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International Journal of Biosensors & Bioelectronics

Mini Review

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Folding nano-scale paper cranes–the power of origami and kirigami in metamaterials

Volume 4 Issue 3 - 2018

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Received: June 18, 2018 | **Published:** June 27, 2018

Abstract

The ancient Japanese art of paper folding has influenced several branches of science from mathematics, physics to materials- and space sciences. One of the main advantages of origami is the precision of the folding mechanism that leads to a well-defined folded state. While the main principles of folding are the same as in original paper folding in a wide range of materials, it is the specific interactions and material properties that enable origami folds on scales from nano- to over 20 meters. In this brief review we discuss origami on a molecular level, covering applications in physics of smart materials such as biosensors, stretchable electronics and nanorobotics.

Keywords: origami, kirigami, biosensors, nanorobotics

Origami self-assembly: tunable nanoscale precision folding

Folding, the mechanism of self-assembly into a compact state is universally observed on different scales in a wide range of materials. In this review, we discuss folding and compaction on molecular scales. Generally, folding can be classified into two groups – specific, whereby the number of folding pathways is limited, or non-specific where associations between all functional units are equiprobable, yet directed by a number of physical principles such as coil-globule transition and nucleation processes, regulating the kinetics of collapse as well as the morphology of the final folded state. Complex events such as aggregation, gelation and molecular folding often incorporate both non-specific and specific collapse pathways, linking the two together in a non-trivial manner. Here, we focus on specific 'designer' folding pathways of origami and kirigami (a variation of origami that involves cuts) on a molecular scale. These particular folds are a result of highly selective interactions that allow one to robustly produce a large number of stable interaction-dependent collapsed morphologies. Even though the folding of origami relies on trivial operations from a mechanistic perspective, the physics of origami folds is intriguing: origami folds can 1) undergo large reversible deformations 2) show nonlinear auxetic behavior– a property of a material with a negative Poisson's ratio (i.e. the material expands when tension is applied) 3) bistability (the origami fold has two stable states – expanded and compressed) and 4) topological locking – an increase in resisting force upon folding.[1] All the physical properties of origami can be tuned by the geometry of the fold (Figure 1). Like origami, kirigami structures provide multifunctional shape-changing capabilities. Due to an increased number of structural degrees of freedom originating from incisions, kirigami-based 3D nanostructures allow for a larger variety of morphologies as well as load bearing capabilities that are not accessible using traditional origami techniques.[2,3]

Origami in soft and biological systems

Colloidal particles and nucleic acids (DNA and RNA) are ideal for creating specific interactions for folding. Patchy colloidal particles have attractive sites ('patches') arranged in precise geometries on the particle's surface, directing and limiting bonding between particles; this interaction anisotropy defines the collective behavior and folding of the system. In nucleic acids, Watson-Crick base-pairing only occurs between certain nucleotides (A-T/C-G), limiting the number of putative interactions between nucleotides and making it possible to create specific folds that form the basis for complex origami patterns (Figure 2).[4] As a result, origami patterns give rise to metamaterials – materials whose morphology gives designed structures novel physical properties beyond the scope of the original material. One of the main applications of soft matter origami is in biosensors–analytical devices that convert a biological response into an electrical signal. An example of a biosensor is an origami-based synthetic nanopore that responds to a change in voltage by a structural change of the channel.[5] Voltage can also control the DNA translocation rate through the channel, giving rise to an artificial nanopore whose behavior can be controlled via an external stimulus.[5] Another biosensing mechanism involves 3D DNA origami nanorobots immobilized on glass optical fiber tips actuated by a target DNA: [6] in this example, bioluminescence is used to identify the DNA sequence of interest. Nucleic acid origami has biomedical applications in drug delivery:[7] origami can be built to function as a container for drug molecules that can be delivered with high precision to the desired location by either making use of specific shapes of the origami 'cages' or through particular surface-target interactions. Interaction specificity can also trigger a change in the morphology of the origami, making use of bistability, which can be utilized in nanorobotics: a folded origami nanorobot can extend upon target recognition, which has been used as a potential form of cancer therapy whereby the origami nanorobot can identify and block tumor-associated blood vessels.[8] Similarly to origami, kirigami-based circuits and sensors can be printed into the flat sheet prior to patterning and folding, creating integrated smart active structures referred to as origami robots.[2,9,10] Molecular kirigami structures are potentially applicable to an even wider range of novel applications, such as kirigami-based bandage and kirigami printed stretchable electronics.[11] For example, lithium ion batteries are able to sustain large strains under deformations, which is fundamental for flexible, stretchable electronics, such as displays, stretchable circuits and wearable electronics(Figure 2).Numerous approaches have been employed to achieve flexible and stretchable energy storage devices using kirigami techniques, demonstrating a visible advantage compared to the origami alternative due to increased internal flexibility of kirigami. In stretchable kirigami structures, three main physical properties have been identified: 1) shear-lag, whereby shear deformation reduces strain on the rest of the structure upon stretching 2) partial loss of bonding characteristics due to cuts introduced in the structure and 3) heterogenous deformation that increases adhesion to the surface upon twisting or bending the structure.[11] In addition to biomedical materials science applications, DNA origami can also be used for building molecular complexes: for instance, 2D DNA origami structures provide a scaffold for building macromolecular constructs by chemical reactions between functional chemical groups placed at separated 'pixels' on two-dimensional origami templates, opening new perspectives for chemical synthesis on a surface that unlike traditional chemical synthesis, makes use of origami fold geometries.[12]

