Towards Circular Economy in Architecture by Means of Data-driven Design-to- Robotic-Production

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Abstract –

While the global impact of plastic waste is increasingly concerning, the application of reused materials in the built environment remains little explored. This paper presents research into the reuse of plastic in architecture by means of computational design and robotic fabrication. Design possibilities using reclaimed plastic artefacts were explored by testing their structural stability and robotically modifying them in order to create a pavilion. While the design conceptualization started with the reclaimed material and the analysis of its potential, the digital workflow involved generative and performance- driven design, structural optimization and geometry generation for robotic fabrication.

Keywords –

Robotic fabrication; Circular economy; Reuse; Plastic; Pavilion; Computational design; Waste control; Human-Robot Collaboration

1 Introduction

Applications of Industry 4.0 technologies, such as automation, Internet of Things (IoT), and cyber-physical systems [3] are relatively new in architecture but they have already proven to revolutionize the way architects think and practice.

For instance, Design-to- Robotic-Production (D2RP) approaches developed at TU Delft since 2014 establish a feedback loop between the design and the production of the 1:1 scale building components [1].

This implies that the initial generative design is optimized in order to address functional, structural, environmental, material, etc. requirements and then converted into robotic tool paths to add, remove or transform materials according to requirements.

The challenge is to identify tasks that can be robotized and develop future interaction scenarios between humans and robots. In this paper, work is presented that explores both while taking the challenges of circular economy into account.

2 Circular Economy

Plastics production has increased twentyfold since 1964, reaching 311 million tons in 2014 [4].

Despite the economic crisis, the world plastics request is continuously increasing and it is expected to almost quadruple by 2050. With the increase of the plastic production, the plastic waste increases as well, so much that the ocean is expected to contain by 2050, more plastic waste (by weight) than fish.

Figure 1. The plastic container is tested for structural strength

Currently, this problem is addressed on two levels, firstly the manufacturing of plastic materials from oil is gradually replaced with renewable bio-sourced materials; secondly the recycling or reusing products is considered. When recycling is not the best option because soiled plastics and multi-layered plastic products may not be suitable or difficult i.e. expensive to be recycled, reuse is considered (Fig. 1).

The research presented in this paper explores how by employing D2RP methods and by applying circular economy principles [5], thus reusing objects otherwise designated for the landfill, an approach that can be applied to various geometries is developed and tested.

The reused objects were searched for in a traditional manner, by going to stores and selecting potentially usable components.

Figure 2. Development of the node from the unrecyclable plastic container using a combination of D2RP and traditional methods

Considering the potential of IoT to connect the D2RP system with materials that are provided with unique identifiers (UIDs) and filter databases for specific plastic materials and products catalogued with respect to their physical and chemical characteristics, it is conceivable that a variety of designs for diverse functions could be easily generated.

2.1 Architectural Structure

From an array of available components, several have been structurally tested and the unrecyclable drill container, which has been chosen to be used in the design, showed a peak close to 80 kg (Figure 1). The test highlighted that the base is the weaker part of the element.

By developing joints (Figure 2) from the drill container that could connect linear frame elements (of Polyvinylchloride or PVC pipes for water supply) with a membrane (of semi-open water repellent fabric) a pavilion has been created (Figure 3).

The vaulted structure has a double-curvature that increases the structural performances. Once inflated, the designed mesh is improved using the Mesh Machine component after which it is tessellated with the Dual Graph component. Joints, PVC pipes, and membrane are then placed resulting in a pavilion that serves as event space.

In order to test structural stability, the mechanical properties of the materials were retrieved from CES Edupack 2018 and used as input for the structural analysis. Furthermore, the structure was analyzed in the Grasshopper plugin Karamba 3D. The latter, being embedded in the parametric design environment of Grasshopper, gives the possibility to combine parametric 3D models with finite element calculations.

