Engineering Origami: A Comprehensive Review of Recent Applications, Design Methods, and Tools

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Origami-based designs refer to the application of the ancient art of origami to solve engineering problems of different nature. Despite being implemented at dimensions that range from the nano to the meter scale, origami-based designs are always defined by the laws that govern their geometrical properties at any scale. It is thus not surprising to notice that the study of their applications has become of cross-disciplinary interest. This article aims to review recent origami-based applications in engineering, design methods and tools, with a focus on research outcomes from 2015 to 2020. First, an introduction to origami history, mathematical background and terminology is given. Origami-based applications in engineering are reviewed largely in the following fields: biomedical engineering, architecture, robotics, space structures, biomimetic engineering, fold-cores, and metamaterials. Second, design methods, design tools, and related manufacturing constraints are discussed. Finally, the article concludes with open questions and future challenges.

1. Introduction

The term *origami* refers to the commonly known ancient art of paper folding. It finds its roots in the composition of the Japanese words *oru*, which means "fold," and *kami*, which means "paper."[1] In the course of its long tradition, it has been known by a variety of names including *orisue* [2] and *orikata*.[3] Despite its popularity, it might be surprising to know that the use of the word *origami* to describe paper folding made its appearance in Japan only in the late Showa Era (1926–1989).[4] Some scholars associate the origin of paper folding to the discovery of paper,[3,5] some are convinced of its Chinese origin,[6–8] while others documented its Japanese [9–11] and European tradition.[12–14] Latest findings suggest that European and Japanese origami arose and evolved independently until the modernization of Japan fostered by the Meiji Restoration.[15] Thus, the idea of origami commonly accepted today could have been developed as a consequence of such a cultural exchange. The present article does not attempt to give a deep understanding of the history of origami, for which the readings of the works by origami experts as Hatori, Lister, Smith, and Oppenheimer are suggested.

Origami is traditionally the art of folding uncut sheets of paper, usually squares, into abstract or realistic subjects.[16] Its initial purpose belonged to religious and recreational activities, strongly influenced by the scarce availability of paper at that time.[17] Despite its ancient tradition, more practical applications emerged only within the past 50 years.[18] Originally practiced with uncut square sheets of paper, origami are now implemented from the nano to the meter scale in a wide range of applications. Latest research advancements enhanced cross-disciplinary applications, resulting in a wide range of origami-based designs in different engineering fields.[19] Many names have been used to describe origami applications in engineering, while the term *origami-based* will be used in this article in accordance with previous studies.[20]

Several topical review articles on origami-based designs have been published, covering important aspects as actuation,[21] thickness accommodation,[22] and fabrication.[23]–[25] Nevertheless, few studies attempted to comprehensively cover design implementation and performance, design methods, and tools.[19] Although the potentials of origami-based designs have been extensively investigated,[26] it is still difficult to see their application

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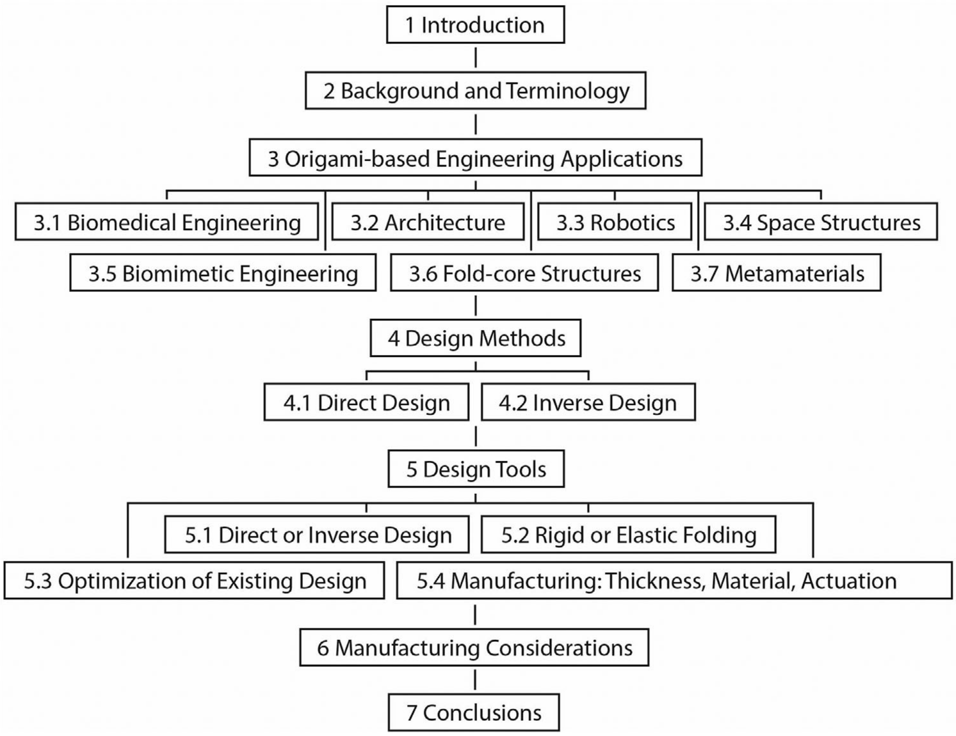

Figure 1. Structure of the paper.

in existing functioning technologies. Limitations are mainly determined by concerning aspects such as the absence of sound design methods and tools, and by fabrication-related issues such as thickness accommodation, folding motion, actuation and durability of systems.

The present article aims to shorten this gap by reviewing recent origami-based applications focusing on design outcomes from 2015 to 2020. Design methods and tools are also discussed, and manufacturing considerations are given. The objectives of the study are as follows: 1) provide a comprehensive review of the latest applications in major origami-based engineering fields. 2) discuss the challenges and limitations of current design processes and computational tools. 3) Identify future trends and potential cross-disciplinary innovations.

The remainder of the paper is organized as follows (**Figure 1**): In Section 2, an introduction to origami background and terminology is provided. The scope of this section is to provide the basic notions that will be necessary to evaluate and analyze design outcomes. Section 3 presents a comprehensive review of origami-based designs in engineering. A selected range of recent applications in biomedical engineering, architecture, robotics, space structures, biomimetic engineering, fold-core structures, and metamaterials is presented. The scope of this chapter is to show how origami-based designs can be implemented and how they perform when compared to existing technologies. Design methods are presented in Section 4, while a discussion on design and simulation tools is provided in Section 5. The strengths and limitations of available software are investigated, and their applicability to design workflows is discussed. Manufacturing considerations related to design methods and tools are given in Section 6. Finally, conclusive remarks are given in Section 7.

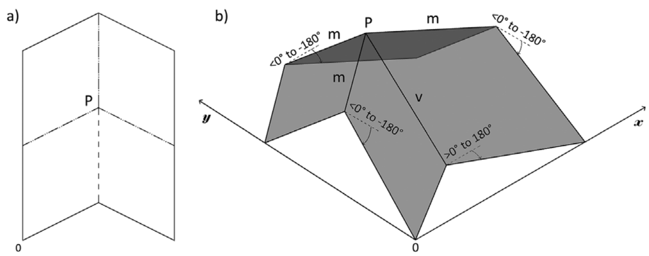

Figure 2. a) single vertex Miura-ori crease pattern. Mountain and valley folds are represented as chain and dashed lines, respectively; P is the single degree-4 vertex. b) folded configuration of the Miura-ori crease pattern; m and v represent mountain and valley folds, respectively.

2. Background and Terminology

The history of origami has seen two major turning points in its course of development. First is the introduction of a common notation system, and second is the application of mathematics to what was the traditional art of paper folding. The earliest notation system was proposed by the origami master Akira Yoshizawa in his book Atarashi Origami Geijutsu (New Origami Art) in 1954.[27] It has been further modified by Randlett and Harbin in 1961, and known as the Yoshizawa–Randlett system,[5] it is still the official notation system of the origami community.

In this part, the basic terminology is presented using the widely known Miura-ori crease pattern as an example (**Figure 2**). An origami can be uniquely defined by its *crease pattern*, the arrangement of folding lines or geometrical patterns within the domain, such as a flat sheet of paper.[28] The *crease pattern* can be further defined by creases, vertices, and facets. A crease is a

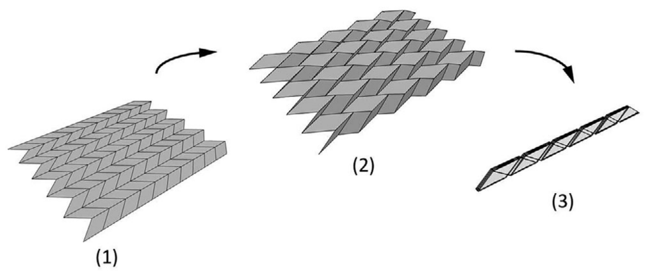

Figure 3. Flat-foldability of a Miura-ori origami. 1) initial fully deployed configuration, 2) intermediate partially-folded configuration, 3) final flat-folded configuration.

line along which a fold takes place, a vertex is a point where a number of creases meet, and facets are the regions bounded by creases.[29] The vertex degree is the number of creases converging to a vertex.[30] A fold is a crease with an assigned fold angle, which is defined as the deviation from the flat state of the intersection between the paper and a plane perpendicular to the fold.[29] Assuming to look at the paper from always the same face of the reference plane where it stands, two types of fold can be defined: mountain fold if convex (angle < 0° to -180°) and valley fold if concave (angle > 0° to 180°) (Figure 2).[31] The Yoshizawa–Randlett notation system represents mountain folds as chain lines and valley folds as dashed lines. Nevertheless, for complex crease patterns, they are consensually represented as solid dark lines (mountains) and saturated dashed lines (valleys).[18] Avila and co-workers presented a comprehensive study on origami fold states, to which the reader is directed for an in-depth discussion on the topic.[32]

An origami is considered flat-foldable, i.e., flat origami, when the fold angles of both mountain and valley have a maximum limit of $-\pi$ and π, as shown in **Figure 3**.[33]

Maekawa, Kawasaki, and Justin developed two theorems, which define the conditions for local flat-foldability:

- The Kawasaki-Justin Theorem: the sum of alternating angles around a vertex is always equal to 180°.[34–36]
- The Maekawa-Justin Theorem: at every vertex, the number of mountain and valley folds always differ by two.[35,37] The theorem implies that the vertex degree is always even and that the facets of the crease pattern can be colorable by two colors without encountering the same two colors at any facet border.

The theorems address local flat-foldability with respect to a single vertex. Differently, the global flat-foldability with more than one vertex was investigated by Bern and Hayes.[28]

At the First International Meeting of Origami Science and Technology held in Ferrara in 1989, Huzita presented six distinct ways to create a single crease by one or more combinations of pre-existing points and pre-existing lines.[38] Justin later added the seventh axioms to the initial set of Huzita, which became to be known as Huzita-Justin axioms.[34,39] The full set of axioms is shown in **Figure 4**.

The recent work of scholars such as Tachi, Demaine, Lang, and Hull strongly contributed to the rise of mathematical studies on origami. Furthermore, it has been demonstrated that origami can be applied to solve mathematical problems such as quadratic, cubic,[40] quartic and quintic equations with rational coefficients,[39] trisect an angle,[40,41] and double the cube.[16,40,42]

Therefore, mathematics has been extensively applied for the design and optimization process of origami structures. It is to note that the mathematical models adopted during the earlier design process often exclude the impact of realistic properties such as the specific material stiffness or thickness. The main reasons behind the omission of such properties are first, the properties are simply not known at the early stage of design process, and second, the omission can help to extend design possibilities. However, as the design stages approach to consider construction practicality, local design alterations become inevitable for adopting appropriate connection solutions that comply with the initial crease pattern.

Once implemented in a monolithic material such as paper, origami can be described as *Compliant Mechanisms* that achieve motion through elastic deformations of creases and/or facets. In particular, because they are fabricated in 2D flat shapes, they can be considered *Lamina Emergent Mechanisms (LEMs)*. Equivalent deployable mechanisms can also be achieved by means of rigid panels and rotational hinges, as shown in **Figure 5**.

3. Origami-Based Engineering Applications

Origami demonstrates the art of geometrical transformation. It is presenting the system in which one can create an artificial transformation between target geometries through folding.[26] As the structural integrity of a built form is in close relation to the geometrical characteristics, it has been a great interest of many to dynamically change the structural integrity of a design through geometrical transformation to meet multiobjectives in a single context. Therefore, origami-based designs have been adopted to explore novel solutions to existing problems across different disciplines. Certainly, the explored qualities in origami vary between disciplines, but the following can provide the key aspects, which have been explored and developed by global researchers:

– Deployability: is the capability of origami to deploy from a 2D/3D initial configuration to a final 3D state. Among others, this characteristic is of particular interest for the development of minimally invasive surgeries in biomedical applications. Moreover, deployability is a desirable characteristic for the design of space structures. Folded compact systems can be efficiently stored inside the limited dimensions of launch vehicles and then deployed in their final desired shape once in orbit.
– Scalability: due to their inherent geometrical properties, origami-based designs can be scalable from the micro to the meter scale. In particular, scalability is always ensured for origami mechanisms, while not always achievable with origami structures. This property remarkably improves the range of applications of origami-based designs, making the implementation of their characteristics generally scale independent.
– Self-actuation: is the capability of origami-based designs to actuate their deployment without external actuators. This property may be applied in the design of origami-based kinetic façades in the architecture industry. Of particular interest also for biomedical designs, robotics and metamaterials,

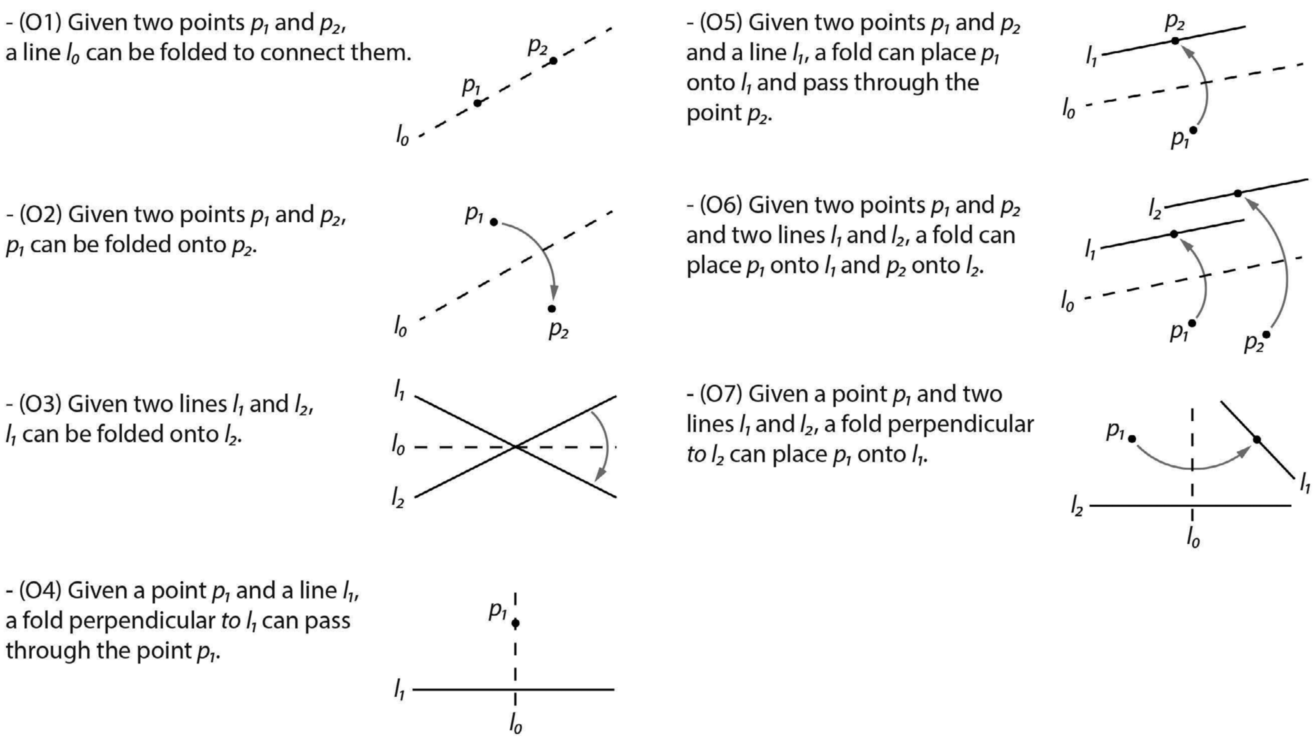

Figure 4. Huzita-Justin axioms.