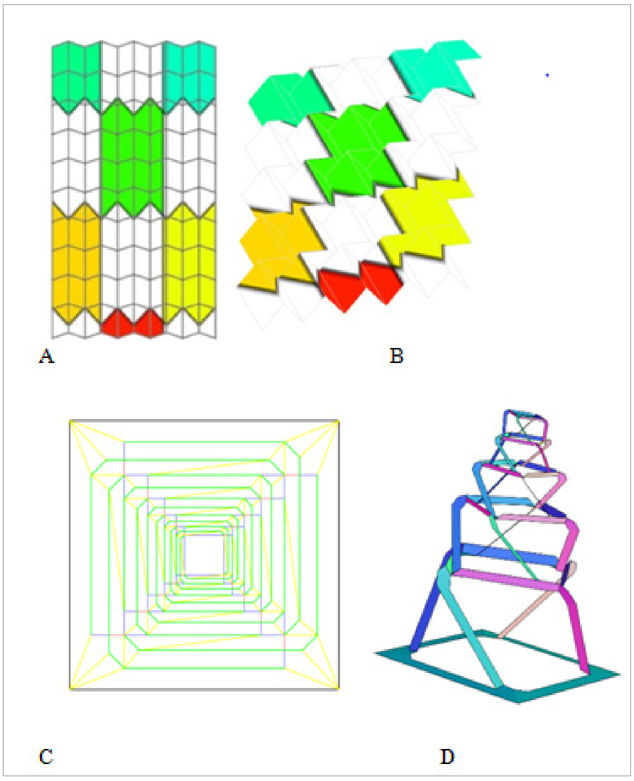

Figure 1 A) Origami folds in 2D with colored regions in an expanded state B) A 3D perspective view of a compressed state of the fold in A C) A kirigami fold in 2D D) A 3D representation of the deformed construct in C.

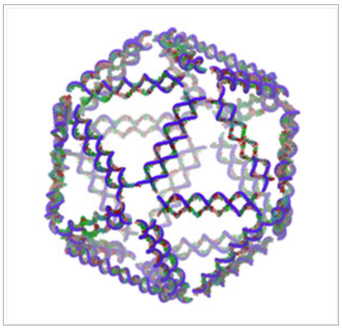

Figure 2 A modeled icosahedral arrangement of DNA origami based on.[4]

Molecular origami and future technologies

Recent advances in molecular origami show that nanorobots can be regulated by a real-time magnetic control system,[13] making it possible to construct complex nano-scale devices that can be manipulated in real time. Lauback et al.,[13] used DNA origami to construct rods, hinges and rotors; the nano-size components were connected by DNA levers to magnetic beads that in turn activated the nanorobot by oscillatory and rotational motions. This is only one example of molecular nanorobotics in action, and this field is constantly evolving towards fully functional self-building and repairing smart nanorobot factories that could potentially tackle problems in engineering and medicine that cannot be addressed otherwise.

Acknowledgements

We gratefully acknowledge the support of the Center for Nonlinear Studies, LANL for this work.

Conflict of interest

Authors declare no conflict of interest.

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Citation: Lappala A, Macauley N. Folding nano-scale paper cranes–the power of origami and kirigami in metamaterials. *Int J Biosen Bioelectron*. 2018;4(3):166–167. DOI: 10.15406/ijbsbe.2018.04.00119