BIOINSPIRED ORIGAMI: INFORMATION RETRIEVAL TECHNIQUES FOR DESIGN OF FOLDABLE ENGINEERING APPLICATIONS

A Dissertation

by

ELISSA MORRIS

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Daniel A. McAdams
Committee Members,	Richard Malak
	Douglas Allaire
	Michael Moreno
Head of Department,	Andres Polycarpou

August 2019

Major Subject: Mechanical Engineering

ABSTRACT

The science of folding has inspired and challenged scholars for decades. Origami, the art of folding paper, has led to the development of many foldable engineering solutions with applications in manufacturing, materials, and product design. Interestingly, three fundamental origami crease patterns are analogous to folding observed in nature.

Numerous folding patterns, structures, and behaviors exist in nature that have not been considered for engineering solutions simply because they are not well-known or studied by designers. While research has shown applying biological solutions to engineering problems is significantly valuable, various challenges prevent the transfer of knowledge from biology to the engineering domain. One of those challenges is the retrieval of useful design inspiration.

In this dissertation work, information retrieval techniques are employed to retrieve useful biological design solutions and a text-based search algorithm is developed to return passages where folding in nature is observed. The search algorithm, called FoldSearch, integrates tailored biological keywords and filtering methods to retrieve passages from an extensive biological corpus. The performance of FoldSearch is evaluated using statistical methods for information retrieval and validated using inter-rater reliability analysis.

The utility of FoldSearch is demonstrated through two case studies where the retrieved biological examples undergo a design abstraction process that leads to the development of bioinspired origami crease patterns and novel foldable structures. The design abstraction process is presented as an additional research contribution and demonstrates the potential to provide bioinspired design solutions for the growing research field of origami engineering.

DEDICATION

For Jody, Jose, and Oliver

ACKNOWLEDGEMENTS

First and foremost, I want to thank Dr. Daniel A. McAdams for being my advisor. His support, patience, and humor have been a tremendous encouragement throughout my doctoral studies. The example of intellectual rigor and academic creativity that he has set will have a lasting impact on my professional career. I am immensely thankful and proud to have been his doctoral student.

I want to express sincere gratitude to my committee members, Dr. Douglas Allaire, Dr. Richard Malak, and Dr. Michael Moreno, for their support in my doctoral studies and invaluable feedback on my dissertation research.

I want to thank my lab mates – Shraddha Sangelkar, Sooyeon Lee, Joanna Tsenn, Jonel Ortiz, Shelby Hopkins, and Devesh Bhasin – for their friendship and encouragement. I especially want to thank Guanglu Zhang. His support, positivity, and academic aggressiveness have motivated me in more ways than he knows.

I cannot truly express how indebted I am to my family. My parents have made significant sacrifices to provide me with opportunities in life that they never had. I am immensely thankful for their love, prayers, and encouragement. My husband has been my stronghold throughout my graduate career. I am certain that I couldn’t have finished my doctoral studies without his loving support.

Finally, I want to thank my Savior and Truest Friend, Jesus Christ. Words fall short of expressing my gratitude for His guiding presence in my life.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Professor Daniel A. McAdams, Professor Richard Malak, and Professor Douglas Allaire of the Department of Mechanical Engineering and Professor Michael Moreno of the Department of Biomedical Engineering.

Jesse O'Connor and Dr. Jian Tao contributed to the early development phases of the search algorithm. Tanner Foster and Khristan-Allen Maney converted the corpus into searchable text files. Kaylee Kaigler provided assistance in the inter-rater reliability analysis. All other work conducted for the dissertation was completed by the author independently.

Funding Sources

Graduate study was supported by various Teaching Assistantships from the Mechanical Engineering Department at Texas A&M University and a Graduate Teaching Fellowship from the College of Engineering at Texas A&M University.

This work was also made possible in part by National Science Foundation NSF EFRI-ODISSEI 1240483. Any opinions, findings, and conclusions or recommendations expressed in this dissertation are those of the author and do not necessarily reflect the views of the National Science Foundation.

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1. INTRODUCTION

Nature offers a wealth of design solutions to its most observant students. One of the most common design techniques that nature employs is folding. Biological folding exists in various forms, including patterns, structures, and behaviors. As an engineering design tool, folding has provided innovative solutions to a variety of engineering problems. Therefore, adapting the folding techniques observed in the biological domain can significantly impact the engineering design domain. Harnessing biological design solutions presents several challenges to engineers. This dissertation addresses these challenges and provides a practical design methodology for engineers seeking inspiration from the greatest source of design knowledge available to mankind – the natural world.

1.1. Bioinspired Origami

One of the most widely used materials for folding is a simple sheet of paper. Origami is defined as the art of folding paper and has applications in mathematics, engineering, and architecture. Many scholars in these fields studying origami are familiar with the Miura-ori and the Kresling folds. However, what many scholars may not be familiar with is that these well-known folds are analogous to or are entirely inspired by folding observed in nature. Origami inspired by nature is defined as bioinspired origami. Establishing design methodologies for bioinspired origami is the focus of this dissertation work.

1.1.1. Organization of the Dissertation

This dissertation covers three different research fields – origami engineering, bioinspired design, and information retrieval. Due to the interdisciplinary nature of this work, separate sections are dedicated to each research area. Sections 2, 3, and 4 present an overview of origami engineering, bioinspired design, and information retrieval, respectively, and discuss the implications of each field in this dissertation work.

Section 5 contains the research approach used to address the challenges of bioinspired origami development. A keyword search algorithm, called FoldSearch, is presented in this section. FoldSearch provides design engineers with biological patterns, structures, and behaviors related to folding. These biological examples can then be used as design inspiration for bioinspired origami development and foldable engineering applications. Various performance analyses and evaluation techniques are presented in this section to validate the performance of the search algorithm.

Section 6 presents two case studies that demonstrate the utility of FoldSearch using design abstraction. Existing design abstraction processes in the literature are discussed. Origami principles and crease pattern development techniques are also discussed in this section and implemented in the two case studies. The case studies lead to the development of novel bioinspired origami and potential engineering design solutions. Finally, a design abstraction process is presented that enables designers to achieve outcomes similar to the results of the case studies.

Section 7 concludes this dissertation with a discussion of contributions, challenges, and future research directions.

1.2. Origami Engineering

Origami, the Japanese art of folding paper, was originally intended for entertainment and creative stimulation. The traditional form of origami involves imposing straight folds, called *creases*, onto a square sheet of paper to produce a three-dimensional shape without cutting or tearing the paper or using any adhesives [1]. Unfolding the three-dimensional shape reveals the original planar sheet with all imposed creases. The network of creases on the planar surface is called a *crease pattern*. Creases can be mountain folds (concave downward) or valley folds (concave upward).

Though traditional origami is restricted to a paper medium, modern-day developments prove that origami principles are useful far beyond mere paper folding. Origami enables reconfiguration and flexibility – two traits particularly useful for various engineering applications and consumer products. Integrating origami principles into product design can also simplify manufacturing processes and reduce fabrication costs [2, 3]. Further, modern-day design challenges include creating products that are multifunctional, smaller scale, deployable, and able to store compactly. Origami may provide solutions to these challenges.

Origami engineering is recognized as a promising research field. The National Science Foundation views origami as "the next topic in engineering – a vision toward the future" and has provided funding for the Origami Design for Integration of Self-assembling Systems for Engineering Innovation (ODISSEI) program with 14 universities involved [4]. Also, the Origami Science, Mathematics, and Education (OSME) conferences are international meetings that showcase the latest research and developments in the field. These endeavors are a testament to the immense promise of origami engineering.

1.3. Bioinspired Design

Using nature as a source of design inspiration is known as bioinspired design. Biological systems are known for energy-efficiency, multi-functionality, and diversity. Therefore, applying biological solutions to engineering problems is significantly valuable. While nature may offer a wealth of design solutions to engineers, various challenges prevent the transfer of knowledge from biology to the engineering domain.

One of those challenges is the different languages spoken by engineers and biologists.

Biological jargon is not readily comprehended by engineers rendering much of the content in biological literature difficult to navigate. Due to the language barrier between the two domains, the retrieval of useful engineering design inspiration that exists in nature poses a challenging task. This dissertation research addresses this challenge through the development of a bioinspired design search algorithm and a design abstraction methodology intended for use by designers in the origami engineering field.

1.4. Information Retrieval

Various information retrieval tools have been developed to address the challenges of bioinspired design. Research has demonstrated the value of using information retrieval techniques to facilitate bioinspired design [12-17]. Bioinspired design search tools, such as AskNature, IDEA-INSPIRE, and DANE, are used for general bioinspired design purposes. Due to the generalized nature of these tools, engineers in niche fields, such as origami engineering, may encounter difficulty using the tools and adapting the biological solutions to engineering problems. Other limitations of existing search tools are considered, which guides the development of a search algorithm designed for bioinspired origami development.

1.5. Research Approach

A keyword search algorithm, called FoldSearch, is designed to specifically retrieve biological examples relevant to foldable engineering applications. A pre-determined list of keywords guides designers with limited knowledge of biological jargon to select a biologically meaningful search term. The search algorithm’s filtering methods also ensure the biological examples returned to the designer are related to biological examples where folding in nature is observed.

1.6. Case Studies

Once a relevant biological structure, behavior, or pattern has been identified through FoldSearch, abstraction of the biological example must be completed to further reveal the potential application to foldable structures and engineering solutions. Abstraction is defined as “the process of refining the biological knowledge (design solutions) to some working principles, strategies or representative models that explain the biological solution and could be further transferred to the target application” [141]. Abstraction allows designers to simplify and extract design principles from biological systems. Abstraction also facilitates analogical reasoning between biological phenomena and engineering applications [141].

The objective of this abstraction and modeling stage is to demonstrate the utility and efficacy of FoldSearch to provide potential solutions for bioinspired design of foldable engineering applications. The abstraction and modeling phase results in the development of two novel origami crease patterns and folded structures.

1.7. Conclusions and Future Work

This research explores nature in search of folding patterns, structures, and behaviors that may be useful for bioinspired design of origami crease patterns and their application to foldable engineering applications. Research has demonstrated the value of using information retrieval techniques to facilitate bioinspired design [12-17] . Therefore, the objective of this research effort is two-fold – 1) to develop and validate a text-based keyword search tool specifically designed to retrieve folding mechanisms and patterns in nature, and 2) to create abstract models of the retrieved biological systems which can be used for the development of novel origami crease patterns and foldable structures. The process for design abstraction of the retrieved biological examples is presented and validated through two case studies as an additional research contribution. Future research directions relate to the improvement of FoldSearch through the integration of advance filtering methods and machine learning techniques, and further evaluation of the design abstraction process through prototyping and fabrication of the proposed engineering applications for the developed bioinspired origami.

2. ORIGAMI ENGINEERING AND PRODUCT DESIGN*

The section reviews origami product design applications and interprets the overall design trends in this emerging field. Section 2.1 contains an overview of origami engineering. Section 2.2 provides a review and analysis of origami-inspired product design over the last four decades along with the research procedures and qualifications for products considered. The sub-sections with Section 2.2 include the product summaries with products sorted according to their respective classification categories. Section 2.3 contains the qualitative analysis of the product comparisons and discusses origami-inspired design trends. Section 2.4 presents the conclusions of this section and suggested areas for future work.

2.1. Overview

The science of folding has inspired and challenged scholars for decades. Researchers have shown that folding can increase stiffness and flexibility of materials, decrease bulk and weight, enable structural transformation, and provide design multifunctionality [5-8]. Folding has provided solutions to a variety of engineering problems, as evidenced by deployable solar arrays and medical stent grafts [9, 10]. Many foldable product solutions are inspired by origami, the art of folding paper [11]. These products are reviewed and summarized in the following section.

2.2. Origami Product Design

A review and analysis of origami-inspired product design over the last four decades (1978-2017) is provided to identify and define the state-of-the-art in the evolving field of origami-based

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* Part of this section is reprinted with permission from "The State-of-the-Art of Origami-Inspired Products: A Review" by Elissa Morris, Daniel A. McAdams, and Richard Malak, 2016. *Proceedings of the ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Volume 5B: 40th Mechanisms and Robotics Conference, pp. V05BT07A014, Copyright © 2016 by ASME.

product design. Two prior reviews of origami-inspired products have been published, but are limited to active structures [2] and mechanical engineering applications only [18]. This review aims to cast a wide net and include products irrespective of function or application. Qualitative product comparisons are made based on the depth of origami inspiration, commercial viability, and scale. A product timeline is also included to illustrate the progression of this emerging design area over the last forty years. The objectives of this section are to identify the wide range of product applications for origami principles and to provide qualitative comparisons of products that reveal interesting trends in origami-inspired design, which may point to areas for future work in this developing field.

To determine what is and what is not considered an origami-inspired product for the context of this review, the following independent qualifications are used:

1. Must be a commercial product application inspired by origami principles.
2. Must be a physically demonstrated product application (prototype) inspired by origami principles.

These two qualifications exclude origami-inspired algorithms, optimization schemes, mathematical frameworks, software packages, design tools, processes, mechanisms, and methods. These qualifications also exclude origami-inspired materials and structures with no demonstrated product application. This section is focused entirely on practical product applications of origami-inspired design.

Many origami-inspired products exist that are merely conceptual designs lacking physical demonstrations. Prototyping reveals potential design flaws neglected in the conceptual design phase. Material intrusions and interferences are difficult to fully predict without a physical proof.

For these reasons, origami-inspired product ideas are not included in this review. Instead, the focus remains on origami-inspired products that are physically demonstrated.

The preliminary list of origami-inspired products is compiled using basic search engines. Keywords searched include the following nouns: product, application, design, and engineering, in combination with any of the following adjectives: origami, origami-inspired, origami-enabled, and origami-based. Each origami-inspired product found using the basic search engine is then searched for in academic publications, such as journal articles or conference papers. Products not found in academic publications are searched for using patent databases. Products not found in academic publications or in patent databases are assigned a website reference, which is generally where the product was initially discovered using the basic search engine. While every effort to avoid website references is made, websites are the only way of locating some products.

A second list of origami-inspired products is compiled using references found in the academic publications and patents used to create the preliminary list of products. This research cycle continues until new products are no longer discovered. Further, the keywords searched using the basic search engine are also searched using Google Scholar and patent databases to reveal additional origami-inspired products not found by the initial research cycle. Related fields such as pop-up engineering and compliant mechanisms are also studied in search of additional origami-inspired products.

The products are classified by the depth of origami-inspiration utilized. The first product classification category includes products that integrate common origami crease patterns. The second category includes products that integrate less common origami crease patterns. The third category includes products that integrate origami-based folding, shape-changing schemes but do not rely on crease patterns to achieve reconfiguration. The last category includes products that are solely inspired by the aesthetics of origami. Each product is briefly described in terms of application and function achieved through integration of origami design principles. Each product is also supplemented with a figure to illustrate the design. Also, a picture of the implemented crease pattern and references for conceptually similar products are included in the product summaries where applicable. Though conceptually similar products are not described in detail within this review, they are included in the qualitative analysis and references are provided within the product summaries.

The three common crease patterns that appear among the reviewed products are the Miura-ori, Waterbomb base, and Yoshimura. Each pattern is explained in further detail in the sub-sections to follow.

2.2.1. Products Using Miura-ori Crease Pattern

The Miura-ori crease pattern features a two-dimensional tiling of a fundamental unit containing four identical parallelograms, shown in Figure 3.1. The Miura-ori forms a developable double corrugation (DDC) surface. Paper folded according to this pattern is flat foldable, rigid foldable and features a single-degree-of-freedom folding mechanism [19]. Therefore, pulling and pushing the two opposite diagonal corners enables a sheet of paper to easily expand and contract [20]. The Miura-ori crease pattern has inspired various products with a wide range of applications as discussed in this sub-section.

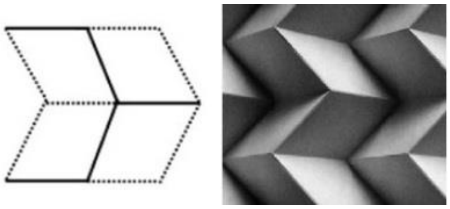

Figure 2.1 Miura-ori crease pattern [18, 19].

The earliest use of the Miura-ori crease pattern is found in deployable maps, illustrated in Figure 2.2 [21]. The map is deployed when the opposite corners are pulled outward along the diagonal of the initial rectangle. Pulling in this manner produces an equal and simultaneous deformation of all units along the diagonal causing the rest of the map to deploy [20]. Integrating origami enables the compact storage of large maps and simplifies the folding and unfolding process.

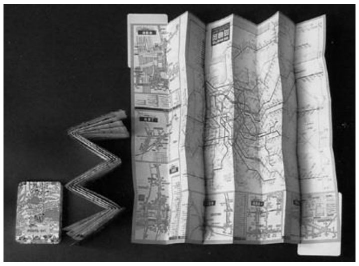

Figure 2.2 Folded map design [19].

Origami is integrated into the design of a planar array blanket used to test the viability of collecting solar energy in space and returning the harvested energy to Earth [9, 22]. The two-dimensional array, shown in Figure 2.3, implements the Miura-ori crease pattern to enable packaging and deployment of the large planar blanket [20, 22].

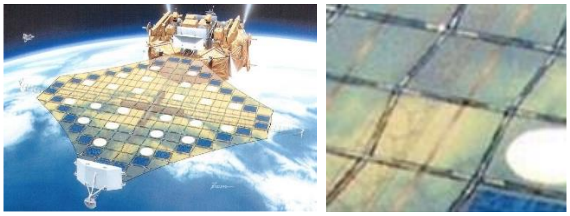

Figure 2.3 (left) Two-dimensional deployable solar array, (right) Close view of array pattern [22].

Sunshields help maintain dimensional stability of telescopes while in space, but they are difficult to design and test because of their large size [23]. Origami provides a solution to these challenges and has inspired the conceptual development of folding sunshields. A modified Miura-ori origami crease pattern is used to create a cylindrical polyhedron shape, shown in Figure 2.4. This pattern simplifies the attachment design between the sunshield and the telescope because the end cross-sections do not change throughout the deployment process [23].

Figure 2.4 Folded and deployed states of sunshield prototype [23].

Paper-based batteries integrate the Miura-ori crease pattern to increase battery's energy per footprint area [7]. Origami enables the battery, shown in Figure 2.5, to achieve high mechanical deformability and high areal energy density compared to conventional energy storage devices [24]. Other origami-inspired batteries include a biobattery shaped like an 8-point ninja star [25] and a stackable, bacteria-powered battery [26].

Figure 2.5 Folding lithium-ion battery using Miura-ori crease pattern [7].

X-ray machines used for imaging during surgical procedures feature a reconfigurable C-arm which travels in and out of sterile environments during operation [27]. Therefore, a shroud is required to provide a barrier between the sterile environment and the non-sterile C-arm. Researchers have developed a deployable shroud based on a modified Miura-ori crease pattern which enables the shroud to expand and contract, illustrated in Figure 2.6. This motion allows the shroud to maintain a sterile environment throughout repositioning of the C-arm [27].

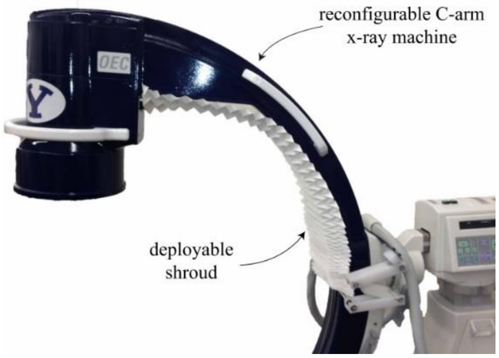

Figure 2.6 Origami-inspired deployable shroud for X-ray machine [27].

An interactive light design integrates the Miura-ori crease pattern to enable flexibility and reconfiguration [28]. Users can manipulate the system to create various light displays, shown in Figure 2.7. Researchers developed the interactive light to foster creative, playful interactions among users [28].

Figure 2.7 User interaction with tessella light [28].

The Miura-ori is used in children's clothing capable of bi-directional expansion, shown in Figure 2.8. The integration of the Miura-ori pattern allows a garment to accommodate children from four to thirty-six months of age, thereby reducing waste [29]. The clothes are made of durable, breathable fabrics and offer a wide range of motion.

