

Developing Architectural Geometry Through Robotic Assembly and Material Sensing

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Abstract Advances in robotic fabrication and computational geometry have opened up new possibilities for including robotic assembly and material selection into the loop. We introduce a method for computing and constructing architectural geometry through the negotiation between the design intention and the constraints of assembly and materials. A small scale experimental structure has been modeled and partially built from EPS foam sheets, using an industrial robotic arm to pick, cut and subsequently assemble the components of the structure. To reduce waste, a sensing procedure was developed to generate component based on the form of the found material piece and fit it in the existing structure, similarly to how the Caddisfly Larvae builds its cocoon exclusively with found material. We aim to investigate how the sensor enabled waste control can potentially adjust the form of the assembled structure.

Keywords Robotic assembling prototyping · Robotic fabrication · Material sensing · Waste control · Architectural geometry

1 Introduction

One of the major trends of contemporary architecture is about free forms, which triggers many geometric problems that are collectively called Architectural Geometry (Pottmann et al. 2014). According to Pottmann (2014), the discussion of the related problems focuses on two main areas: rationalization- and fabrication-aware design, which are also referred to as post-rationalization and pre-rationalization (Kolarevic 2003). Fabrication-aware design as digital modeling which automatically generates buildable formal solutions, poses more unsolved problems (Pottmann et al. 2014). Robotic fabrication as one of the advanced

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prototyping methods provides potentials for finding formal solutions in this research area. It has been used to demonstrate the advances in performing custom fabrication such as wire-cutting (McGee et al. 2012), milling (Menges 2012) or incremental-forming (Kalo and Newsom 2014).

Recently, increasing attention is being paid to robotic assembly research. For instance, designers have used robotic arms to assemble custom brick walls (Gramazio et al. 2010) and assemble on-site constructions¹ or prototype tower models (Budig et al. 2014; Gramazio et al. 2012). More assembly based research projects have automated the construction of complex timber structures² and roofs.³ This paper presents a robotic assembling prototyping method, in which fabricating and assembling irregular components are controlled by sensor enabled material selection. The form of the structure is modeled and constructed by iteratively computing feedback from the negotiation between the design intention and the constraints of robotic assembly and found materials.

2 Form, Assembly and Material

The form of a constructed structure is intrinsically linked with the assembling process and the material it is built with. Construction by a Caddisfly larvae serves as a precedent where a cocoon is assembled on shape recognition in found material elements, and fit into local context of the cocoon (Stuart 2000) (Fig. 1a).

A study of human assembly of laser cut parts varies this to precomputed and custom cut pieces instead of found ones (Fig. 1b). Whereas constraints of assembly and materials are critical to design and construction of architecture, here, a Caddisfly larvae cannot customize found materials but instead develop an ability to assemble the fragments by finding a fitting position in context. In a context of robotic fabrication, this approach can act as a valuable framework for formal feedback in robotic construction and assembly.

3 Methodology: Robotic Assembly Prototyping with Sensor-Enabled Material Selection

This methodology is used for a project with assembly based robotic fabrication setup using EPS foam sheets with sensor-enabled material selection. The core challenge is to achieve the integration of picking, cutting, and fitting the components of a structure. In this research, a 6-axis ABB IRB 7600 industrial robot arm was used to run the prototyping. The components are cut by hot wire from

¹www.gramaziokohler.arch.ethz.ch/web/e/forschung/273.html.

²www.gramaziokohler.arch.ethz.ch/web/e/forschung/184.html.

³www.gramaziokohler.arch.ethz.ch/web/e/forschung/201.html.

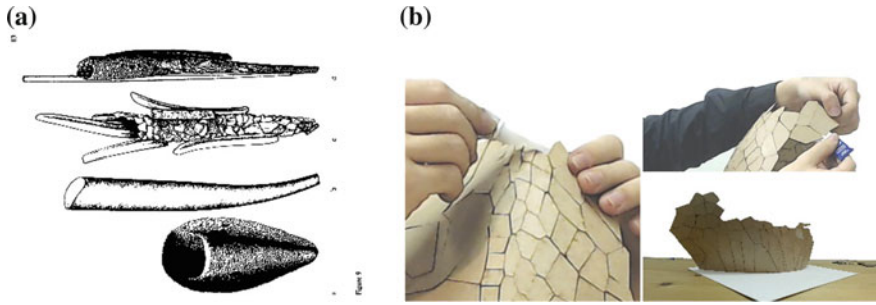


Fig. 1 **a** Diverse array of case morphologies among families of Caddisfly (© Alison Elizabeth Stuart 2000), **b** Human assembly based on pre-computed and custom cut pieces instead of found pieces

24 × 48 × 1 in. Expanded Polystyrene (EPS) Foam Sheets. Special end-effectors with small diameters were designed to avoid collisions with the cutting tool and to hold components of different sizes. Hot glue is used to quickly attach the components into fitting positions.