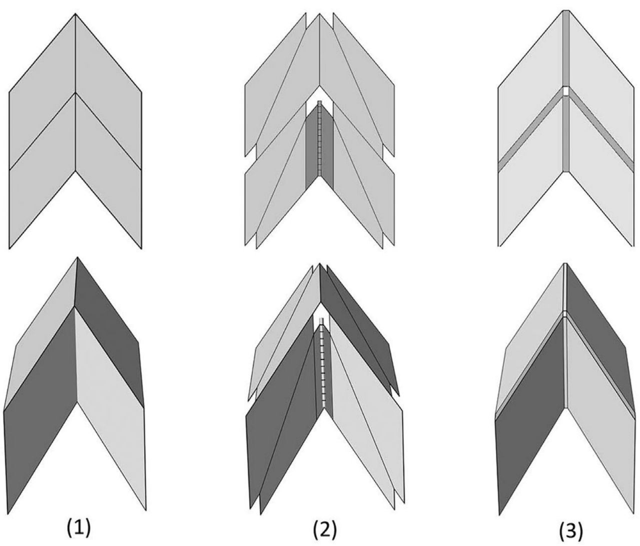

Figure 5. Conventional origami and origami-based structures. 1) conventional Miura-ori unit, 2) equivalent unit engineered with rigid panels and rotational hinges, 3) equivalent unit engineered with rigid panels and compliant hinges.

self-actuation could be a desirable property for dynamic reconfigurable designs regardless the field of application.

– Reconfigurability: is the capability of origami-based designs to dynamically change their shape according to specific design constraints. Once designed, one crease pattern could achieve different 3D configurations without further geometrical alterations. Reconfigurability can be applied to adaptive structures that require changes in their shape in response to dynamic environmental stimuli, and is of particular interest for systems showing multistability, i.e., more than one stable state during their folding motion.
– Tunability: is the capability of origami-based designs to be tailored for a specific task changing their geometrical properties. Besides relevant for any kind of application and optimization process, this feature is particularly interesting for the design of metamaterials and fold-core structures. Being structure-dependent, novel metamaterials could be tailored to achieve specific behaviors not present in conventional materials, while fold-cores could be designed and optimized to achieve specific mechanical properties only varying their geometrical parameters. This property could allow to achieve flexible origami-based designs and optimized design workflows.
– Easiness in manufacturing: one advantage of origami-based designs is the capability to be manufactured in 2D and then assembled in their final 3D configurations. This feature can substantially speed up fabrication processes, simplify production, storage, and material usage in comparison to conventional designs.

3.1. Biomedical Engineering

The biomedical industry is probably one of the most advanced fields in the research and application of origami-based devices. Desirable properties such as multistability, auxetic behavior (negative Poisson's ratio), tunability of geometry and mechanical properties, easiness in manufacturing and scalability of systems have been well implemented in origami-based designs at different scales for both in vivo and ex vivo applications. Nevertheless, not all the devices are able to meet the demanding clinical requirements, with issues related to compatibility of materials used, the efficiency of actuation technologies and overall reliability and durability of systems that are still a concern.

Origami-based structures can be scaled and optimized in respect of specific design constraints, thus being easily manufactured and reconfigurable in novel flexible solutions. In particular, the capability of origami to move from a folded to a deployed state is of great interest for biomedical designs.[43] Recent advances in self-folding technologies[21,44,45] could be of particular interest for the development of novel minimally invasive procedures, while the applicability of optimized 3D assembly methods based on bending, curving, and folding have also been investigated.[46]

The application of reconfigurable origami-based self-folding designs encountering highly limited movements has been explored for human tissue engineering.[47,48] Because biological tissues are sensitive to contamination, self-folding structures are preferred over the use of external actuators to avoid contacts. Therefore, optimal designs should have few degrees of freedom, while the transformed geometry should closely match the tissue structures. Mehner and co-workers proposed an origami-based solution to engineer human tissues through folding and directed cell assembly of a 2D scaffold (**Figure 6**a).[47] Their work focused on replicating the structure and function of liver lobules. The two selected crease patterns were considered not feasible due to the degrees of freedom of their folding motion and the inaccurate replicability of the liver lobules structure. The self-folding of the proposed scaffold made of biocompatible and biodegradable polymers was also investigated in conjunction with polymer bilayer actuators. Although successful, the investigation was developed based on FEM simulations and experimental tests with much simpler geometries than the proposed crease patterns. Therefore, its applicability to complex geometries is still to be investigated. Furthermore, one requires to develop crease patterns based on more systematic design processes, which can provide sound justification for the choice of crease patterns.

Kim and co-workers investigated the applicability of origami-based designs to tissue engineering proposing a cylindrical paper-based scaffold for the regeneration of damaged tissues (Figure 6b).[48] The paper-based scaffold, which thanks to his macroporous structure has the advantage to allow nutrient transportation and oxygenation, has been further treated with an initiated chemical vapor deposition (iCVD) method to enhance its mechanical stability under wet conditions. The proposed system has been successfully applied without stenosis in a trachea regeneration operation in rabbits. The paper-based scaffold allowed for optimal regeneration of the damaged area of the trachea without granulation tissue ingrowth or graft failure. Moreover, the correction has been performed with simple wrapping and folding steps, thus preventing the use of sutures. Such structures can be easily designed in their 2D configurations before folding and being locked into desired shapes without additional components. Their scalability and flexibility could allow to obtain different shapes for full organ reconstruction.

Origami properties such as deployability, auxetic behavior, and multistability have also been implemented in the design of novel deployable orthopedic implants.[49] Investigating the application of origami-based designs in orthopedic systems, Bobbert and co-workers proposed a novel origami-based design to repair vertebral compression fractures (Figure 6c).[50] Their system implements an origami-based technique to design an initial 2D flat shape made of six square panels and fold it into its first stable 3D cube configuration. Subsequently, the cube is inserted into the vertebra and expanded to its final stable 3D configuration by means of a silicon balloon and kirigami actuators. Several single-layer (consisting of one cube) and multilayers (consisting of up to three cubes stacked inside each other similarly to Russian Matryoshka) specimens made of polylactic acid (PLA), aluminum and titanium have been fabricated and tested. The proposed origami-based implants showed an optimized deployment, mechanical properties, and manufacturability. The design has great expansion capacity, and it can be offered to many patients with different sizes. Furthermore, the possibility to implement the system in multilayer solutions could provide enhanced mechanical properties for obese patients. Aspects such as deployment ratio, mechanical properties, pore size, and porosity could be parametrically designed and adjusted to meet specific requirements. This approach could lead to less invasive and more flexible solutions in comparison with conventional technologies. Further studies should investigate the clinical adaptability of the proposed design, possibly keeping costs affordable as they are in the current prototyping stage.

Origami-based designs have also been implemented for the development of novel surgical tools. Banerjee and co-workers proposed an origami-based deployable surgical retractor with the aim to improve the interaction between instruments and tissues in face-lift operations (Figure 6d).[51] Inspired by the wings of birds, the soft retractor features a Chinese fan-shaped geometry with a zig-zag paper pattern. It implements tactile sensors made of flexible piezoresistive fabric and printed conductive ink able to report force and stress measurements in real time. Fixed on a deployable system that controls its movement, the stiffness of the multilayer origami-based paper structure can be tailored by means of a layer-jamming-mechanism (LJM). Cadaver tests showed that the proposed system is able to perform a facelift incision with a width of 9 cm and higher, thus fulfilling surgical requirements. Compared to typical rigid retractors, the proposed system can better distribute forces on skin while avoiding damaging the tissue. Moreover, the system is easy to fabricate, safe and inexpensive, having also the advantage to provide real-time feedbacks on forces applied on the skin to surgeons, who can further tailor them accordingly.

The execution of surgical procedures has recently been optimized by the development of robot-assisted surgeries (RAS). Novel robotic devices have been implemented to assist surgeons or even perform operations independently.[52,53] Sargent and co-workers proposed an origami-based system (OriGuide) to optimize the ex vivo support for the insertion of flexible instruments in RAS (Figure 6e).[54] Starting from an adaptation of the Kresling pattern to a cylindrical structure, they designed an antibuckling system to support an endoscope used for bronchoscopy surgeries. Fabricated in polyethylene terephthalate (PET), the structure features 8 bistable stories and 16 monostable stories in an alternating order. The implementation of alternating bistable stories, which are locked in one of their bistable states, is of particular interest because it adds localized support points for the endoscope, thus increasing its stability

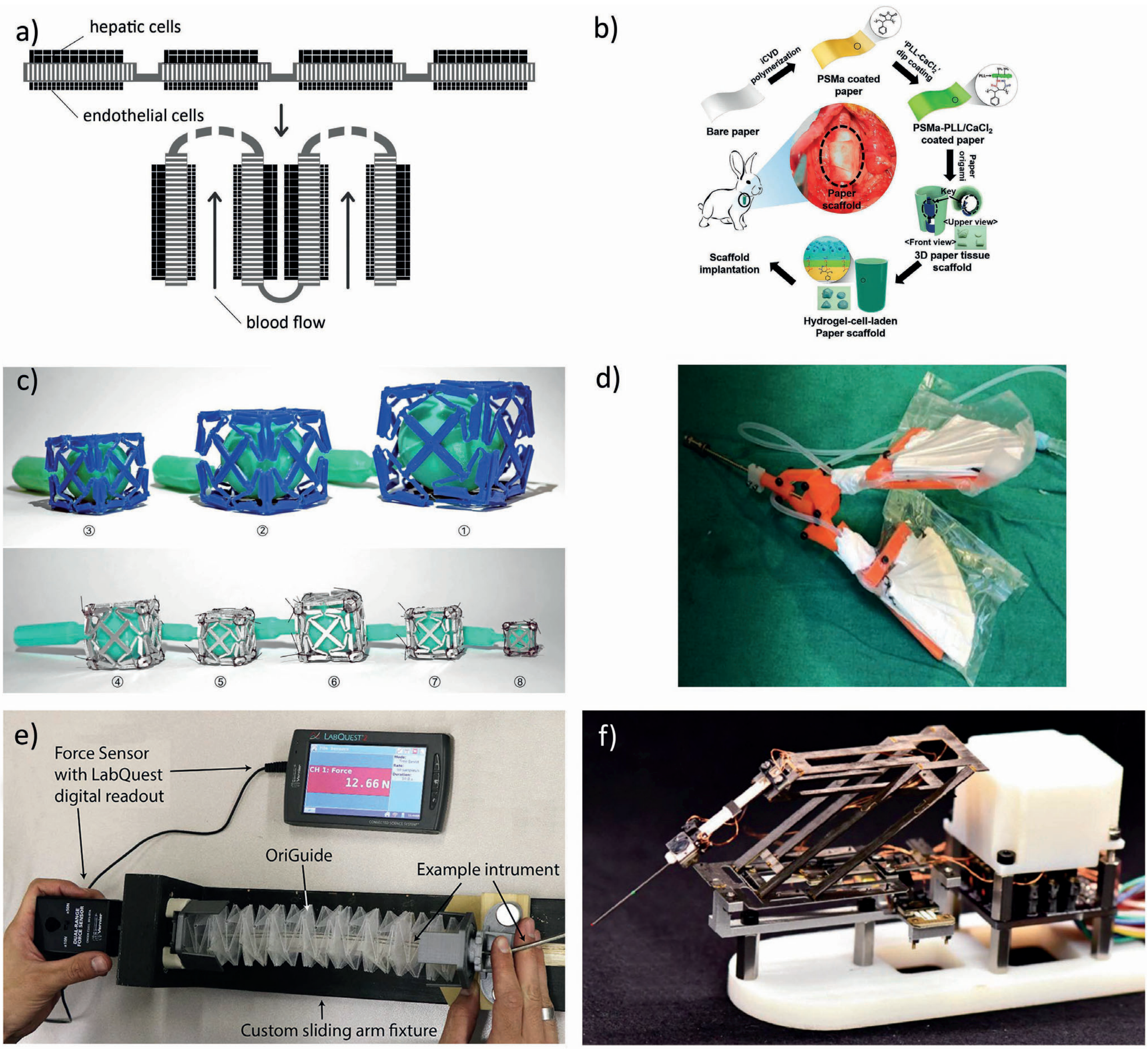

Figure 6. Origami-based biomedical devices. a) conceptual design of an origami-based scaffold. Adapted with permission.[47] Copyright 2015, AMS. b) Hydrogel-laden paper scaffold for rabbit trachea tissue replacement. Reproduced with permission.[48] Copyright 2015, National Academy of Sciences. c) Origami-based orthopedic implant for vertebral compression fractures. Reproduced under the terms of the Creative Commons License CC BY 4.0.[50] Copyright 2020, The Authors, published by Elsevier. d) Origami-based surgical retractor. Reproduced with permission.[51] Copyright 2020, ASME. e) OriGuide support system for RAS procedures. Reproduced with permission.[54] Copyright 2020, ASME. f) Origami-based robot for assisted microsurgery. Reproduced with permission.[55] Copyright 2020, The Authors, published by Springer Nature Limited.

without breaking the continuity of the envelope. Experimental tests showed that the proposed origami-based structure increased the buckling strength of 10 N or greater when compared to an unsupported endoscope. Among the advantages provided by the design there is the capability to be customizable in its geometry to fit surgical requirements of different operations, a tailored compression ratio, tunable buckling strength, and protection from external contamination. Moreover, the system is composed by few elements being easy and inexpensive to fabricate. Future work should investigate the performance of other suitable geometries and materials, as well as testing the durability and reliability of the system that can potentially be applicable in other fields such as flexible electronics and space structures.

Suzuki and Wood extended the application of origami-based designs at smaller scales proposing a millimeter scale system for robot-assisted retinal microsurgeries (Figure 6f).[55] Implementing a pop-up mechanism, the structure is made of revolute flexural joints and rigid links fabricated with micromachining and lamination techniques. Piezoelectric linear actuators drive the motion of the system, while a contactless optical sensing method checks the displacement in real time. The proposed origami-based pop-up mechanism allowed to achieve on average a size

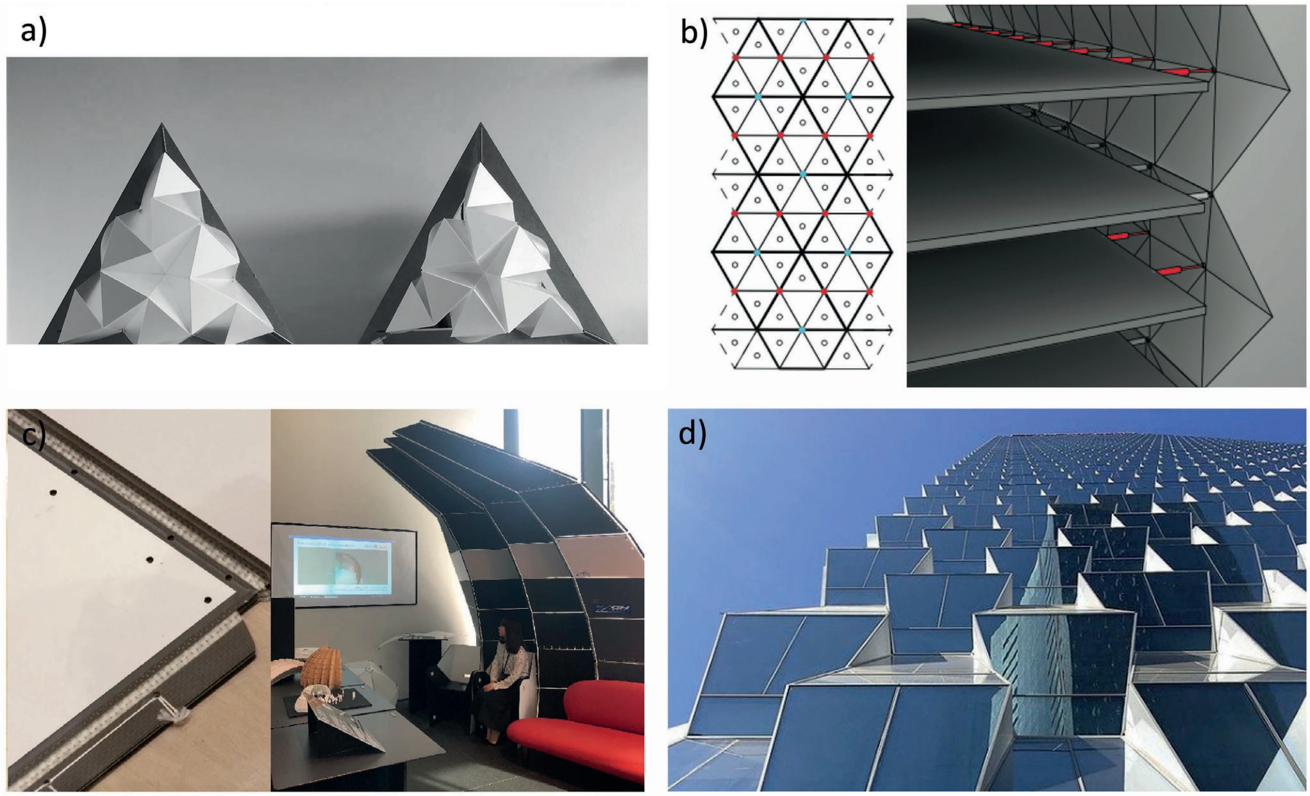

Figure 7. Origami-based designs for architectural applications. a) Kumorigami adaptive shading system. Reproduced with permission.[57] Copyright 2018, American Society of Civil Engineers. b) Origami-based adaptive diagrid envelope. Reproduced with permission.[64] Copyright 2019, SPIE. c) Origami-based foldable canopy. Reproduced under the term of Creative Commons Attribution 4.0 International License.[65] Copyright 2020, The Authors, published by Springer. d) Beijing Greenland Center by SOM.[66] Image courtesy from Eric R. Keune A.I.A.

four times smaller and a weight 1000 times lighter than comparable conventional systems for retinal surgeries. Compared to manual operations, the device has been able to reduce deviations of desired trajectories by 68%, having a motion precision of 26.4 µm and a position precision of 0.21 mm. The device showed good accuracy although bigger systems with higher payload capacity and precision are currently available in the market.[56] An advantage of the system is that it can be fabricated and assembled starting from a single 2D sheet of material, thus remarkably reducing costs and the complexity of the process.