Figure 2.8 Petit Pli expandable children's clothing [29].

2.2.2. Products Using Waterbomb Base Crease Pattern

The Waterbomb is the oldest known base in origami history, shown in Figure 2.9. The Waterbomb base crease pattern is flat and rigid foldable with a bistable folding mechanism. Tessellations of the Waterbomb base enable a product to collapse, generating axial contraction segments [30]. The Waterbomb base is used in various product applications as demonstrated in this sub-section.

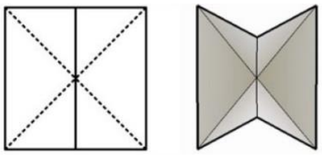

Figure 2.9 Waterbomb base crease pattern [30].

The ball-shaped Waterbomb crease pattern is used to create a robot with deformable wheels, shown in Figure 2.10 [31]. Passive springs and shape-memory alloy spring actuators are employed to deform the wheel [31]. Origami principles enable movement predictions of morphing structures, simplifies fabrication, increases system robustness, and helps maintain the structural integrity of the wheels [32]. Other crease patterns and shape-changing schemes have been successful in the development of wheeled robots and crawling robots [3, 33-35].

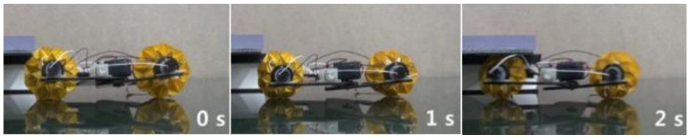

Figure 2.10 Robot quickly navigating obstacles using deformable origami wheel [31].

Traditional stent grafts consist of a two components: a deployable wire mesh and a soft membrane that covers the mesh. Geometric differences between the wire mesh and the soft membrane cover may cause complications during stent deployment. Origami has provided a solution to this challenge through a deployable stent graft made from one solid piece of foldable foil [36]. The novel stent graft integrates tessellations of the Waterbomb base crease pattern which allows the stent graft to maintain flexibility and deploy simultaneously in a longitudinal and radial manner [36]. A card model of the stent graft is shown in Figure 2.11.

Figure 2.11 Steel stent graft models [37].

A revolutionary acoustic system, termed Resonant Chamber, integrates origami principles to enable adaptive sound [38]. Waterbomb base triangular tessellations are used for the acoustic panel design, shown in Figure 2.12. This crease pattern allows the flexible panels to move, thereby dynamically altering acoustics [38].

Figure 2.12 (left) Resonant chamber installation, (center) Magnified panel view, (right) Actuators and wiring system behind panels [38].

2.2.3. Products Using Yoshimura Crease Pattern

The Yoshimura crease pattern is shown in Figure 2.13. This crease pattern features diamond tessellations folded along diagonals [18]. Like the Miura-ori and waterbomb base, the Yoshimura crease pattern is flat and rigid foldable. The Yoshimura crease pattern enables translational motion as demonstrated by the products in this sub-section.

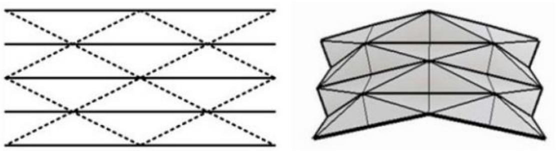

Figure 2.13 Yoshimura crease pattern [30].

Origami has been used to develop deployable shelters intended for disaster relief situations and temporary housing for homeless persons [39-41]. Cardborigami, shown in Figure 2.14, is a deployable shelter that can be assembled in under one minute by a single person [39]. The Yoshimura crease pattern enables the shelter to be portable, lightweight, and easy to assemble.

Figure 2.14 Cardborigami shelter [39].

Retail kiosks integrate a modified Yoshimura crease pattern to achieve a reconfigurable structure [42]. The kiosks are comprised of folded steel panels with hinges that enable the structure to open and close, illustrated in Figure 2.15. In the open state, the folded design creates a canopy for customers. An electric winch is used to operate a counterweight system, which opens the kiosks. The kiosks implement a pivoting, hollow steel frame making the structures lightweight and portable [42].

Figure 2.15 Opening and closing retail kiosk [42].

Horatio Han has conceptually designed a hard boot that integrates the Yoshimura crease pattern to create extendable sections, shown in Figure 2.16 [43].

Figure 2.16 Boots with flexible origami sections [43].

The Yoshimura pattern is used in the design of a ballistic shield prototype, shown in Figure 2.17 [44]. Compared to conventional designs, the shield is lightweight and can collapse and expand quickly allowing for more efficient use in emergency situations. The curved design also provides users with flank protection unlike conventional straight shields. The bulletproof barrier can be used by law enforcement and by schoolchildren during emergency situations.

Figure 2.17 Collapsible ballistic shield [44].

Emergency cargo delivery using traditional drones exposes users to spinning propeller blades posing a considerable safety risk. Thus, researchers have used the Yoshimura pattern in the design of a collapsible drone with a protective cage for safer cargo delivery, shown in Figure 2.18 [45]. The drone cage provides a barrier between the propeller blades and the user allowing the user to safely catch the drone as it approaches. Also, the entire drone and cage easily fold down providing a solution for convenient storage and transportation.

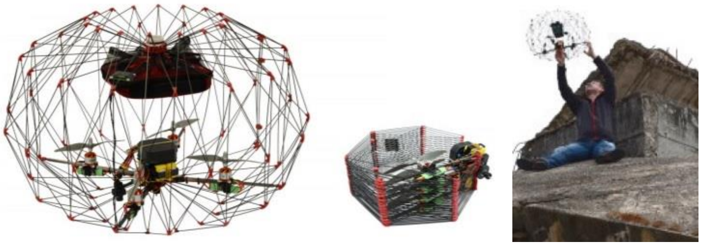

Figure 2.18 (left) Expanded cargo delivery system containing first aid kit, (middle) Collapsed cargo delivery system, (right) User safely catching drone [45].

2.2.4. Products Using Less Common Crease Patterns

The following products integrate novel or less common origami crease patterns. The patterns vary in complexity depending on the product application. Illustrations of the crease patterns used are included in the product summaries where possible.

Researchers have developed a deployable solar array model for space, called Hanaflex, based on the modified Flasher crease pattern, shown in Figure 2.19 [46]. Origami enables compact storage of the array during transport to space. The diameter of the array in the folded state is nearly one-tenth the diameter of the array in the deployed state [46]. With an expected 25-meter deployed diameter, Hanaflex has the potential to collect massive amounts of solar energy which could sustain long distance space missions [46].

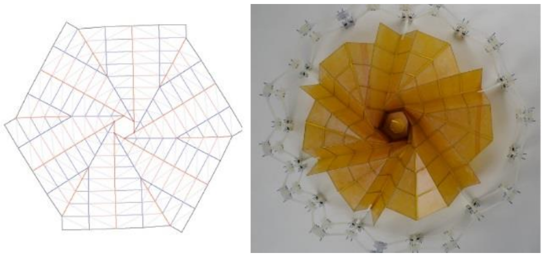

Figure 2.19 Modified Flasher crease pattern used for deployable solar array [46].

Origami has been used for a deployable space telescope known as the Eyeglass [47]. The Eyeglass telescope features a diffractive lens that is lightweight and foldable. The lens is folded according to a unique origami crease pattern that enables portability and deployability. To date, researchers have developed a 5-m prototype lens, shown in Figure 2.20. The aperture of the telescope is expected to be 25-100m once completed [48].

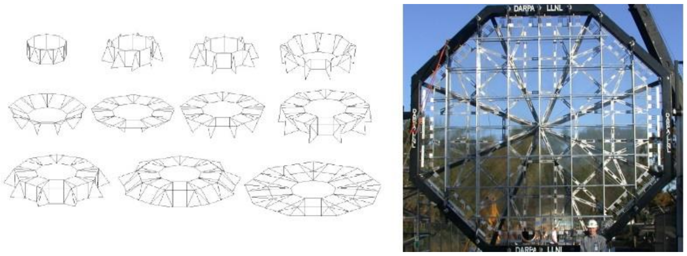

Figure 2.20 Eyeglass deployment schematic [47] and fully deployed prototype [49].

Less common crease patterns are integrated into the design of various robots for minimally invasive surgical procedures [50, 51]. One example is found in the ingestible robot contained in an ice capsule that dissolves when inside the body, shown in Figure 2.21. Once the ice dissolves, the robot deploys and navigates the body with a remote magnetic field. The robot can retrieve foreign objects (i.e., button batteries) and acts as a drug delivery system to treat stomach wounds.

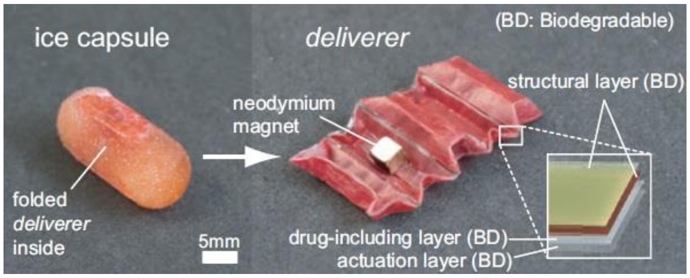

Figure 2.21 Ingestible ice capsule holding deployable origami-inspired robot capable of treating stomach wounds [51].

Researchers have adapted the Chomper crease pattern to create origami-inspired forceps, called Oriceps, to assist with robotic surgical procedures, shown in Figure 2.22 [52]. The integration of origami principles in the forceps design can reduce part count required for manufacture and simplify sterilization processes. The unique crease pattern is scalable allowing the forceps design to be useful at macro and microscales.

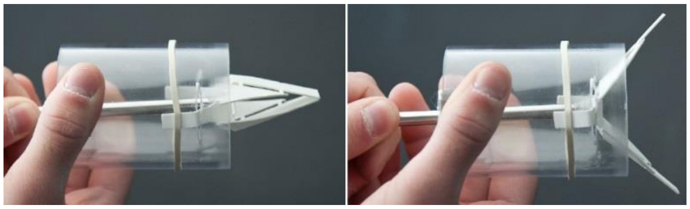

Figure 2.22 Oriceps in closed and open states [52].

A modular origami pattern called the “twisted tower” is used for the design of a robotic arm, shown in Figure 2.23 [53]. The arm features layers of modular units created from individual origami segments. The “twisted tower” pattern enables twisting and bending motion when fully assembled and allows the robotic arm to have a high linear extension-to-contraction ratio [54]. The robotic arm is useful for manufacturing, medicine, and space applications.

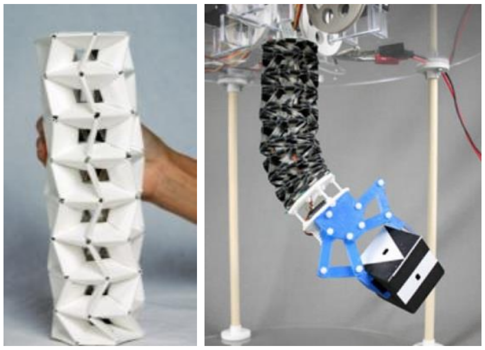

Figure 2.23 (left) Twisted tower paper model, (right) Bending motion of assembled robotic arm [54].

The Turkish fold is used for maps, called PopOut Maps, shown in Figure 2.24 [55]. The crease pattern allows the map to be folded and unfolded by simply opening and closing the cover [56].

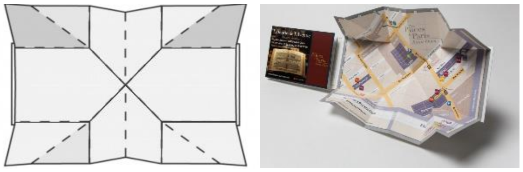

Figure 2.24 Deployable map design [55].

Conventional ice buckets tend to be bulky items. However, a champagne ice bucket is transformed into a deployable, portable product with the integration of origami folds, shown in Figure 2.25 [57]. The ice bucket is included in the champagne packaging because it is lightweight and thin in the folded state. The ice bucket is watertight, reusable, and easy to store.

Figure 2.25 Foldable ice bucket [57].

Origami has inspired the production of biodegradable takeout containers that resemble a blooming flower when unfolded, shown in Figure 2.26 [58]. The unique crease pattern creates a self-locking mechanism when folded which enables the container to close without use of adhesives. Fuse et al. has developed a similar design for origami-inspired paper food containers [59].

Figure 2.26 Origami-inspired takeout packaging [58].

A wine carrier integrates an origami crease pattern to enable portability and compact storage shown in Figure 2.27 [60]. The handle wraps around the tote to maintain the collapsed form.

Figure 2.27 (left) Crease pattern section view [60], (center) Expanded state, (left) Collapsed state [61].

Origami has inspired the novel design of a backpack through a unique crease pattern comprised of isosceles triangles, shown in Figure 2.28 [27]. The backpack pattern appears similar to the Yoshimura crease pattern at first glance. However, the Yoshimura pattern specifies mountain and valley folds while the backpack pattern does not. This allows the material to conform to the contents inside reducing relative motion and ultimately providing increased protection of the contents [27].

Figure 2.28 Isosceles triangle crease pattern used for backpack design [27].

Designers have created pots that integrate a triangular origami crease pattern which allows the roots of a plant to expand the pot as they grow [62]. The expanding pots, shown in Figure 2.29, eliminate the need for re-potting through the growth process.

Figure 2.29 Expanding origami-inspired pots [62].

A series of disposable trash cans integrate various unique crease patterns [63]. The trash cans are stored flat, easily assembled, and secured closed using a thread, shown in Figure 2.30.

Figure 2.30 Crease pattern used for disposable trash can [63].

Aside from paper folding activities and books, few children's toys integrate origami-inspired design. Shown in Figure 2.31 is a child's blanket that also functions as a toy which can be folded into a different shapes [64].

Figure 2.31 Reconfigurable children's blanket [64].

AnneeLondon produces an origami-inspired bicycle helmet capable of folding into a compact shape less than half of the deployed size, shown in Figure 2.32. The helmets ability to fold down allows for convenient packing when not in use. The flexible shell design can also maintain safety integrity despite multiple impacts lending to greater durability and higher safety ratings compared to conventional helmets [65].

Figure 2.32 Folding bicycle helmet [65].

2.2.5. Products Using Simple Folding, Shape-Changing Schemes

The products within this sub-section do not use origami in the traditional sense. Most of the products within this category do not begin from a planar orientation and do not use any specific crease pattern. Rather, the shape-changing qualities and folding characteristics of origami inspire the products in this category.

Origami has inspired the development of the Oru Kayak [66]. The kayak can be manually folded into the form of a storage case and unfolded into a rigid watercraft, illustrated in Figure 2.33. The integration of origami principles reduces manufacturing costs and allows the kayak to be portable and easily assembled. Folding from one solid plastic panel also minimizes seams, which prevents leakage and contributes to the kayak’s high strength-to-weight ratio. The structural integrity of the kayak is maintained with the addition of various removable components, such as a cockpit rim and floorboards [66].

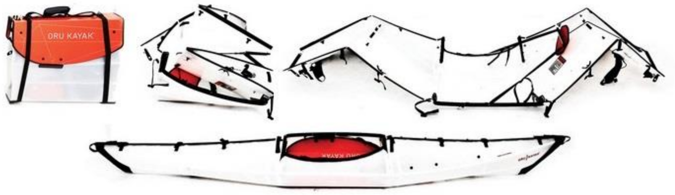

Figure 2.33 Unfolding process of Oru kayak [67].

A company has adapted the shape-changing abilities of origami for an entire line of home products, such as shelving, kitchen carts, and garden storage [68]. The products unfold for simple assembly and fold into a compact form when not in use, shown in Figure 2.34 [69].

Figure 2.34 Folding tool rack/workbench [68].

A revolutionary motorized stroller inspired by the shape-changing characteristics of origami can fold into a compact configuration and unfold at the push of a button, illustrated in Figure 2.35 [70].

Figure 2.35 Motorized folding stroller [71].

An origami-inspired bicycle, shown in Figure 2.36, has been developed to manually fold into a compact configuration for improved portability and storage [72].

Figure 2.36 Folding bicycle [72].

A deployable bridge intended for disaster relief situations has been designed using origami principles [73]. A scissor-structure is integrated to allow the bridge to transition from a compact, portable form into an expanded truss structure, shown in Figure 2.37 [74]. Origami principles have inspired other bridge designs, such as the Rolling Bridge by Heatherwick [75, 76].

Figure 2.37 Emergency bridge in folded and deployed configurations [73, 74].

Origami principles have inspired the design of antennas [77-79]. One example is a reconfigurable antenna that maintains constant resonant frequency and input impedance during deployment, shown in Figure 2.38. This antenna features a bidirectional radiation pattern in the planar spiral state. The radiation pattern becomes more directional as it is expanded to a conical spiral state. These origami-inspired shape-changing abilities produce a high-gain antenna once expanded and improve portability [78].

Figure 2.38 Spiral antenna in flat and expanded configurations [78].

The folding and unfolding mechanisms featured in the James Webb telescope are also origami-inspired [80]. This telescope is expected to have 6-times the light-collecting power of the Hubble telescope. The mirror segments and sunshield are designed to fold for compact storage during transport and deploy once in space, illustrated in Figure 2.39 [80].

Figure 2.39 Deployment process of the James Webb telescope [23].

Various quadrotor designs have integrated origami principles for search and rescue missions [8, 81]. The miniature aerial robot in Figure 2.40 has been developed with arms that automatically fold and self-deploy using origami principles. The quadrotor's arms are made of thin fiberglass adhered to a lightweight, inextensible fabric. The crease pattern is engraved into the fiberglass and the arms are manually folded along the creases. The fiberglass breaks when initially folded, but the fabric layer holds the fiberglass pieces together and allows folding motion along the creases. The propellers generate torque, which deploys the folded arms, illustrated in Figure 2.40. The origami-inspired arms enable compact storage of the quadrotor, increased arm stiffness, minimal weight, and design simplicity [8].

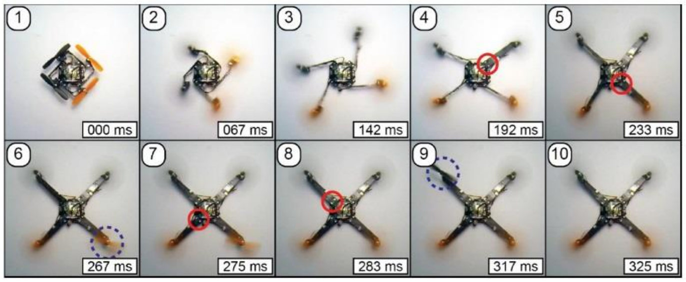

Figure 2.40 Deployment process of quadrotor arms [8].

Many origami-inspired children's toys exist in the form of paper folding crafts. However, few of these products are intended for applied use after the folding is complete. Kamigami Robots are children's toys that combine paper folding and application [82]. Children fold the flat components and install the electronics to assemble their robot, shown in Figure 2.41. Interestingly, the robot design originates from scientific research [83].

Figure 2.41 Components used to create a fully assembled Kamigami Robot [82].

Researchers have integrated origami principles with optical design to create a lightweight, durable microscope, called Foldscope, shown in Figure 2.42 [84]. The card stock body of the microscope is folded to provide alignment of the lens and light source. Foldscope is inexpensive to produce, compact, and portable, making it useful for various fields such as education, science, or medicine in developing countries [84].

Figure 2.42 Foldscope before and after assembly [84].

Horatio Han has used origami principles to create footwear called Unifold [43]. The footwear is easy to assembly, customizable, and inexpensive to produce compared to conventional footwear production, shown in Figure 2.43 [43].

Figure 2.43 Unifold footwear folded from planar state [43].

Industrial Origami is a company that specializes in origami-inspired manufacturing processes and materials design. They have developed numerous folding applications such as appliance drawers, electrical enclosures, heavy equipment, bearing retainers, stoves, and packing materials, shown in Figure 2.44. Deriving inspiration from origami provides numerous benefits for their products, such as reduced part count, simplified assembly, lower production costs, and increased rigidity of the finished structures [85].