3.1 Geometry and Material Constraints

Based on the constraints of the chosen EPS foam sheets, all the component geometries need to be flat. The *Tangent Plane Intersection Mesh* developed by Troche is used to generate a planar hexagonal mesh from a double curved surface (Troche 2008). To develop the thickness of the components, all the components are offset outwards with the thickness of the foam sheets (1 in.). The resulting offset mesh of constant thickness cannot be a polygon mesh of equal valence (Pottmann et al. 2007). To maintain the valence of the offset polymesh, the edge surfaces of each component become twisted (Fig. 2).

Component sizes are based on the curvature of the design surface and assembly, so that curvature details are maintained while the total amount of cutting lines is optimized. In addition, size was further evaluated for pick-up limits of the end-effector, and the fabrication constraints of the foam sheets.

3.2 Sensor Enabled Picking

Without sensing, the EPS foam sheet has to be prepared carefully and positioned in the modeled orientation. As a result, scraps are created by cutting off undesired foam. Sometimes the placement inaccuracies result in partial cuts. The total waste consists of the scraps and the partial cut sheets. Reusing these oddly shaped pieces makes positioning them manually much harder. Thus, Kinect sensing was used to identify component orientation in the found material piece (Fig. 3). So a procedure

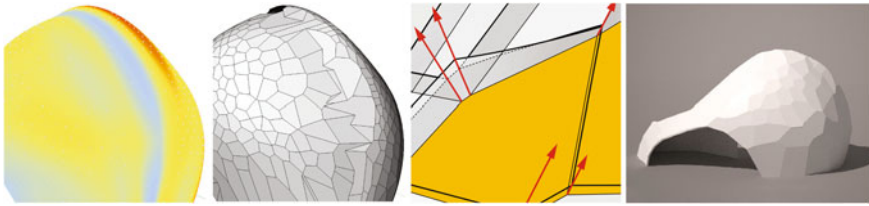


Fig. 2 Curvature and components (*left 2*), polygon mesh offset outwards (*center*), project geometry (*right*)

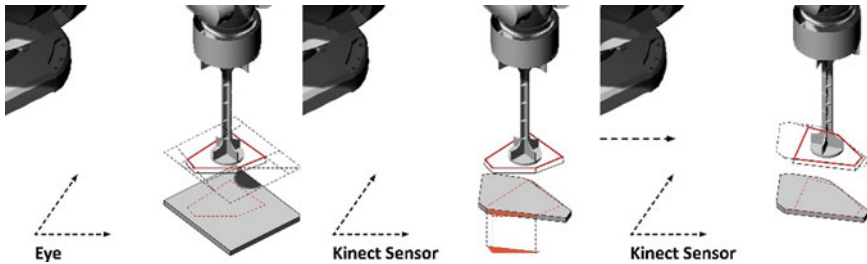


Fig. 3 Kinect sensing for manually identifying components orientation and size

was developed using computer vision to detect the shape of a scrap piece and automatically determine the correct pickup position for a to-be-cut component. For this, a Kinect sensor delivered data into Processing as two separated point clouds using the “SimpleOpenNI” library⁴ and coding reference (Borenstein 2012).

For the end effector, the center of the point cloud is averaged to be at the end effector center. For the foam, the point cloud of the central area of the top surface is averaged (to reduce noise) to be the height of the pickup surface. Both the center of the end effector and the projected point cloud of the foam are read by Grasshopper (GH) with the add-on “gHowl”⁵ into a digital model with their coordinate system origin being the Kinect position. Given the absolute coordinates of the end effector center in the digital model, the material point cloud can be calibrated into the model space. From the point cloud, a Laplacian Mesh is created by GH as the geometric domain of the found piece. Finally, the component is parametrically oriented into the piece by aligning the longest edges.