3.2. Architecture

Recent developments in contemporary architecture led to an increased complexity of building skin elements, thereby unveiling the needs of new flexible and adaptable solutions. Despite often adopted for purely aesthetical purposes, origami-based designs could be able to provide enhanced structural performance, reduce energy demands and develop adaptive and climate responsive designs. Among their properties, some are of particular interest for architectural applications: easiness in manufacturing and assembly, the capability to form watertight continuous surfaces, low energy actuation for structures with few degrees of freedom, possible self-actuation, and controlled motion.

Origami-based designs found interesting applications in the engineering of façade technologies thanks to the capability to be implemented in flat and curved surfaces, be reconfigurable, allow tessellations and design of hierarchical kinetic structures. Pesenti and co-workers presented an origami-based adaptive shading system able to passively control indoor visual and thermal comfort (**Figure 7**a).[57–59] First, the performance of the proposed shading device has been assessed with simulation tools. Results showed that the geometry and the entity of the materials played a significant role in meeting the comfort requirements, which were found strictly correlated to both glare and illuminance. The most efficient design, built with a Ron Resch pattern, could lead to a total building energy consumption of 42.5 kWh m^{-2} y^{-1}, which would respect the latest guidelines of the European Union for nearly zero energy buildings (NZEB) of similar typology.[60] Subsequently, a physical model of the Ron Resch shading device has been fabricated laser cutting a translucent polypropylene (PP) sheet. A system of shape memory alloys (SMA) wires has been implemented for the actuation. Although the responsiveness, i.e., the time required to fully fold and unfold, is generally a concern for such types of structures, experimental data showed that the proposed SMA actuation system was able to complete the full reconfigurable circle of folding and unfolding in less than three minutes. Due to the not reversible motion of SMA, a system of springs have been implemented to move back in place the

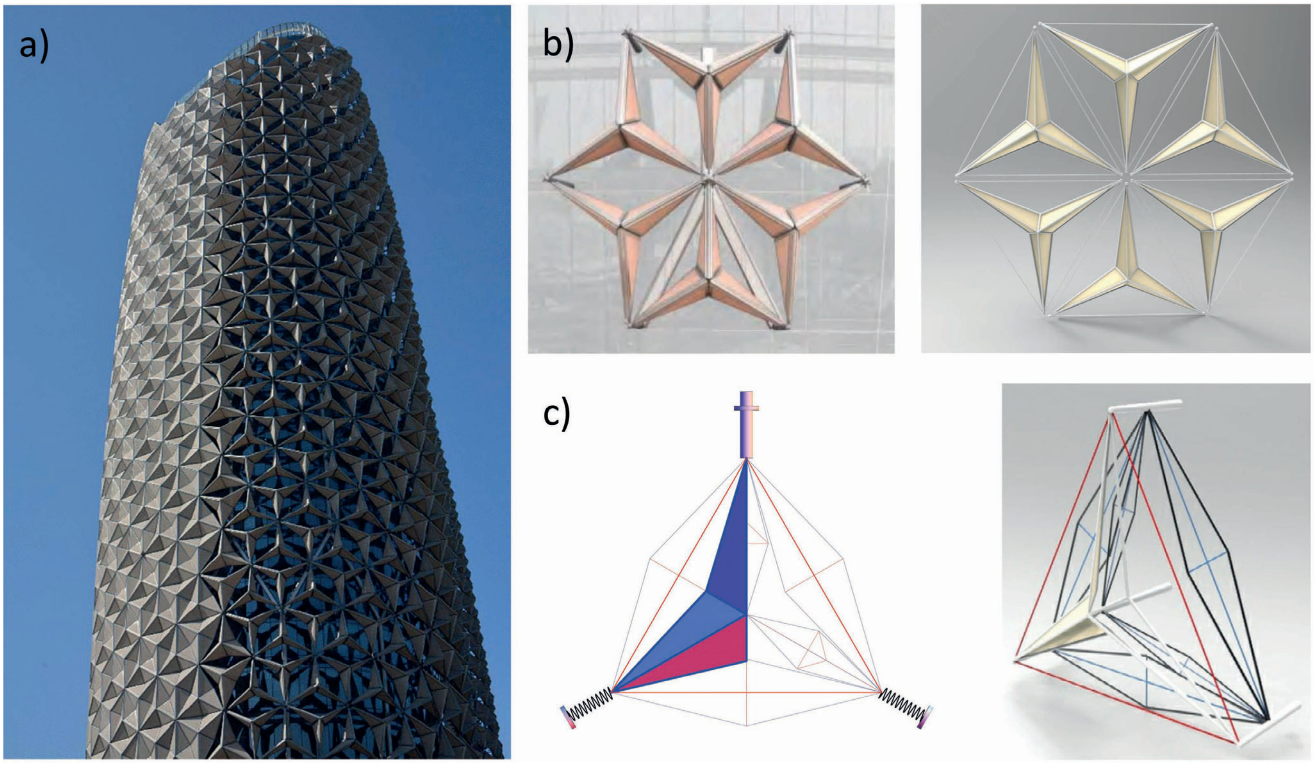

Figure 8. Optimization of the adaptive envelope of the Al Bahar towers. a) View of the existing adaptive envelope. Reproduced with permission. Copyright Terri Meyer Boake. b) Hybrid origami/tensegrity adaptation of the system. Base system (left), optimized system (right). Reproduced under the terms of Creative Commons Attribution License (CC BY).[61] Copyright 2019, The Authors, published by National Academy of Sciences. c) Further optimization of the system with energy harvesting ability. Front and side view of a partially closed configuration of the base unit. Reproduced with permission.[63] Copyright 2020, Elsevier.

structure, inevitably reducing the performance of the actuators, which finally led to an overall surface reduction of 20%.

Despite showing potentials, the application of origami-based designs in conjunction with SMA actuators is still far from being implemented in real-life applications. Challenges that concern reliability, durability, and efficiency of the actuation still need to be solved. Particularly, as SMA actuators consume large amounts of energy, shading designs implemented to reduce energy consumption may yield to inefficient solutions if actuated by such not well-performing active means. In addition, because SMA actuators provide not reversible reconfigurations, complex systems made of springs or other equivalent elements have to be designed to allow reconfigurability. The efficiency of such systems when performing several multiple reconfigurable circles are still not well documented, as well as the performance of SMA actuators in outdoor environments.

An innovative origami-based adaptive envelope has been proposed by Babilio and co-workers, who investigated the performance of a novel hybrid origami/tensegrity system (**Figure 8**b).[61] Starting from the original adaptive envelope of the Al Bahar Towers (Figure 8a), which is composed of 1,049 origami-based shading elements, a new tensegrity[62] module has been proposed. The proposed design achieved a total weight reduction of 50% when compared to the original one. Moreover, the parallel actuation method works with a stroke that is equal to 33% of that needed to actuate the original module. Although numerical data are not available for comparison, the design is also expected to reduce operational costs and the environmental impact of the system.

A further optimization of the system has been proposed by Miranda and co-workers (Figure 8c).[63] They investigated the addition of 3D D-bar elements featuring piezoelectric cables capable of harvesting the stored mechanical energy and further convert it into electrical power. Implementing the proposed structure on the original façade design of the Al Bahar Towers would lead to an electric energy production for each building equal to that produced by 233 PV panels and 87 microeolic rooftop turbines with 1 m^2 of surface area. It should be noted that the base design of the Al Bahar Towers is not perfectly flat but "water-tight" in its final unfolded shape, while the modules of the two newly proposed designs can be unfolded flat in their final configuration. Although the proposed designs showed to be able to improve the efficiency of the system, overall operative costs, as well as maintenance expenses should be further addressed.

An origami-based design has also been proposed to optimize the structural performance of a dynamic façade system (Figure 7b).[64] Taking the Hearst Tower in New York as a base model, the authors developed an origami-based adaptive diagrid façade (ADF) driven by a set of linear actuators. They performed computational fluid dynamic (CFD) simulations to investigate the behavior of three different ADF configurations under extreme wind loading. Simulation results showed that the origami-based ADF was able to reduce wind loads acting on the building for all its three configurations. Comparing the performance of the three configurations to an equivalent shoebox model, simulation results showed a reduction of wind loads ranging from 16.9% to 43.8%. Still at an early stage of its development, the proposed model is a promising novel approach for origami-based systems with structural capabilities. Nevertheless, its application will require further studies to be implemented in real-life scenarios.

Ando and co-workers investigated the design, optimization, and fabrication of a deployable origami-based canopy (Figure 7c).[65] They proposed a rigid-foldable and flat-foldable modular system made of quadrilateral panels that can be deployed with one DOF after assembly. An innovative aspect of their design process is the implementation of a multiobjective optimization (MOO) method to optimize properties such as structural stiffness, acoustic, and energy performance. The final design has been fabricated with panels made of carbon fiber reinforced plastics (CFRP) and joints made of grass fiber reinforced plastics (GFRP) with embedded fiber reinforced plastic (FRP) hinges. Advantages of the system include easiness in manufacturing, transportation, and assemblage. The modules can be fabricated by standard CNC techniques, transported in their flat state and assembled and disassembled on-site because they do not use permanent linkages. Despite the implementation of MOO, variables were limited to the geometrical properties of the selected origami pattern. This approach strongly limits the potential of MOO, which in future works could be applied to navigate more extensive design domains and be a supportive tool in the selection of the origami pattern. Although in this study acoustic and energy performance have been investigated only geometrically, MOO could also be implemented to support material selections, thus leading to more accurate simulation analysis.

Not only applied for deployable structures, origami-based designs found further application in static designs. Schultz and Katz presented a preliminary investigation on the performance of the origami-based façade of the Greenland Center in Beijing (Figure 7d).[66] Daylight and stress ratios have been used as metrics to evaluate the efficiency of the design. The selected design maximized self-shading and energy efficiency while respecting geometric and technical constraints. The design and optimization processes were driven by primary constraints (building energy efficiency, buckling strength, and minimum volume) and secondary constraints (geometric, leasable floor plate, constructability, aesthetic). The optimal typology was achieved by maximizing the protrusion depth and pleat width in accordance with optimal self-shading capabilities and buckling resistance. According to simulation results, the final design increased the building energy efficiency by 30% and decreased the material volume by almost 10%. Future works could be oriented to determine the correlation between origami geometrical properties and the optimization of selected parameters. Such findings could lead to the development of a general design method that could more systematically explore the capabilities of a broader range of origami geometries.

Although appealing origami-based designs have been developed, several limitations are still far to be addressed especially for kinetic systems. When moving to the fabrication stage, preliminary prototypes are commonly manufactured with hinge/plate structures that fold rigidly. Despite the advantages given by such systems, the high number of components and complex actuation methods could lead to unexpected complications and reduced performance. In addition, the high number of gliding and rotating cycles performed by the hinges may lead to expensive maintenance or even failure. To overcome this issue, designers have been inspired by nature to develop novel hingeless origami-based systems. Promising results have been achieved by Flectofold, a bioinspired origami-based adaptive system that will be further discussed in Section 3.5.

3.3. Robotics

Inspired by nature and with the aid of research advancements in smart materials, origami-based designs found successful applications in robotics since the early 21st century.[67] Folded microrobots manufactured with lamination-based processes were early precursors of origami robots,[68,69] which fabricated in plane and then assembled by folding are applicable to a wide range of typologies. Moving from a starting 2D to a final 3D configuration, they provide a simplified and efficient design process, while ensuring fast reconfiguration and prototyping. Thanks to tailored geometries and tunable actuation properties, origami-based robots can adapt their shape in response to the environment or task changes. They can be manufactured by a wide range of materials as metal, paper, and plastic, combining features as autonomous locomotion, shape change, and self-assembly. Successfully designed and fabricated from the millimeter to the centimeter scale, origami-based applications include robots that are able to crawl, walk, jump and swim.

Pagano and co-workers proposed an origami-based crawling robot fabricated by folding sheets of paper following the Kresling pattern (**Figure 9**a).[70] The prototype is composed of two origami towers nested inside a paper bellow and connected by 3D printed end plates. Expansion and contraction of the internal bistable origami structures are actuated by DC motors, which provide locomotion and steering. The robot showed an optimized locomotion facilitated by the buckling of the thin panels of the towers. Zhakypov and Paik presented an origami-based robot able to crawl and jump (Figure 9b).[71] Its stiff body is composed of a sheet of glass-reinforced epoxy laminate, while its actuation is driven by linear and torsional SMA wires. Taking advantage of bistability, they were able to optimize the snapping mechanism of a prototype of 6 g weight and 5 cm length, generating a maximum vertical jump of 45 mm. Karras and co-workers presented an origami-based walking pop-up robots tailored for space missions (Figure 9c).[72] Using a new textile-enhanced rigid-flex printed circuit board (PCB), the prototype is able to decouple mechanical and electrical functions of the chassis flexures, thus improving the kinematics and durability of the system. Thanks to the reconfigurability of its two wheels, the rover was able to drive under obstacles as low as 4 cm, climb a 35° plywood slope and drive through a 40° slope.

Improvements in the mobility of origami-based robots have been achieved by different prototypes of deformable wheels. Lee and co-workers presented an origami-based deformable wheel robot able to overcome obstacles of different nature adapting its shape to variable environmental configurations.[73] Research findings have been further implemented in the fabrication of SNUMAX, the winner of the RoboSoft Grand Challenge

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Figure 9. Origami-based robots. a) Multi-stable crawling robot. Reproduced with permission.[70] Copyright 2017, IOP Publishing Ltd. b) Crawling and jumping origami-based tripod. Reproduced with permission.[71] Copyright 2018, IEEE. c) PUFFER, origami-based rover for space missions. Reproduced with permission.[72] Copyright 2017, IEEE. d) SNUMAX, robot with origami-based wheels. Reproduced under the terms of Creative Commons Attribution License (CC BY).[74] Copyright 2016, The Authors, published by Frontiers Media S.A. e) Vacuum-driven origami-based gripper. Reproduced with permission.[76] Copyright 2019, IEEE. f) Origami-based three-finger manipulator. Reproduced with permission.[77] Copyright 2017, Cambridge University Press.

