Self-organized Structure in Theory and Production: Contemporary Origami as Mathematical, Mechanical and Cultural System

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Abstract. Origami is an extensively discussed subject in art, design and mechanism, but new discipline to study with the perspective of inter disciplinary science and cultural history. This paper assumes basic awareness of the artistic and design concept of the audience. It further investigates origami, together with history of math, as a clue of cross cultural study and technology development of the 20th century. Also, it discusses how its self-organization structure is formed artistically, scientifically and industrially, with its special role in art modernization. The paper referee to theories by R. L. Wilder and Thomas. S. Kuhn. Based on the volumetric examples of origami usage, it introduces the topics of science communication and generative design history marked by software development. It tries to construct a multi-aspect view of cultural history through technology, and manifests the perspective of art and humanities in it.

Keywords: History of math · Computing art · Design history

1 Introduction

Origami is an old subject in art, design and mechanism, but new discipline to study with the perspective of inter disciplinary science and cultural history. In art and mechanics, origami manifests the universality of mathematics across generations, industries, media, cultures, aesthetics and functions. Its construction as an art subject, a mathematical field, and an engineering subdivision has involved the spontaneous participation of interdisciplinary scholars, and there are particular origami associations in the United States and Japan, with a elaborate system of software, monographs, and papers, reflecting origami's efficient self-organizing ability as a production method in theory and practice. Volumes of existing research and applications in engineering, mathematics and arts leaves little need for case enumerating, but a more in-depth cross-cultural and history of technology study is the next step, providing a valid paradigm for the possibility of integrating computer-based technological work into cultural and artistic production.

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2 Origami as Cross-Cultural Subject and Inter-disciplinary Clue of 20th Century History of Science and Technology

The development of origami as a cross-disciplinary practice is often vaguely attributed to the borrowings of Japanese artistic tradition by computing technology, as if there were a simple chronological and causal relationship between the two. But this may only be a speculation that is taken for granted. Origami is a technological tradition closely related to the the distribution of mathematical centers of pre-modern human society. It originated in various civilizations around the globe in different forms and on similar principles, similar to the case of printmaking. Referring to the theoretical insights of R. L. Wilder, who combined the history of mathematics and anthropology, origami could be an important clue to the cultural tradition of mathematics and a cutting tool for cross-cultural comparison [1]. The appearance of Japanese origami in the Heian dynasty began with the introduction of Chinese paper. The corresponding term of Papiroflexia in Spanish, introduced in 12th century from Arabian society, is consistent with the pattern of mathematical knowledge producing and transmission in East Asia and Europe [2]. Yoshizawa's overseas exhibition was first held at the Amsterdam City Museum in 1955, and according to the history summarized by Erik and Martin Demain, Josef Albers began the modern European and American origami art stream from the Bauhaus and Black Mountain Institute in the 1920s, which is clearly not in the same vein as the Japanese craft tradition represented by Yoshizawa [3].

Origami as a technical discipline is a clue of 20th century history associating craftsmanship and generative design, which exemplifies the importance of introducing artistic and cultural perspective as viewing the history of technology. It also reveals the diverse relationship that has occurred between the history of mathematics and modern art, a relationship that has yet to be studied in greater depth. The model designed by Duks Koschitz of the Bauhaus is already very close to the parametric design in form, which shows a priori of how craftsmanship extends in the history of computing technology. The priori was clearly identified by the artists like Erik Demain in the Computer Science department in MIT, whose thesis focused on waterproof structures, but his origami creations carried on the legacy of Albers and Koschitz, among others [3]. Meanwhile, the origami sculptures of Paul Jackson and others are closer to the minimalist art of the 1960s onwards [4]. Considering the constructivism movement initiated by Bourbaki School in abstract math in the same century, whose influence in art was waning at the time [5]. Origami is thus part of the whole reaction of visual creation on science in the century. Meanwhile, Process Art (also known as "systems art") and Cybernetic Art emerged in Europe and the United States, with artists in residence at the Department of Mathematics and Physics at the University of Bristol. Simon Thomas has used the language of mathematics to produce a great deal of public art, such as PLANE LINER, a work in residence at Bristol University's Physics Department [2]. It shares the methodology of origami, and is composed by a three dimensional mathematical function, where the sculptural shape is theoretically infinitely extensible, but the apex is always empty.