3.3 Hot-Wire Cutting

For robotic fabrication, the edge surfaces of a component are sorted by segment order of the inner polyline. Each edge surface is divided into several section planes and the surface is oriented to align with the cutting tool by the planes to cut off the unwanted

⁴www.code.google.com/p/simple-openni/.

⁵www.grasshopper3d.com/group/ghowl.

part (Figs. 4 and 5). The project adopts here the Mussel add-on for Grasshopper developed by Johns⁶ to generate Rapid Code to control the tool paths of robot arm.

3.4 Fitting to Existing Structure

The component remains attached to the end effector and is fitted into the assembly position until human operator fills hot glue into the gaps to attach it to the neighbors. A non-trivial problem is determining the collision free assembly sequence of parts. The components are sorted by the height of their area centers to establish the assembly sequence and to ensure that the arm will always approach the already installed components safely from above. The cutting and assembly tool paths are compiled into a program simulated in ABB Robot Studio.⁷ The robotic arm effectively acts as a temporary “scaffold” to secure the new component in its correct position. Once the new component is glued to the existing ones, the new component becomes part of the structure and the arm can be removed (Fig. 6).

4 Formal Feedbacks from Waste Control

Fitting a found material piece least altered into the existing assembly is achieved by orienting the geometry measured by Kinect in the parametric model. The current top edge of the structure is modeled by isolating the boundary of the inner polygon of the structure model. The lowest point on the top edge is located and the predicted material is oriented by referencing to the two attached edges of the lowest point. The oriented material is shifted to cover the lowest segment of the edge. It is reoriented to be tangent to the design surface and is trimmed off by the top edge. The left over geometry is extruded to the material thickness by referring to the vertex normal of the polygon of the existing structure (Fig. 7). The generated component defines the new tool paths and updates the existing model as the input of next generation.

4.1 Linking Formal Adjustment and Waste Control

Fitting the found material piece determines the generation of components and how they are cut and fit into the existing structure. By changing the fitting strategy and the form of the found piece, the structure is remodeled by the assembling of components that are made within the material constraints. A relationship between the formal adjustment and the sensor enabled waste control can be roughly approximated (Fig. 8).

⁶www.grasshopper3d.com/group/mussel.

⁷www.new.abb.com/products/robotics/robotstudio.

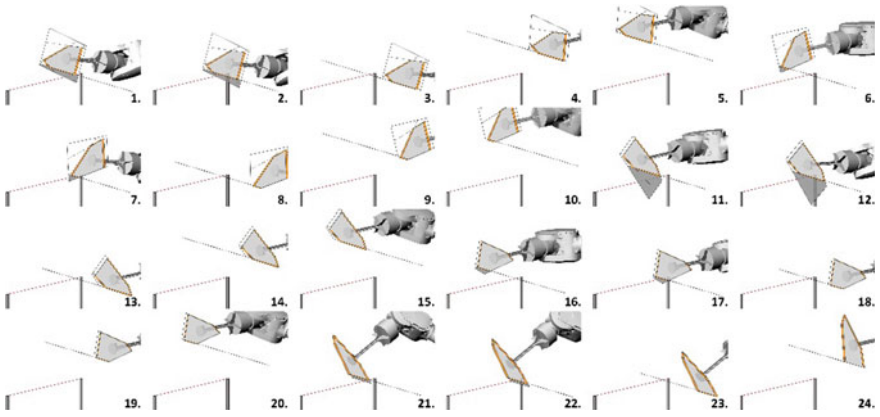


Fig. 4 Tool paths sequenced by moving foamsheets through hot wire

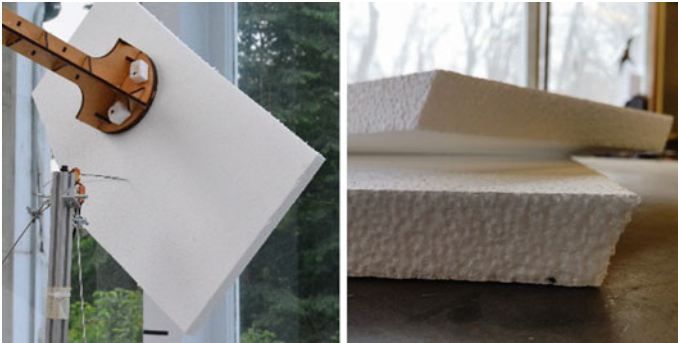


Fig. 5 Cutting components with a hot wire in different angels and the twisted edge surfaces

