or simple 3d geometries like circular column cages, or planar 3d wire panels. The main contribution of this paper is the development and experimental assessment of this novel robotic fabrication process using a novel custom designed robotic end-effector. The work presented in this paper fills a critical technological gap by enabling the full automation of variable, differentiated free-form meshes that can serve as reinforcement and formwork for non-standard concrete elements.

This paper is divided into seven sections. In Section II, first a novel process for building 3d steel meshes with variable curvature and variable cell sizes is described. Based on this description a specification list is prepared for the design of a robotic setup which can successfully automate the process. Thereafter, in Section III the design of a full robotic setup including a custom built end-effector is detailed. In Section IV, a simulation and control framework is discussed which enables the full automation of this robotic setup. The experimental results and validation of this research work are described in the Section V. The conclusion and perspectives of the current research work are laid out in Section VI.

II. Process Description

A. Mesh Mould Metal process

The mesh morphology, an example of which is shown in Fig. 3, is influenced by a set of parameters. The density of the steel mesh is determined by the cell sizes on its two surfaces and the distance between them. Another important

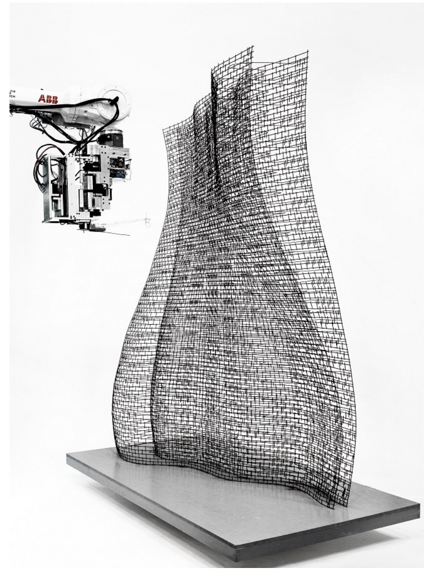


Fig. 3: Fabricated mesh prototype displaying varying curvature in different directions. These meshes can be used for building non-standard steel reinforced concrete structures without requiring external formwork. On the left hand side, the robotic end-effector designed for the process can be seen.

feature of the mesh morphology is the interior structure connecting the two surfaces. The cell sizes should be such that it retains the fresh concrete during the filling process but still allows the concrete to protrude through its openings in order to cover the mesh surface. The interior connecting structure between the two surfaces should allow the concrete to distribute evenly within the mesh. The overall density of the mesh should be such that it can withstand the hydrostatic pressure of the wet concrete. The distance between the two surfaces can be varied to adjust the amount of concrete used and to save material where it is not needed. The density of the mesh can be varied, for example in order to distribute the steel content according to the expected external load bearing conditions for optimised structural performance. The global geometry of the mesh, which may be motivated by reasons of architectural design, structural or ecological considerations, also introduces the need for having variable cell sizes with variable local orientations.

As such, the Mesh Mould Metal process consists of positioning steel wires in 3d space and processing steel wires locally. It utilizes two principal components: 1) Continuous wire in the horizontal plane ($\mathbf{x_g}$,$\mathbf{y_g}$) 2) Discrete wire elements. This subsection describes how the process is performed locally emphasizing on the elementary steps, as shown in Fig. 4. These steps are described with respect to the global reference frame (O_g,$\mathbf{x_g}$,$\mathbf{y_g}$,$\mathbf{z_g}$). By varying, θ_1 and θ_2 double curved geometries can be designed. This process allows for varying the cell sizes by varying the variables d_1 and d_2. This local process can then be performed globally by programming the elementary steps and varying θ_1, θ_2, d_1, d_2 to achieve locally and globally differentiated meshes of varying curvature in dual directions with varying cell sizes.