Following up the structural analysis, joints, PVC pipes and membrane were further developed and tested. The node was developed by removing and folding parts, so that the folded part of one component fits perfectly into the cut part of another component. The connection is then secured by rivets (Figure 2).

With the robot, the component can be cut at a specific optimum angle in a precise and accurate way. Because of the complexity of the geometry, all the components that form the connections need to be custom cut at a specific angle, thus the use of robotic fabrication will make the process more accurate and faster compared to traditional methods.

The workflow involved several steps such as robotic cutting (drilling holes and material removal), manual folding (with a heat gun), manual gluing of the washers and connecting parts with rivets using pop rivet gun.

While the robotic tool path was integrated into only one path for drilling holes and milling i.e. cutting, which made the process faster and more efficient, the folding of the material of the component itself, the gluing and connecting with rivets remained manual.

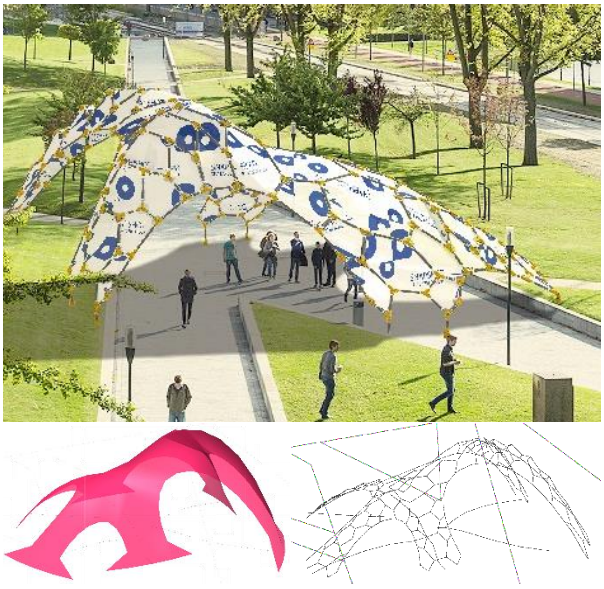

Figure 3. Generative design optimized in order to address functional, structural, environmental, material, etc. requirements

The robotization of the folding, gluing, and connecting with rivets would have required additional investigation, which due to time constraints has only been simulated as robot-robot cooperation and envisioned as Human-Robot Collaboration (HRC).

2.2 Human-Robot Collaboration

In order to semi-automate the fabrication of the node, a multi-robot setup has been proposed in combination with an HRC approach. In this context, HRC is defined as work performed simultaneously and co-located by a robot and an operator during production [2].

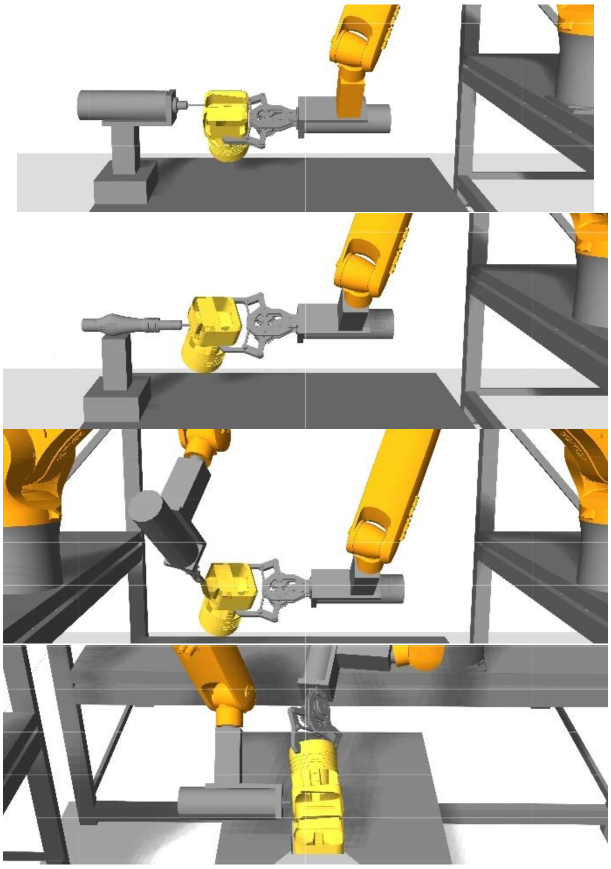

Figure 4. Picking of the first component using the master robot, which is equipped with a gripper, moving then the object around the milling tool and performing the necessary material removal (first image), heating (second image), folding (third image) and placing the rivets (fourth image).