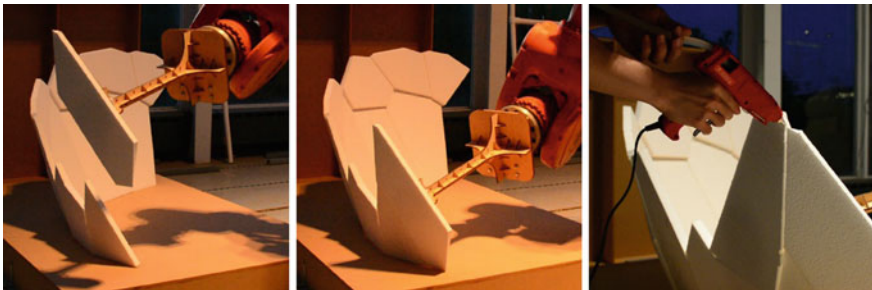


Fig. 6 Assembling components with the end effector and gluing for attachment

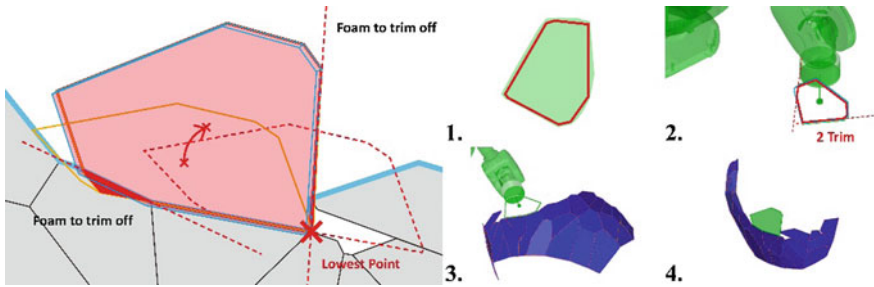


Fig. 7 The new components are generated from the geometric detection of found piece

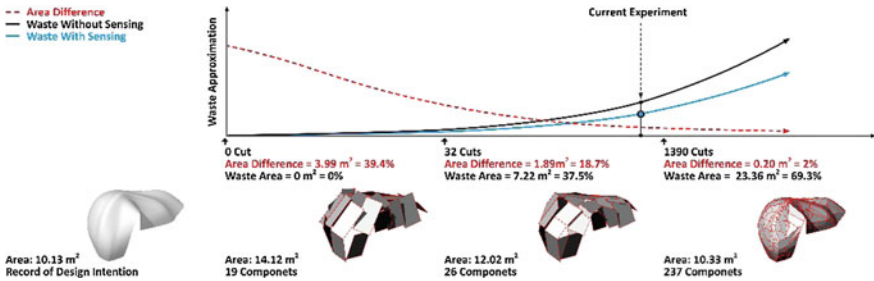


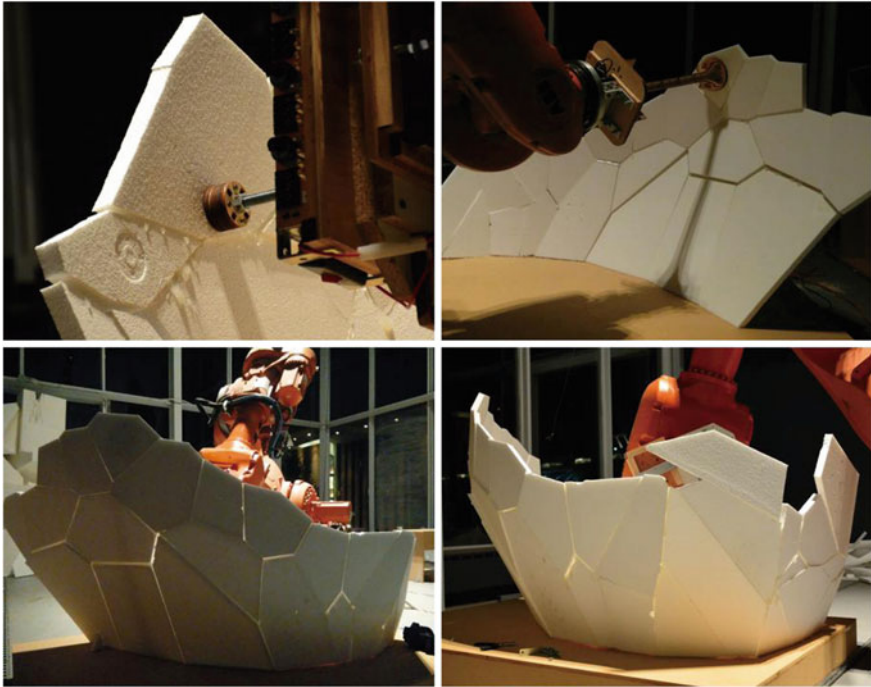
Fig. 8 The amount of waste and area difference between the designed and modeled geometry. In the waste control test, some scraps are reused so the waste is reduced by sensing