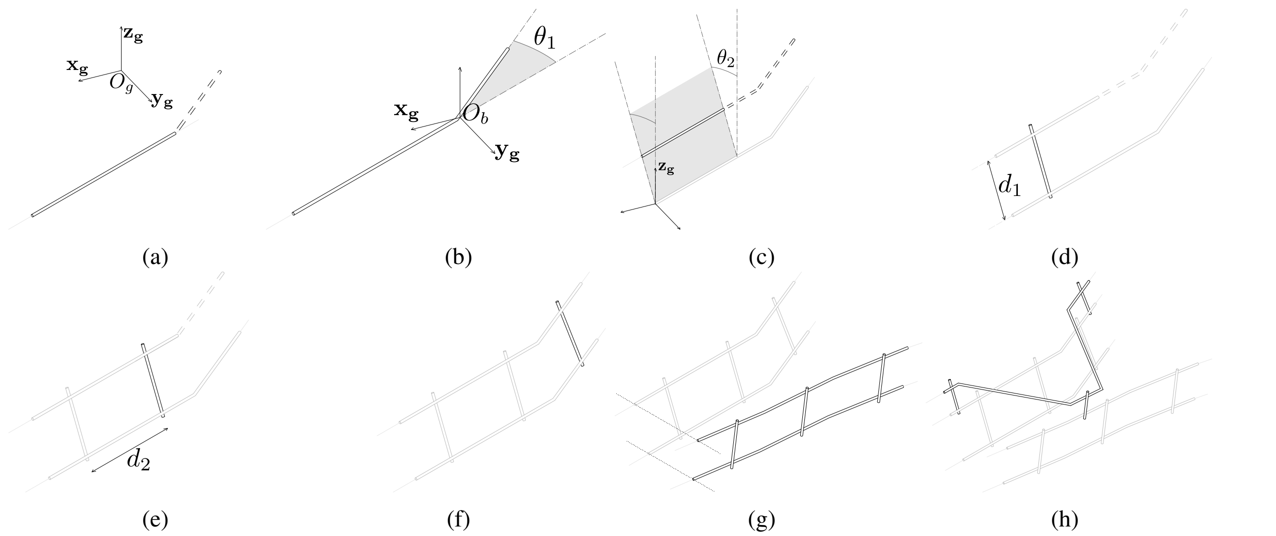


Fig. 4: The MMM process schematics: (a) A continuous wire is being laid in the horizontal plane ($\mathbf{x_g}$,$\mathbf{y_g}$). (b) Wire can be bent at any point along its length to provide varying curvature, quantified by the variable θ_1. (c) Another continuous wire is laid out in the horizontal plane, where the plane formed by two continuous wires do not need to be vertical. The angle between this plane and $\mathbf{z_g}$, denoted by θ_2, can be changed to allow for varying curvature with respect to $\mathbf{z_g}$. (d) & (e) The two continuous wires are joined together by the discrete wire elements, while the top continuous wire is being laid. The discrete wire elements are always perpendicular to the two continuous wires and form clear cross-wire joints which are then welded together. The distance between the two continuous wires in the horizontal plane and between the discrete wire elements can be varied, which is quantified by the variable d_1 and d_2, respectively. (f) A discrete wire element is inserted and welded. (g) A part of the second surface of the mesh is generated. (h) Two mesh surfaces are joined by an interior structure consisting of a horizontal wire which is bent and welded to the two mesh surfaces using discrete wire elements.

B. General specifications/functional requirements

The following specifications and functional requirements for the robotic setup, required to execute this process, can be derived from the above description which involves primarily the positioning and processing of the steel wires.

1) Global positioning of steel wires: These requirements are set with respect to the global reference frame, as shown in Fig. 4(a). They come from the need of building a continuous mesh without any restriction to the length of the mesh. This involves placement and feeding of horizontal wires, including changing the distance d_2 along the length of the horizontal continuous wire. Furthermore, discrete steel wire elements need to be inserted at an angle θ_2 with respect to the $\mathbf{z_g}$. The above two positioning requirements, dictate that the robotic arm, serial, parallel or hybrid, must have atleast 5-DOF (Degree of freedom) with 3T-2R (T-Translation, R-Rotation) motion pattern, which is able to translate its end-effector in $\mathbf{x_g}$, $\mathbf{y_g}$ and $\mathbf{z_g}$ directions and also allow to change the orientation of its end-effector about two axes, $\mathbf{x_g}$,$\mathbf{y_g}$. Moreover, since we need to build continuous mesh without any restriction to the length, a mobile base is needed. This mobile base should be able to translate itself in (O_g,$\mathbf{x_g}$,$\mathbf{y_g}$) plane to extend the limited workspace of the above robotic arm to build a continuous mesh.