(Figure 9d).[74] The faces of the wheels, which implement a Waterbomb origami pattern, have been fabricated with PET film, while fold lines were made of fabric. The folding is actuated by a simple pulley mechanism consisting of a Kevlar wire covered by a Teflon tube and a coil spring. Wheels are able to change their width from 200 to 110 mm and bear more than 10 kg. Thanks to the adaptability of its origami-based wheels, SNUMAX can pass through small gaps, overcome rough terrains and climb stairs. A different version of the robot has been presented by Lee and co-workers, who proposed an optimized version of the wheel.[75] A coil spring with a wire on its center is used to actuate the deformation, while a rubber band is wrapped around the circumferential direction of the wheel to provide restoring force after folding. Weighting 9.7 g, the prototype is able to bear more than 400 times its weight. The wheel diameter can change from 28 to 68 mm, allowing the robot to pass through a 50 mm gap and climb a 50 mm step. Despite origami-based wheels can provide optimized mobility by means of few mechanical parts and actuators, future works should be focused on the actuation and durability of systems. Novel designs should be able to embed power supply systems in their structure to avoid cable connections to external supplies that will inevitably limit their mobility. In addition, current designs extremely stress the creases of patterns, which are in direct contact with the external surfaces and may therefore being prone to failure. The durability of such systems should be further investigated, as well as the possibility to design membrane structures able to protect the crease pattern without hindering its folding/unfolding motion.

Although most of the research in origami-based robots has been focused on achieving mobility, origami-based grippers and artificial hands have also been successfully tested and prototyped. Li and co-workers proposed a vacuum-driven gripper made of a flexible thin membrane manufactured following an origami Waterbomb tessellation (Figure 9e).[76] Experimental tests showed that different combinations of origami-based structures and skins yield to grippers tunable for different tasks. The gripper can lift a large variety of objects without damage, including delicate food and bottles of nearly 2 kg. Moreover, it can lift objects up to approximately 70% of its diameter with a grasp force equal to more than 120 times its own weight, thus showing adaptability and robustness. Questions regarding which materials would optimize the strength and reliability of the gripper are still open, while optimized configurations obtainable by variation of shape, dimension, and modification of the origami pattern require further investigations.

Jeong and Lee presented a gripper based on the origami twisted tower (Figure 9f).[77] The robotic arm is actuated by four cables with pulleys driven by servo motors, while the three fingers are individually actuated by a single cable directly attached to a mini servo motor. The performance of the gripper was investigated under grasping and lifting tests using a shuttlecock, an egg shell and a cube block with varying weight. The rate of successful grasping ranged from 0% to 100%, strongly influenced by object shape, weight, and orientation. The origami-based gripper is able to better absorb excessive forces applied to objects through force distribution and structural deformation when compared to a rigid gripper. This makes it a better candidate for the manipulation of fragile and irregularly shaped objects. The limited cost of the prototype is a temporary advantage that might be lost in solving structural problems and improving materials durability, which at the current stage require further studies.

3.4. Space Structures

Space missions require structures able to be stowed in the limited constraints of launch vehicles and work in a scale that ranges from 10 to 1000 m in their final deployed state. Three main characteristics have to be kept in mind when designing space structures: they must be lightweight, small during transportation from the ground to space, and of large size when deployed in orbit. Since the first application proposed by Miura and Natori,[78] researchers came up with several origami-based designs able to overcome the challenges of shipping and functional requirements of space systems. Origami-based technologies can be applied in the design of deployable, adaptive, and lightweight structures with advantages as reduced friction, elimination of lubricants, increased precision, and ease of miniaturization.[79]

The design of an innovative origami-based starshade is part of an on-going NASA project (**Figure 10**a).[80-84] Working in connection with an independent space telescope, Starshade has the aim to shade the telescope by star lights, thus enabling the imaging of exoplanets orbiting around those stars. The structure has a deployed diameter of 34 m, with a 20 m inner disk and 28 external flowerlike petals, each 7 m in length. The inner disk is an optimized version of the Flasher origami pattern covered with a shield material consisted of multiple layers of carbon-impregnated black Kapton. The petals are made of a thin carbon fiber composite structure covered with the same shield material of the inner disk. The structure is reported to fold smoothly and predictably, being able to fit within the 5 m constraint of launch vehicles with a high deployed to stowed ratio. An innovative aspect of its design is the application of an inverse design workflow to determine the most suitable crease pattern geometry. The algorithm takes as input material thickness, deployed diameter, stowed diameter, stowed height, and the numbers of gores produced by the system. A suitable crease pattern is an output along with information on packing efficiency, stowed volume, gore strain, and material compression.

The same algorithm used to generate the Starshade crease pattern has been applied for the design of a large dual elliptic solar reflector.[85] Again adapted from a Flasher crease pattern (Figure 10b), the selected geometry allows to achieve a deployed dimension 40 times greater than the stowed one. The two reflectors, which are made of aluminized Mylar and composite fabric, are designed to be separated by a deployable boom and then deployed by means of an inflatable torus. FEM simulations showed that the proposed design would be able to deploy flat in respect of deflection limitations requirements. Although the proposed design can outperform existing systems in terms of reduced weight, enhanced deployment ratio, and parameterization of its geometry, further studies are required to address concerning aspects such as actuation, control of the deployment motion, and fabrication of the system.

Another adaptation of the flasher pattern has been implemented by Zirbel and co-workers, who proposed Hanaflex, an origami-based deployable system for solar arrays (Figure 10c).[86] The proposed adaptation of the Flasher pattern can reach a deployed dimension 10 times greater than its initial stowed state. One of the most relevant advantages of the system is that additional rings can be added to the base unit without altering the height of the stowed geometry and minimally increasing its diameter. The system is designed to be deployed by a motor-driven perimeter truss. Deployed stiffness, deployed strength, stowed volume-specific power, and mass-specific power have been analytically investigated showing to be able to meet the NASA design requirements. Despite showing an enhanced deployment ratio when compared to traditional planar arrays, Hanaflex is composed by a higher number of segments that may lead to limitations. In fact, a higher number of panels yield more complex electrical connections of the PV cells, thus increasing the weight and risk of failure of the system. Moreover, the effect that wirings may have in the folding motion has not been investigated. The deployment motion of the system is not reversible, and although the implementation of this feature would be beneficial, it still remains challenging.

Despite deployability, geometry optimization, and material composition of origami-based space structures have been extensively investigated, actuation systems still rely on sophisticated

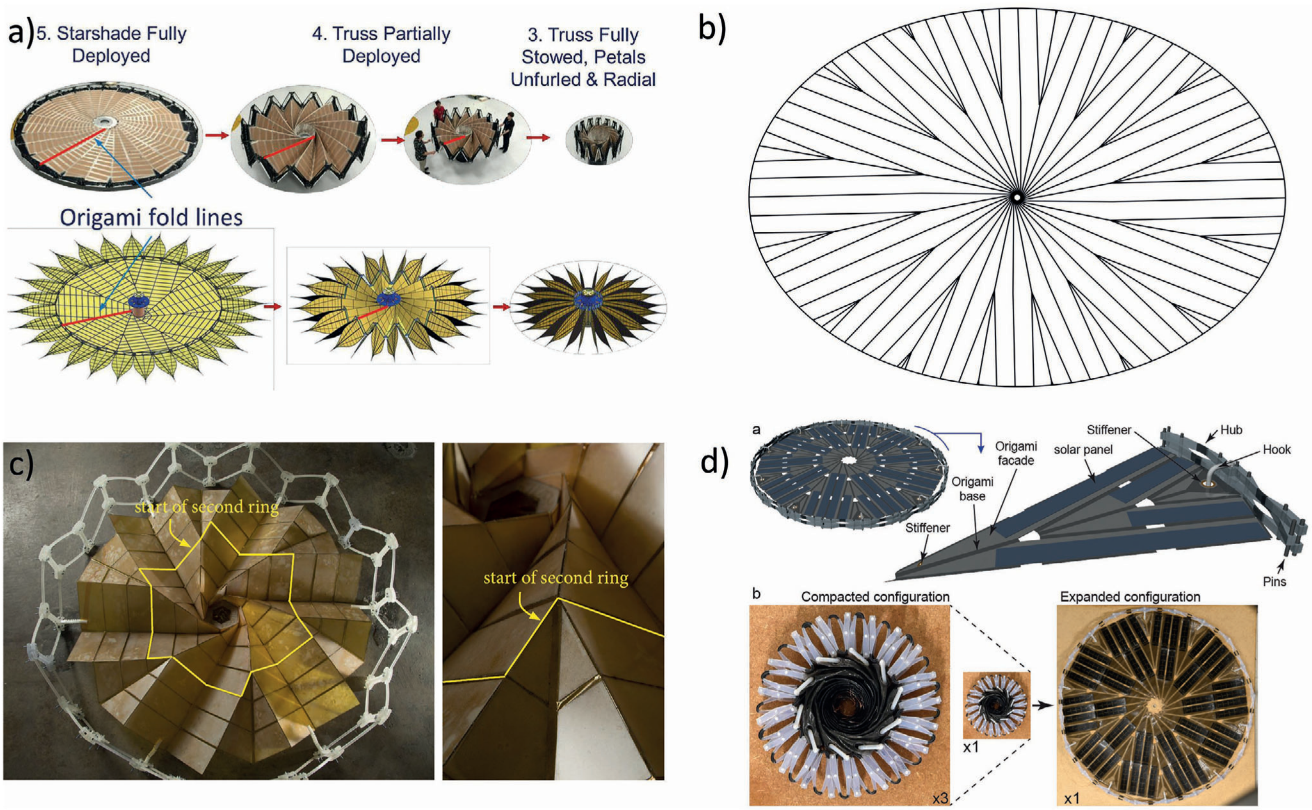

Figure 10. Origami-based space structures. a) Starshade deployment motion. Reproduced with permission.[80] Copyright 2016, SPIE. b) Crease pattern for a dual elliptic solar reflector. Adapted with permission.[85] Copyright 2017, IEEE. c) Hanaflex solar array. Reproduced with permission.[86] Copyright 2015, SPIE. d) Self-folding solar array. Reproduced under the term of Creative Commons Attribution 4.0 International License.[87] Copyright 2019, The Authors, published by American Physical Society.

networks of motor-driven actuators. With the aim to simplify actuation systems and reduce the actuators stowed mass during the shipping phase, Chen and co-workers proposed an origami-based self-deployable solar array that is programmed to activate in response to changes in the surrounding temperature (Figure 10d).[87] The structure is 3D printed with shape memory polymers and is composed of an optimized origami Flasher sheet embedded in a ring scissor mechanism. The deployment actuation is primary driven by the outer ring and second enhanced by the origami sheet due to the shape memory effect. The scissor mechanisms and the origami sheet were both optimized to provide the maximum deployment expansion ratio and to carry the maximum number of solar panels, respectively. The final prototype showed an expansion ratio of 1000% without external actuators or power supply. The origami-based design provided a simplified actuation and a controlled deployment, while reducing the total mass of the system and improving its stowability for the shipping phase. Nevertheless, it should also be noted that its deployment mechanism is not reversible, which is not a limitation for structures requiring only one deployment, but may be for systems designed to be reconfigurable.

Despite being particularly suitable for the design of space structure, the applicability of origami-based designs to real-life projects is still limited. Their application in space missions is often limited by the assessing of complex aspects such as the non-linear dynamic of deployment.[88] The complexity of mechanical systems and the impossibility to be tested in orbit require simplified design processes, optimized simulation tools and experimental tests, which should be able to provide reliable data for the optimization and assessing of final products.

3.5. Biomimetic Engineering

Biomimetic is the scientific field that attempts to design and optimize systems through the mimicking of biological entities.[89] The latter, being the result of millions of years of adaptation to life, inspired researchers in the addressing of several engineering problems. Hence, burrs led to the invention of Velcro,[90] lotus plants inspired self-cleaning textiles,[91] studies on humpback whale flippers improved aircraft wing design,[92] and many others.[93] The investigation of origami-based applications in biomimetic engineering is motivated by the observation that a large number of natural systems from both plant and animal kingdoms present origami-related phenomena as corrugation, buckling, deployment, folding, self-actuation, hierarchical patterns, and shape adaptation. It is thus not surprising to know that pine-cones inspired the Waterbomb pattern, and that the Kresling pattern is related to the abdominal bellows of hawk-moths (**Figure 11**a).[94] Biological systems as the folding of hornbeam

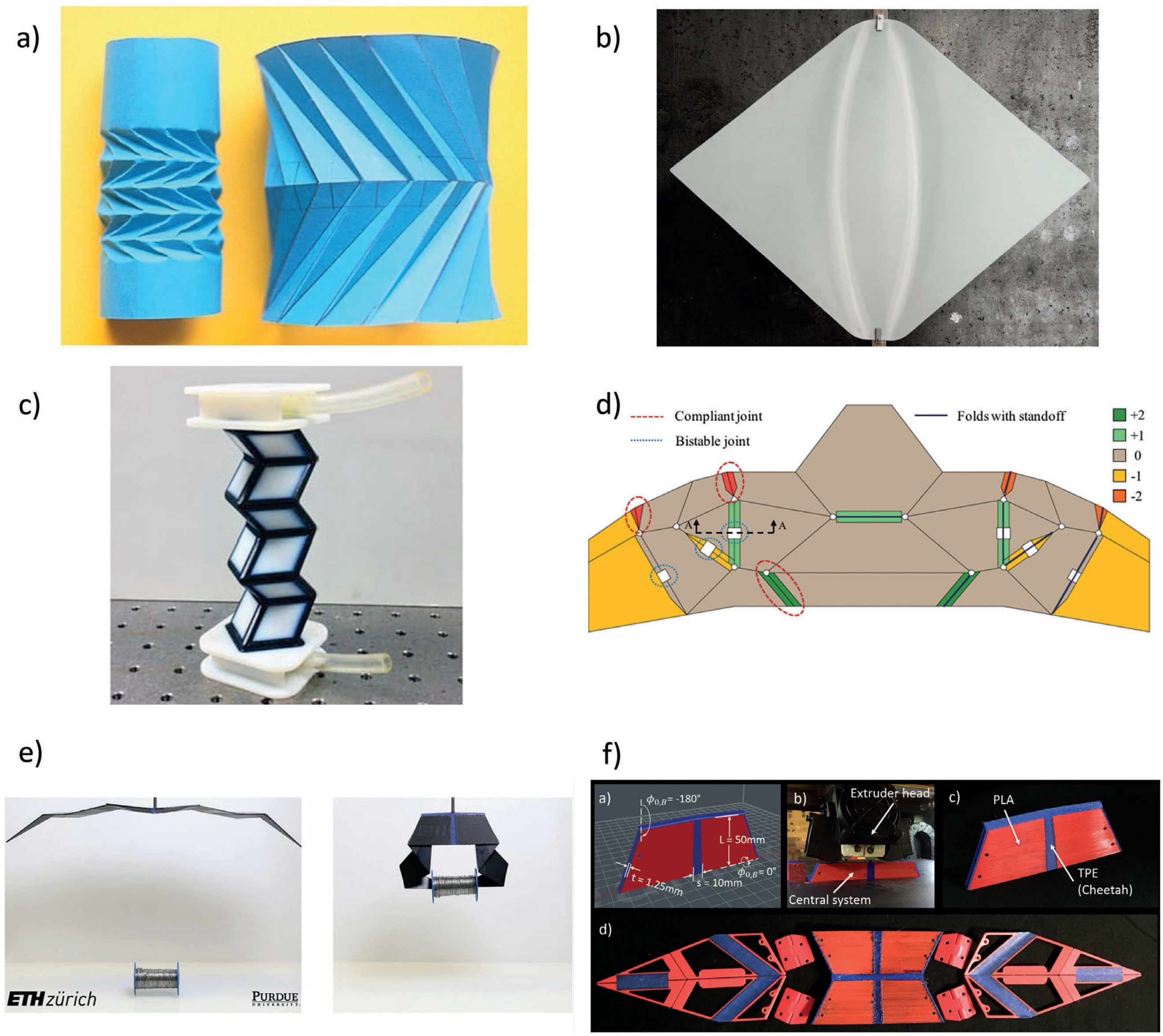

Figure 11. Bioinspired origami-based devices. a) The Kresling pattern, a twist buckled multifunctional origami related to the micro-scale abdominal bellow-pattern of hawkmoths. Reproduced with permission. Copyright Biruta Kresling. b) Flectofold kinetic façade shading system. Copyright itke/ITFT, University of Stuttgart and Axel Körner. Further details can be found in Ref. 101–105. c) fluidic origami-based device. Reproduced with permission.[106] Copyright 2015, IOP Publishing Ltd. d) unmanned aerial vehicle with bioinspired origami-based folding wings. Reproduced with permission.[108] Copyright 2016, IEEE. e) *Spring Origami* gripper. Reproduced with permission.[109] Copyright 2015, The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. f) *Spring Origami* gripper with optimized actuation system. Reproduced with permission.[110] Copyright 2019, SPIE.

leaves,[95–97] maple leaves,[98] morning glory flower,[99] and potato flowers[97,100] have also been successfully mimicked by origami.