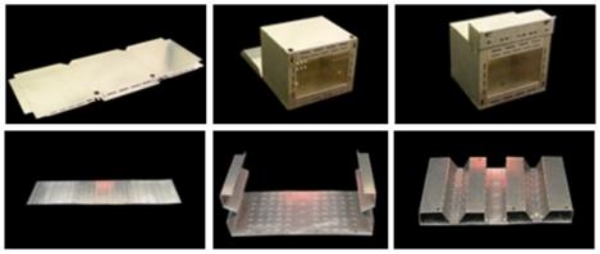

Figure 2.44 Sheet materials folded into stove and corrugated structure [85].

Origami principles have inspired the development of three-dimensional microfluidic devices used for diagnosis of various illnesses such as cancer [86]. The disposable testing device, shown in Figure 2.45, is prepared with microfluidic channels and reagents that react with test samples to detect the presence of disease, similar to a home pregnancy test. Traditionally, paper immunodevices are created by stacking separate layers and securing the layers in place using tape. However, origami-inspired immunodevices do not require tape because they are created by folding the attached tabs inward and held in place with an aluminum housing, which reduces the possibility of contamination and adsorption [87]. Using origami principles reduces costs and improves user friendliness of these immunodevices intended for communities with limited resources [86].

Figure 2.45 Front and back of microfluidic paper-based immunodevice [86].

Origami has inspired the development of a self-folding microgripper for minimally invasive surgical procedures, such as biopsies [88]. Conventional minimally invasive surgical tools must be connected to wires or tethers for operation, which limits maneuverability. The microgrippers do not require connections for operation. Rather, the microgrippers fold through thermal actuation and are magnetically navigated throughout the body making them superior to conventional devices. Though Figure 2.46 shows a metal microgripper, researchers are developing a polymeric microgripper to improve biocompatibility [89].

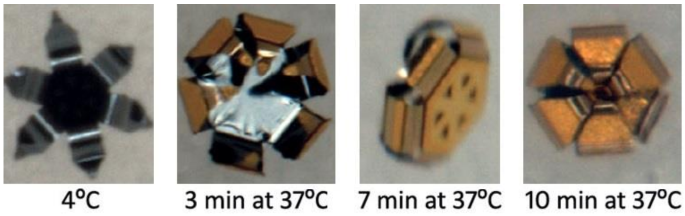

Figure 2.46 Self-folding sequence of thermally actuated microgrippers [88].

Another origami-inspired children’s toy is an educational book that features triangles which fold in and out revealing numbers, words, and animal pictures, shown in Figure 2.47 [90].

Figure 2.47 Children’s folding book [90].

A lightweight, folding pocket knife that conveniently fits in a wallet derives inspiration from origami shape-changing principles, shown in Figure 2.48 [91]. The credit card-shaped panel features hinges that fold around the blade to create a knife handle [92].

Figure 2.48 Folding pocket knife [91].

Deriving inspiration from a folded paper airplane, Arthur Chang developed a portable armrest divider intended for use on airplanes [93]. This origami-inspired device snaps onto the armrest and allows travelers sitting beside each other to simultaneously enjoy their own armrest space, shown in Figure 2.49 [94]. The armrest divider is thin, lightweight and can be stored flat for portability.

Figure 2.49 Airplane armrest divider [93].

Several origami-inspired designs have been applied to electronic device covers [95]. Isaiah Coberly has designed a reconfigurable case shown in Figure 2.50 [96]. The cover protects the device and provides a stable support structure that can be manually adjusted for numerous display options. The folded state relies on triangular-shaped structures that change size between adjustments [97]. The fluid motion between adjustments allows the user to find the desired viewing angle with ease. The cover is flexible enough to provide stability on a variety of surfaces, such as a tabletop or the user's lap [96].

Figure 2.50 Reconfigurable cover for electronic device [96].

An origami-inspired modular lighting system allows users to create custom light displays by unfolding triangular panels, shown in Figure 2.51 [98].

Figure 2.51 Interactive lighting system [98].

Researchers have developed an interactive audio-tactile system called ORFI, shown in Figure 2.52 [99]. ORFI features origami-shaped soft modules of various sizes containing bendable sensors, a microcomputer, and a radio transmitter and receiver to enable wireless communication between the modules [99]. Changes in light, video, and music occur when a user moves or bends the origami-shaped modules. ORFI is intended to enhance communication and interaction for people with disabilities [100].

Figure 2.52 (left) ORFI modules and video projection, (right) User interacting with modules [99].

Origami has inspired a unique assembly of highly efficient light bulbs called Nanoleaf [101, 102]. The dodecahedron shape, shown in Figure 2.53, enables LED lights to shine around the entire bulb surface. The bulb surface material is cut using a laser-scoring process and folded into the final shape [101].

Figure 2.53 Nanoleaf light bulbs [101].

Researchers have developed an origami-inspired solar-tracking concentrator array for planar photovoltaics, shown in Figure 2.54. Traditional photovoltaic systems with solar concentrators are bulky and expensive. However, integrating an origami-inspired design of the solar concentrators results in reduced volume, weight, and cost [103]. Further, the lightweight design lends to a reduction in actuation energy required.

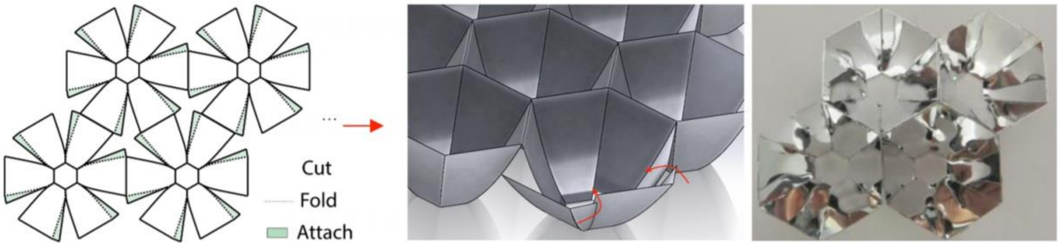

Figure 2.54 Solar-tracking concentrator array [103].

Mori is an origami-inspired modular robot prototype, shown in Figure 55. Mori features a simplified, low-profile design that can connect to other modules manually and reconfigure through folding actuation mechanisms located along the edges of each module. Non-modular robotic origami movement is generally constrained to the folding structure dimensions. However, modularity allows robotic origami to reconfigure without such structural constraints. Mori's functionality is demonstrated in Figure 2.55 where it maneuvers through a gap in a wall, retrieves an object, and reconfigures into a three-dimensional structure with other modules.

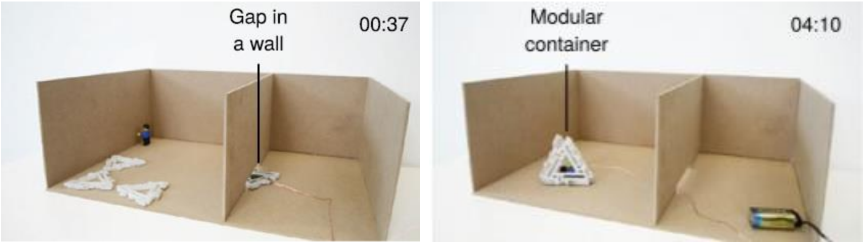

Figure 2.55 Maneuverability and reconfiguration of modular origami-inspired robot [104].

Origami has inspired the design of novel optoelectronics, shown in Figure 2.56. The electronic eye camera system features folded planar substrates creating a hemispherical focal planar array. Integrating origami principles into the camera design provides a simplified fabrication process and imaging results that conventional camera systems cannot capture. The origami-inspired camera system also features a high density array with numerous photodetectors compared to conventional planar optoelectronics [105].

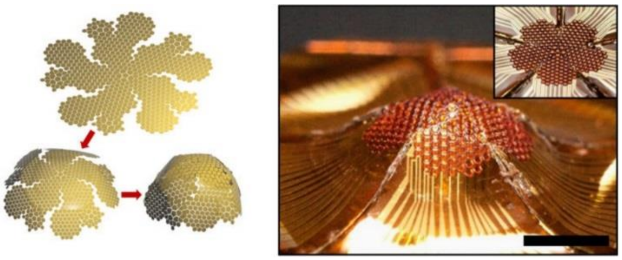

Figure 2.56 (left) Folding illustration of origami-inspired electronic eye camera, (right) Formation of eye camera prototype [105].

Researchers have developed origami-inspired artificial muscles, shown in Figure 2.57. The muscles feature a compressible skeleton structure and a flexible outer skin while a fluid medium is used to actuate the artificial muscle. The muscles are capable of various motions, such as contraction, bending, and torsion, and have demonstrated behaviors similar to natural muscles. The origami-inspired design of these artificial muscles allows low-cost fabrication, multiple degrees-of-freedom, and scalability [106].

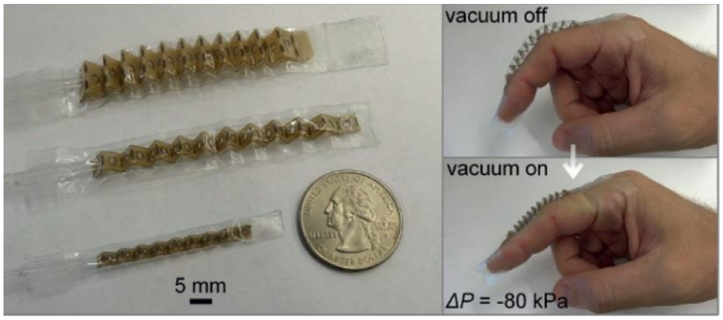

Figure 2.57 Artificial muscles comprising linear zigzag structures before and after fluid-driven actuation [106].

2.2.6. Products Using Origami Aesthetics

The aesthetics of origami inspire the products within this category. These products achieve no functional value through origami other than an aesthetically pleasing form. The focus of this sub-section lies primarily on products that achieve functional value through the integration of origami design principles. Therefore, aesthetically inspired products are not the focus of this review, and the products reviewed within this category are certainly not the only aesthetically inspired products that exist. However, the products reviewed within this category are an acceptable representation of products inspired by the aesthetics of origami.

A wireless computer mouse features unconventional planar surfaces inspired by the aesthetics of origami, shown in Figure 2.58 [107].

Figure 2.58 Origami-inspired computer mouse [107].

Sungmin Han has created various handbags with origami-inspired features [108, 109]. Each bag is sewn according to a simple crease pattern to create various handbag styles. Issey Miyake and other designers also use origami as design inspiration for handbags and clothing [110, 111]. Handbags designed by Finell are shown in Figure 2.59.

Figure 2.59 Origami-inspired handbags [111].

Bed linens integrate a printed origami crease pattern comprised of isosceles triangles, shown in Figure 2.60 [112].

Figure 2.60 Origami-inspired linens [112].

Various origami crease patterns have inspired the design of wallpaper prints, shown in Figure 2.61 [113]. The wallpaper appears textured due to the crease patterns, but each design is digitally printed so the wallpaper lays flat.

Figure 2.61 Origami-inspired wallpaper patterns [113].

Origami has inspired the design of home décor items such as tablemats, shown in Figure 2.62 [111]. The mats can serve as individual placemats or connect together to create runners. The ridges of the tablemats also collect spills and prevent spreading.

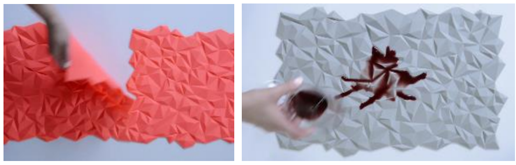

Figure 2.62 Origami-inspired tablemats [111].

2.3. Overall Trends in Origami Engineering and Product Design

A qualitative analysis based on product comparisons is made to reveal trends in origami-inspired product design. The comparisons are based on depth of origami integration (common crease pattern, less common crease pattern, simple folding schemes, aesthetics), commercial viability (commercial product versus physical prototype), and product scale. While the authors have made every effort to include as many origami-inspired products as possible, it is impossible to claim that this review includes every origami-inspired product. Therefore, the qualitative analysis is based on a sample, which are the products reviewed in this sub-section.

Of the 36 products that are commercial products, 5 designs integrate common crease patterns, 9 designs integrate less common crease patterns, and 15 designs integrate simple folding, shape-changing schemes. All 7 aesthetically inspired designs are commercial products. These trends, shown in Figure 63, may imply that products integrating simple origami shape-changing schemes experience greater success commercially.

Of the 40 products that are physical prototypes, 14 designs integrate common crease patterns, 9 designs integrate less common crease patterns, and 17 designs integrate shape-changing schemes. Interestingly, the physical prototypes integrate greater depth of origami inspiration compared to the commercial products, as illustrated in Figure 2.63.

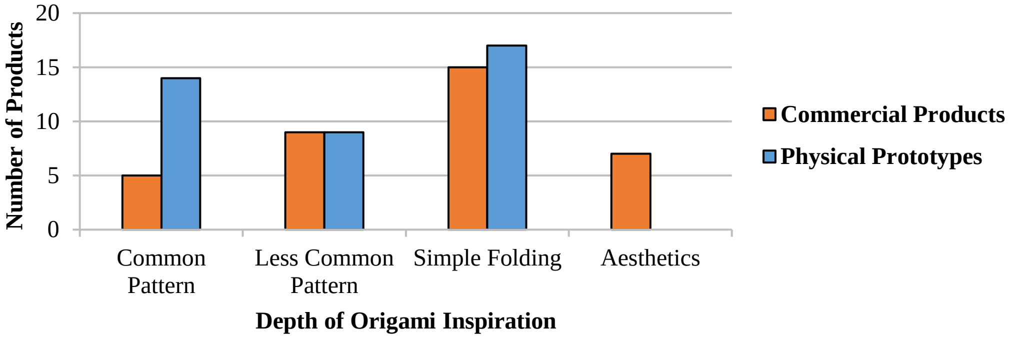

Figure 2.63 Depth of origami inspiration utilized based on commercial viability of products.

While origami-inspired design is integrated across very small scales of 0.003m (microgrippers) and very large scales of 20m (telescopes), the majority of products fall within the small-scale range (less than 1m in size). The difference of product quantities within the various scales may be due to the lack of advanced manufacturing technology, which prevents development of origami-inspired products at the very small and larger scales. Often, origami-inspired designs feature more complex manufacturing requirements where intricate folding and assembly is required. Approximately 58% of origami-inspired products are between 0.1m and 1m in size with approximately 9% of products greater than 5m, illustrated in Figure 2.64.

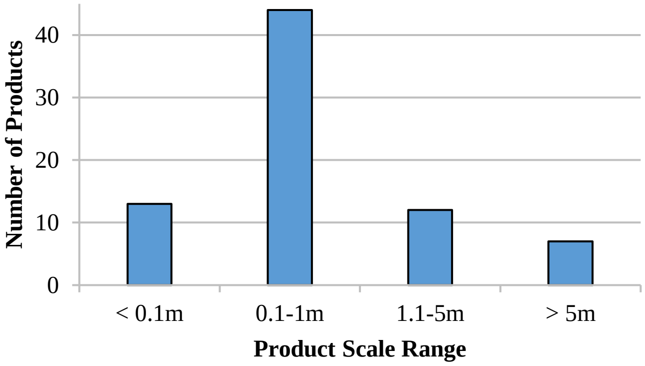

Figure 2.64 Scale ranges for origami-inspired products.

A timeline of origami-inspired product design is shown in Figure 2.65. The timeline represents the year products were developed according to references provided. Only two origami-inspired products that meet the independent qualifications defined in Section 2.2 were developed prior to the year 2001. The pioneer of origami-inspired product design, Koryo Miura, applied origami to map folding in 1978 [21]. Miura also applied origami to solar panel folding in 1985 [9]. The x-axis of Figure 65 begins at year "< 2001" and shows only these two products during this time period. The sparse product development from 1978-2010 is likely due to the research focus on origami mathematics and theory rather than origami product design. Often, the mathematics and theory of an emerging research field must be rigorously defined prior to prolific engineering application. Approximately 70% of origami-inspired products were developed in the last five years. Therefore, integrating origami principles into product design is a fairly new concept and emerging design methodology.

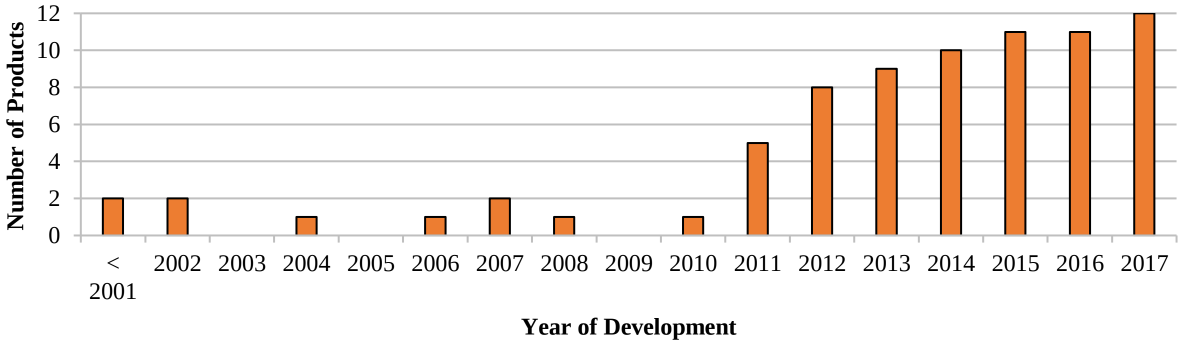

Figure 2.65 Origami-inspired product development timeline.

2.4. Summary

This section provides a survey of origami-inspired products to identify and define the state-of-the-art in the evolving field of origami-inspired product design. Products are categorized based on the level of design integration of origami principles. A qualitative analysis is performed based on various product comparisons. This qualitative analysis reveals several interesting trends in the field. Products integrating simple folding schemes experience greater success commercially. Physical prototypes integrate greater depth of origami inspiration compared to the commercially successful products. While the profession of each designer cannot be determined with absolute certainty, it may be estimated that academic researchers in engineering and mathematical disciplines develop the majority of products that integrate established origami crease patterns such as the Miura-ori, Waterbomb base, and Yoshimura. Interestingly, non-engineers develop the majority of products inspired by the folding behavior of origami and the aesthetics of origami. The products in these two categories saturate the commercial market compared to products integrating greater depth of origami inspiration. A balance between designer expertise and attaining commercial success of the product may be beneficial for the future of origami-inspired product design. The lack of advanced manufacturing technology may also be an issue hindering the commercial viability of physical prototypes featuring more complex origami-inspired designs, where intricate folding and assembly is required. Therefore, the development of innovative manufacturing methods is a potentially promising research area to advance origami-inspired product design. Overall, integrating origami principles into product design is a new and emerging design methodology with opportunity for contribution and improvement.

3. BIOINSPIRED DESIGN[*]

This section focuses on the relationships between bioinspired design and origami. Section 3.1 presents an overview of bioinspired design including the foremost challenges in this field. Section 3.2 provides three separate examples of origami crease patterns and associated engineering applications that are analogous to or are entirely inspired by biological examples. Section 3.3 summarizes the relationships between origami and nature and the impact these relationships have on this dissertation work.

3.1. Overview

Using nature as a source of design inspiration is known as bioinspired design. Biological systems are known for energy-efficiency, multi-functionality, and diversity. Therefore, applying biological solutions to engineering problems is significantly valuable. While nature may offer a wealth of design solutions to engineers, various challenges prevent the transfer of knowledge from biology to the engineering domain. One of those challenges is the retrieval of useful design inspiration.

3.2. Bioinspired Origami

The prior research efforts that motivate this dissertation are discussed in the following sub-sections. The research areas discussed include relationships between origami and nature and bioinspired design search tools.

Three fundamental origami crease patterns are analogous to or entirely inspired by biological

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[*] Part of this section is reprinted with permission from "Development of a Keyword Search Algorithm for Bioinspired Design of Foldable Engineering Applications" by Elissa Morris and Daniel A. McAdams, 2017. *Proceedings of the ASME 2017 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Volume 5B: 41st Mechanisms and Robotics Conference, pp. V05BT08A053, Copyright © 2017 by ASME.

structures. To demonstrate the contribution and impact of origami-inspired design, engineering applications are provided for each biologically analogous crease pattern.