2) Local positioning and processing of the steel wires: These requirements come from the need of processing the continuous horizontal wires and the discrete wire elements to form welded 3d steel wire meshes. The horizontal wires need to be bent by a variable angle θ_1. Instead of having pre-cut discrete wire elements, we decided to use continuous wires which are cut in situ so as not to introduce a pre-processing step. Since the length of these discrete wire elements are variable depending on d_1, it was also deemed impractical to have this as a pre-processing step. So, being able to cut steel wires, is an added functional requirement. In situ processing of continuous wires to be cut into discrete wire elements requires a grasping and feeding mechanism. Moreover, in order to guarantee a reliable cross welding connection, a mechanism to bring the horizontal and the discrete wire elements together and apply a clamping force is needed. The specific requirements, such as the torque required for bending the steel wires, the cutting force required for producing discrete wire elements, the clamping force required for producing good quality welds vary greatly depending on the diameter of the steel wires being processed. The design of a specialized robotic end-effector which accomplishes these functionalities is detailed in Section III-B for processing steel wires of up to 3mm diameter.

III. Description of the Robotic Setup

The above functional requirements are met by the use of a previously developed [13], [14] mobile robotic system called In situ Fabricator (IF) and through a specialized robotic end-effector designed for the MMM process. In this section, the IF system is briefly described in the light of the functional requirements which it needs to fulfill for the MMM process. Then the mechatronic design of the end-effector is detailed corresponding to the previously developed requirements.

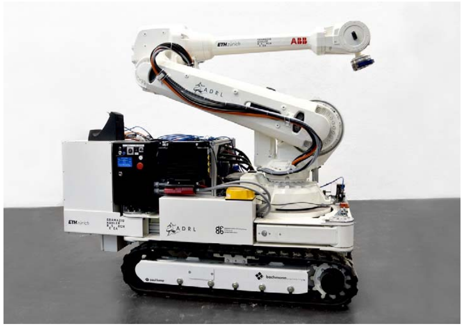


Fig. 5: In situ Fabricator is a generic, versatile mobile robotics system designed to bring digital fabrication directly onto the construction site [13], [14].

A. In situ Fabricator

Our current version, as shown in Fig. 5, is comprised of an ABB IRB 4600 industrial robotic arm and a mobile base consisting of hydraulically actuated tracks. The ABB IRB 4600 is a 6-DOF arm with 2.5m reach. Even though, the robotic arm in IF has one more DOF than required for this process, it satisfies the minimum requirements for the MMM process. The mobile base of IF allows to it move in (O_g,$\mathbf{x_g}$,$\mathbf{y_g}$) plane and therefore the 2.5m reach of the ABB IRB 4600 is not a restriction for the length of the mesh which can be built with it. However, in this paper the experimental results have been obtained while keeping the IF base static. Therefore, the length of the mesh prototypes discussed in Section V are limited by the reach of the ABB arm. Research in the autonomous repositioning and localization of the IF are on-going and first results have been presented in [13], [14] for automated brick-work. However, these results are not part of this paper. Due to the versatility of IF, it was decided to use it for serving the functional requirements coming from the global positioning of the steel wires, rather than developing a specialized system for the MMM process.

B. Design of the robotic end-effector

The motions in the mechanisms designed for performing the functions outlined in Section II-B.2 are with respect to the reference frame of the ABB IRB 4600 end-effector, (O_f,$\mathbf{x_f}$,$\mathbf{y_f}$,$\mathbf{z_f}$). The actual physical prototype of the robotic end-effector and its sectioned views, about its plane of symmetry, are shown in Fig. 6 and Fig. 7, respectively. This robotic end-effector is comprised of a front unit and a rear unit, which serve different functionalities.