Inspired by the folding/unfolding of the *Aldrovanda vesiculosa*, a research group from the University of Stuttgart developed Flectofold, a hingeless deployable system for architectural applications.[101–105] Flectofold can be described as an origami-based compliant mechanism with curved creases that fold by elastic deformation of its constitutive flexible elements (Figure 11b). An interesting feature of the system is that to small bending deformations of the pneumatically actuated central part correspond large folding motions of the attached surfaces. Moreover, the required actuation force, sensitivity, and bending deformation of the system can be tailored by the radius variation of the curved creases. Experimental tests performed on a prototype made of glass fiber reinforced polymers (GFRP) and PVC showed that the system can be actuated with a pressure less than 0.3 bars.[102] Current limitations of the system include scalability issues due to the simultaneous flexibility and stiffness required by the structure, as well as implementations on doubly curved facades. Nevertheless, the development of Flectofold may be of great inspiration for future biomimetic origami-based structures. Research results showed that it is possible to design durable and efficient hingeless adaptive systems with curved-creases for architectural applications, which are a typology currently scarcely investigated.

Also inspired by plant movements, Li and Wang investigated a novel fluidic origami-based device (Figure 11c).[106,107] Mimicking the driving forces of plant movements, the proposed two prototypes embedded important features observed in plants, such as fluidic cellular organization and multistability, into a tubular structure made of two different Miura-ori sheets connected together. Experimental results revealed a pressure-dependent multistability of the structure, which showed monostable and multistable folding configurations. The system has been able to provide shape morphing by changing the fluid volume, and variable stiffness by constraining it. Research outcomes showed how different Miura-ori designs could affect stability and pressure–stability relationship. Possessing rapid and distributed shape change capabilities, the device could be suitable for applications like morphing aircraft wings and kinetic structures.

Relevant research efforts have been made to study the kinematics of wing systems of insects by means of origami. Dufour and co-workers investigated the folding of the wings of Coleopterans to manufacture an artificial origami-based wing for a mini unmanned aerial vehicle.[108] The wing has a symmetric structure composed of an innermost Miura-ori and an outermost coleopteran-inspired pattern (Figure 11d). Panels are manufactured with a composite made of Depron foam and a polyester membrane bonded with vacuum cured epoxy, while the bistable hinges are made of pre-stretched latex membrane. The design has been successfully prototyped showing desirable properties as high folding ratio and single degree of freedom for optimized deployment. Future work will be focused on the determination of a design process for the selection and optimization of the crease pattern. Autonomous folding and integrated actuation will be also investigated.

Faber and co-workers investigated the functionalities of the wings of *Dermaptera* and applied them in a *Spring Origami* gripper (Figure 11e).[109] The bistability of the wings was one of the most relevant features discovered. They documented how wings behave as a classic Miura-ori pattern during folding, while becoming a concave pyramid after fully opening and passing through an unstable flat state. Actuated by a low-energy input, the gripper showed stability in both open and closed configurations with the capability to lift objects until a maximum of its own weight. The prototype has been manufactured by multimaterial 4D printing of stiff polymer facets and rubber-like hinges. Simple variations of pattern geometry and materials properties enhanced the tunability of the energy barrier between bistable states with a quick snap through of 80 ms. The final prototype is programmable, 4D printable, and able to perform fast morphing in the response of environmental stimulus triggers. The work of Faber and co-workers have been further developed by Rojas and co-workers, who proposed an improved origami-based spring gripper capable of grasping objects 60 times its weight with minimal sensing and actuation (Figure 11f).[110] Admitting local deformations in crease regions, the *Spring Origami* method allows to fold complex patterns that otherwise would not be able to fold rigidly. In addition, the extensional and rotational joints may be implemented to design multistable structures with locking properties. This approach may be of particular interest for biomimetics and optimization of complex patterns that cannot be folded by means of conventional rigid-folding motions.

Despite still underexplored due to the complexity and richness of our biological system, biomimetic origami-based designs promise to bring innovations in different engineering fields. For example, the analysis of tree leaves could be applied to the study of folding patterns for membranes,[111] while the motion of plants can be mimicked by polymer-based self-folding structures[112–114] and engineered in the design of novel adaptive[94,115–117] or self-actuating systems.[118] The establishment of a design methodology to observe biological systems and transpose their properties into the origami world could give a relevant contribution to the advancements of origami-based applications in the field.

3.6. Fold-Core Structures

Fold-core structures have been extensively implemented in the design of sandwich panels. Mainly applied in aeronautic and aircraft engineering,[119–122] their potential applications range from civil[123] (**Figure 12**a) to space structures.[124] Although desirable structural properties can be already achieved by means of honeycomb cores,[125] origami-based designs promise to reach optimized performance[126] and tackle current limitations as gas and fluid flow within fold-core systems.[127] Origami-based cores could be tailored to optimize the compressive strength of structures under loading acting normal to the sandwich surface, as well as supporting the latter from local bending. Their high in-plane strength and tunable deformation modes under compression could provide enhanced mechanical properties with lightweight design solutions. Applicable to flat and curved panels[128] at different scales, such designs promise to bring innovative solutions in the development of novel fold-cores technologies.[129]

Despite the mechanical behavior of different origami-based fold-cores has been studied,[130–132] the majority of the investigations have been focused on Miura-ori pattern and its derivative.[133] Single,[134–137] double,[138,139] and multilayers[140–145] fold-cores have been studied, as well as the impact that geometrical variations have on performance.[146] Liu and co-workers investigated the compressive behavior of a Miura-ori cylindrical fold-core sandwich (Figure 12b).[135] Experimental results showed that its load-bearing capacity outperforms the one of traditional grid stiffened cylinders by several times. Xiang and co-workers proposed a parametric study to investigate the mechanical behavior of Miura-ori fold-cores (Figure 12c).[136] Analytical and simulation results under quasi-static three-point bending showed that sandwich plates have double energy absorption capabilities compared to monolithic plates. The two structures showed similar energy absorption properties under static uniformly distributed small pressure loading, while sandwich plates outperformed monolithic plates under larger pressures.

Pydah and Batra studied the response to high-intensity dynamic load of single Miura-ori fold-cores.[137] Simulations results showed better energy dissipation properties through plastic deformation than comparable honeycomb structures. In addition, they investigated the energy dissipation performances of double-core sandwich structures made by combinations of Miura-ori and

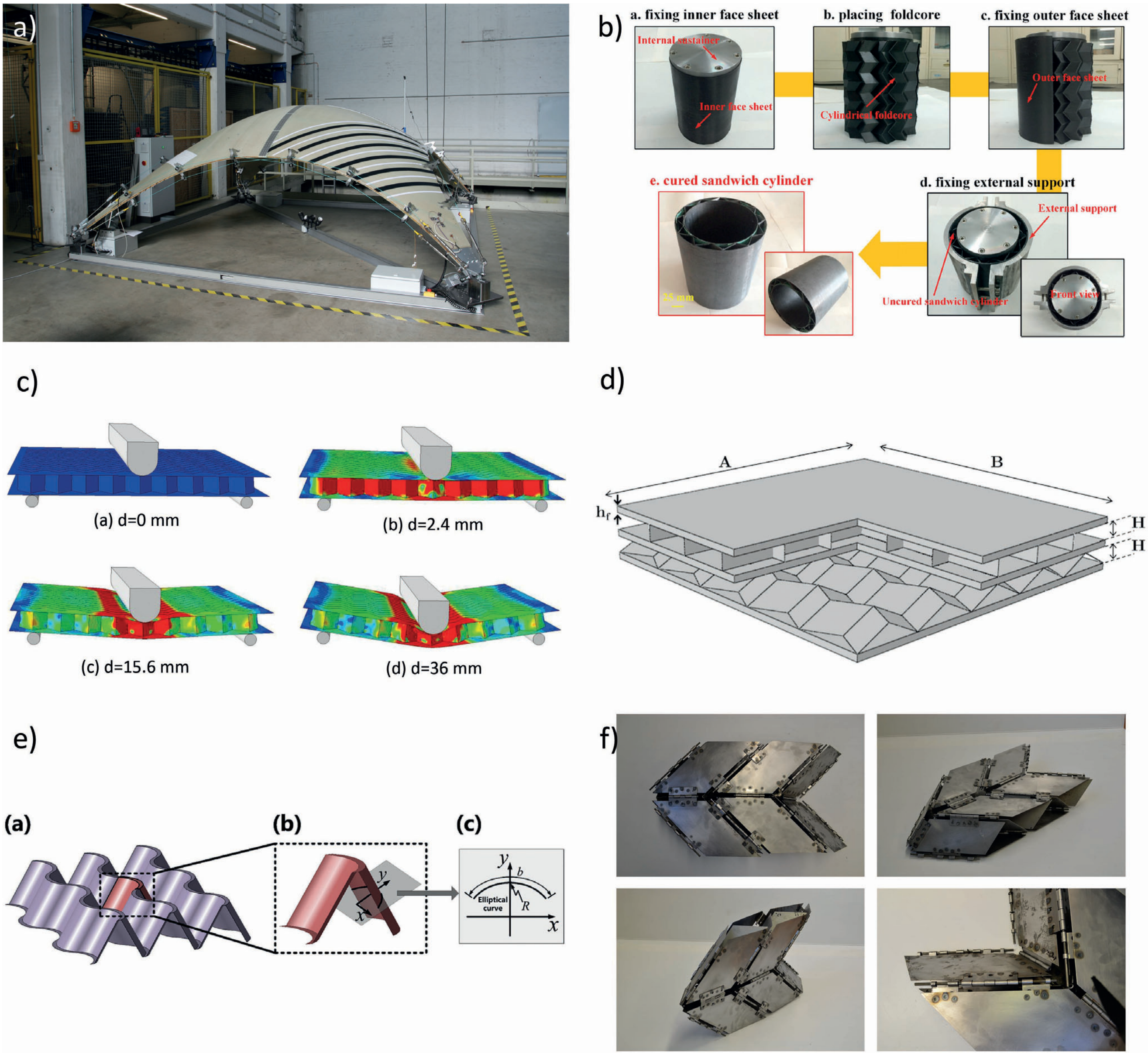

Figure 12. Origami-based fold-cores. a) synclastic ventable sandwich shell using folded cores. Image courtesy of ILEK. Further details can be found in Ref. 123. b) Carbon-fiber-reinforced cylindrical fold-core. Reproduced with permission.[135] Copyright 2019, Elsevier. c) Miura-ori sandwich plate. Reproduced with permission.[136] Copyright 2018, Elsevier. d) Two-core Miura-ori/honeycomb sandwich structure. Reproduced with permission.[138] Copyright 2018, Elsevier. e) Curved-crease origami-based fold-core. Reproduced with permission.[147] Copyright 2019, Elsevier. f) Rigid-foldable morphing sandwich structures. Reproduced with permission.[152] Copyright 2015, Elsevier.

honeycomb layers (Figure 12d).[138] Results showed that double-core structures can be configured to achieve enhanced energy dissipation properties and that the implementation of a bumper in the system could consistently increase the load-bearing capacity. Klett and Middendorf analyzed the kinematic properties of multi-layer fold-cores.[140] Results showed that geometric optimization can lead to optimized configurations suitable for different design requirements that can draw or outperform the performance of equivalent honeycomb structures.

Zhang and co-workers investigated the blast loading response of four different Miura-ori stacked fold-cores.[142] Results showed that the original folding angle influences Poisson's ratio and that a bistable configuration can be achieved and programmed. Klett and co-workers studied the behavior of cellular stacks under torsional loading.[143] Results showed that the dynamic response of the structure can be tailored by modifying folding pattern and sheet thickness. Versatility and easiness in manufacturing are the most relevant strengths of the system.

The implementation of curved creases has also been suggested.[147–149] Du and co-workers presented a curved-crease structure with better anti-buckling capacity than the equivalent straight-crease fold-core, reporting desirable compressive properties and easiness in fabrication (Figure 12e).[147] Zang and co-workers investigated the performance of curved-crease fold-cores made of thermoplastic materials.[148] They reported the higher energy absorption capabilities of fold-cores composed by PEEK polymer and demonstrated that wave pattern configurations are correlated with mechanical properties. Gattas and You investigated the behavior of curved-crease fold-cores under low-velocity impact loads.[149] Experimental studies showed that geometric imperfections strongly affect structure performance, while numerical investigations showed that curved-crease fold-cores had higher energy absorption properties than equivalent straight-crease ones. Although the numerous advantages achieved by the described studies, one common limitation can be noted in all the applications: they hinder the deployment of the fold-core, which is one of the main advantages and desirable features of origami-based designs. In order to overcome this limitation, novel morphing sandwich structures (MSSs) have been proposed.[150] Combining traditional folded sandwich structures with layered assembly techniques,[151] MSSs have been successfully manufactured (Figure 12f).[152]

The reviewed studies showed how the majority of the designs are based on the Miura-ori pattern. Further research should focus on investigating the capabilities of other patterns, as well as finding a systematic method for their selection in accordance to design requirements. The selection of the core material, which should desirably have high elastic modulus and strength while being easily foldable, is also of particular concern. New methods to manufacture origami-based cores preserving their mechanical properties and select base materials should be further investigated. Despite broadly applied to improve mechanical properties, the implementation of origami-based designs to reduce vibration forces acting on structures is still an underexplored topic that could lead to interesting research outcomes. Another interesting field of studies could be the one of origami-based fold-core systems with noise reduction properties.

3.7. Metamaterials

The term metamaterial originally referred to artificial composites with electrical properties defined by their structure rather than the materials they are composed of.[153] Deriving by the Greek word meta (μετά), which means "beyond," the term metamaterial is nowadays used to describe artificial materials with properties not possessed by materials found in nature. Their structure-dependent features can be tailored and optimized in accordance with specific requirements, making them a good candidate to solve engineering problems of different nature.[154,155] The study of origami-based metamaterials is motivated by the observation that origami patterns have the capability to enable the design of materials with enhanced mechanical properties,[156–161] acoustic properties,[162,163] and shapes that can adapt in response to environmental stimuli.[164]

Wickeler and Naguib investigated the modeling process and mechanical testing of two novel origami-based metamaterials (**Figure 13**a).[161] The models, featuring a triangular and a rectangular-based crease pattern, have been additively manufactured with polylactic acid by means of a fused deposition modeling method. Experimental tests showed that a sharper fold angle allowed to achieve a better resistance to compression loads, with the triangular based crease patterns outperforming the rectangular based ones. Comparing their specific compression moduli to the ones of similar structures, the triangular based patterns have a compression modulus on average more than four times greater, while the rectangular based patterns have it more than three times greater. Nevertheless, the rectangular based pattern experienced creases fractures, which were caused by the material print direction and the loads acting between the manufactured layers when the model was compressed. It is also possible that such fractures helped the model at absorbing impact loads, as this design did it more effectively than the triangular one. Varying materials, production methods, and implemented geometries could lead to a better understanding of the systems and to the development of shared design workflows and guidelines.

Zhai and co-workers presented an origami-based mechanical metamaterial with on-demand deployability and selective collapsibility (Figure 13b).[157] They achieved a flexible system with tunable stiffness suitable for the design of reconfigurable structures. Validated under manual actuation, the system can be scaled and optimized by embedding different types of automatic actuations. Zhou and co-workers presented two origami-based mechanical metamaterials based on the Miura-ori pattern.[156] Research findings showed self-locking properties and high stretching and bulk moduli, which could lead to achieve interesting acoustic properties.