The fabrication sequence of the joints includes two fixed tools, a milling tool and a heat gun, and two moving tools, a gripper and a bolting tool. Hence the component will not be fixed in front of the robot as in the first scenario but it will be moving with it.

The first step of the fabrication sequence will consist in picking up the first component using the master robot, which is equipped with a gripper, moving then the object around the milling tool and performing the necessary material removal (Figure 5).

After that, the object is positioned in front of the heat gun, in order to heat the folding line of the component for one or two minutes, time enough for the plastic to become malleable and for the second robot to come in and easily fold the material using a gripper. The above-mentioned sequence between the two robots is repeated for all the other components.

The last step of the fabrication sequence regards the connection of the objects to each other. The connection will be performed by the second robot, which is equipped with a bolting tool, in collaboration with the master robot, which will hold the component in place.

This proposed HRC approach relies on practical methods facilitating collaborative sawing [7], collaborative polishing [8], etc. It involves limited Artificial Intelligence (AI) that enables the physical collaboration between two robots [7].

This approach is transforming the D2RP process of the joints into a choreography of two cooperating robotic arms alternating their roles along the fabrication process.

In this context, the human may not only orchestrate the sequence of actions implemented by the robots but may help with tasks that could be easier implemented by humans as for instance, inserting the rivets in the holes.

3 Future Steps: Cyber-physical Systems

While the presented research has taken advantage of D2RP and explored the potential of human-robot cooperation, it has not exploited the potential of IoT, which allows selection of materials form a vast variety of materials appropriate for circular economy approaches.

It furthermore, speculated but did not develop and test HRC approaches, which have the potential to make the sequence and safety of human-robot interaction possible.

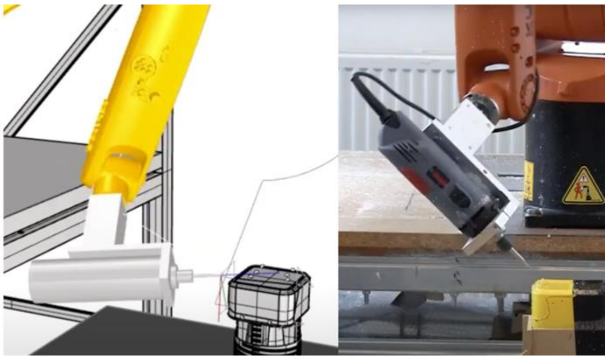

Figure 5. Simulated and prototyped subtractive D2RP link the virtual and the physical worlds

Both involve tagging and tracing, machine and deep learning in order to establish a cyber-physical system that in time could become an automation ecosystem, wherein architects and constructors collaborate with robots and customers can purchase online customizable designs using an automated marketing platform that puts the manufacturing plant in action.

The virtual and the physical D2RP&O processes are linked (Fig. 5) and need to take into account the inherent multifaceted nature of building from the early design to the latest building operation phase. Challenges in terms of scale, multi-tool and multi-robot production and operation need to be examined in order to achieve chained processes by linking virtual models (such as Rhino 3D model with Grasshopper plug-ins such as Millipede, Ladybug, etc. for simulating structural and environmental performance) with robotic devices. The aim is to develop/implement chained D2RP&O processes in which robots take specific roles while all (human and non-human) members of the setup including respective (virtual and physical) systems receive feedback at all times.

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