3 Self-organized Scientific Paradigm and Science Communication

3.1 Mathematical Structure in Geometry and Numerical Analysis

The self-organizing feature allows and deserves origami to be examined more critically as what Thomas. S. Kuhn calls a scientific paradigm [6]. The mathematical structure determines the academic architecture itself. Different research orientations determine the choice of mathematical models. Each particular model determines an scholarly branch. Industries and sectors could collaborate with separate branches with minimized communication cost with the language of mathematics. "Self-organizing" here has multiple indications in the context. It, at least, includes: the universality of the mathematical language that allows origami to effectively surpasses the barriers of different cultural systems; mathematical principles functions as meta-model of design and public art, with production procedures clearly drawn; mathematical forms eliminates the boundaries between art and industrial applications, virtual and physical worlds, allowing the same set of theoretical language to be applied across a wide range of media, but with a different emphasis between the geometric formal induction of the former and numerical analysis of the latter. Unlike digital art and general origami works, the vast amount of origami research in architecture, mechanics, and dynamical systems is based on structural affordances and realistic feasibility. DNA origami, on the other hand, is more informational than geometric, except that its idea of modularity is connected to origami in three dimensions. It is a metaphor for the rapid growth of knowledge and the expansion of the scientific paradigm [7].

An easily overlooked fact is that origami itself involves a relatively wide range of branches of mathematics, which underlies the reason why mathematicians and physicists actively maintain the self-organizing community: in the process of making, presenting, and writing on origami, the extremely complex and divided contemporary mathematics is communicated at low cost among peers. The underlying logic expand to differential equations and group theory as the folding complicates. The action of "folding a trace on a piece of paper" in real space is mathematically equivalent to "drawing a straight line on a plane in three-dimensional space and folding the plane along this line". "planning the action steps of folding traces" is the process of "deducing geometric and algebraic transformations of a plane along a straight line", which results in the writing and deduction of analogous algorithms.

Abstract math related to origami are discussed in detail by three European professors in "*The Art of Mathematics*", edited by Yau Shing-Tung, who relate its principles to partial differential equations [8]. Drawing a crease diagram on a piece of paper, once the folding action takes place, is equivalent to a smooth plane undergoing a transformation leading to some position discontinuity, so the crease diagram is reduced to a discontinuous point set. The relationship between origami and more complex mathematics is established in the repetition and organization of such simple actions, such as performing the Fujimoto approximation of N-equivalence folding in a way that can be taught in connection with number theory and discrete dynamics, and Hull's classroom lecture notes that include homomorphic algebra, and origami demonstrations of Gaussian curvature.

3.2 Software Development in History of Technology

Due to its feature of unifying visual presentation and shape analysis, origami in industrial design exemplifies the history of computing technology marked with software development. Kawasaki and Maekawa's theories are extensively elaborated in every topic defined by a single geometric case. Cases divide by rigid and non-rigid folding. The rigid folding surface is always a rigid plane, and the crease is regarded as a rotating axis. Non-rigid folding does not have this assumption, that can occur within the folding surface twisting, bending and other deformation, can produce deformation [9]. Force tolerance and shape sustainability are calculated through softwares like Adams (Automatic Dynamic Analysis of Mechanical System) [10].

In terms studying computing art, architecture and public art in forms, the approach of history of technology marks their innate relation in the bottom, which origami makes explicit. Dating back to 1960, Denavit and Hartenberg in Northwestern University were awarded the first National Science Foundation research grant in the U.S. in kinematics to develop a numerical analysis tool for digital computers, which later was upgraded to Adams by their students. 1961, Northwestern University acquired an IBM 709 digital computer based on FORTRAN IV from the Boeing airplane, which was not powerful as hand calculator today [11]. In the same era, in 1960, Thomas Banchoff began using software to simulate the projection of high-dimensional objects in two dimensions, and his collaborator, Davide Cervone, created a new work in 2002. In the 1970s, mathematicians at IBM developed fractal geometry [2]. After 2000s, Roland Snooks, one of the practitioners of "Swarm Intelligence" (the intelligent behavior of many low-intelligence individuals through simple cooperation with each other), has created architecture and public art that includes algorithm-led self-similar geometries, with surfaces that can be left to robotic arms and robots [12].

In addition, specialized origami softwares that still serves paper-folding, such as Geogebra and Geometer, provide a category that drive complicate math theory illustrations (i.e. differential equations) closer to computing language. Repetition of several folds can be calculated to approximate a parabola is summarized in Geogebra as a direct Lotus instruction; the result of solving cubic equations by the Lill method of paper folding is a reenactment of the 19th century Austrian engineer Eduard Lill's construction and the discoveries of the 20th century mathematician Margherita Bolech. Systematic treatises that combine mathematics and art include *The Secrets of Origami - Mathematical Methods in Ancient Art* by R. Lang, *The Secrets of Origami Design* by Thomas Hull, etc., and works of many Japanese scholars [13, 14].

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