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Self-Adaptive Multi-Purpose Modular Origami Structure

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Abstract

A research line in architecture and interior design has been focused for years on the selection of materials with properties specifically tailored for light, thermal and acoustic comforts. An adaptive origami-based structure is here proposed in order to overcome the limited capability of a single material to adjust its response to environmental changes. Such structure is highly flexible, with applications ranging from indoor to outdoor environments. We focus on building facades, to show some results relevant to a small-scale prototype aimed to provide shading to the sunlight.

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Keywords: responsive architecture; adaptive systems; deployable structures; modular origami structures; self-sensing and actuation; digital prototyping;

1. Introduction: Origami and self-adaptive structures

Origami, from the Japanese words “ori”, meaning folded, and “kami”, meaning paper, is the ancient art of paper folding. Its original purpose was not strictly utilitarian, but rather recreational and artistic [6]. Nowadays, origami has

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become an inspiration for engineers, architects and designers, leading to many types of applications, from cardboard containers to deployable space structures [1,2,10]. The optimization of the geometry of origami-like structures, with the goal of exploiting at maximum their deployability, has also led to a number of ideas for developing novel so-called metamaterials, see e.g. [3,4], which are by definition micro- or nano-structured materials engineered in order to attain properties not available in nature. Future trends in this field are supposed to pave the way to structural designs showing unprecedented features, among which the capability to self-adjust the geometry of structural parts in response to the variations of the surrounding environment [5].

As far as the relevant terminology is concerned, an origami is defined by the fixed or configuration-invariant way in which a flat surface is folded. The folds are called creases, which are in turn defined through their endpoints or vertices. The regions bounded by the creases are the faces. Creases can be distinguished into “mountains” and “valleys”, depending on the folding direction; for mountain folds, faces on both side of the crease can be thought of as rotating into the page, while for valley folds, they can be thought of as rotating out of it [8,9].

With the major aim of designing new smart structures, the concept of origami is here exploited for a specific geometry, chosen as a module of an adaptive solution with multiple applications, either in external or internal areas of near-future buildings [7,11]. The proposed solution can be shown to promote the energy efficiency of buildings, and to also improve their comfort performance, standing as a possible answer to one of today’s main urban challenges. Different applications of the adaptive structure are here envisaged depending on the physical properties of the panels mounted on the frames, e.g. in interiors for sound absorption and acoustic insulation, and in exteriors for shading, UV filter or light refraction systems. Some results are reported in what follows for a preliminary small-scale prototype, moved linearly at a single pivot key-point selected on the basis of the origami kinematics during folding and unfolding.

2. Features of adaptive origami structures

As already pointed out, a large part of existing solutions for adaptive, or morphing civil structures lacks in flexibility and adaptiveness. In this Section, we briefly try to pinpoint some of the striking advantages offered by the exploitation of the folding/unfolding process of rigid origami structures; the rigidity feature of the considered sub-class of origami stems from the deformation-free field in each face of the structure during the whole deployment.

The selected structural module is of a Resh and Christiansen type consisting in thirty-three panels, whose fully and partially deployed configurations are shown in Figure 1 (see also Figure 2). More complex flat geometries can then be obtained through clustering, i.e. by the repetition of a single module.

The triangular shape of all the panels has been chosen in order to have spatial folding/unfolding movements controlled at a central vertex, called pivoting point: depending on its position, basically on its out-of-plane motion perpendicularly to the folded, reference configuration, the spatial arrangement of the entire module is defined. The origami module is connected to the supporting structure by means of spherical joints that allow any rotation. The mentioned pivoting point (see Figure 1) follows a linear trajectory during folding/unfolding, and this allows an overall geometric amplification of the visible surface, set as the projection of the total module surface onto an a-priori defined plane (like e.g. the facade one). The kinematics of the origami has been simulated in Grasshopper, and the constraints at the connections with the base structure have been studied in order to avoid (as much as possible) bifurcation and other kinds of geometrical instabilities. This has been achieved through solving the equations of motion with MATLAB. It was in fact noticed while actuating the small-scale prototype depicted in Figure 2, that the structure may display instability when it opens with some spatial orientations of the flat support structure, possibly depending on the relative orientation of the plane of the fully deployed origami and the gravity direction even if the structural weight is supposed to be almost negligible. The problem can be explained by the lack of rigidity at the joints between faces, and has been solved by adding an extra stiffness through linear or rotational springs.