3.2.1. Tree Leaves Analogous to Miura-ori Pattern

The most common origami crease pattern is the Miura-ori developed by Koryo Miura. The Miura-ori features a regular corrugation pattern, called the Developable Double Corrugation (DDC) surface, shown in Figure 3.1 (left). The DCC surface features tessellations of a fundamental unit comprised of four identical parallelograms [19]. The Miura-ori is a natural minimum-energy folding pattern and has a single degree-of-freedom folding mechanism [20]. Therefore, pulling and pushing the two opposite diagonal corners enables a sheet of paper to easily expand and contract. This fold pattern has inspired various product applications, from folding maps to deployable solar arrays [9], shown in Figure 3.2.

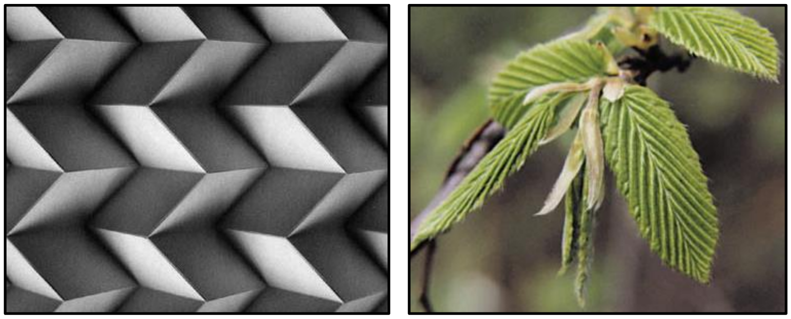

Figure 3.1 (left) Folded Miura-ori crease pattern [20], (right) Hornbeam leaves [114].

Similarities exist between the Miura-ori crease pattern and unfolding mechanisms of hornbeam and beech leaves [114]. The leaves feature several parallel lateral veins symmetrically arranged along a straight central vein generating a regular, corrugated pattern, shown in Figure 3.1 (right). Using a paper model to simulate the unfolding process of the leaf, researchers show that kinetic energy during unfolding increases with increasing vein angles. Researchers speculate the function of the corrugated pattern may be related to mechanical support of the plant structure or to the transportation of fluids throughout the leaf [114].

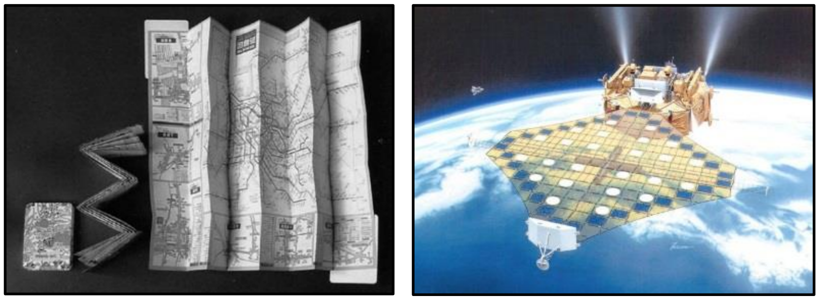

Figure 3.2 Miura-ori applications: (left) [19], (right) Deployable solar array [22].

Considering the energy efficiency of natural systems, it is interesting that the Miura-ori features a minimum energy folding mechanism due to its corrugated surface similar to the corrugated patterns of hornbeam and beech leaves. Other energy-efficient systems may exist in nature that may be useful for the development of crease patterns or deployable structures.

3.2.2. Hawkmoth Analogous to Kresling Pattern

Researchers have developed abstract models of the giant hawkmoth's abdominal air sac [115, 116]. This bellows-like sac pumps blood throughout the insect's circulatory system. The microscopic pattern of the abdominal sac is analogous to the geometry of an origami crease pattern, called the Kresling, shown in Figure 3.3 [116, 117].

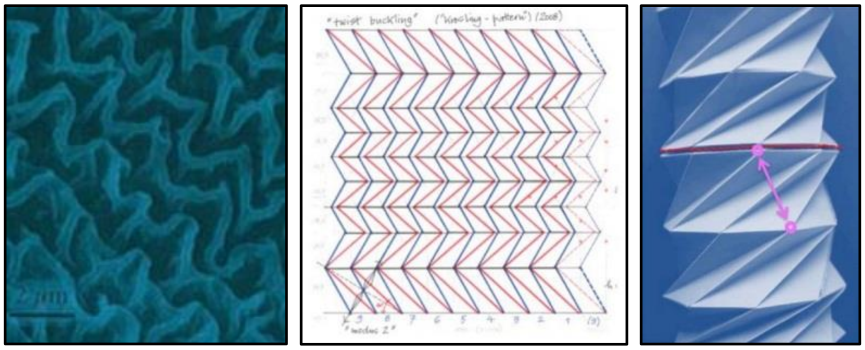

Figure 3.3 (left) Hawkmoth air sac pattern, (center) Kresling crease pattern, (right) Folded Kresling cylinder [116, 118].

The Kresling is a natural twist buckling pattern that allows simultaneous two-directional expansion with minimal shear stress folding mechanisms [118]. Researchers use the Kresling pattern for the design of sunshields for an X-ray telescope, shown in Figure 3.4 [23].

Figure 3.4 Kresling pattern application: (left) Folded sunshield prototype, (right) Deployed sunshield prototype [23].

3.2.3. Pinecone-inspired Pineapple Pattern

Biruta Kresling is a pioneer in bionics – the study and application of biological principles to engineering problems - with expertise in deployable and foldable biological structures. Kresling, along with her student N. Maillard, studied the morphology of pine cones to understand its mechanical principles during opening. Changes in humidity cause the scales of pine cones to open, or deploy, allowing seed dispersal [119]. Kresling and her student created an abstract model of the diamond-shaped scales on the surface of pine cones which inspired the development of an origami crease pattern called 'ananas' (translated pineapple), shown in Figure 3.5 [120].

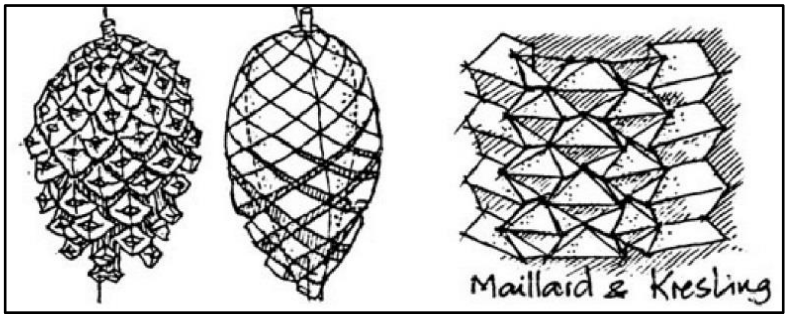

Figure 3.5 Abstraction of pine cone surface inspires pineapple crease pattern [120].

The pineapple pattern features tessellations of the oldest known base in origami history, the waterbomb [121]. While the waterbomb existed prior to the pineapple pattern, the bioinspired manner in which Kresling and her student assembled the bases is novel. When folded, the geometry of the pineapple pattern generates structures with negative Poisson's ratio (i.e., auxetic) and produces shapes capable of positive or negative Gaussian curvature [118, 122]. The most notable application of the pineapple pattern is the medical stent graft developed by Kuribayashi [10, 118], shown in Figure 3.6.

Figure 3.6 Pineapple pattern application: Medical stent graft for osophogeal cancer treatment [37].

3.3. Summary

Prior work clearly demonstrates that the abstraction of biological structures can lead to the development of novel foldable solutions for engineering problems. However, prior work is limited to the study of insect wings, insect abdominal air sacs, and the structural and physical properties of plants. Though not explicitly stated in the literature, these biological analogies used to inspire the design of foldable engineering applications were likely discovered either through brute force methods or chance. Certainly, the examples studied previously are not the only examples of foldable structures and inspiring geometries in nature. Therefore, this research effort aims to provide a more refined method for the discovery of folding patterns, structures, and behaviors in nature using basic information retrieval techniques in lieu of brute force methods most likely utilized in prior research efforts.

4. INFORMATION RETRIEVAL*

This section discusses information retrieval tools that have been developed for bioinspired design. Section 4.1 presents the importance of utilizing information retrieval techniques when addressing the challenges posed by bioinspired engineering design. Section 4.2 discusses existing bioinspired design search tools. Section 4.3 contains the limitations of these existing tools and how these limitations help define the objectives of this dissertation research.

4.1. Overview

Information retrieval involves the extraction of relevant documents, or passages, from an extensive collection of documents, or a corpus. Precision, recall, and f-measure are statistical measures used to evaluate the performance of the information retrieval techniques employed. These statistical measures are discussed at length in Section 5 of this dissertation. Information retrieval methods enable web search engines (i.e., Google, Google Scholar, Web of Science, etc.) to be used on a daily basis by billions of users. While web search engines are useful for generic, everyday searching, their performance is limited when searching for bioinspired design inspiration.

This performance discrepancy is largely due to the inefficient transfer of knowledge from the biological domain to the engineering domain, which poses a significant challenge to effective bioinspired design. Research has demonstrated the value of using information retrieval techniques to facilitate bioinspired design [12-17]. Therefore, various information retrieval tools with curated databases have been developed and are discussed in the following section.

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* Part of this section is reprinted with permission from "Development of a Keyword Search Algorithm for Bioinspired Design of Foldable Engineering Applications" by Elissa Morris and Daniel A. McAdams, 2017. *Proceedings of the ASME 2017 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Volume 5B: 41st Mechanisms and Robotics Conference, pp. V05BT08A053, Copyright © 2017 by ASME.

4.2. Information Retrieval for Bioinspired Design

The text-based search tools discussed in this section include AskNature, IDEA-INSPIRE, and DANE.

AskNature is an online, searchable repository of biological content categorized by function [123]. The searchable content consists of journal articles gathered and regulated by professional biologists [15]. IDEA-INSPIRE is a software program capable of searching two distinct databases – a database of natural systems with content related to plant and animal domains or a database of artificial systems related to the engineering domain [14]. Design solutions are structured using a causality model for natural and artificial systems. DANE is another design tool with a curated database searchable by function. DANE provides an interactive design environment that relies on a Structure-Behavior-Function categorization scheme to sort biological systems [16].

4.3. Summary

Bioinspired design search tools, such as AskNature, IDEA-INSPIRE, and DANE, feature curated databases. Curated databases are inherent limitations because design opportunities are confined to the curator’s selected content. Instead, a database comprising various biological literature sources from a variety of biological disciplines is a less constrained approach. Further, these search tools are used for general bioinspired design purposes. Due to the generalized nature of these tools, engineers in niche fields, such as origami engineering, may encounter difficulty using the tools and adapting the biological solutions to foldable engineering problems.

While the design tools above facilitate general bioinspired design, this dissertation work is specifically focused on the retrieval of biological analogies for the design of foldable engineering applications. Therefore, a keyword search algorithm is developed to specifically retrieve biological patterns, structures, and behaviors related to folding. A search algorithm designed for this distinct purpose does not exist in the literature. A pre-determined list of keywords guides the designers with limited knowledge of biological jargon to select a biologically meaningful search term. The search algorithm's filtering methods also ensure the biological examples returned to the designer are related to folding.

5. RESEARCH APPROACH*

This section is devoted to the research approach and methods used in this dissertation work. Section 5.1 provides the problem identification and the motivation for this research. Section 5.2 discusses the development of the text-based search algorithm including the keyword selection, the biological corpus, filtering methods, and algorithm functionality. Validation procedures of the text-based search algorithm are described in Section 5.3. The impact and remaining challenges for this research are discussed in Section 5.4.

5.1. Problem Identification and Motivation

The science of folding has inspired and challenged scholars for decades. Researchers have shown that folding can increase stiffness and flexibility of materials, decrease bulk and weight, enable structural transformation, and provide design multifunctionality [5-8]. Folding has provided solutions to a variety of engineering problems, as evidenced by deployable solar arrays and medical stent grafts [9, 10]. Many foldable product solutions are inspired by origami, the art of folding paper [11]. In origami, a crease pattern refers to the network of creases produced by folding. Interestingly, three fundamental origami crease patterns are similar to or are entirely inspired by structures and patterns observed in nature.

Using nature as a source of design inspiration is known as bioinspired design. Biological systems are known for energy-efficiency, multi-functionality, and diversity. Therefore, applying biological solutions to engineering problems is significantly valuable. While nature may offer a

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wealth of design solutions to engineers, various challenges prevent the transfer of knowledge from biology to the engineering domain. One of those challenges is the retrieval of useful design inspiration.

This research explores nature in search of folding patterns, structures, and behaviors that may be useful for bioinspired design of foldable engineering applications. Research has demonstrated the value of using information retrieval techniques to facilitate bioinspired design [12-17] . Therefore, the objective of this research effort is two-fold – 1) to develop and validate a text-based keyword search algorithm specifically designed to retrieve folding mechanisms, behaviors, and patterns in nature, and 2) to create abstract models of the retrieved biological systems to inspire the development of origami crease patterns and novel foldable structures. The process for design abstraction of the retrieved biological systems is formalized and validated as an additional research contribution in Section 6.

5.2. FoldSearch Development

FoldSearch is a text-based search algorithm developed to mine biological text for passages describing biological structures, behaviors, and/or patterns related to folding. These retrieved passages serve as design inspiration that may be potentially useful for the development of foldable engineering solutions. The algorithm searches biological text files using specified keywords and filtering methods. Components of the search algorithm are discussed in the following sub-sections, including keyword selection, the biological corpus, filtering methods, readability, and functionality.

5.2.1. Keyword Selection Procedures

“Fold” is the fundamental keyword for the search algorithm and serves as the starting point for keyword list development. The list currently includes 20 keywords which assist the retrieval of folding and/or foldable structures in nature from biological text. Before discussing the development of the entire keyword list, the complexities of formally defining “fold” within a biological context is presented.

The general definition of “fold” is “to lay one part over another part of” or “to reduce the length or bulk of by doubling over” [124]. Folding enables shape transformations, such as the transition from a two-dimensional surface to a three-dimensional structure. These transformations are characteristic of traditional origami where a flat piece of paper is folded to create a three-dimensional shape. When using a paper medium, sharp folds are attainable due to essentially zero thickness of the sheet. However, zero thickness materials are uncommon in the natural world, which makes folding in nature much different.

In the context of nature, the use of the word “fold” is more abstract. Folding in a biological context can refer to a simple movement required to achieve some function. To illustrate, a chameleon’s hyoglossus complex *folds* compactly like an accordion during storage inside the mouth and rapidly *unfolds* to capture prey [125]. Folds also refer to naturally occurring patterns. To illustrate, layers of rock and sediment undergo deformation over time due to various external forces causing the formation of geological *fold* patterns [126]. Folds may also refer to biological structures. To illustrate, the larynx contains membranous tissues, called vocal *folds,* which produce sound through vibration and regulation of air flow [127]. As the examples in Figure 5.1 demonstrate, “fold” is used in various forms in a biological context. Understanding these forms guides the selection process of meaningful keywords for the search algorithm.

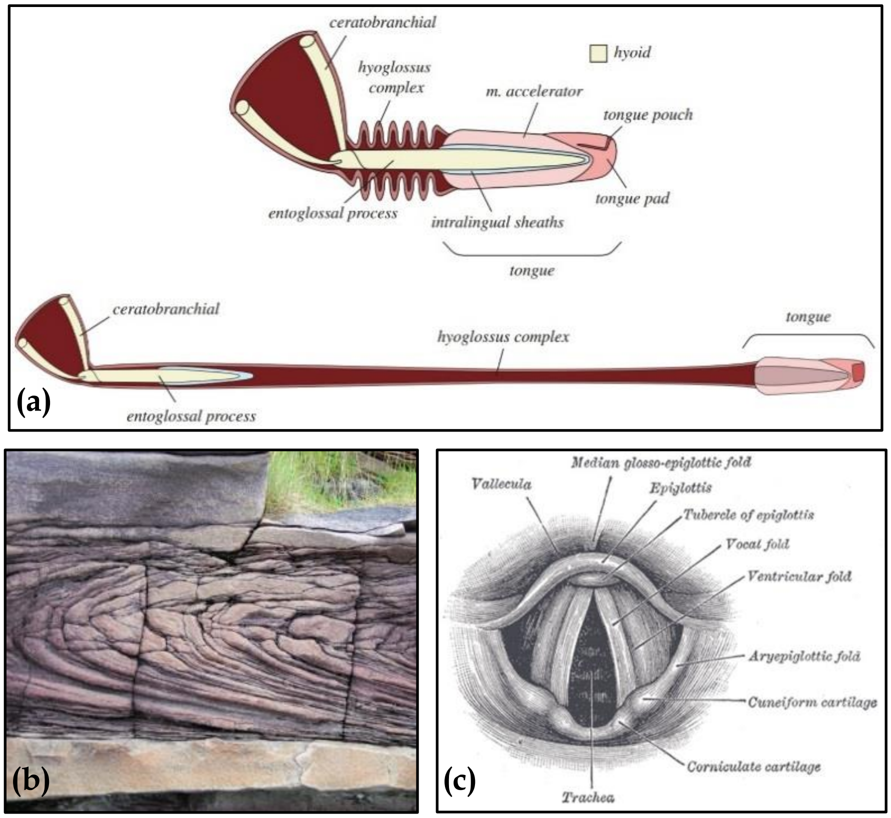
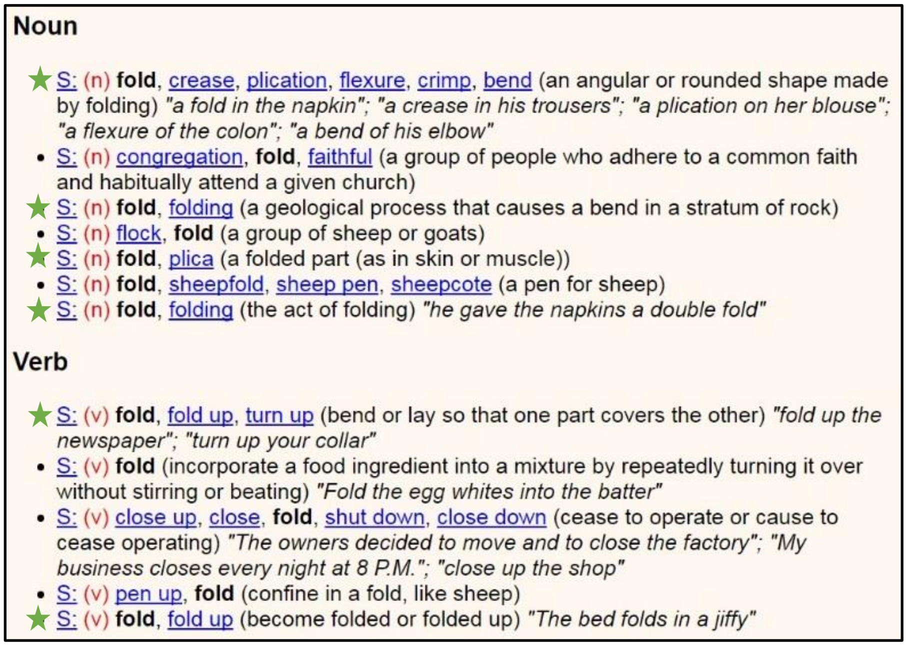


Figure 5.1 (a) Folded and unfolded configurations of chameleon hyoglossus complex [125], (b) Geological fold patterns observed in sediment [126], (c) Anatomy of vocal folds in open position [127].

The development of the keyword list is divided into three phases. The first phase includes compiling “fold” synonyms as they are discovered through a literature review of biological articles. In the second phase, an additional literature review of biological articles is conducted using the discovered terms from phase one. New “fold” synonyms are then added to the keyword list. In the third phase, final terms are added to the list using WordNet, the renowned English lexical database [128]. WordNet contains definitions of “fold” in noun and verb forms. Additional keywords are collected based on biologically relevant definitions of “fold” within WordNet. For example, the first definition shown in Figure 5.2 (“an angular or rounded shape made by folding”) is considered a potentially biologically relevant definition of “fold.” Therefore, the synonyms associated with that definition are included in the keywords list (“crease,” “plication,”, “flexure,” “crimp,” and “bend”). However, the second definition shown in Figure 5.2 (“a group of people who adhere to a common faith and habitually attend a given church”) is not considered a biologically relevant definition of “fold.” Therefore, the synonyms associated with that definition are not included in the keywords list (“congregation,” “faithful”). All biologically relevant forms of “fold” using WordNet are indicated with green stars in Figure 5.2. The overall process illustrating the three phases of keyword compilation is shown in Figure 5.3.