The front unit serves primarily to bend continuous horizontal wires. The principle utilized for bending is illustrated in Fig. 8. The bending actuator, coupled with spur gears, provides a bending moment of 1.9Nm about the axis $\mathcal{A}_1$ to bend the wire according to mesh requirements coming from the variable θ_1 (Fig. 4(b)). The electrodes serve as obstacles which are pushed against each other by a pair of grasping actuators. To ensure proper bending of the wire, it is necessary that the wire is constrained to the horizontal plane and the part AO of the wire, shown in Fig. 8, is kept straight. End B of the wire in Fig. 8 is fixed to the mesh and held by the electrodes, so that it does not transmit

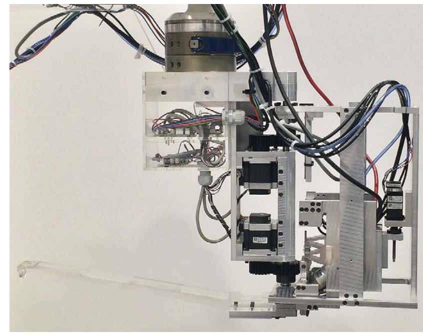
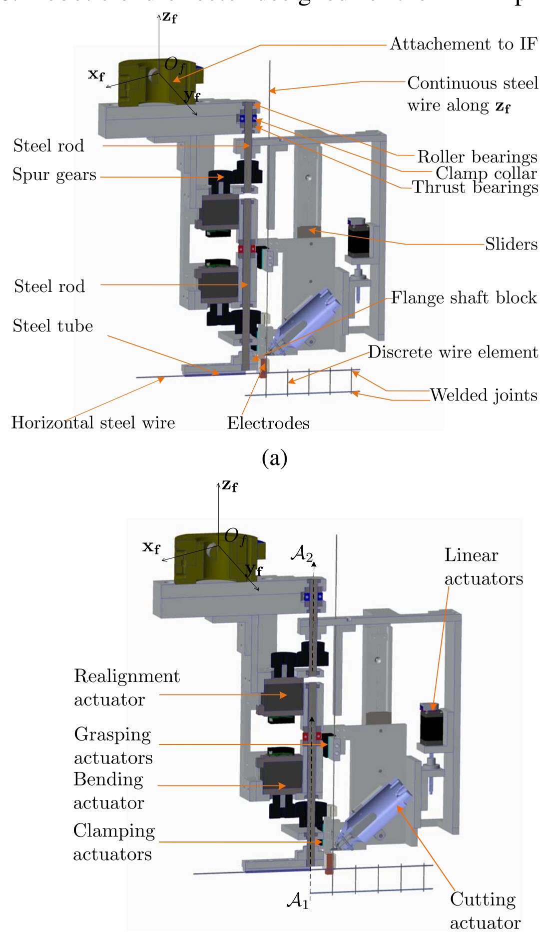


Fig. 6: Robotic end-effector designed for the MMM process.



(a)

(b)

Fig. 7: Sectioned views of the robotic end-effector: (a) It highlights the passive components, the body parts and the transmission, used for the design of the mechanisms. (b) It highlights the active components, actuators, used for actuating the mechanisms. The bending, realignment and the linear actuators are electric stepper motors, whereas grasping, clamping and cutting actuators are pneumatic actuators.

the reaction forces to the mesh while bending. Furthermore, point A of the wire passes through a small steel tube which is attached to an aluminium plate perpendicular to the bending axis $\mathcal{A}_1$, which keeps the wire straight and constrained to the horizontal plane. While the wire is being bent, the electrodes are not electrically charged and no welding occurs.

Moreover, the robotic end-effector consists of a rear unit

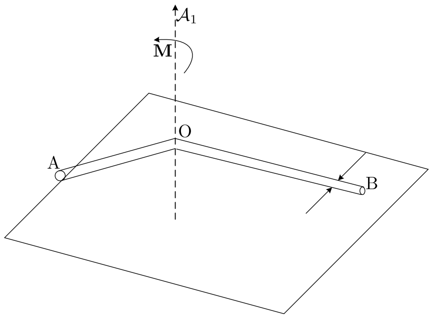


Fig. 8: Bending mechanism: It consists of rotating the wire around the axis $\mathcal{A}_1$ by applying a moment $\mathbf{M}$ about it, while the wire is held by a pair of obstacles, represented by a pair of arrows, to keep the other end fixed.