The self-adaptiveness is finally guaranteed by a network of (micro-)sensors for, at least, lighting and temperature, embedded in the modules. Such sensors provide the information to the PID positional control logic, which moves the structure accordingly through an electric motor. For the prototype of Figure 2, what described here above has been developed with an Arduino system.

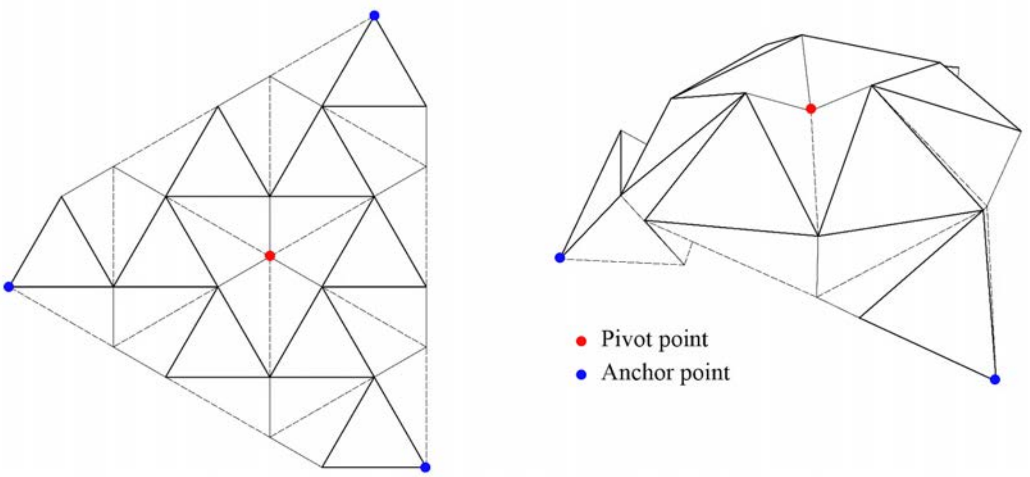

Figure 1. Fully (left) and partially (right) deployed geometry of the origami structure, with pivot and anchor points highlighted.

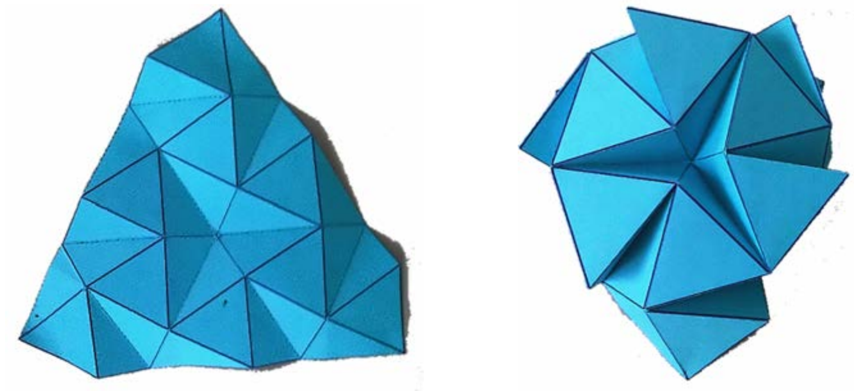

Figure 2. Small-scale prototype of the selected origami, fully (left) and partially (right) deployed.

3. Applications

The developed concept finds its place in the current scenario of smart buildings, which imply a powerful synergy between technology and human interaction. The origami structure can be integrated in different types of buildings, for facade applications or coverture of pavilions. Its adaptivity allows the adoption for both indoor and outdoor uses. It can be easily personalized, exploiting different materials (and relevant physical properties) or movement features. Finally the buildings do not need to be initially conceived to incorporate the origami structure, as it can be mounted in a later stage.

3.1. Interior applications

A possible interior use is related to acoustic adjustment: in concert halls, but also theatres, libraries and university classrooms origami modules can be mounted on walls and/or ceiling, and their deployment can be adopted to keep the noise level under control. Several modules can be placed on a regular pattern; in the basic configuration, all the modules are closed, and when the sensors detect the attainment of an a-priori defined noise threshold, they can be adjusted in their geometry to modify the acoustics of the room. Part of the origami faces are supposed to be made of soundproof materials, such as perforated wood or foam; hence, the sought acoustic function is achieved by increasing the exposed absorbing surface; see e.g. the sketch in Figure 3.