Babaee and co-workers proposed an origami-based metamaterial with reconfigurable acoustic waveguides (Figure 13c).[162] Experimental results showed that the cellular structure can be reconfigured to achieve different acoustic responses and wave radiation patterns. The acoustic mechanisms are broadband and can be reproduced at different scales. Furthermore, Nanda and Karami proposed an origami-based metamaterial with tunable bandgaps.[163] Experimental results on the structure composed by beams and torsion springs showed that the wave transmission characteristics can be tunable by fold angle variations. Research findings can have application in the design of deployable structures with tunable vibration suppression and adaptive filtering properties.

Boatti and co-workers presented an origami-based metamaterial able to change its shape in response of temperature variations (Figure 13d).[164] They manufactured a Miura-ori tessellation with mono and bilayer faces with different crease stiffness. Experimental and simulation results showed that different responses to variation in temperature can be achieved modifying bilayer facets location and creases stiffness. Furthermore, they demonstrated that the coefficient of thermal expansion could be tailored by folding the Miura-ori pattern. Tested at the centimeter scale with a structure made of paper and polyethylene, the proposed design can be potentially extended to different materials and scales.

Despite the majority of existing studies have been focused on the implementation of Miura-ori based designs,[158,159] their mechanical characteristics have been extensively studied only under out-of-plane compression. Few studies investigated the in-plane mechanical behavior of Miura-ori based metamaterials. A recent study published by Karagiozova and co-workers investigated the influence of cellular topologies on dynamic strength and energy

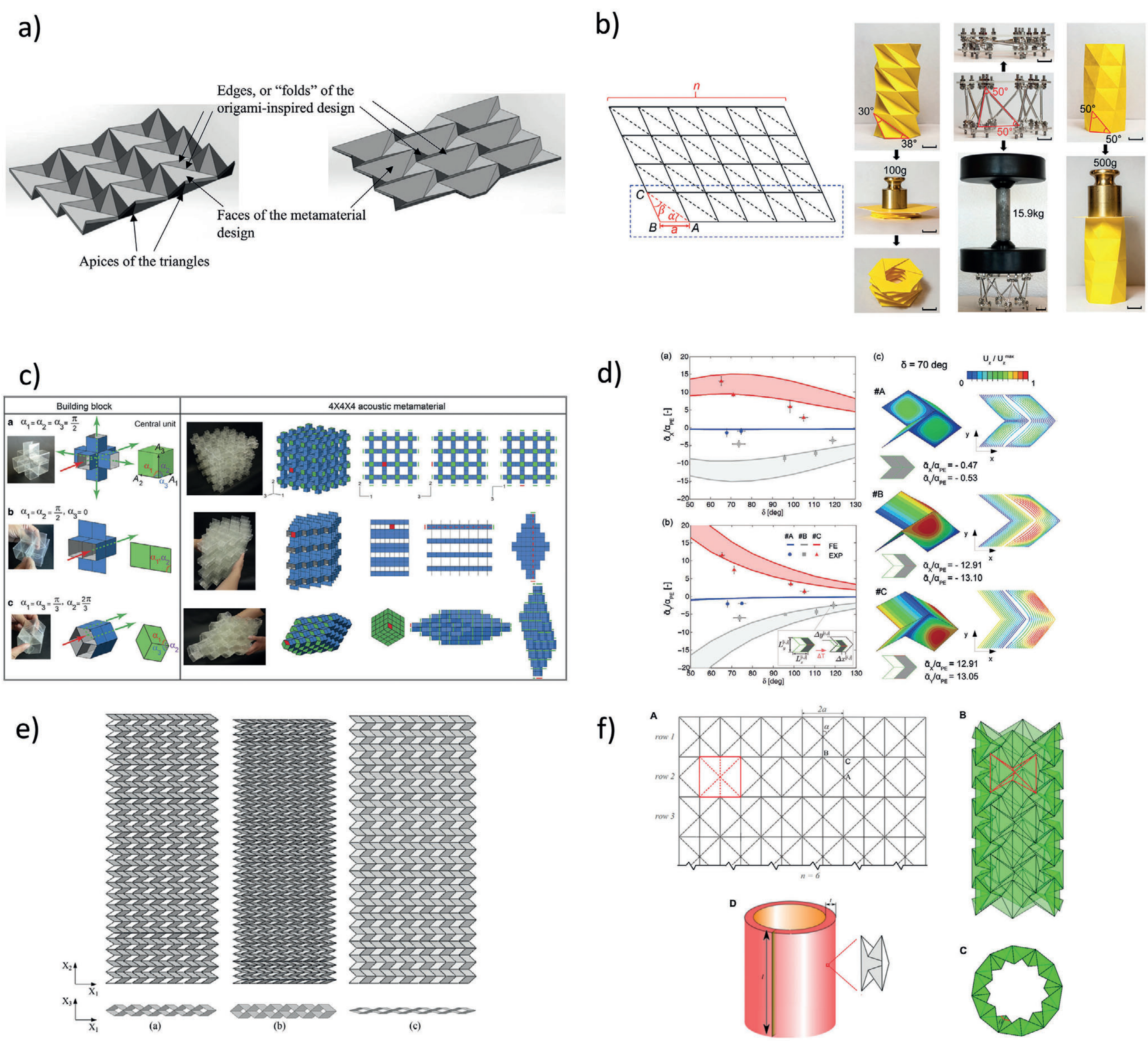

Figure 13. Origami-based metamaterials. a) Origami-based tessellated metamaterial, triangular pattern (left), rectangular pattern (right). Reproduced with permission.[161] Copyright 2020, Elsevier. b) Origami-based metamaterial with tunable stiffness. Reproduced with permission.[157] Copyright 2018, National Academy of Sciences. c) Reconfigurable origami-based metamaterial with acoustic properties. Reproduced with permission.[162] Copyright 2016, The Authors, some rights reserved; exclusive licensee AAAS. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC). d) Origami-based metamaterial with tunable thermal expansion. Reproduced with permission.[164] Copyright 2017, Wiley-VCH. e) In-plane compression investigation of Miura-ori-based metamaterials. Reproduced with permission.[160] Copyright 2019, Elsevier. f) Origami-based metamaterial with programmable stiffness. Reproduced with permission.[166] Copyright 2020, Elsevier.

absorption of in-plane compressed Miura-ori-based metamaterials (Figure 13e).[160] Simulation results showed that, similarly to other conventional metamaterials, the energy absorption capacity of the Miura-ori-based structure increases with the increasing of the loading rate. Moreover, it has been noted that the localization of the propagation of velocity and nominal strains along the model are more pronounced in structures with smaller dihedral angles. Although the deformation process of the model resembles the shock wave propagation phenomenon, it has been revealed that such a method cannot the used to describe the compression behavior of Miura-based metamaterials.

Regarding the deformation mode, it should be noted that the majority of the common metamaterials implements a single-step pathway and a single deformation mode. Inspired by the work of Meng and co-workers,[165] who presented a novel metamaterial with multiple pathways and deformation modes, multi-step origami-based metamaterials could be developed featuring origami properties such as snap-through and multistability. A

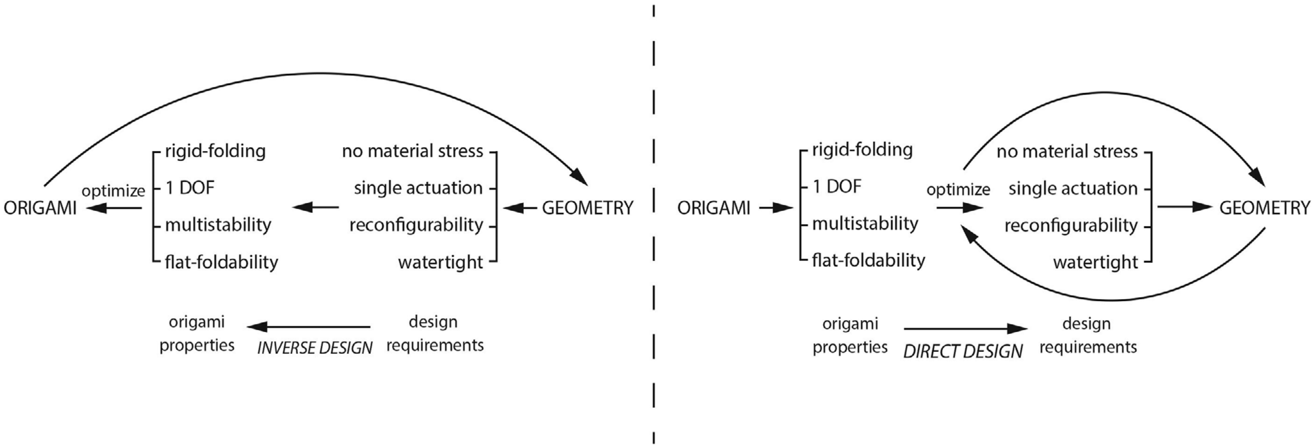

Figure 14. Origami-based design processes. Diagram for the inverse design method (left), and the direct design method (right). It should be noted that design requirements and origami properties are not meant to be exhaustive but provided as example.

related research has been published by Mukhopadhyay and coworkers, who presented an origami-based metamaterial with programmable deformation-dependent stiffness and shape modulation capabilities (Figure 13f).[166] Depending on its microstructural configuration, the proposed model was able to achieve different values of deformation-dependent programmable stiffness, ranging from near-zero to very high values. Moreover, they revealed that a general shape of the tubular structure could be distantly changed and controlled by means of a far-field load, thus not implementing complex systems of sensors and actuators.

Although origami-based metamaterials possess several desirable properties, connection techniques to create systems made of such elements present challenges. Particularly for systems in which reconfiguration capabilities are the main feature provided, connecting origami-based structures to other systems may lead to shortcomings as the loss of desired degree-of-freedom or the loss of structural stability. The scalability of several systems at both nano and large centimeter scale is still a concern, while some techniques are still not able to couple folding and unfolding actuations. Future innovations could be brought by the implementation of the latest research findings in the field of origami-based active structures.[21]

4. Design Methods

A vast amount of research has been undertaken from the early design concept to the prototyping phase of origami-based designs. Nevertheless, few studies investigated the role played by design methods in the determination of design outcomes.[20,167] Previously discussed applications showed that innovations are more often achieved by novel implementations and adaptation of known crease patterns than by the discovery of new ones. Hybrid designs composed of different patterns, variations of the same one,[128] and coupling between origami and other technologies such as tensegrity[61,63] have also been scarcely investigated. These limitations may be determined by the fact that still no one shared design method has been established to design, modify, adapt, and fabricate origami-based designs. Current design processes often rely on the skills of experienced origamists, paper models, and trial and error processes. In addition, design stages are often approached independently, with final aspects such as thickness accommodation and material selection that are scarcely used to inform early design decisions. The absence of an integrated design method may lead to designs impractical to fabricate or with reduced performance in real-life applications. Therefore, a systematic and integrated approach would be desirable to improve the quality and novelty of origami design outcomes regardless the field of application.[168–170] Two different design approaches are known in the origami community:

- Direct design: the process of applying or adapting a known crease pattern to solve a design problem.
- Inverse design: the process of selecting, optimizing, or generating crease patterns that can be folded to meet specific design requirements.

A schematic representation of the inverse design method and direct design method is given in **Figure 14**.

4.1. Direct Design

In the direct design method, which is the one commonly applied, a known crease pattern is selected according to its capability to solve a design problem. Such selection is generally performed by experienced designers, who know how origami properties such as rigid-foldability, and multistability may be implemented to achieve structures with desired design requirements. Nevertheless, the pattern selection is always performed at an early stage of the design, thus missing relevant informations that commonly become available at later stages. In addition, because further specific design requirements may lead to the modification of the selected pattern, its original properties may not always be preserved. It should also be noted that properties such as rigid foldability and single DOF could be achieved when not possessed by the base crease pattern with geometry modifications and thickness accommodations. These aspects reveal the limited applicability of the direct design method for finding new and optimal design solutions. A further limitation of the method is that the prior selection of the pattern strongly limits the design domain.

Table 1. Origami tessellations and desirable characteristics.

Tessellations	Rigid foldability	1-DOF	Flat foldability	Multistability	Negative Poisson's ratio
Miura-ori	Yes	Yes	Yes	Yes	Yes
Waterbomb	Yes	Yes (only when symmetric folding is ensured)	No	Yes	No
Yoshimura	Yes	Yes	Yes	No	No
Kresling	No	No	Yes	Yes	No
Flasher	Yes (modification of the base pattern required)	Yes (modification of the base pattern required)	No	No	No

Pattern adaptations seldom involve geometrical modifications, but rather focus on material and fabrication changes. Recent works attempted to tackle this problem by implementing optimization algorithms to investigate geometrical variations.[65] Despite showing promising results, design outcomes remain limited by the prior selection of the pattern, which could be desired in some cases but a limitation in others. Due to the paramount importance of the pattern selection, a systematic method should be developed to support designers in this crucial step. The implementation of a searchable database would allow taking decisions that are more informed and flexible. Such database could provide an interactive list of origami patterns with associated properties, which analyzed in comparison with design requirements could lead to the selection of most suitable crease patterns. A preliminary list of known origami tessellations with relevant properties is given in **Table 1**.

4.2. Inverse Design

The inverse design is a novel method that could lead to more flexible and accurate design outcomes. In the inverse approach, crease patterns are selected among existing ones, modified or generated starting from specific design requirements. Still at the beginning of its development, the method has been mainly applied to approximate target shapes. Zhou and co-workers proposed the vertex method to generate Miura-based developable crease patterns able to fit given 3D geometries,[171] while Wang and co-workers investigated the design of Miura-based origami approximating cylindrical structures.[172] Despite being flexible and potentially applicable to other patterns, the main limitation of these methods is that they are not applicable to doubly curved geometries. This limitation has been overcome by the work of Song and co-workers[173] and Dudte and co-workers,[174] who developed different approaches to generate origami patterns able to approximate doubly curved geometries. Nevertheless, their method remains limited to specific types of Miura-based patterns, and can only target axisymmetric geometries. Building further on these works, He and Guest proposed a method to approximate free-form surfaces with Miura-based tessellations.[175] Despite being able to approximate nondevelopable surfaces with developable rigid-folding Miura-based patterns, their method is not always able to find a feasible solution to the inverse problem. Further developments could be brought by the implementation of recent findings in crease patterns generation methods. Lang and Howell proposed a method to generate rigid-foldable quadrilateral meshes (RFQM) starting from developable surfaces.[176] Their method not only allows to systematically explore the full design domain achievable by RFQM configurations, but can further be extended to arbitrary patterns composed by triangles and/or polygons of higher orders. If developed to take into account desired folded shapes, such a method could give an unprecedented design freedom and flexibility in solving the inverse problem. Despite still limited to shape optimization, inverse design methods could also be implemented to solve packaging, deployment and material usage optimizations. For example, could an arbitrary origami pattern be generated to achieve a desired folding motion? Alternatively, could a pattern be generated to approximate a target surface and achieve a desirable deployed/folded ratio? Such tasks remain challenging and will require further work to be accurately addressed.

5. Design Tools

A large portion of the studies reviewed in Section 3 is in absent of clearly stated design processes. The majority of the works adopt direct design methods, which are generally focused on adaptation or modification of known crease patterns. It has been noted that, although clearly defined, origami-based design phases are often intertwined, thus requiring constant exchanges of data. Crease pattern selection, kinematic analysis, structural optimization, actuation, and fabrication are tasks that require tailored and integrated design workflows to be efficiently solved. Leading researchers in the field have developed many design tools, and their adequate utilization is thought to excel the development of origami-based solutions.[177] In the current section, 17 origami related software are reviewed. They are discussed in respect of their main functions and suitability to different stages of design processes.