Noun

★ S: (n) **fold**, crease, plication, flexure, crimp, bend (an angular or rounded shape made by folding) *"a fold in the napkin"; "a crease in his trousers"; "a plication on her blouse"; "a flexure of the colon"; "a bend of his elbow"*
- S: (n) congregation, **fold**, faithful (a group of people who adhere to a common faith and habitually attend a given church)

★ S: (n) **fold**, folding (a geological process that causes a bend in a stratum of rock)
- S: (n) flock, **fold** (a group of sheep or goats)

★ S: (n) **fold**, plica (a folded part (as in skin or muscle))
- S: (n) **fold**, sheepfold, sheep pen, sheepcote (a pen for sheep)

★ S: (n) **fold**, folding (the act of folding) *"he gave the napkins a double fold"*

Verb

★ S: (v) **fold**, fold up, turn up (bend or lay so that one part covers the other) *"fold up the newspaper"; "turn up your collar"*
- S: (v) **fold** (incorporate a food ingredient into a mixture by repeatedly turning it over without stirring or beating) *"Fold the egg whites into the batter"*
- S: (v) close up, close, **fold**, shut down, close down (cease to operate or cause to cease operating) *"The owners decided to move and to close the factory"; "My business closes every night at 8 P.M."; "close up the shop"*
- S: (v) pen up, **fold** (confine in a fold, like sheep)

★ S: (v) **fold**, fold up (become folded or folded up) *"The bed folds in a jiffy"*

Figure 5.2 WordNet output – green stars indicate relevant forms used to expand keyword list [129].

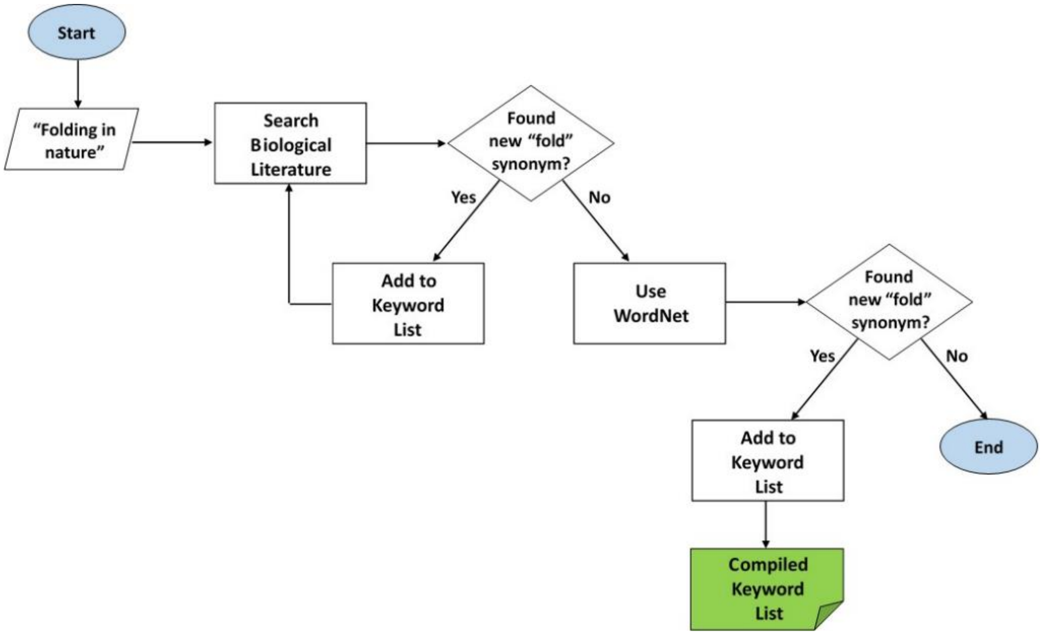


Figure 5.3 Biological keyword compilation process.

Naturally, this compilation process generates a large list of potentially biologically meaningful keywords for the base word "fold." The compiled list of keywords resulting from this process is shown in Table 5.1 and contains 58 keywords. The list must only include biologically meaningful forms of the base word "fold" when searching a biological text. These 58 keywords are assumed to be biologically relevant but that assumption must be tested.

Table 5.1 List of 58 potentially biologically meaningful keywords using compilation process illustrated in Figure 5.3.

Potential Biological Keywords			
Assemble	Crimp	Inflate	Ripple
Actuate	Curl	Invaginate	Roll
Bend	Curve	Kink	Shape Change
Bloom	Deform	Loop	Snap
Buckle	Deflect	Move	Spread
Collapse	Deploy	Open	Stack
Coil	Elongate	Orient	Stretch
Compact	Expand	Oscillate	Switch
Compress	Explode	Pleat	Transform
Conform	Extend	Plicate	Transition
Contort	Flex	Reconfigure	Tropism
Contract	Flip	Response	Tuck
Corrugate	Fold	Resurrect	Turn
Crease	Furl	Retract	Twist
			Wrap
			Wrinkle

To determine keyword performance in a biological context, information retrieval metrics are calculated by searching all 58 potentially biologically meaningful keywords using three different biological text files. These information retrieval metrics include precision, recall, and f-measure, or F1, scores. The equations for these performance measures are shown below, where 'document' refers to passage [130].

$$Precision = \frac{Relevant\ retrieved\ document}{Retrieved\ document}$$

$$Recall\ = \frac{Relevant\ retrieved\ document}{Relevant\ document}$$

$$F1\ score = \frac{2 * (Precision \cdot Recall)}{Precision + Recall}$$

Precision measures the number of relevant passages that are retrieved compared to the total number of passages containing the biological keyword. Recall measures the number of relevant passages retrieved compared to the total number of relevant passages containing the biological keyword. The f-measure, or F1 score, combines precision and recall values to indicate overall performance.

The text files used for the keyword analysis are *The Grand Design: Form and Colour in Animals* [131], *Life: The Science of Biology* [132], and selected volumes from the *Journal of Animal Behavior*. These three text files are among the smallest in the biological corpus used for the search algorithm, which is discussed further in Section 5.2.2 of this dissertation. One may assume that using the smallest text files in the biological corpus would produce less accurate results for the keyword analysis compared to using the largest text files in the biological corpus. To test this assumption and justify the text file selection made for the keyword analysis, the three selected text files are compared with the largest text file in the corpus which contains selected volumes of *Current Biology*. The comparison is based on three metrics: text file word count, combined keyword frequency (i.e., the number of times the keywords appear within the document), and overall frequency (the percentage of keyword appearances within the document with respect to the total word count of the document). The comparison results are shown in Table 5.2. The results show that file size is not necessarily the best indicator for selecting a text file for the keyword analysis process. It should be noted that *The Grand Design: Form and Colour in Animals* [131] is the least formal biological text in the corpus, intended for more casual reading. *Life: The Science of Biology* [132] is a more advanced form of biological literature because it is a college-level biology textbook. The most advanced biological texts are the journal publications, which include *Journal of Animal Behavior* and *Current Biology*. The text file comparison results in Table 5.2 indicate that the more basic forms of biological literature yield better overall frequency percentages compared to the more advanced forms of biological literature. It can also be argued that if a keyword does not perform well in the most basic forms of biological literature, then the keyword may not perform well in the more advanced forms of biological literature either. To ensure the selected keywords are meaningful across a broad spectrum of biological literature, the keyword analysis uses three different text files – one text file with a basic form of biological content, one text file with collegiate-level biological content, and one text file with more advanced, research-based biological content.

Table 5.2 Text file comparison.

Text File	Text File Word Count	Combined Keyword Frequency	Overall Frequency
Current Biology	25.43 million	22649	0.09%
The Grand Design	0.08 million	191	0.24%
Life: The Science of Biology	0.32 million	433	0.14%
Journal of Animal Behavior	1.82 million	486	0.03%

The keyword analysis consists of two parts. The first part requires searching all 58 keywords shown in Table 5.1 using two text files – *The Grand Design: Form and Colour in Animals* [131] and *Life: The Science of Biology* [132]. Precision, recall and f-measure are calculated for each keyword. To compare these information retrieval metrics between the two text files, a scoring system is developed. Resolutions on whether to keep the keywords, delete the keywords, or evaluate the keywords using the third text file are made using this scoring system. The scoring system is shown in Table 5.3 which includes the score with its associated definition, keywords, count, and resolutions. Out of the 58 keywords, 33 keywords are eliminate from the final keyword list, 13 keywords are kept for the final keyword list, and 12 keywords require further analysis using a third text file. Scoring and resolutions for part one of the keyword analysis is described below.

Table 5.3 Keyword scoring results – Part 1.

Keyword Scoring Results - Part 1						
Score	**0**	**0***	**1**	**2**	**3**	**4**
Score Definition	**Disagree**	**0 Results/0 Relevant**	**Agree 0 Results**	**Agree 0 Relevant Results**	**Agree Low Precision**	**Agree Keep**
Keywords	Bend	Conform	Actuate	Assemble	Move	Coil
	Bloom	Contort	Buckle	Collapse	Open	Compact
	Compress	Deploy	Corrugate	Deform		Curl
	Contract	Flip	Crease	Kink		Curve
	Elongate	Invaginate	Crimp	Loop		Expand
	Extend	Orient	Deflect	Response		Flex
	Spread	Pleat	Explode	Transform		Fold
	Stretch	Ripple	Furl	Turn		Inflate
	Tuck	Switch	Oscillate			Retract
	Twist	Transition	Plicate			Roll
	Wrap		Reconfigure			Shape Change
	Wrinkle		Resurrect			Snap
			Tropism			Stack
Count	12	10	13	8	2	13
Resolution	**Compare with 3rd text file**	**Delete**	**Delete**	**Delete**	**Compare with filtering**	**Keep**

A score of “0” is assigned to keywords that disagree in performance between the two text files. Twelve of the 58 keywords receive this score. Considering a disagreement exists in performance between the two text files, further evaluation of these 12 keywords is needed using a third text file. A score of “0*” is assigned to keywords that return 0 passages (or “results”) in one text file and 0 relevant passages in the other text file. Ten of the 58 keywords receive this score. Considering these 10 keywords do not retrieve any passages or any passages that are relevant when searching biological literature, these keywords are eliminated from the keyword list. A score of “1” is assigned to keywords that return 0 passages in both text files. Thirteen of the 58 keywords receive this score. Considering these 13 keywords do not retrieve any passages when searching biological literature, these keywords are also eliminated from the keyword list. A score of “2” is assigned to keywords that return 0 relevant passages in both text files. Eight of the 58 keywords receive this score. Considering these 8 keywords do not retrieve any relevant passages when searching biological literature, these keywords are also eliminated from the keyword list. A score of “3” is assigned to keywords that produce low precision values (< 20%) in both text files. The precision value threshold of 20% is used to ensure a conservative approach to keyword elimination. Two of the 58 keywords receive this score. The low precision scores are reasonable considering the keywords (“move” and “open”) are arguably the least specific keywords in a biological context out of all 58 keywords. These 2 keywords retrieve thousands of passages that are irrelevant to folding in nature. Considering these 2 keywords generate low precision when searching biological texts, these keywords are compared with precision values achieved using the filtering methods of the algorithm. These filtering methods are described in detail in Section 5.2.3 of this dissertation. The precision values achieved using the filtering methods for these 2 keywords remains low (< 20%). Therefore, these 2 keywords are eliminated from the keyword list. A score of “4” is assigned to keywords that produce good precision values (> 20%) in both text files. As stated before, the precision value threshold of 20% is used to ensure a conservative approach to keyword elimination. Thirteen of the 58 keywords receive this score. Considering these 13 keywords achieve acceptable precision values (> 20%), these keywords remain on the keyword list.

The second part of the keyword analysis is to search all 12 keywords that received a score of “0” in Part 1 of the keyword analysis using a third text file – selected volumes from the *Journal of Animal Behavior*. Similar to Part 1 of the keyword analysis, precision, recall and f-measure are calculated for each keyword. The same scoring system is used to compare these information retrieval metrics between the three text files. Resolutions on whether to keep the keywords, delete the keywords, or evaluate the keywords using the filtering methods of the algorithm are made using this scoring system. The results from part two of the keyword analysis are shown in Table 5.4 and are described below.

Table 5.4 Keyword scoring results – Part 2.

Keyword Scoring Results - Part 2						
Score	**0**	**0***	**1**	**2**	**3**	**4**
Score Definition	**Disagree**	**0 Results/0 Relevant**	**Agree 0 Results**	**Agree 0 Relevant Results**	**Agree Low Precision**	**Agree Keep**
Keywords	Contract Wrap	Wrinkle		Bloom Compress	Bend Extend Spread Twist	Elongate Stretch Tuck
Count	2	1	0	2	4	3
Resolution	**Compare with filtering**	**Delete**	**Delete**	**Delete**	**Compare with filtering**	**Keep**

Similar to part one of the keyword analysis, keywords that receive a score of “0*”, “1”, and “2” are eliminated from the keyword list and keywords that receive a score of “4” remain on the keyword list. Using these rules, 3 keywords are eliminated and 3 keywords are kept. Six keywords receive a score of “0” (keywords that disagree in performance between the three text files) and “3” (keywords that produce low precision values). These 6 keywords are compared with precision values achieved using the filtering methods of the algorithm among the three text files. These filtering methods are described in detail in Section 5.2.3 of this dissertation. If acceptable precision values (> 20%) are achieved in 2 out of 3 text files using the filtering methods of the algorithm, the keyword remains on the keyword list. The keyword is eliminated from the keyword list if it achieves poor precision values (< 20%) in 2 out of 3 text files using the filtering methods of the algorithm. Using these rules, 4 keywords remain on the keyword list (“bend”, “extend”, "twist", and "wrap") and 2 keywords are eliminated ("contract" and "spread"). Therefore, 7 keywords remain on the keyword list following Part 2 of the keyword analysis. Overall, the 13 keywords kept from Part 1 of the keyword analysis and the 7 keywords kept from Part 2 of the keyword analysis comprise 20 keywords on the final keyword list shown in Table 5.5. These 20 keywords are the most effective at retrieving passages from biological literature where folding in nature is described. Therefore, they serve as the keyword choices that users may select within the search algorithm, FoldSearch. In addition, the search algorithm integrates custom word stemming, a common information retrieval technique, to search for all relevant forms of each keyword. For example, when a user searches the keyword "fold," the algorithm also retrieves passages containing different forms of "fold" such as "unfold", "folding," "folds," "folded" and so forth.

Table 5.5 Final list of 20 biologically meaningful keywords after scoring analysis.

Biological Keywords			
Bend	Elongate	Inflate	Stack
Coil	Expand	Retract	Stretch
Compact	Extend	Roll	Tuck
Curl	Flex	Shape Change	Twist
Curve	Fold	Snap	Wrap

5.2.2. Biological Corpus

The search algorithm returns passages containing the selected keyword from a biological corpus. The corpus consists of large portions of journal publications and biological textbooks converted into searchable text files. These publications feature content related to different fields of biology, such as zoology, ecology, animal behavior, natural materials, and botany. The variety of research areas comprised within the corpus facilitates the retrieval of a variety of biological structures, behaviors, and/or patterns related to folding. The text files that comprise the corpus are listed in Table 5.6 along with approximate word counts. Indeed, the publications selected are a small sample of all biological literature and knowledge.

Table 5.6 Publications in biological corpus with approximate word counts.

Journal/Book Title	Word Count (millions)
Current Biology	25.43
Journal of Animal Ecology	9.58
Plant Physiology	7.45
Nature Materials	6.90
Journal of Zoology	4.05
Basic and Applied Ecology	3.25
Journal of Animal Behavior	1.82
Life: The Science of Biology	0.32
Elementary Biology	0.17
The Grand Design	0.08

5.2.3. Filtering Methods of Search Modes

The keyword search algorithm, FoldSearch, features three search modes – Raw Search, Descriptive Search, and Ignore Search. Each search mode employs different filtering methods which are detailed in this section. A performance comparison between the three search modes is included at the end of this section along with a flowchart illustrating the overall process of the algorithm.

The first search mode is Raw Search which retrieves every passage containing the selected biological keyword with no filtering methods integrated. No filtering methods are utilized in the Raw Search mode. Therefore, using Raw Search produces thousands of passages for each keyword. Most of these passages are irrelevant or redundant. To improve the quality of results, two distinct filtering search modes are available to the algorithm user – Descriptive Search and Ignore Search.

Descriptive Search integrates a list of descriptive words that commonly appear in relevant passages. Relevant passages including the biological keyword typically include the keyword used in conjunction with a word that relates to geometry, structure and shape, biological nouns, direction, and/or pronouns. Consider the following retrieved passage describing the biological processes involved in the movements of a sea anemone, from *Life – The Science of Biology* [132]:

> *"To* **extend** *its body and its tentacles, the anemone closes its mouth and constricts muscle fibers that are arranged in circles around its body."*

The selected biological keyword is bolded in the above passage ("extend"). The descriptive words are underlined and include words relating to pronouns ("its"), structure and shape ("body" and "circles"), and biological nouns ("muscle"). To illustrate further, consider the following retrieved passage describing the pattern on a peacock's train, from the *Journal of Animal Behavior*:

> *"The asymmetrical minor eyespot and sword feathers along the lower edges of the left and right sides of the erect train (Fig. 1b) were* **curved** *and arranged with their concave edges downwards, such that a dense fringe of green barbs bordered the bottom edge of the erect train* [133]*."*

The selected biological keyword is bolded in the above passage ("curved"). The underlined descriptive words in this passage relate to geometry ("asymmetrical"), pronouns ("their"), direction ("downwards"), and biological nouns ("barbs"). When users select the Descriptive Search mode, passages are retrieved that contain their selected biological keyword from Table 5.5 and at least one descriptive word. As the above examples show, retrieved passages often contain more than one descriptive word. Passages that contain the selected biological keyword but do not contain at least one of the descriptive words are not retrieved. Table 5.7 shows the descriptive words categorized by word type. For example, descriptive words such as "upward" and "toward" are related to direction and movement. Therefore, these words fall into the Direction/Movement category. Further, descriptive words such as “ball” and “flat” are related to shape and structure. Therefore, these words fall into the Shape/Structure category. In addition, the search algorithm integrates word stemming, a common information retrieval technique, to search for all relevant forms of each descriptive word. For example, Descriptive Search mode retrieves passages containing different forms of the descriptive word “it” such as “it’s” and “itself.” Descriptive Search mode reduces the amount of irrelevant passages that FoldSearch retrieves because of the integration of the descriptive words list. Overall, the quality of results are improved compared to Raw Search mode, thereby saving designer’s time when searching for design inspiration.

Table 5.7 Words used in Descriptive Search mode.

Descriptive Words				
Origami/Geometry	**Shape/Structure**	**Biological**	**Direction/Movement**	**Pronoun**
Angle	Architecture	Antennae	Above	Her
Array	Arrangement	Barb	Against	His
Crease	Ball	Denticle	Back	It
Division	Body	Fin	Backward	Their
Geometry	Circle	Flower	Behind	
Grid	Flat	Leaf	Below	
Lattice	Form	Muscle	Beneath	
Mesh	Hexagon	Petal	Downward	
Mosaic	Jointed	Plant	Forward	
Network	Oblate	Proboscis	Interlocks	
Origami	Octagon	Scales	Inward	
Packing	Pentagon	Seedling	Movement	
Pattern	Profile	Spindle	Outward	
Reflection	Shape	Stem	Over	
Rigid	Shell	Tail	Toward	
Rotational	Size	Tendril	Under	
Symmetry	Sphere	Tissue	Upward	
Tessellation	Spiral	Web		
Thickness	Square	Wing		
Tiles	Structure			
Translational	Surface			
Vertex				

Ignore Search is the third search mode available in the FoldSearch algorithm. This search mode uses stop words as a filtering method for irrelevant passages. Using the Raw Search mode for each biological keyword retrieves thousands of passages related to microscale biology. The Ignore Search mode is created on the basis that bioinspired origami (and bioinspired design, in general) frequently uses macroscale biology. Therefore, the Ignore Search mode integrates stop words related to microscale biology. In this way, passages retrieved using the Ignore Search mode are more likely to describe biological structures, behaviors, and/or patterns related to folding at the macroscale. The stop words list is originally developed through evaluation of irrelevant passages when searching the biological keyword "fold" and collecting words that commonly appear in those passages. To illustrate, the literature is saturated with protein folding research, but protein folding is not commonly used as design inspiration for foldable engineering applications. Considering this disparity, protein folding is difficult to connect to the design of foldable mechanisms. Therefore, the passages about protein folding are not considered useful, and the words found in these passages are used as stop words. Some examples of these stop words include "protein," "genome," "DNA,", and "polypeptide." While words related to protein folding yield irrelevant passages when searching the biological keyword "fold," this does not necessarily mean that a similar result can be expected for the other biological keywords. Therefore, additional stop words related to microscale biology are added to the stop words list as different biological keywords are searched and irrelevant passages are evaluated. When users select the Ignore Search mode, passages are retrieved that contain their selected biological keyword from Table 5.5 and none of the stop words. Passages that contain the selected biological keyword and at least one of the stop words are not retrieved. All stop words are shown in Table 5.8. Ignore Search mode reduces the amount of irrelevant passages that FoldSearch retrieves because of the integration of the stop words list. Overall, the quality of results are improved compared to Raw Search mode, thereby saving designer’s time when searching for design inspiration at the macroscale.