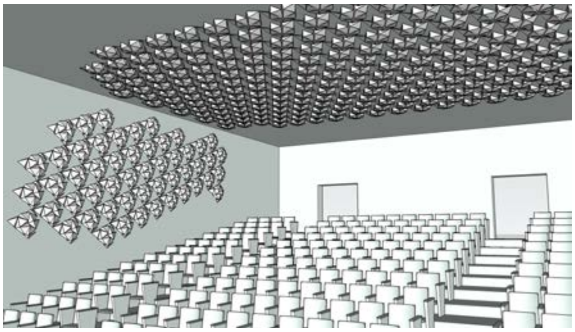

Figure 3. Example of adaptive origami modules mounted on walls and ceiling of a (conference) room.

3.2. Exterior applications

The major foreseen application in external conditions is the shading one. In this case, the structure is supposed to be made of a lightweight (aluminium or composite) skeleton frame, not affected by aging due to possibly harsh weather conditions. The faces are instead supposed to be covered by panels with different aims: those exposed when the origami is completely folded will be made of acrylic glass with shading PVC applied; the other ones will let the light pass through whenever the origami opens. Applications may include covering of pavilions in public spaces, both for lighting and weather protection purposes, see Figure 4.

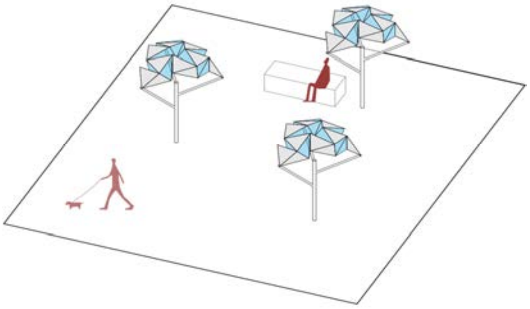

Figure 4. Example of adaptive, tree-like origami modules for lighting and weather protection in public spaces.

This type of application has an additional energy saving purpose: by optimizing light conditions, and thus by controlling the indoor temperature, it allows the reduction of energy consumption, which leads to a minimization of the impact on the environment and the overall expenses. An example of lighting control offered by panels mounted on building facades is reported in Figure 5. Here, by exploiting the small-scale prototype and assuming the translucency of the panels to be different depending on their rules, as specified here above, an idea is provided in terms of interior lighting levels granted by the adaptive origami module at two different degrees of deployment. The application on facades also permits an immediate and effective characterization of the buildings, leaving a permanent mark in the architecture of a city.

6. Conclusions

In this work, by integrating an origami-based thin and lightweight structure with a sensing and actuation system, a self-adaptive smart structure has been proposed. The adoption of origami in architecture and interior design can have an impact due to different reasons, like e.g. customization, sustainability and aesthetic value. Further to that, the required technology is relatively easy to implement and maintain.

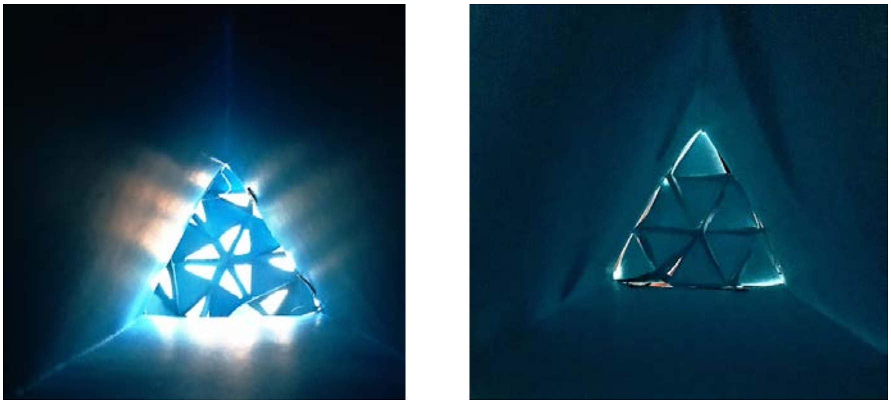

Figure 5. Interior lighting levels due to different degrees of deployment of the adaptive origami module mounted on building facades.

Materials, manufacturing of the structure and energy consumption during the whole life-cycle are not supposed to be highly expensive, so allowing the costs to be affordable. Simulations and prototypes developed in this activity have confirmed the claimed flexibility: panel materials can be chosen depending on the specific application (glasses for UV filter, temperature control or light refraction and wood for sound absorption and acoustic insulation). Although at a preliminary stage, the prototypes have also shown great responsiveness to the modern urban needs listed in the Introduction, with easiness of actuation and control. From an aesthetical point of view, it is hoped the present idea can revolutionize the way in which we currently conceive buildings and spaces: the origami structure allows infinite possibilities of customization, satisfying practical users' needs and being also environmental friendly.

Acknowledgments

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