5 Conclusion and Future Work

This project has conceptualized and prototyped a robotic assembly method based on the combination of design intention, the constraints of assembly and the constraints of found materials, with several prototype studies. By robotically fabricating and assembling irregular components from EPS foam sheets, the project built a link between computing programs, fabricating tools and sensors with formal feedbacks. By detecting found materials, fabrication was measured and modeled within the material constraints in digital space to reduce fabrication waste and control assembling tool paths.

Future research includes several new steps: Firstly, the sensing technique can be developed to track differences between the physical and the digital models, and allowing for compensation. Secondly, assembly has been restricted to manual fixing components, which should be replaced by robotic fixing. Thirdly, the sensing procedure could check potential structural failures while the object is assembled. Finally, a more robust and optimized computation is required to model the relationship between waste control and adjustment. Similar to the cocoon of Caddisfly larvae, the assembly outcome will be different based on the material context in

which it is built. Further material prototyping will deliver feedback for adjusting the form of a structure. Yet the first results discussed here on geometric detection of found material piece, robotic assembly and minimizing waste are contributing to the design of new methods for freeform architecture.



References

- Borenstein, G 2012, *Making things see: 3D vision with kinect, processing, Arduino, and MakerBot*: O'Reilly Media, Inc, O'Reilly Media, Maker Media, Inc, Sebastopol.
- Budig, M, Lauer, WV, Petrovic, R and Lim, J, 2014, 'Design of Robotic Fabricated High Rises', in McGee W and Ponce de Leon (eds), *Robotic Fabrication in Architecture, Art and Design 2014*, Springer, Cham, pp. 111–129.
- Gramazio, F, Kohler, M and D'Andrea, R 2012, 'Flight Assembled Architecture', Editions HX, Orléans.
- Gramazio, F, Kohler, M and Oesterle, S 2010, 'Encoding material', *Architectural Design*, vol.80, no.4, pp. 108–115.
- Kalo, A, and Newsum, MJ 2014, 'An Investigation of Robotic Incremental Sheet Metal Forming as Method for Prototyping Parametric Architectural Skins', in McGee W and Ponce de Leon (eds) *Robotic Fabrication in Architecture, Art and Design 2014*, Springer, Cham, pp. 33–49.
- Kolarevic, B 2003, *Architecture in the Digital Age: Design and Manufacturing*, Spoon Press, New York, pp. 127–140.

- McGee W and Ponce de Leon (eds) *Robotic Fabrication in Architecture, Art and Design* 2014, Springer, Cham, pp. 33–49.
- Menges, A 2012, 'Morphospaces of Robotic Fabrication', in *Rob| Arch* 2012, Springer, Springer-Verlag, Vienna, pp. 28–47.
- Pottmann, H, Asperl, A, Hofer, M and Kilian, A 2007, *Architectural Geometry*. Bentley Institute Press, Exton.
- Pottmann, H, Eigensatz, M, Vaxman, A and Wallner, J 2014, 'Architectural geometry', *Computers and Graphics*, vol. 47, pp. 145–164.
- Stuart, AE 2000, 'The Utility of Behaviour in Macroevolutionary Studies, Analyses of Caddisfly (Trichoptera) Case Building Behaviour, Publisher, Location'.
- Troche, C, 2008, 'Planar Hexagonal Meshes by Tangent Plane Intersection', *Advances in Architectural Geometry* vol.1, pp. 57–60.