Table 5.8 Stop words used in Ignore Search mode.

Stop Words					
Actin	Chromatin	Gene	Lipid	Protein	Substrate
Amino Acid	Chromosome	Genome	Mitosis	Putative	Syndrome
Antibody	Cofactor	Hairpin	Molecule	Reductase	Thread
Bind	Collagen	Helix	Monomer	Residue	Topology
Bond	Cytoplasm	In vivo	Mutant	RNA	Tubule
Cell	Dimer	Ion	Nano	Septin	VPS
Chain	DNA	Jelly roll	Periplasm	Sequence	Wild-type
Chromatid	Domain	Kinase	Polypeptide	Strand	

The performance between the three search modes in terms of overall precision and f-measure is compared using three different text files - *The Grand Design: Form and Colour in Animals* [131], *Life: The Science of Biology* [132], and selected volumes from the *Journal of Animal Behavior*. The results from this performance comparison are shown in Tables 5.9 and 5.10. Precision, recall, and f-measure scores are calculated using the summation of passages retrieved and total relevant passages retrieved by searching all 20 biological keywords. Table 5.9 presents data separated by text file, while Table 5.10 presents an overall representation combining all three text files.

When evaluating the data presented in Table 5.9, it is useful to realize the differences between the three text files. *The Grand Design: Form and Colour in Animals* [131] is the least advanced form of biological literature within the corpus. It is a graphical book intended more for casual reading and focuses on basic biology. *Life: The Science of Biology* [132] is a more advanced form of biological literature because it is a college-level biology textbook. Naturally, it contains more biological jargon and advanced biological concepts at the microscale. The selected volumes from the *Journal of Animal Behavior* are the most advanced form of biological literature within the corpus because they are journal publications. Therefore, this text file contains the highest level of biological jargon and content related to niche biological research. Overall, the data in Table 5.9 demonstrate that the filtering methods have different outcomes depending on the form of biological literature used.

With the exception of one equivalent case where Raw Search and Ignore Search show the same precision scores from the *Journal of Animal Behavior*, all other comparisons show Raw Search with lower precision than Descriptive Search and Ignore Search. This result is reasonable considering Raw Search uses no filtering methods. Therefore, it is expected that Raw Search would retrieve a higher number of passages, both relevant and irrelevant, thereby lowering precision. Raw Search yields a perfect recall percentage compared to the other search modes, which is also due to the lack of filtering methods used in this search mode. The difference between precision and recall is anticipated, considering the literature confirms a trade-off exists between precision and recall in information retrieval [130].

When evaluating data from *The Grand Design: Form and Colour in Animals* [131], Raw Search yields a higher f-measure than Descriptive Search and Ignore Search, indicating better overall performance. Further, all three search modes yield similar precision scores from *The Grand Design: Form and Colour in Animals* [131]. A possible reason for these results could be that the effects of filtering aren’t significant on a basic form of biological literature when using the curated list of biological keywords that have demonstrated effectiveness retrieving passages that describe biological structures, behaviors, and/or patterns related to folding. The biological keywords may be sufficient on their own to effectively retrieve relevant passages from simple biological texts.

Ignore Search yields a slightly higher f-measure score than Descriptive Search from *Life: The Science of Biology* [132]. Interestingly, this text file has more content related to microscale biology than the other two text files. Therefore, the improved information retrieval metrics for Ignore Search are reasonable because this search mode integrates stop words directly related to microscale biology. Descriptive Search retrieves more passages related to microscale biology than Ignore Search, which decreases the amount of relevant passages and negatively affects f-measure scores. However, the minimal difference between the overall performance of the two search modes may indicate that the filtering methods utilized in Descriptive Search are just as effective even though scale is not considered in this search mode.

When observing performance metrics from the *Journal of Animal Behavior*, Descriptive Search yields significantly higher precision and f-measure scores (between 22%-25% greater) than Raw Search and Ignore Search. This result indicates that the filtering methods used in Descriptive Search may be better suited for more advanced forms of biological literature where field-specific jargon is used and content focuses on niche biological research.

Table 5.9 Search modes performance comparison based on text file.

Text File	**Raw**			**Descriptive**			**Ignore**		
	Precision	**Recall**	**F-Measure**	**Precision**	**Recall**	**F-Measure**	**Precision**	**Recall**	**F-Measure**
The Grand Design	60%	100%	75%	63%	70%	66%	63%	89%	74%
Life: The Science of Biology	20%	100%	33%	28%	70%	40%	32%	63%	42%
Journal of Animal Behavior	19%	100%	32%	41%	85%	55%	19%	80%	30%

To gain an overall perspective of performance between the search modes regardless of the text file used, information retrieval metrics are calculated using the summation of passages retrieved and total relevant passages retrieved across all three text files using all 20 biological keywords. The data from this performance comparison is shown in Table 5.10. The Descriptive Search mode yields the highest f-measure, indicating better overall performance than the other search modes. The Ignore Search mode has a greater f-measure than Raw Search, indicating the usefulness of its filtering methods. Combining the strengths of Descriptive Search and Ignore Search into one search mode may yield even greater performance metrics and serves as a future improvement for FoldSearch.

Table 5.10 Overall search modes performance comparison.

Search Mode	Precision	Recall	F-Measure
Raw	26%	100%	42%
Descriptive	41%	74%	53%
Ignore	32%	78%	45%

The flowchart shown in Figure 5.4 illustrates the algorithm’s overall process and the three different search modes functionality. The first step is loading the biological corpus into the appropriate directory so that the algorithm can scan the corpus. The FoldSearch algorithm is then deployed. System recommendations include using the Anaconda distribution of Python and a Linux operating system. FoldSearch will then display the list of biological keywords and the user selects the keyword most appropriate for their search. The next step is to select the search mode. If Raw Search is selected, all passages are printed containing the selected biological keyword. If

Descriptive Search is selected, only passages containing the selected biological keyword and at least one of the descriptive words are printed. If Ignore Search is selected, only passages containing the selected keyword and none of the listed stop words are printed. As a final step, the total number of passages (occurrences) are printed.

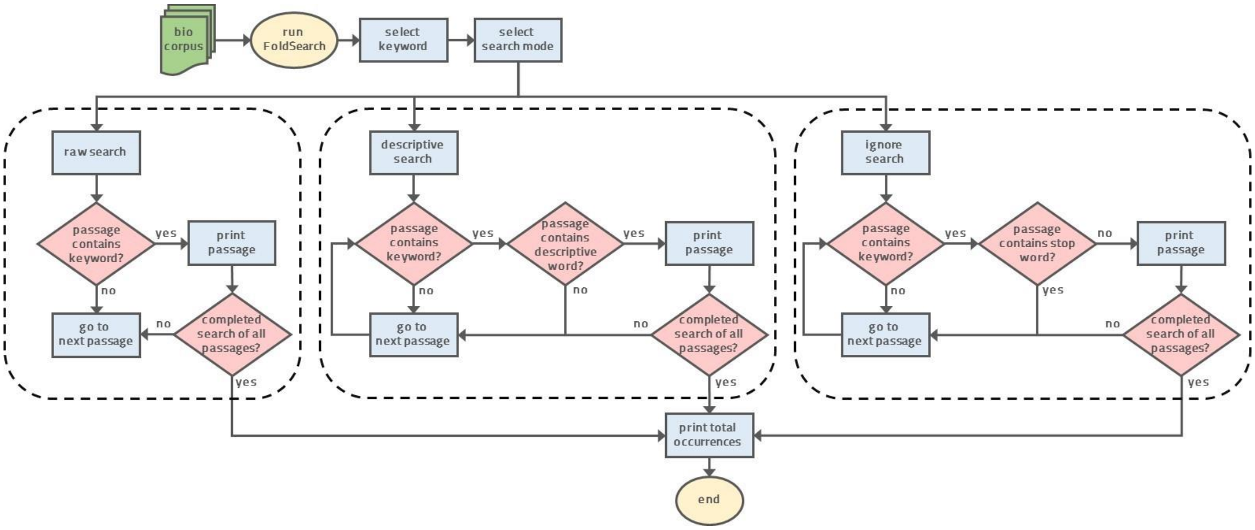
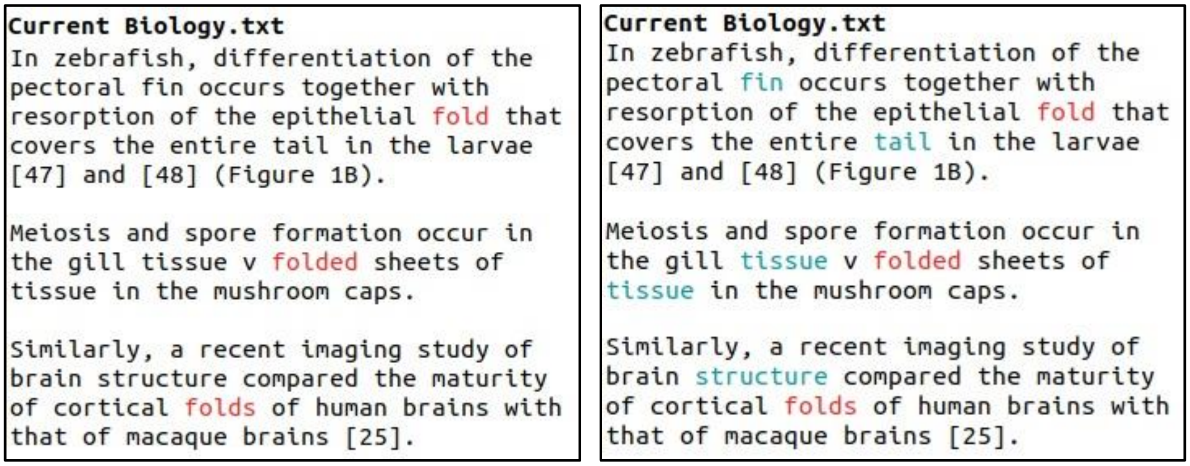


Figure 5.4 FoldSearch algorithm flowchart.

5.2.4. Readability

To increase readability and avoid overwhelming users with information, the output of FoldSearch returns short passages. For the Raw Search mode and the Ignore Search mode, the selected biological keyword is highlighted in red to enable users to quickly locate their keyword of interest. Passages are separated by a blank space to indicate each separate passage. Lastly, the biological text file titles are displayed in bold at the beginning of each search to determine the source of interesting passages if the user desires further context. These methods used to increase readability for the Raw Search mode and the Ignore Search mode are illustrated in Figure 5.5 (left). The Descriptive Search mode integrates the same readability methods as detailed above but also highlights the descriptive words in blue, allowing the user to quickly scan the context of the short passage. The readability methods used in the Descriptive Search mode are illustrated in Figure 5.5 (right).



```
Current Biology.txt
In zebrafish, differentiation of the
pectoral fin occurs together with
resorption of the epithelial fold that
covers the entire tail in the larvae
[47] and [48] (Figure 1B).

Meiosis and spore formation occur in
the gill tissue v folded sheets of
tissue in the mushroom caps.

Similarly, a recent imaging study of
brain structure compared the maturity
of cortical folds of human brains with
that of macaque brains [25].
```

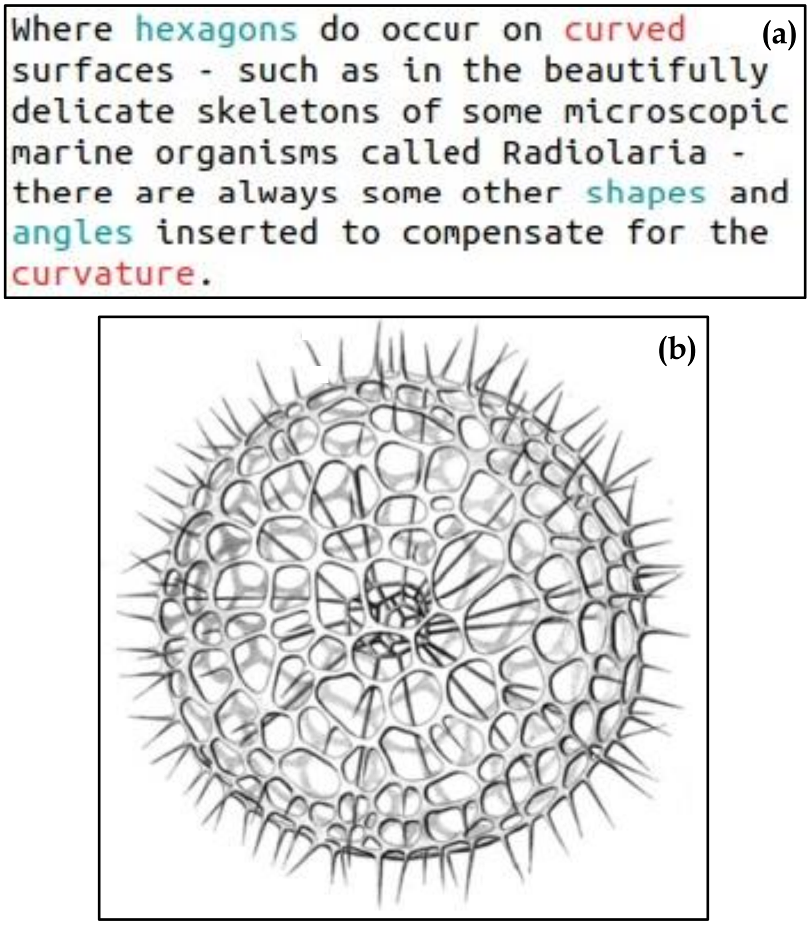
```
Current Biology.txt
In zebrafish, differentiation of the
pectoral fin occurs together with
resorption of the epithelial fold that
covers the entire tail in the larvae
[47] and [48] (Figure 1B).

Meiosis and spore formation occur in
the gill tissue v folded sheets of
tissue in the mushroom caps.

Similarly, a recent imaging study of
brain structure compared the maturity
of cortical folds of human brains with
that of macaque brains [25].
```

Figure 5.5 Methods to increase readability – (left) Raw Search and Ignore Search mode: Results displayed in short passage form, keywords highlighted in red, references bolded, (right) Descriptive Search mode: similar readability methods used and descriptive words highlighted in blue.

5.2.5. Functionality

This section presents results using various biological keywords and text files. Though the results presented are only a small sample of the numerous biological systems retrievable through FoldSearch, the sample is representative of the search algorithm's functionality in retrieving passages that describe biological structures, behaviors, and/or patterns related to folding. Each result provides an example of biological design inspiration for foldable engineering applications.

Searching the keyword “curve” returns a passage describing microscopic Radiolaria skeletons, shown in Figure 5.6 (a) [131]. The curved surface of the marine organisms features a hexagonal pattern, as illustrated in Figure 5.6 (b) [134]. The passage explains how other shapes are necessary to achieve this curved surface comprised predominately of hexagons. The hexagonal packing pattern featured on Radiolaria skeletons may inspire design solutions for creating curved structures out of flat sheets, which has applications in manufacturing and architecture.



Where hexagons do occur on curved surfaces - such as in the beautifully delicate skeletons of some microscopic marine organisms called Radiolaria - there are always some other shapes and angles inserted to compensate for the curvature.

Figure 5.6 (a) Passage retrieved from FoldSearch [131], (b) Cellular packing structure of Radiolaria skeleton [134].

Searching the keyword “compact” retrieves a passage regarding bone structure. Compact bone is made of Haversian systems, or osteons. These osteons feature layers of bone in concentric tubes with central canals that contain blood vessels and nerves, shown in Figure 5.7. Adjacent osteons are distinguished by glue lines which allow the bone to resist fracture [132]. The architecture and function of osteons may inspire solutions for folding patterns and engineering applications requiring compact design and strength.

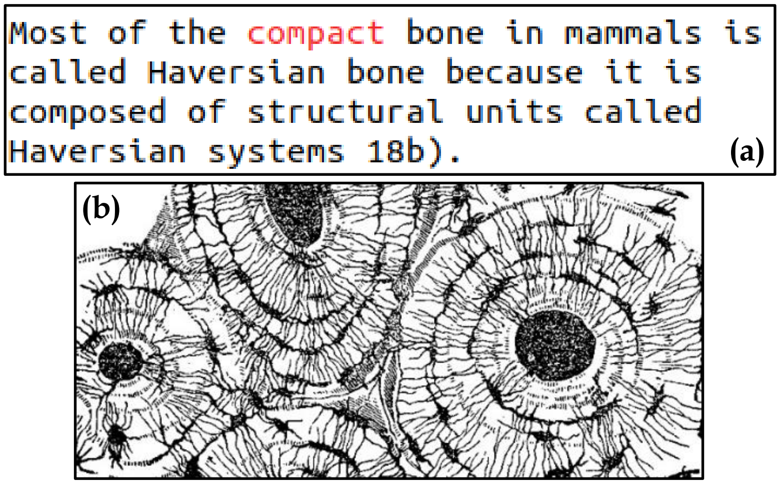
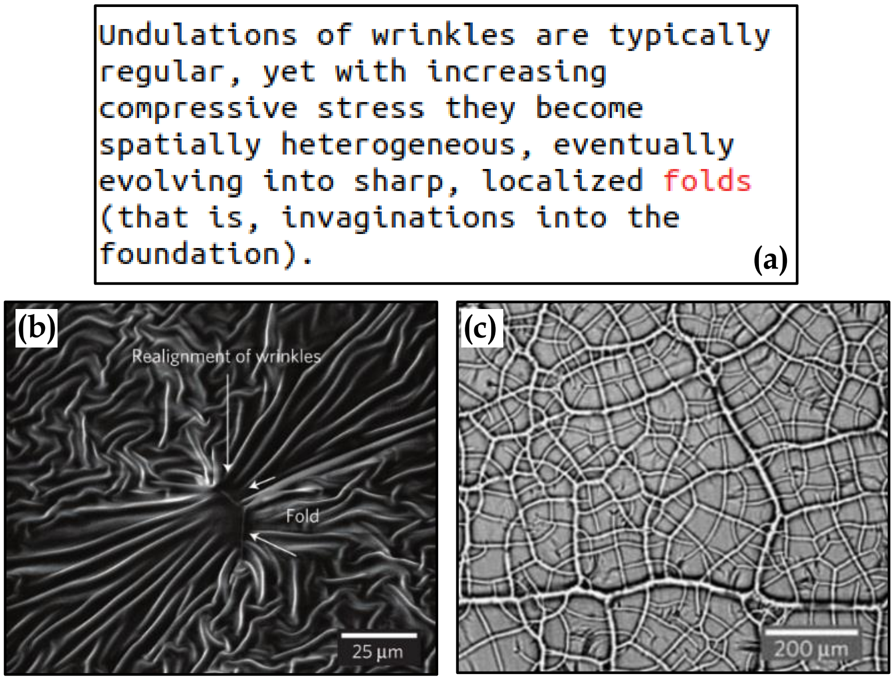

Most of the compact bone in mammals is called Haversian bone because it is composed of structural units called Haversian systems 18b).

Figure 5.7 (a) Passage retrieved from FoldSearch, (b) Transverse section schematic of osteons in compact bone [127].