5.1. Direct or Inverse Design

Two different approaches may be adopted when designing with origami. When adopting the direct design method, known crease patterns may be designed with tools such as EOS and ORIPA. EOS (E-Origami System)[178–181] is a mathematica-based[182] code that implements the Huzita-Justin axioms to fold origami sheets. Because every fold has to be performed independently, EOS can be used for preliminary investigations of folding sequences and avoided when dealing with complex structures. Such structures can be better addressed by ORIPA,[183] which allows to design and fold flat-foldable crease patterns (**Figure 15**b). ORIPA provides an intuitively interface tailored for the design and modification of crease patterns. Although the flat-foldability of patterns can be

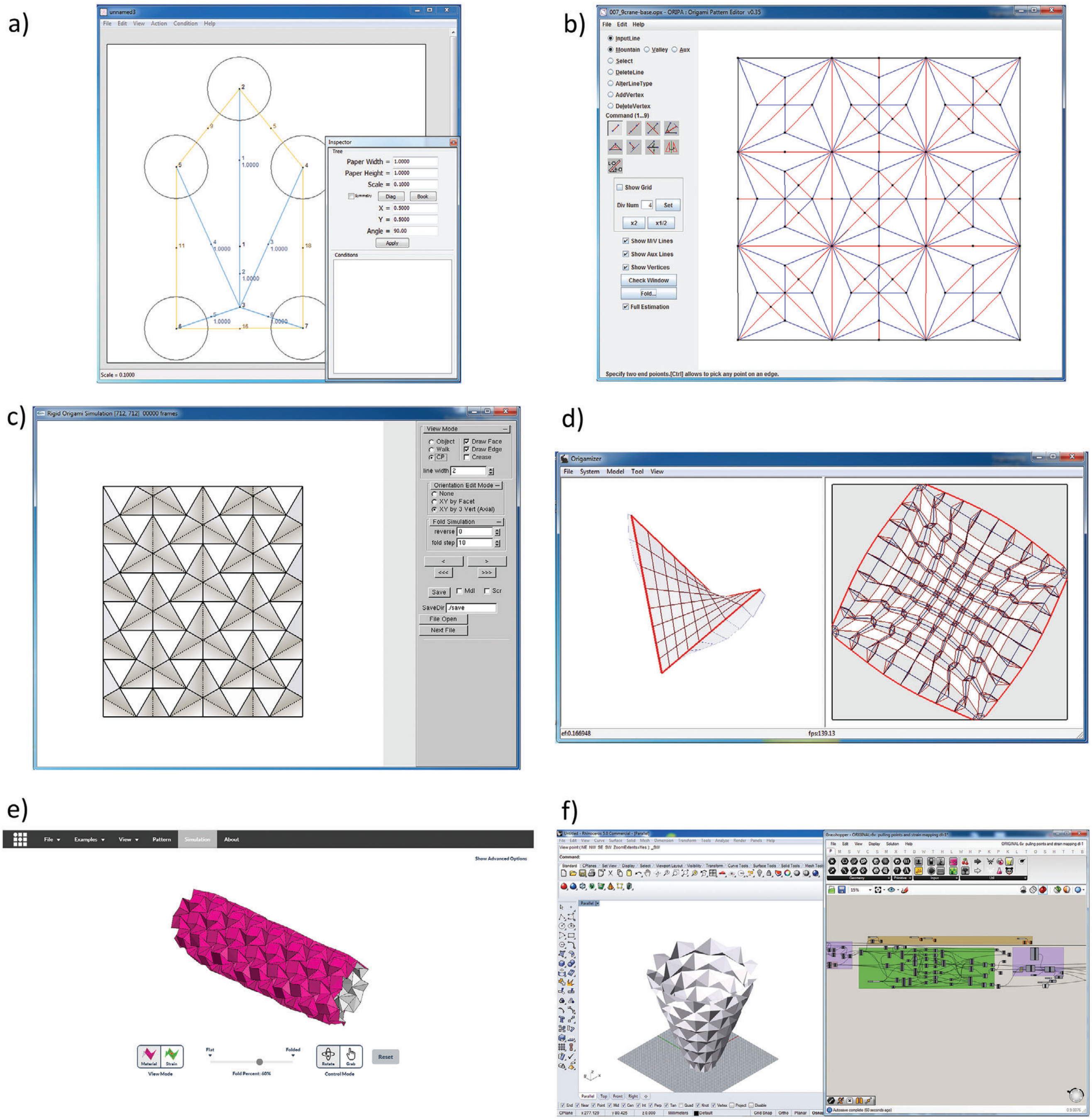

Figure 15. Software interface of: a) TreeMaker; b) ORIPA; c) Rigid Origami Simulator; d) Origamizer; e) Origami Simulator; f) Rhinoceros3D/Grasshopper.

assessed, only their final folded state is visualized. ORIPA may be of great help when designing crease patterns, while the folding simulation can be better addressed by other tools. A further limitation of both ORIPA and EOS is that they allow to design only flat-foldable origami made of square sheets of paper.

When dealing with the direct design of origami tessellations, one may consider to use Tess and Tessellatica.[184] Tess allows to explore known crease patterns based on twist folds, which can be selected from the software database and further modified. Nevertheless, the generated tessellations are not always foldable. Tess does not provide import features, thus not allowing interoperability with other software. Tessellatica is a Mathematica package developed for the design of origami twists, tessellations, tilings, and other known patterns such as flashers, Miura-ori, and their derivatives. Crease patterns can be imported or designed with tailored algorithms that allow generating simple tessellations and more complex combinations of different units. The package allows designing, folding, and optimizing origami patterns in respect of a vast amount of origami-based constraints including developability and flat-foldability. Crease patterns can be folded into 2D and 3D shapes, while desired folded forms can also be defined and then unfolded. This feature allows users to define simple inverse design processes involving folded shape optimizations. Tessellatica allows designing crease patterns with curved folds, performs rigid an elastic folding, generate tailored files for ORIPA and MATLAB, and provide manufacturing oriented export features. Despite being powerful, Tessellatica is a complex tool that can be used in its full potential only by experienced origami designers. In addition, compatibility issues with the Windows version of Mathematica limit its use to Mac and Linux users. Despite focused on simulation, tools such as Kangaroo[185,186] and Crane[187] can take advantage of the powerful design platform provided by the Rhino/Grasshopper interface.[188] The latter offers a vast amount of design options, as well as an enhanced interoperability with other software. These tools will be discussed in detail in the following sections.

Implementing the inverse design method, tools such as Treemaker, Origamizer, and ORI-REVO allow to generate unknown crease patterns from given constraints. TreeMaker[189,190] determines crease patterns with mountain and valley assignments starting from a 2D tree graph input by the user (Figure 15a). The tree graph, composed of line segments and points in which line segments meet or end, must represent an abstraction of the desired folded shape.[18] An efficient crease pattern, i.e., the larger possible base for a given size square, is calculated running a nonlinear constrained optimization.[16] TreeMaker can lead to the design of complex origami-based structures, although it can only realize shapes composed by uniaxial bases starting from square sheets. Such complexity may often lead to crease patterns impractical to fold or difficult to fabricate. The same issue may be faced when using Origamizer,[191] a tool for generating continuous crease patterns able to fold into arbitrary 3D polyhedral (Figure 15d). It implements the tucking molecules method, which allows to tuck and hide unwanted areas of papers.[192] Patterns obtained with this method cannot be fabricated with thick or stiff materials, thus substantially limiting industrial applications. In addition, depending on the complexity of the given polyhedron, more than 3/4 of the crease pattern can be composed by tucking facets, thus negatively affecting the efficient usage of base material. Recently, a new improved Origamizer algorithm has been proposed,[193] although not yet implemented in an official release of the software. When dealing with target shapes composed of rotational sweeps, one can generate crease patterns with ORI-REVO.[194,195] Desired shapes are obtained by rotating an arbitrary 2D polyline around an axis for $360/N$ degree intervals, where $N > 2$. Polylines can be modified while keeping track of the crease pattern and 3D model variations in real time. This method allows to successfully design axisymmetric origami structure, although the design of triangular facets models is still a concern.[196] A limitation of the above mentioned tools is the incapability to deal with origami with curved creases. ORI-REF [197] provides a simplified method to design developable surfaces with curved folds. It is based on a mirror reflection method that analytically obtains curved folded shapes starting from a base geometry. The user can interactively modify the input mesh keeping track of folds in real time in a 3D environment. Although fast and accurate in the determination of the folded shape, ORI-REF is limited to planar curves and does not provide the crease pattern of generated geometries. Once defined with the above-mentioned tools, the foldability of crease patterns can be further assessed with simulation tools.

5.2. Rigid or Elastic Folding

When exploring the foldability of new design solutions, often the detailed mechanical parameters are omitted in the early design stage, and one can quickly start the process by choosing between rigid or elastic folding methods. Rigid folding structures are often preferred as the connection solutions in the later stage will be less complex. However, the numbers of geometrical configurations that can be created with rigid folding are limited. To extend the design domain, one can move on to elastic folding structures, in which the facets (panels) are assumed to have some rigidity, but eligible for bending under pressure to achieve specific geometrical configurations. This will be the case of origami with curved creases.

Tools such as Rigid Origami Simulator[198] (Figure 15c), Rigid Origami Folder,[199,200] Freeform Origami,[201,202] Tessellatica[184] and Crane[187] can be used to simulate the deployment of rigid folding structures. An advantage of such tools is that they all provide continuous folding motions from unfolded to folded configurations. All the mentioned software define geometries as rigid polygons connected by hinges according to the N4B5 discretization method.[203] This method also allows to perform nonrigid folding motions with small deformations. Rigid Origami Simulator and Rigid Origami Folder do not provide design options, with geometries that once imported cannot be modified inside the platform. When using Rigid Origami Simulator, flat-origami cannot always be visualized properly, while global self-intersection and stacking order problems may occur during the simulation.[204] Rigid Origami Folder is a command-line tool that does not provide a user-friendly interface. Despite giving the advantage to visualize the deformation of panels under nonrigid folding motions with small deformations, the strain value of each panel is simplified as the strain of the most deformed edge of the panel. Tessellatica allows to design and fold rigid-foldable quadrilateral meshes with a set of edge constraints. It can perform both folding and unfolding motions, being able to fold also patterns with sequential flat folding motions.

Although all the software determines folded states by folding angle of panels, only Freeform Origami and Crane implement external constraints such as anchor points for vertices and edges. Freeform Origami allows to drag the geometry at any folded configuration while keeping the given constraints of the original pattern such as developability, flat-foldability, and many more. Mountain and valley assignments can be embedded in the imported geometry, defined within the software interface if not present and modifiable if present. An interactive user-friendly interface and a vast amount of assignable constraints are the strengths of Freeform Origami, while the absence of design tools and the addressing of collision between facets at each vertex are potential drawbacks.[202]

Crane adopts a hard constraint solver similar to the one of Freeform Origami. It is implemented in the Grasshopper interface for Rhinoceros3D (Figure 15f) and provides a flexible set of tools for the design and simulation of rigid-origami structures. Crease patterns can be designed from scratch or generated from scanned images, while mountain and valley folds can be designed or automatically assigned to geometries. Different from Freeform Origami, users can not only interact with the geometry but also modify it at any folding configuration. This feature allows altering the geometry of crease patterns to fit folded configurations to desired shapes. Despite implementing less geometrical constraints than Freeform Origami, Crane provides a higher level of flexibility integrating both design and simulation of rigid-origami. It should be noted that a limitation of the abovementioned software is that they all perform simulations taking into account only the folding angles of panels. Although some of the software allows to implement external constraints, no one of them allows to apply external forces to the geometry.

Tools such as Origami Simulator,[205] Kangaroo,[185,186] MERLIN2[206] and Tessellatica[184] can be used to simulate the deployment of elastic folding structures. Origami Simulator and MERLIN2 simulate the folding and perform structural analysis of origami patterns with different approaches. Origami Simulator attempts to fold every crease simultaneously, calculating displacements of the nodes under axial and angular constraints using an explicit method (Figure 15e).[205] Differently, MERLIN2 performs nonlinear displacement-based formulations to construct quasi-static finite element analyses of structures. MERLIN2 takes into account the entire nonlinear deformation process by solving the modified generalized displacement control method (MGDCM) algorithm.[207] Origami simulator provides a more user-friendly and dynamic interface, allowing to fold an higher number of origami patterns, including kirigami and patterns with holes. Nevertheless, MERLIN2 provides a more realistic simulation of doubly curved out of-plane deformations and isotropic in-plane behavior of the panels. In fact, despite both software discretize geometries as structures made of bars and nodes, Origami simulator defines them according to the N4B5 method,[203] while MERLIN2 implements both N4B5 and the more accurate N5B8 method.[208] It should also be noted that Origami simulator implements arbitrary constraints to prevent shearing and stretching of models, also allowing intersection of panels. Despite leading to less accurate results, this approach provides a correct representation of the global behavior of the folding motion, with a reasonable trade-off between accuracy and simulation speed. The use of Origami Simulator should be preferred to investigate full global motions according to folding angles, while MERLIN2 should be adopted for more accurate analysis implementing external forces and constraints. Both software provide a simplified strain calculation of panels. Origami Simulator implements a Cauchy strain visualization, while MERLIN2 implement a Green-Lagrange strain analysis.

Kangaroo[185] integrates design tools and a simulation engine in a flexible platform. It is based on a particle-spring system, which performs interactive simulations by means of a projection based dynamic relaxation method.[186] Similarly to Crane, Kangaroo is implemented in the Grasshopper interface for Rhinoceros3D,[188] and can therefore utilize the same design tools. Comparing with previous software, Kangaroo provides a higher level of freedom when defining simulation settings, with accuracy of results strongly depending on the skills of the user. At present, no specific commands for origami-based designs are implemented in the platform. Geometries are defined as spring-particles systems, which can implement any bar-node discretization method.[208] Such methods could also be applied to fold origami with curved creases.[209] Folded states can be defined by folding angle and external forces, while a huge number of constraints are also supported. Despite not readily available in the software, simplified structural analysis can also be performed. A limitation of the engine is that it does not always allow to correctly visualize the sequential folding motion of structures, while the complexity of the simulation settings may often lead to inconsistent results. Tessellatica simulates the elastic folding of patterns encountering small strains with nonlinear constrained optimizations. The bending and folding of quad meshes along their diagonals are computed similarly to the N4B5 method with additional external constraints applicable to vertices. Because a drawback of the method is that self-intersection may occur, additional constraints can be given to edges to avoid local self-intersection.

5.3. Optimization of Existing Design

Despite several software can be used to simulate both rigid and elastic folding motions, only few of them can also be applied to optimize crease patterns. Once the design is set, it would be desirable to not only analyze its performance but also refine it in respect of certain parameters. Origami mechanism topology optimizer (OMTO),[210,211] is a MATLAB-based graphic interface for topology optimizations of origami-based designs. Despite allowing to generate crease patterns and solve displacement objective problems, OMTO would be highly impractical for complex designs. Limitations include the support of only three types of grids where the user is allowed to define his design constraints, limited number of applicable constraints, and the possibility to investigate only designs starting with continuous flat sheets. In addition, OMTO does not allow file imports, and crease pattern, objective plot, and folded pattern can only be exported as image files, thus remarkably limiting the interoperability with other software. Tessellatica could be used to optimize crease patterns according to constraints such as developability and flat-foldability. Tailored algorithms could also be defined to triangulate quads encountering bending. Despite being flexible and adaptable to optimization tasks involving both geometry and material properties, Tessellatica does not provide any straightforward optimization workflow.

To perform advanced optimization workflows one can look into combined tools such as Rhinoceros3D with Grasshopper based optimization components. Grasshopper is a visual programming interface that allows interoperability among its plug-ins.[212] Kangaroo and Crane are built inside Grasshopper, and can therefore be combined with several tailored optimization components. Single-objective optimization tools such as Galapagos,[213] Silvereye,[214] and Optimus,[215] and multiobjective optimization tools such as Octopus,[216] Opossum,[217] and Wallacei[218] can be coupled with Kangaroo and Crane to generate novel optimization workflows. Recent studies investigated the feasibility of such tools showing promising results.[65] One of the main characteristics of Grasshopper is that it allows to customize functions and integrate components not initially thought to work together. This feature gives an unprecedented freedom to designers, who could be able to design, simulate, and optimize origami-based structures in one shared platform. Grasshopper is a complex tool that requires a consistent initial investment of time to get familiar with the software environment and the many available components. Nevertheless, its flexibility and shared interface make it a good candidate for the development of future origami-based software.

5.4. Manufacturing: Thickness, Material, Actuation

In the later design process, one must include practical design parameters such as thickness and stiffness of the material choices. Among the above-mentioned tools, all the software able to perform Elastic Folding motion allows to modify stiffness parameters. Nevertheless, their application remains limited to models with negligible thickness, generally well-performing with paper-based structures. Among the software performing Rigid Folding motion, only Crane gives a limited control of material properties. In fact, the rigidity of the panels can be determined by the user, although this feature alone gives little information on the material entity. Differently, Crane provides useful tools for thickness accommodation and fabrication. Tapered solids[219] with thin layer hinges can be quickly generated from zero-thickness geometries, as well as thick panels with single and double hinges. Cutting lines can then be generated and final designs exported for fabrication with CNC machines, laser cutters, and 3D printers. Similar features are provided by Tessellatica, which supports perforated laser-scoring, veneer laser-scoring, and 3D printing oriented output.