which does the local positioning and processing of discrete steel wires in order to weld them to continuous horizontal wires. The clamping actuators provide actuation for grasping the continuous wire along $\mathbf{z_f}$ which is then fed by a pair of linear actuators to the required lengths, depending upon the mesh requirements coming from the variable d_1 (Fig. 4(d)). The grasping actuators provide a grasping force of 100N and the linear actuators have a stroke length of 55mm. After the continuous wire along $\mathbf{z_f}$ has been positioned correctly, the grasping actuators are released and the wire is welded at the two cross-wire joints, one at a time using a capacitive discharge resistance spot welding machine. While welding of the cross-wire joints occurs by discharging the capacitors of the welding machine, the clamping actuators provide a clamping force of 500N. After both cross-wire joints have been welded, the cutting actuator activates the scissors and the continuous wire along $\mathbf{z_f}$ is cut producing discrete wire elements. Moreover, after the horizontal wire has been bent, the rear unit has to be aligned back with the front unit to continue placing the discrete wire elements in that direction. This is achieved by use of the realignment actuator, which rotates the rear unit about $\mathcal{A}_2$, independently of the rear unit.

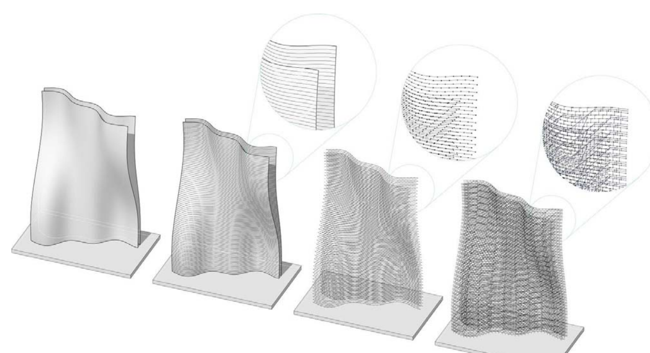
One of the features of this robotic end-effector is the split-axis design where two separate units, rear and front, are being rotated about the two concurrent axes independently. The two steel rods in Fig. 7(a) form the axes-$\mathcal{A}_1$,$\mathcal{A}_2$. The rear unit is rigidly attached to $\mathcal{A}_2$ using flange shaft blocks and to $\mathcal{A}_1$ using roller bearings. The axes-$\mathcal{A}_1$,$\mathcal{A}_2$ are held in place by friction between the steel rods and the clamp collars. Moreover, they are additionally supported by a combination of roller and thrust bearings. The robotic end-effector is attached to the IF using an off-the-shelf connecting piece.

IV. Geometry parametrization, simulation and control framework

To facilitate both the design and fabrication of complex geometric structures by designers and planners, the planning, simulation and control framework should form one integrated system. Therefore, the control interface to the mobile robot IF (respectively its simulator) and the custom designed robotic end-effector, presented in this paper, is directly embedded within an architectural planning environment, in this case the software plugin *Grasshopper for Rhinoceros*.

A. Geometry generation and parametrization

The basic generative design concept for a MMM wall can be outlined as follows: A set of two arbitrary NURBS (non-uniform rational basis spline) surfaces serve as input geometry for the generation of the MMM fabrication data set (Fig. 9). As such, in a first step, a set of fabrication specific rules are mapped onto the surfaces in order to generate the geometry for the structure of the mesh, as well as an underlying topology graph which contains all necessary information for fabrication. Generally, the parameters for geometry processing and surface discretization are application dependent [11], [15]. Specifically for the MMM construction system, they are primarily defined by the horizontally oriented, layer-based fabrication strategy. The generative algorithm outputs a geometry consisting of line segments, which approximate the two input NURBS surfaces, but still integrate all fabrication based constraints: A set of lines in the horizontal direction describe the continuously bent steel wires, which are connected by layer-wise laterally displaced line elements, representing the discrete wire elements of the mesh. In every other row, an intermediate interior layer is introduced, structurally connecting the two outer mesh surfaces through switching back and forth from one surface to the other at predefined intervals (Fig. 4(h)). The underlying resulting graph consists of nodes containing all necessary information for the fabrication such as end-effector position and orientation, bending angles or feeding length for the discrete wire elements. Finally, the mesh generation algorithm



(a) (b) (c) (d)

Fig. 9: Mesh generation process: (a) An arbitrary set of two NURBS surfaces serve as the input geometry. (b) The surfaces are sliced by parallel planes in the horizontal direction, according to the direction for fabrication and the cell height defined by variable d_1 in Fig. 4(d). (c) The resulting curves from the surface are subdivided in accordance with the cell width defined by variable d_2 in Fig. 4(e). (d) The individual horizontal layers are finally connected by discrete wire elements with a layer-wise displacement. The underlying poses for the ABB end-effector and the robotic end-effector task routines, such as bending angles or lengths of discrete wire elements, are then stored for each node.