Searching the keyword “fold” retrieves a passage discussing the formation of isotropic patterns in materials. Compressive strain causes undulations to emerge on the surface of thin, layered materials [135]. Increasing compressive strain causes the undulations to fold, creating a random network of creases, shown in Figure 5.8. However, manipulating the boundary conditions and geometry provides pattern development control [135]. The mechanisms controlling the development of these material crease patterns may provide design solutions for planar structures where strain localization is significant.



Undulations of wrinkles are typically regular, yet with increasing compressive stress they become spatially heterogeneous, eventually evolving into sharp, localized folds (that is, invaginations into the foundation).

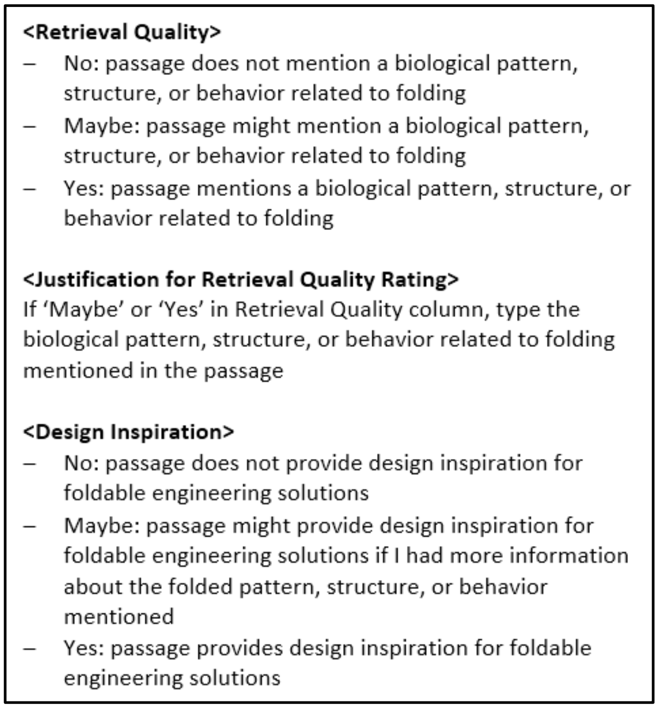
Figure 5.8 (a) Passage retrieved from FoldSearch, (b) Micrograph of wrinkled surface and initiation of fold formation, (c) Final network of wrinkle-to-fold transition [135].

5.3. FoldSearch Validation

This section discusses validation of FoldSearch using inter-rater reliability analysis. Comparing the search algorithm's performance to other existing bioinspired design search tools is provided as further validation.

5.3.1. Inter-rater Reliability Analysis

An inter-rater reliability analysis is performed using two raters to measure agreement on retrieval quality and design inspiration. Figure 5.9 shows the rubric provided to both raters to guide the rating process of 100 randomly selected passages. The retrieval quality rating measures agreement between raters regarding whether or not the passages describe biological structures, behaviors, and/or patterns related to folding. The design inspiration rating measures the agreement between raters regarding whether or not the passages provide design inspiration for foldable engineering applications. A three-point scale is used for both the retrieval quality ratings and the design inspiration ratings, as shown in Figure 5.9. As an additional measure to ensure accuracy, raters are asked to identify the biological pattern, structure, or behavior in the passage if they give a ‘Maybe’ or ‘Yes’ rating for retrieval quality. Once the rating process is complete, agreement is calculated using Cohen’s kappa with quadratic weighting [136, 137]. The minimum Cohen’s kappa with quadratic weighting is 0.62 for retrieval quality and 0.51 for design inspiration. According to Landis and Koch, the kappa values indicate substantial agreement between raters for retrieval quality and moderate agreement between raters for design inspiration [138]. The inter-rater reliability results demonstrate agreement regarding the usefulness of each passage.



<Retrieval Quality>

- No: passage does not mention a biological pattern, structure, or behavior related to folding
- Maybe: passage might mention a biological pattern, structure, or behavior related to folding
- Yes: passage mentions a biological pattern, structure, or behavior related to folding

<Justification for Retrieval Quality Rating>

If ‘Maybe’ or ‘Yes’ in Retrieval Quality column, type the biological pattern, structure, or behavior related to folding mentioned in the passage

<Design Inspiration>

- No: passage does not provide design inspiration for foldable engineering solutions
- Maybe: passage might provide design inspiration for foldable engineering solutions if I had more information about the folded pattern, structure, or behavior mentioned
- Yes: passage provides design inspiration for foldable engineering solutions

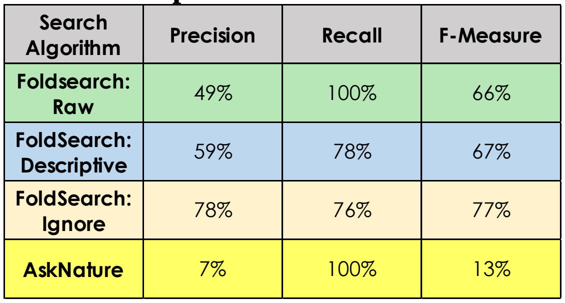
Figure 5.9 Rubric provided to raters for inter-rater reliability analysis.

5.3.2. Performance Comparison to Other Search Tools

Further validation involves a performance comparison of FoldSearch versus AskNature, a commonly used bioinspired design search tool. Information retrieval metrics (precision, recall, and f-measure) are calculated to measure the performance of FoldSearch and AskNature. FoldSearch features a broad database (corpus) containing biological texts from various fields. FoldSearch also features different search functions depending on the user's needs. As discussed in Section 4.3 of this dissertation, AskNature features a curated database and search function is limited. Considering these differences, the performance comparison provides insight to the efficiency of FoldSearch versus AskNature.

To calculate the information retrieval metrics for FoldSearch, three text files from the biological corpus are used and data is calculated for all three search modes. The biological keyword searched using FoldSearch and AskNature is "fold." Passages are evaluated to determine relevancy using the same method of identifying passages as implemented in the inter-rater reliability analysis. The performance comparison data is shown in Table 5.11.

Table 5.11 Performance comparison between FoldSearch and AskNature.



Search Algorithm	Precision	Recall	F-Measure
Foldsearch: Raw	49%	100%	66%
FoldSearch: Descriptive	59%	78%	67%
FoldSearch: Ignore	78%	76%	77%
AskNature	7%	100%	13%

All three search modes of FoldSearch have significantly higher precision and f-measure scores than AskNature. The differences between precision and recall among all search modes is anticipated considering the literature confirms that a trade-off exists between precision and recall in information retrieval [130]. The f-measure, which combines precision and recall values to indicate overall performance of a search algorithm, is calculated as 13% for AskNature. The significantly higher f-measure scores of FoldSearch are promising and suggest the potential of the search algorithm to retrieve useful design inspiration for foldable engineering applications compared to conventional bioinspired search tools.

5.4. Summary

FoldSearch provides designers with a useful, directed methodology to extract examples of folding in nature. These extracted folding examples serve as design inspiration for foldable engineering applications. The various validation methods discussed throughout this section of this dissertation demonstrate the usefulness and strengths of the search algorithm. The inherent limitations of conventional keyword search tools for bioinspired design, such as curated databases and limited search function, are not present in FoldSearch. FoldSearch can be used on various forms of biological literature and across a broad spectrum of biological research fields.

While the primary objective of the search algorithm development is to provide designers with nature’s wealth of untapped, foldable design solutions, the efficiency and readability of FoldSearch can be improved to more effectively mine the biological domain. Combining the strengths of the Descriptive Search mode and the Ignore Search mode into one inclusive search mode may yield even greater performance metrics. Currently, the Descriptive Search and Ignore Search modes employ a universal list of descriptive words and/or stop words that are applied to all biological keywords. This “cookie-cutter” approach to biological keywords may be a limitation of the current FoldSearch code. The search modes may be independently refined by creating a unique set of descriptive words and/or stop words for each individual biological keyword.

Other improvements include integration of advanced filtering techniques, such as the bioinspired design classifier developed by Glier et al. [139]. The classifier may be adopted to discard a greater number of irrelevant results and improve overall efficiency of the keyword search algorithm. Integrating machine translation techniques, such as the lexical substitution method proposed by Lee et al. [140], may also increase readability of the search results for designers with non-biology backgrounds.

6. CASE STUDIES*

This section provides two case studies to demonstrate the functionality of FoldSearch in supporting bioinspired design of novel foldable structures. Section 6.1 discusses abstraction in the context of bioinspired design and provides two examples of established abstraction methods as used in the development of bioinspired origami. Section 6.2 reviews the rules of flat foldability in origami and how these rules are implemented for the case studies. Section 6.3 details the first case study which involves the design abstraction of hexagonal packing patterns found in tortoise shells and pangolin scales. Section 6.4 details the second case study which involves the design abstraction of the woodlouse's shape transformation. Section 6.5 provides a design methodology implementing FoldSearch based on the process from the two case studies. The impact of the case studies and design abstraction process is summarized in Section 6.6.

6.1. Design Abstraction

Once a relevant biological structure, behavior, or pattern has been identified through FoldSearch, abstraction of the biological example must be completed to further reveal the potential application to foldable structures and engineering solutions. Abstraction is defined as "the process of refining the biological knowledge (design solutions) to some working principles, strategies or representative models that explain the biological solution and could be further transferred to the target application" [141]. Abstraction allows designers to simplify and extract design principles from biological systems. Abstraction also facilitates analogical reasoning between biological

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* Part of this section is reprinted with permission from "Development of a Keyword Search Algorithm for Bioinspired Design of Foldable Engineering Applications" by Elissa Morris and Daniel A. McAdams, 2017. *Proceedings of the ASME 2017 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Volume 5B: 41st Mechanisms and Robotics Conference, pp. V05BT08A053, Copyright © 2017 by ASME.

phenomena and engineering applications [141]. As shown in Section 3 of this dissertation, prior work clearly demonstrates that the abstraction of biological structures can lead to the development of novel foldable solutions for engineering problems. However, the biological solutions used to inspire origami crease patterns developed in prior research efforts were likely discovered either through brute force methods or simply by chance. FoldSearch provides a more directed method for finding biological structures, behaviors, and/or patterns related to folding. Therefore, two retrieved biological systems from FoldSearch (such as those discussed in Section 5 of this dissertation) undergo a design abstraction process. This abstraction and modeling stage demonstrates the utility of FoldSearch to provide potential solutions for bioinspired design of foldable engineering applications. The abstraction and modeling phase results in the development of two novel origami crease patterns and folded structures, similar to Kresling's work [120].

6.1.1. Existing Design Abstraction Processes for Bioinspired Origami

Abstraction is one of the most difficult aspects of bioinspired design [142]. Prior research efforts provide general guidelines and tools to support the abstraction process [14, 16, 143-145]. However, this dissertation work is focused on abstraction processes specifically for bioinspired foldable engineering applications. Kresling and Baerlecken, et al. provide foundational steps for the design of bioinspired folding applications, which are detailed below.

Kresling proposes a process for adapting biological structures or patterns for origami engineering applications that includes the following four steps:

1) Describe the biological structure in terms of geometry and function,
2) Perform experiments that induce buckling of paper or polypropylene models and analyze resulting failure patterns that model the biological structure,
3) Design fold patterns using rules of geometry and mechanics as observed in the failure

patterns from Step 2, and

4) Apply the fold patterns to engineering problems [118].

These four steps are demonstrated in the development of the twist-buckling pattern used in the design of deployable sunshields. Kresling developed abstract models of the giant hawkmoth's abdominal air sac, shown in Figure 6.1 (a) [115, 116]. This bellows-like sac pumps blood throughout the insect's circulatory system. According to Step 1 of Kresling' process, the air sac pattern is described in terms of geometry and function, but Kresling does not divulge in her work how this biological pattern is initially discovered. Step 2 of Kresling's process requires experimentation to induce buckling behavior, shown in Figure 6.2 (b), using paper attached to cardboard tubes. The resulting failure patterns on the paper are similar to the hawkmoth's air sac pattern. Step 3 of Kresling's process uses geometry and mechanics of these failure patterns to design origami crease patterns, illustrated in Figure 6.1 (c). The resulting crease pattern is a natural twist buckling pattern that allows simultaneous two-directional expansion with minimal shear stress folding mechanisms [118]. The final step involves the application of the developed crease patterns to engineering solutions. The bioinspired twist-buckling pattern is used in the design of deployable sunshield prototypes that will be used on X-ray telescopes, shown in Figure 6.1 (d).

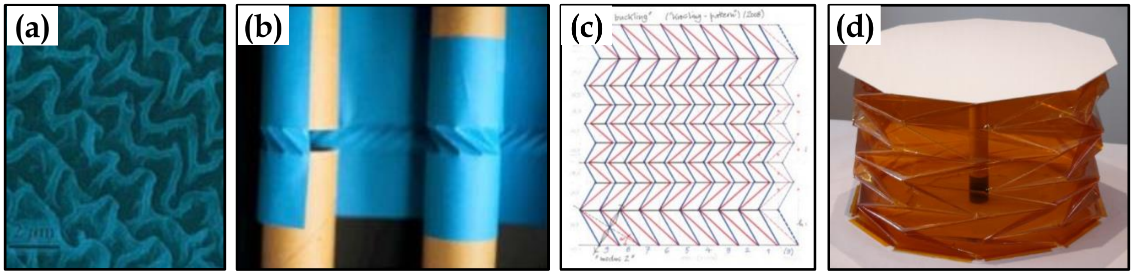


Figure 6.1 (a) Hawkmoth air sac pattern, (b) Experiments inducing buckling behavior and resulting failure crease pattern, (c) Kresling origami crease pattern, (d) Pattern application to deployable sunshield prototype [23, 118].

Baerlecken, et al. describe a slightly different design process from biological inspiration to origami structures using the following four phases:

1) Selective modeling of folding mechanisms in nature,
2) Propose origami equivalents based on biological models,
3) Transfer models and principles to parametric system followed by structural evaluation, and
4) Create prototypes through digital fabrication and perform further testing of structural properties [146].

These four phases are developed out of a case study using bioinspired origami for architectural applications. The researchers implemented these four phases for the design of a retractable roof using an "origami truss" [147]. According to Phase 1, the pattern of the various biological structures and patterns were modeled into large scale arrays to reveal the pattern's utility in a retractable roof. Insect wings and plant leaves, specifically earwig wings, maple leaves, and hornbeam leaves, were considered and modeled into large arrays, or tessellations. The researchers do not reveal how these three biological examples are initially discovered. Out of these three biological examples modeled, the hornbeam leaf was selected as the best fit for an origami truss application, shown in Figure 6.2 (a). Phase 2 requires the proposal of origami equivalents based on the hornbeam leaf model. The Miura-ori pattern is selected as the origami pattern for the retractable roof design, shown in Figure 6.2 (b). In phase 3, researchers perform a structural evaluation of the Miura-ori tessellation using LS-DYNA, illustrated in Figure 6.2 (c). The final phase requires the creation of digital prototypes of the Miura-ori origami truss, shown in Figure 6.2 (d), and testing additional structural properties [147].

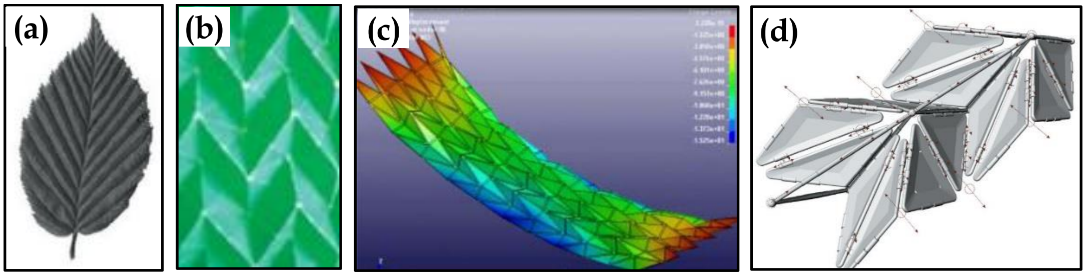


Figure 6.2 (a) Hornbeam leaf selected as biological model, (b) Miura-ori as origami equivalent of Hornbeam leaf, (c) Modeling and structural analysis of origami equivalent, (d) Digital fabrication of truss prototype for further testing of structural properties [146-148].

While the above design processes provide a foundation for the development of bioinspired folding applications, the method by which the biological solutions are initially discovered is missing from both processes. The lack of information regarding the discovery of the selected biological examples likely indicates that brute force or simple chance were the methods used to extract biological inspiration. FoldSearch is a solution to this inefficiency by providing designers with a directed method for extracting design inspiration from the biological domain. Therefore, a design abstraction process is developed through the completion of two case studies. The case studies also serve as experimental validation of the utility of FoldSearch. The case studies examine biological patterns, structures, and behaviors discovered using FoldSearch. The abstraction process is applied to each biological example in an effort to develop novel folding techniques and crease patterns and to propose engineering applications for these folding designs.

6.2. Guidelines Used to Create Bioinspired Origami

The creation of origami crease patterns using flat sheets of paper is bounded by a certain set of constraints. While kirigami allows for certain manipulations of the paper to occur, the rules of traditional origami folding are followed in the two case studies. Therefore, cutting, tearing, and stretching of the paper is not allowed. The geometric constraints of flat foldability are also applied and reviewed in Section 6.2.1. Considering the widespread application of tessellations (i.e., symmetric repetition of an origami base throughout the crease pattern) in engineering applications, the case studies also implement variations of symmetrical repeats. The types of symmetrical repeats are discussed in Section 6.2.2.

6.2.1. Flat Foldability

An origami model is considered flat foldable if it can be folded flat without causing damage to the crease pattern, such as crumpling or tearing the paper in any area. Flat foldable origami features straight creases throughout the model that are mountain folds or valley folds. The Miura-ori, the Yoshimura, and the Waterbomb base are all examples of flat foldable origami. Considering flat foldability is significantly valuable for various engineering applications, as the origami-inspired products in Section 2 demonstrate, the three conditions for flat foldability are applied to the case studies. The first two conditions are mathematical theorems that are fairly straightforward to apply when creating and studying crease patterns: Maekawa-Justin's theorem and Kawasaki-Justin's theorem. The third condition for flat foldability is more complex to apply and is discussed in detail later in this section.

The first condition a crease pattern must satisfy for flat foldability is Maekawa-Justin's theorem, which states the following [149]:

> *"Let M and V denote the number of mountain and valley creases, respectively, that meet at a flat vertex fold. Then $M - V = \pm 2$."*

A crease pattern satisfies Maekawa-Justin's theorem if the number of mountain and valley folds at each vertex always differs by 2, demonstrated in Figure 6.3 (left). Because this theorem requires that all vertices have an even number of creases, flat foldable crease patterns are 2-face colorable. A crease pattern satisfies the condition imposed by Maekawa-Justin's theorem if two alternating colors are used to fill in the planar regions throughout the crease pattern without ever having the same colors touch, illustrated in Figure 6.3 (right) [149].

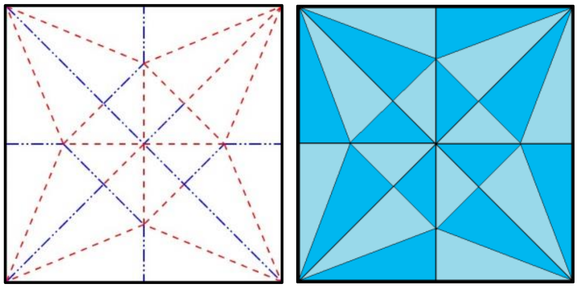


Figure 6.3 Maekawa-Justin's Theorem: (left) Counting mountain and valley folds at each vertex to ensure difference by 2, (right) Using two alternating colors to ensure an even number of creases [150].

The second condition used to verify flat foldability of a crease pattern is Kawasaki-Justin's theorem, which states the following [149]:

> *"A vertex fold v folds flat if and only if the alternating sum of the consecutive angles between the creases at v equals to zero."*

Crease patterns satisfy the condition imposed by Kawasaki-Justin's theorem if the summation of odd angles at any vertex is equivalent to 180° and the summation of even angles at the same vertex is equivalent to 180° (i.e., the alternating sum of all angles at any vertex is equivalent to zero), as Figure 6.4 demonstrates.