Despite origami-based fabrication approaches have been widely applied in the manufacturing industry, only recently manufacturing-oriented software has been developed. PopupCAD[220–222] is a manufacturing-oriented interface that allows to design laminate devices with standard constructive solid geometry (CSG) operations. Design models can be imported or designed by means of the PopupCAD sketcher interface. Preliminary zero-thickness designs can be generated with tools such as ORIPA or Grasshopper and then imported into PopupCAD for fabrication-related operations such as material assignments, joints, cuts, and holes location. An advantage of PopupCAD is that it supports lines, polylines, circles, and polygons, thus being able to process also origami with curved creases. Interactive Robogami[223,224] is another manufacturing-oriented interface developed for the design of robots that can be fabricated as flat sheets and subsequently folded into their final 3D shape. Its design process follows an assembly-based method in which components are selected from a database and used to compose the final structure. Components can be parametrically modified ensuring the manufacturability of the design, although design outcomes are restricted to the availability of a limited number of them. For this reason, interactive Robogami is a tool with limited applications, although future developments could let users design their own components, thus enriching the quality of the database. An interesting feature of interactive Robogami is the implementation of actuators into the geometry. Differently from other software, which mimic actuation with fictitious external forces or contemporary folding of creases, interactive Robogami allows to design geometry and motion. The platform allows implementing servomotors and electronic plans based on the kinematic of the assembly. The gait of the robot can be designed and the influence of motion on the geometry can be assessed and optimized. Although implementing only one type of electronic circuit, Interactive Robogami is the only tool that currently integrates actuators into origami-based designs in a manufacturing-oriented workflow.

Figure 16 integrates the above-mentioned software in the different design phases of origami-based engineering applications. The design process has been decomposed in four main phases: define problem, origami solution, analysis and prototyping, which have been further subdivided into several subtasks. It should be noted that with design constraints we refer to origami related constraints such as developability and flat-foldability. Reading the scheme from left to right, it is possible to define different design workflows, which could allow to move from the preliminary definition of design constraints and base geometry to the final prototyping phase. For example, a base geometry can be input into *Origamizer*, which will determine a crease pattern that can be folded and modified with Freeform Origami. The final design could then be imported into Rhinoceros3D or PopupCAD, which can further define thickness and materials. The present diagram has the only scope to theoretically define software capabilities and potential interoperability, as the latter is often limited and has to be defined case by case. In fact, software that allow to design crease patterns often do not export required file formats, while simulation engines may be not capable to fold certain patterns. A summary of tools capabilities is given in **Table 2**. It should be noted that the capabilities of rigid-folding tools to fold a limited number of elastic folding structures are not listed in the table and not represented in the following scheme.

At the time of writing, no one software is able to singularly define and solve every step of the complex origami-based design process, as well as no one workflow can be recognized as the most suitable for all kinds of design outcomes. Software input and output formats seldom take into account the potential interoperability with other platforms. Therefore, the development of a shared interface with common input/output formats would be beneficial for the origami community. It could lead to smoother design workflows, enhanced cross disciplinary applications and improved design outcomes.

6. Manufacturing Considerations

Fabricating origami-based designs is a challenging task that may hinder the efficiency of design processes. Because a remarkable distance is present between traditional origami and engineered designs, fabrication techniques play an important role in translating properties from paper models to final products. At early design stages, origami is commonly approximated as zero-thickness mechanisms with purely geometric kinematics. Material properties are further taken into account, but always implemented with mono-material simplified models resembling paper-like behavior. At later stages, sound designs are converted into structures with real materials and finite thickness, in a process that may lead to practical complications.

Not a concern in paper folding, thickness accommodation becomes a relevant design constraint for origami-based applications. An extensive review on the topic has been written by Lang

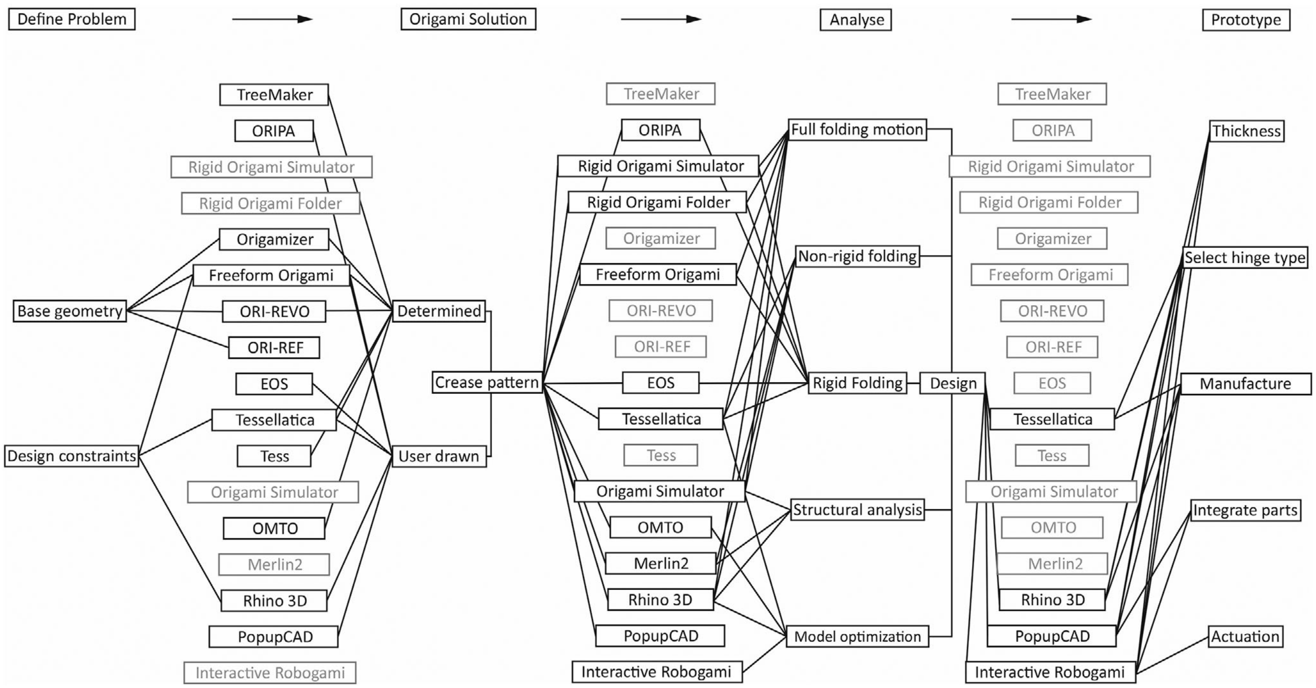

Figure 16. Origami-adapted design workflow with software integration.

Table 2. Overview of software capabilities.

Software	Interoperability	Design	Folding motion	Fabrication	Crease pattern	Curved-crease origami	Structural analysis
TreeMaker	No	Yes	No	No	Output	No	No
ORIPA	Yes	Yes	Flat folding	No	Input/output	No	No
Rigid origami simulator	Yes	No	Rigid folding	No	Input	Simplified	No
Rigid origami folder	Yes	No	Rigid folding	No	Input/output	No	Yes
Origamizer	Yes	No	Unfolding only	No	Output	No	No
Freeform origami	Yes	No	Rigid folding	No	Input/output	Simplified	No
ORI-REVO	Yes	Yes	No	No	Output	Simplified	No
ORI-REF	Yes	No	No	No	No	Simplified	No
EOS	Yes	Yes	Simplified	No	No	No	No
Tessellatica	Yes	Yes	Elastic and rigid folding	Yes	Input/output	Yes	No
Tess	No	No	No	No	Output	No	No
Origami simulator	Yes	No	Elastic folding	No	Input/output	Yes	Yes
OMTO	No	Limited	No	No	Output	No	No
MERLIN2	Yes	No	Elastic folding	No	Input	Yes	Yes
Rhino3D	Yes	Yes	Elastic and rigid folding	Yes	Input/output	Yes	Yes
PopupCAD	Yes	Yes	No	Yes	Input	Simplified	No
Interactive Robogami	No	No	No	Yes	No	No	No

and co-workers,[22] to which the reader is redirected for an in-depth discussion. Although different techniques have been proposed in literature, each of them comes with limitations in applications and performance. Despite the rich development of thick accommodation methods, few studies investigated how to effectively implement such systems in design processes. An interesting approach has been proposed by Crampton and co-workers, who developed an automated method to assign thickness to origami-based structures.[225] Their system allows to generate full 3D geometry and assembly elements of a thickness accommodation method previously selected by the user. Developments of the system may lead not only to generate desired 3D models, but also help designers selecting the most suitable thickness accommodation method in respect of design constraints. Despite automated thickness accommodation methods have been integrated in the software Crane, they still cover a limited number of methods. When dealing with structures made of thick panels, rigid-foldability is a primary concern. Among the advantages provided by rigid-origami structures, there is the possibility to achieve purely geometric mechanisms independent of materials properties and minimized DOF.[226]

Such property can be addressed at early design stages, with the selection of rigid-foldable crease patterns that could remarkably simplify subsequent fabrication stages. Recent studies investigated the influence of mountain/valley assignments[227,228] and dihedral angles[229] on the rigid foldability of origami patterns. A better understanding of such properties may be desirable to implement Inverse Design methods to generate rigid-folding patterns or modify existing ones according to design constraints. Of particular interest is the work of Zimmerman and co-workers, who implemented a heuristic algorithm to transform non rigid-foldable crease patterns into rigid-foldable ones by means of vertices location adjustments.[230]

Origami-based designs can be fabricated in a wide range of materials and with different fabrication methods.[231–233] Because the assemblage of structures achieved with such methods can be challenging, designs with a reduced number of components have been proposed.[234] Recent advancements have been brought by the application of 3D printing technologies,[235–237] although their application is currently limited from the nano to the centimeter scale. At a larger scale, the implementation of hingeless origami-based structures with curved creases showed promising results.[101,102] Nevertheless, their development is limited by the lack of tailored design and simulation tools. Despite novel methods have been developed to assess the global folding motion of origami with curved creases,[209] they have been scarcely implemented in available software packages.

Actuation is a major aspect scarcely taken into account during design stages.[238] For static designs, automated tools and folding methods have been developed, although their applicability remains limited.[239–241] For deployable structures, 3D printing methods have been coupled with smart materials to print 4D active structures with preprogrammed configurations.[242–245] Despite avoiding the use of external actuators, 4D printing methods are scale dependent, their folding motions are not always reversible, and a restricted number of materials is currently usable. From the centimeter to larger scales, actuations are usually driven by servo-motors, while novel approaches investigated pressure driven actuators[101,102] and the usage of smart materials like SMA springs.[57–59] In the majority of available simulation tools, folding motions are driven by fictitious forces that contemporary fold all the creases. This approach could be suitable to investigate 4D printed structure, despite being not applicable to designs implementing sequential folding. Due to the simplification of the actuation system, fabricated models may have reduced performance when compared to simulation results.[57] A more accurate implementation of actuators into simulation tools would allow to preliminary know required forces and assess the efficiency of models at early design stages. Preliminary steps in this direction have been taken by simulation packages like MERLIN2 and Interactive Robogami. Nevertheless, their features have to be considerably extended to bring effective advantages in the design of origami-based systems.

7. Conclusions

The present review investigated the implementation of origami-based designs in biomedical engineering, architecture, robotics, space structures, biomimetic engineering, fold-core structures, and metamaterials. It has been shown that origami-based designs are able to solve engineering problems of different nature and scale. Despite the broad range of applications, the complexity of design processes, the lack of optimized design tools, and fabrication-related constraints have been recognized general issues regardless the field of application. A comprehensive review of a vast amount of research outcomes confirmed that there are no established design processes among the origami community.

Recent developments of software interfaces have also been presented, and their capabilities to support design processes have been discussed. Although a wide range of design and simulation tools is currently available, the majority of them have been developed independently and are not suitable to be integrated into efficient design workflows. Although origami-based applications are encountering a fast development, several challenges still need to be addressed:

- Elastic folding: the majority of the reviewed origami-based designs implement rigid folding motions. Despite the favorable properties provided by rigid folding, new studies on novel elastic foldable crease patterns should be performed to find innovative design solutions. A better understanding of the correlation between folding motions and material behavior could foster the development of a new generation of origami, which could also enhance the still underexplored applications of origami with curved creases.
- Curved-crease origami: the capabilities of origami with curved creases are still largely underexplored. Only recently mechanical models able to simulate the behavior of curved-crease structures have been developed, with few simulation tools that are currently able to support the simulation of such models. The development of origami-based structures with curved creases may lead to designs that better take advantage of materials behavior, possibly leading to more efficient folding motions and actuation systems.
- New materials: the development of curved-creased origami and elastic-folding geometries in general is strictly related to the implementation of new materials capable to withstand folding stresses without failure. Because of the different nature of origami-based designs, no material can be considered generally applicable before being validated by experimental tests. New hybrid systems could also lead to a new generation of designs not investigated before. A new systematic approach able to integrate the material selection within the design process would lead to improved design solutions. For example, a database able to connect crease patterns and material requirements could help designers in the material selection. Such system could suggest which material characteristics would be suitable for a given crease pattern, as well as which material combination between plates and hinges would be optimal for a certain design solution.
- Common design workflow: is missed among origami designs regardless the field of application. The definition of a

generalized and integrated design process would be highly beneficial for the achievement of optimized solutions and trans-disciplinary innovations. Currently, the Direct Design method is the most applied, while the Inverse Design approach has been implemented for a limited range of target geometries and origami patterns. How to efficiently find and modify existing crease patterns, as well as creating new ones are still challenging tasks. If systematically defined, a generalized design method could take great advantage by the implementation of optimization algorithms. For example, Interactive Evolutionary Algorithms could allow to explore broader design domains without looking for any particular configuration. Selected design outcomes could then be optimized by means of single-objective or multiobjective optimization algorithms.

– Thickness accommodation: is still a major issue in the engineering of origami-based structures. It has been shown how major studies focus on origami with zero-thickness, although no straightforward solutions have been developed to quickly convert functioning zero-thickness structures into functioning systems with finite thickness. The implementation of evaluation criteria could avoid to work on infeasible solutions and let thickness properties be a driven design factor from the beginning of the process.
– Actuation: current manufacturing techniques limit the availability and scale of application of a wide range of materials. Despite smart actuators as shape memory alloys (SMAs) have been extensively investigated, their implementation remains challenging. Recent advances in smart materials and manufacturing techniques as 3D and 4D printing could open new ways for the design of origami-based active structures. An interesting approach could be the coupling of lightweight 3D printed structures with stimuli-responsive materials. Such design would be able to respond to environmental variations without requiring external actuators. For example, self-folding motions could take advantage of composite materials with different thermal expansion coefficients, or material characteristics such as hygroscopicity of wood. Further research efforts should be undertaken for the development of reliable and efficient actuation systems.
– Software: interoperability would be highly desirable to enhance the quality of design outcomes. The development of a shared platform would be beneficial, as current software are mostly stand-alone interfaces with a low level of interoperability. Although a huge variety of platforms exist to generate folding patterns and obtain final folded configurations, the analysis of folding sequences remains challenging. Addressing the material behavior of origami undergoing elastic folding is still problematic, and the simulation of origami with curved creases is scarcely implemented. Further innovations in the simulation of origami-based structures could be brought by software such as Blender and Houdini. Implementing real-time physics and rendering engines, they could be highly suitable to simulate global geometrical and material behavior of origami-based structures at an early stage of the design. New design and simulation platforms should also take into account the importance of thickness accommodation and actuation, thus providing optimized tools to designers to deal with such aspects.

Origami-based designs demonstrated to be a flexible tool for the implementation of innovative engineering outcomes. Thanks to recent research findings, their applicability promise to be broadened and optimized. It is hoped that this comprehensive review of origami-based applications, design methods and tools may help to foster trans-disciplinary innovations.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

deployable structures, metamaterials, origami, origami-based engineering, tunable materials

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