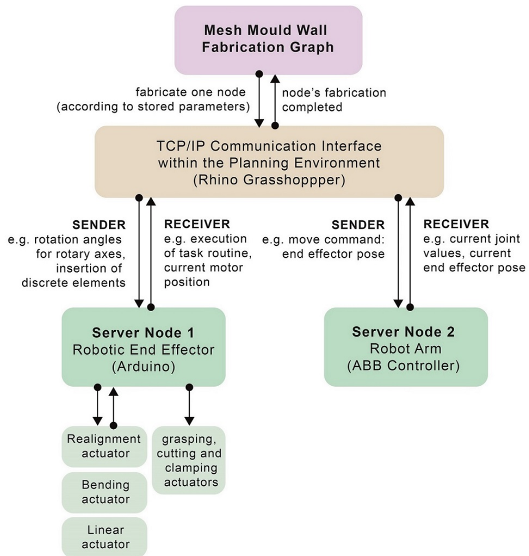


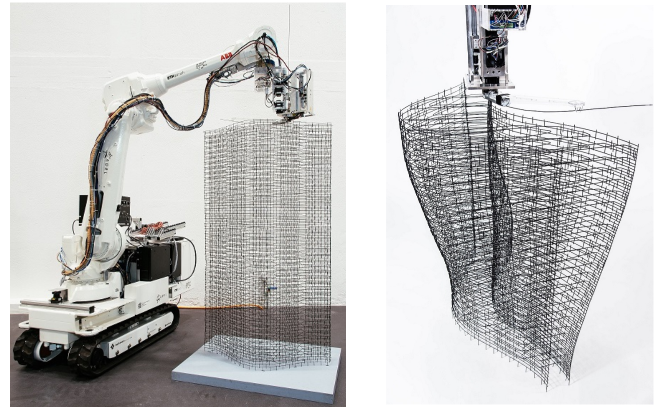
Fig. 10: Control framework/communication protocol.

also incorporates a geometric collision check between the robotic end-effector and the resulting mesh. As such, nodes with discrete wire elements whose insertion would cause a collision are tagged as such and are skipped during the fabrication process.

B. *Simulation of fabrication process and control framework*

Within the high-level planning environment of *Grasshopper for Rhinoceros*, a custom communication protocol built on top of TCP/IP allows the online control of the overall building process. The underlying principle has already been described elsewhere in more detail [14], however at this point, the interface to control the robot arm was extended to additionally control the custom robotic end-effector, presented in this paper. Commands are sent through a Python interface connected to a server running on the robot's ABB arm control software, as well as to a server running on an *Arduino* micro-controller that controls the robotic end-effector task routines (Fig. 10). The parameters for each command are read out from the individual graph nodes of the mesh. The commands for the robotic end-effector to execute a certain pre-programmed macro routine (such as for example bending the steel wire) are sent via Ethernet as soon as the ABB arm has reached its assigned position and orientation. The command is then given for the ABB arm to continue to the next node position only after the robotic end-effector has successfully executed that task routine. The dedicated interface allows the operator to start, pause or stop the fabrication within the planning environment, to store the state of each node (unbuilt or built), as well as to change parameters during fabrication.

Finally, this planning tool also allows for the simulation and animation of the fabrication process. For the simulation of the arm movement, the "*move*" commands are sent to the proprietary ABB arm simulator "*Robot Studio*", while its execution can be monitored within *Grasshopper for Rhinoceros*. The simulation of the arm is necessary to check and ensure its reachability for each node position.



(a) (b)

Fig. 11: (a) Single curved and (b) double curved mesh.

Additionally, mechanisms of the robotic end-effector (such as for bending and feeding of the steel wire) are simulated and animated in parallel, allowing to visually and geometrically detect collisions between the robotic end-effector and the mesh geometry. The combination of both, the animation of the robotic end-effector and the animation of the ABB arm, in addition to the visualization of the mesh geometry, allows a step by step visualization of the iterative build-up process before starting the actual fabrication.

V. Experimental Results

In order to validate the functionality of the robotic fabrication system, three mesh prototypes of various sizes and geometric complexity have been fabricated. The first prototype, a 1.2m long single curved mesh with variable thickness across the two sides, was built up to the height of 2m (Fig. 11(a)). The mesh was fabricated from 2.5mm steel wires and consisted of 5700 discrete wire elements and 100 horizontal layers, resulting in average cells sizes of 40mm of width by 20mm of height. The second prototype, a 1.2m long, double curved mesh, with variable wall thickness ranging from 80mm to 450mm of width, was built up to a height of 1m (Fig. 11(b)). A third prototype was fabricated under the real world conditions of a construction site. As such, the robotic setup was transported to *NEST*, an experimental building project by the Swiss Federal Laboratories for Materials Science and Technology[2]. Over the term of one week, a geometrically complex, double curved steel mesh up to a height of 2.2m was fabricated. The mesh displayed various curvature radii, variable thickness, variable cell sizes and cantilevers up to 0.5m (Fig. 12(a)). The undulating geometry of the wall was informed by structural considerations, for example through stiffening the structure by increasing the amplitude of its undulation. In order to not only prove the automated robotic fabrication of the steel meshes, but also to validate the overall feasibility of the construction system, the first, single curved mesh prototype (Fig. 11(a)) was filled with concrete. A specialized concrete, a Sika Monotop 412N, was chosen because it has adequate yield stress to keep the

[2]https://www.empa.ch/web/nest/aboutnest

(a)

(b)

Fig. 12: (a) Fabricated double curved steel mesh on site NEST. (b) Concrete filling and surface finishing of the fabricated single curved mesh shown in Fig. 11(a).

material inside the mesh. The concrete was filled from the top up to the full height of 2m and was subsequently manually finished using a serrated trowel. After an initial curing phase, a second layer of a finer mortar, a Sika Monotop 723N, was applied and manually smoothed by a craftsman, leaving behind a concrete surface of high visual quality (Fig. 12(b)). Due to general doubly curved nature of the fabricated walls, automation of concrete filling and further finishing remains a challenge and is a subject of our current investigation.

VI. Conclusion and Future Work

The fabrication setup as a whole, including the new robotic fabrication process, the new custom designed robotic end-effector and the computational framework, including simulation and control, proved to work well together. In this paper we were able to successfully demonstrate the fully automated fabrication of several mesh prototypes with complex geometries, which would be hard, if not impossible, to be fabricated with conventional fabrication techniques. Moreover, the first preliminary concrete filling experiments, an on-going investigation and analysis which do not form part of this paper, assured that the mesh cells size were adequately fine-tuned to withstand the formwork pressure of the concrete during filing. The subsequent finishing process left no doubts over the high surface quality and therefore the applicability of the system, in architecture, in the near future.

However, also some critical points were observed: At the beginning and the end of the mesh, where the surfaces are not yet connected by the interior structure, mesh deviations from the simulated models, up to 15mm, were observed. These deviations are caused by the build-up of residual stresses from the bending and welding of the steel wires in the mesh. In order to be able to dynamically react to such inaccuracies, we are currently working on the implementation of a feedback system using cameras, for finding the actual position of the wire at the beginning and the end of the mesh. Moreover, after conducting initial structural performance tests subject to external loading conditions, a first structural model was elaborated, suggesting that wire diameter below 4mm requires mesh cell sizes in the range from 10mm to 15mm. Small cell sizes within that range however, would lead to increased fabrication time. Therefore, increasing the wire diameter to 6mm would, in terms of fabrication time and structural performance, be the more efficient choice. Consequently the current development of a second generation robotic end-effector is specified for the use of up to 6mm steel wires. The full potential of the system, in terms of geometric freedom, structural performance, material efficiency and in situ fabrication logistics will be demonstrated in a 1:1 pilot project on the aforementioned NEST building in the year 2018. As such, a 13m long, 3m high, fully load bearing steel reinforced concrete wall will be constructed as part of a larger 2-storey building.

VII. Acknowledgment

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