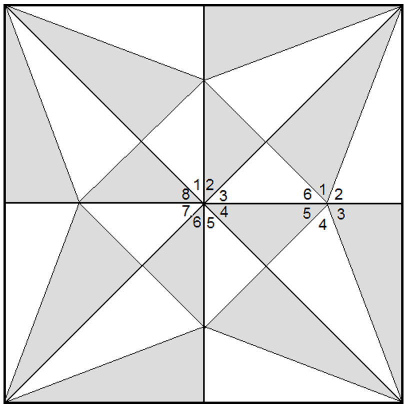


Figure 6.4 Kawasaki-Justin's Theorem: the alternating sum of angles at any vertex is equal to zero [150].

The third condition of flat foldability requires that the self-intersection of the sheet never occurs during the folding process. Though the first two conditions of flat foldability are straightforward to apply to crease patterns, the third condition is not. Detecting whether self-intersection occurs in a crease pattern is essentially what contributes the most difficulty to flat foldable origami modeling [149]. To demonstrate this complexity, several crease patterns have been published that satisfy the first two conditions of flat foldability, but not the third condition regarding self-intersection, rendering the crease pattern impossible to fold [151]. Research has also shown that determining flat foldability of a crease pattern is a NP-complete problem, primarily due to the third condition of flat foldability [152]. Considering these complexities of origami modeling, each pattern created through the case study process is initially evaluated to determine if the pattern satisfied the first two conditions of flat foldability and, if so, the crease pattern is folded by hand to rule out self-intersection possibilities.

6.2.2. Types of Symmetrical Repeats

Numerous successful implementations of origami-inspired products feature symmetrical repetitions of an origami base to create a foldable surface. Renowned origami artist, Paul

Jackson, in his book “Folding Techniques for Designers from Sheet to Form,” states the following [153]:

> *“The essence of pattern-making, including crease patterns, is symmetry.”*

The four types of symmetrical repeats are translation, reflection, rotation, and glide reflection, shown in Figure 6.5. Translation is defined as the linear repetition of an origami base. Reflection is defined as the mirrored linear repetition of an origami base. Rotation is defined as the repetition of an origami base around a point. The most complex symmetrical repeat is glide reflection, which features translation and reflection of an origami base in a line. Glide reflection symmetry is not required to occur in a straight line [153].

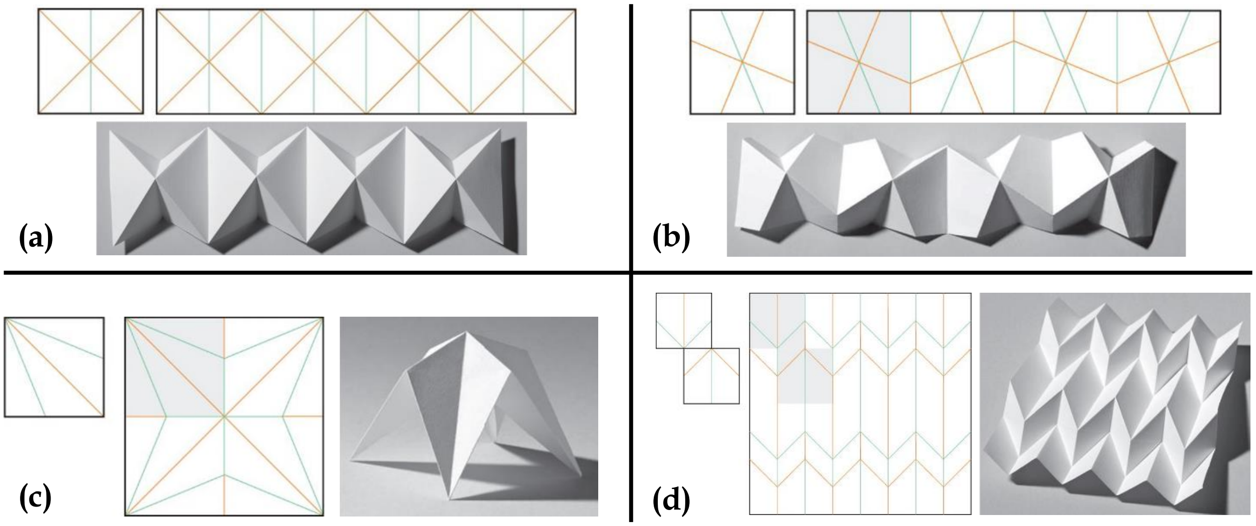
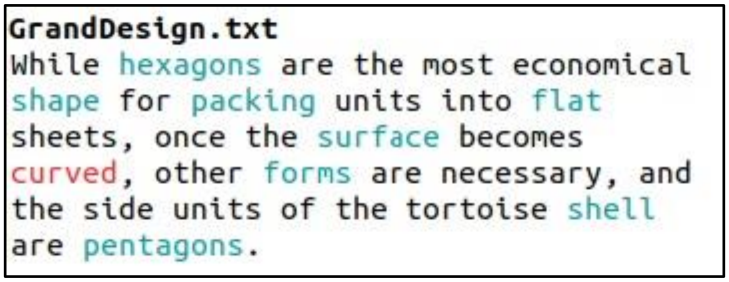


Figure 6.5 Symmetrical repeat types and folded models: (a) Translation, (b) Reflection, (c) Rotation, (d) Glide reflection [153].

As Figure 6.5 illustrates, using an origami base in any of the symmetrical repeat yields interesting folded shapes. Combinations of these symmetrical repeats can also be applied to create interesting folded forms. Therefore, these four symmetrical repeats serve as guides to novice and skilled origami designers alike when using FoldSearch to create bioinspired crease patterns.

6.3. Case Study: Tortoise Shell/Pangolin Scale-Inspired Crease Pattern

Using FoldSearch as the initial step in this case study, the passage shown in Figure 6.6 is extracted from *The Grand Design: Form and Colour in Animals* [131] when searching the biological keyword "curve" in the Descriptive Search mode. This passage mentions the hexagonal pattern featured on tortoise shells.



```
GrandDesign.txt
While hexagons are the most economical
shape for packing units into flat
sheets, once the surface becomes
curved, other forms are necessary, and
the side units of the tortoise shell
are pentagons.
```

Figure 6.6 Passage retrieved from FoldSearch discussing hexagonal packing pattern on tortoise shell [131].

Before selecting this passage as a final candidate for the case study, additional context is desired and manually searched within the text file. The following passage provides more insight and additional biological examples similar to the tortoise shell pattern, such as the scales of a pangolin, shown in Figure 6.7 [131]:

> *"The same is true of the tortoise's shell, where remarkably regular hexagons in the centre are bounded by pentagons (five-sided shapes) which fuse to give a straight edge to the shell; exactly the same happens in insect wings. Three-way junctions also tend to occur where pieces of similar size and shape must be overlapped to cover a surface, as in the feathers of a bird, the scales of a fish, or the scales of a pangolin."*

Figure 6.7 Hexagonal packing patterns: (left) Tortoise shell, (right) Pangolin scales [131, 154].

The next step involves researching the biological examples provided in the retrieved passage and the additional context. Sketches are made of the patterns observed and different configurations of hexagonal patterns combined with other shapes are considered. Interestingly, nature tends to employ the most economical packing patterns – in this case, a hexagonal packing pattern. Because hexagons can only interlock perfectly in a flat plane and nature favors curved surfaces, distortion occurs at the edges on curved surfaces. Therefore, nature makes use of other shapes at the edges, usually pentagons, to achieve curvature. These principles are taken into account when creating a crease pattern and additional creases are added between the hexagons. The rules of flat foldability are applied to each crease pattern and various symmetrical repeats are considered to achieve a flat foldable surface. Because self-intersection of the sheet is difficult to predict, each pattern that satisfied Maekawa-Justin's theorem and Kawasaki-Justin's theorem was folded by hand to ensure folds were not penetrated by the sheet. The final crease pattern features horizontal translation and vertical reflection of the origami base, as illustrated in Figure 6.8 (left). The folded form of this crease pattern, shown in Figure 6.8 (right), appears remarkably similar to the scales of a pangolin.

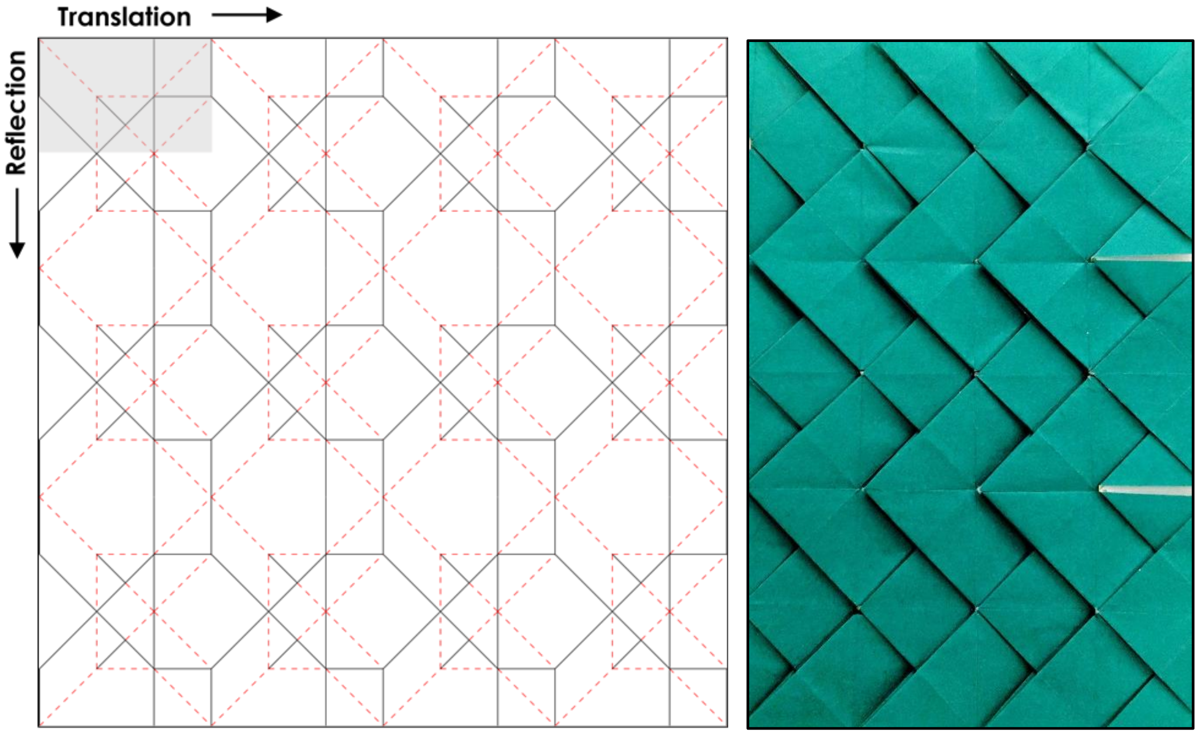


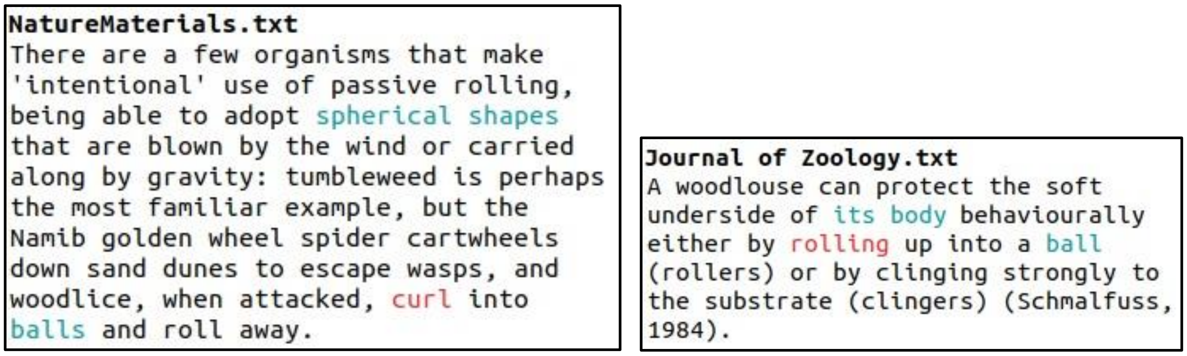
Figure 6.8 Origami inspired by packing patterns of tortoise shell and pangolin scales: (left) Crease pattern showing origami base in grey and applied symmetrical repeats, (right) Folded form.

Ideally, every created crease pattern using this method would have a clear and direct engineering product application. In this case, the engineering product application of the folded form resulting from this case study is uncertain. Despite the lack of a clear product application, the folded form accomplishes the initial case study objective, which is to demonstrate the utility of FoldSearch in extracting biological patterns, behaviors, and structures related to folding that can be used to create bioinspired origami.

6.4. Case Study: Woodlouse-Inspired Crease Pattern

The overall process used to create bioinspired origami in Section 6.3 is also implemented in this case study. However, the initial step is more selective. The first case study did not begin with any design constraints or any particular design problem in mind, which resulted in a novel crease pattern with no clear engineering application. This approach is similar to Kresling's design abstraction process, discussed in Section 6.1.1., where random biological examples are studied to create origami with no preconceived purpose for the resulting crease patterns, which explains why engineering applications for Kresling's work were developed several years after the bioinspired crease patterns were published. However, Baerlecken's design abstraction process differs in the sense that it begins with a specific engineering application in mind before studying biological examples. The second case study presented here begins somewhere between Kresling's random approach and Baerlecken's directed approach. Therefore, this case study begins with the need of an unspecified engineering application for the bioinspired origami created. FoldSearch retrieves passages relevant to biological patterns, structures, and behaviors. The first case study features a passage focused on the pattern observed in nature – hexagonal packing. Because the second case study requires an actual engineering application outcome and engineering design solutions typically revolve around function, the selected passage is focused on biological behaviors (i.e., functions) related to folding.

FoldSearch retrieves a passage explaining biological examples of "passive rolling" from an article in *Nature Materials* when searching the biological keyword "curl" in the Descriptive Search mode [155]. FoldSearch retrieves a similar passage discussing a woodlouse's protection tactics from an article in the *Journal of Zoology* when searching the biological keyword "roll" also in the Descriptive Search mode [156]. The retrieved passages describing this behavior are shown in Figure 6.9.



NatureMaterials.txt

There are a few organisms that make 'intentional' use of passive rolling, being able to adopt spherical shapes that are blown by the wind or carried along by gravity: tumbleweed is perhaps the most familiar example, but the Namib golden wheel spider cartwheels down sand dunes to escape wasps, and woodlice, when attacked, curl into balls and roll away.

Journal of Zoology.txt

A woodlouse can protect the soft underside of its body behaviourally either by rolling up into a ball (rollers) or by clinging strongly to the substrate (clingers) (Schmalfuss, 1984).

Figure 6.9 Passages retrieved from FoldSearch discussing behaviors of a woodlouse [155, 156].

The rolling behavior of a woodlouse is then studied as the next step in the design abstraction process. The exterior or a woodlouse features jointed, hard plates that act as body armor. When threatened, a woodlouse will roll into a ball that is difficult to penetrate, which allows the woodlouse to roll away from predators, illustrated in Figure 6.10.

Figure 6.10 Rolling behaviors of a woodlouse [157].

Abstractions are made of the flexible, jointed segments and the observed rolling behavior of the woodlouse. Initially, three-dimensional folded models are created to mimic the movement of the jointed segments. However, considering the practicality of flat foldability, the focus shifts to a two-dimensional design abstraction of the woodlouse. The rolling behavior is “flattened” onto a two-dimensional plane and the transition from a linear state to a circular shape influences the origami design. The final crease pattern features repetition of angled folds to enable curvature. The pattern includes horizontal translation and vertical reflection of the origami base, as illustrated in Figure 6.11 (left). The folded form is able to transition from a flat linear to a flat circular state, similar to the woodlouse, shown in Figure 6.11 (right). The addition of linear creases midway between each side of the crease pattern allows the flat folded form to transition into a three-dimensional structure.

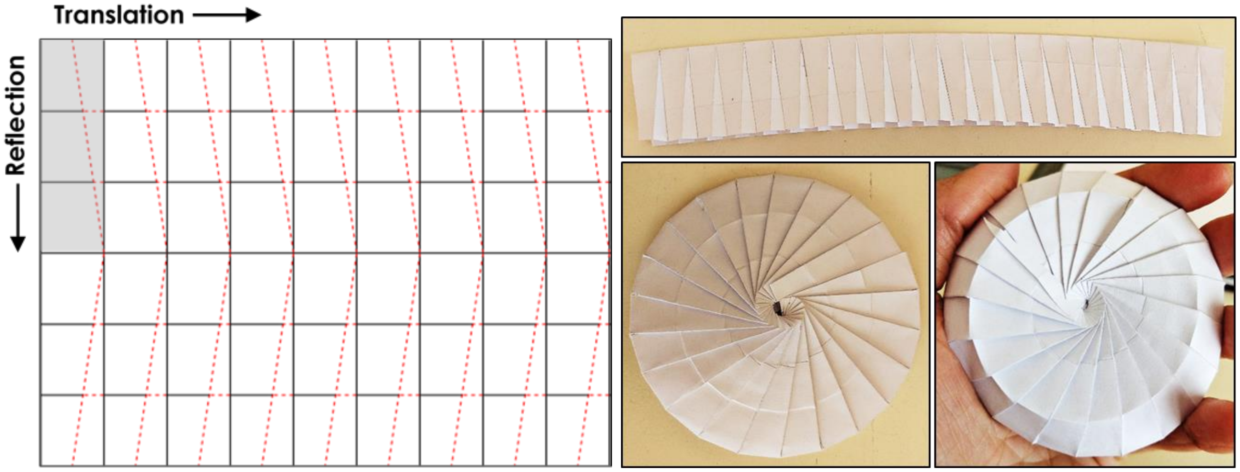


Figure 6.11 Origami inspired by rolling behavior of woodlouse: (left) Crease pattern showing origami base in grey and applied symmetrical repeats, (right) Folded form in linear and circular states.

A potential engineering application for the woodlouse-inspired crease pattern include a trapping device, conceptually similar to the ingestible robot designed to retrieve foreign objects swallowed by children such as button batteries and magnetically navigated out of the body [51]. The woodlouse-inspired origami can transition from a linear state to a circular state, thereby creating an enclosure enabling retrieval or trapping of objects. Another potential engineering application is a one-wheeled robot capable of discrete maneuverability, conceptually similar to the deformable wheeled robot capable of navigating different crawl spaces [31]. The woodlouse-inspired origami can lay flat in a discrete mode when needed and transform into a ball shape capable of transport through remote navigation. Developing prototypes of these suggested engineering applications is outside of the scope of this work. However, the folded form accomplishes the case study objective in demonstrating the utility of FoldSearch in extracting biological patterns, behaviors, and structures related to folding that can be used to create bioinspired origami with potential engineering applications.

6.5. Generalized Bioinspired Origami Design Process Using FoldSearch

The two case studies employ a similar approach in creating bioinspired origami. Therefore, a design process is presented here based on the steps taken throughout the case studies. While sharing some similarities with Kresling and Baerlecken's design processes for the adaptation of biological structures for origami and foldable engineering applications, the primary difference is that this process provides designers with a directed method for discovering design inspiration from the biological domain through the use of the FoldSearch algorithm.

The bioinspired origami design process includes the following steps:

1) Use FoldSearch algorithm to extract bioinspired design inspiration for given design problem or for random idea generation,
2) Research functionality and geometry of biological examples of interest,
3) Adapt biological example to origami using design abstraction (i.e., curved shapes to straight lines, flattening three-dimensional structures to two-dimensional sheets),
4) Design crease patterns that mimic biological abstractions using origami principles (i.e., flat foldability conditions, symmetrical repeats),

5) Fold crease patterns to evaluate structural properties and functionality of folded form,
6) Apply structural properties and functionality of folded form to engineering applications.

These steps provide a design methodology for creating bioinspired origami using the FoldSearch algorithm. The design process does not require absolute conformity to the six steps and can be adapted to suit the designer’s needs. For example, the rules of flat foldability do not necessarily need to be applied. Further, the designer may create digital crease patterns and use origami computer simulation, such as Rigid Origami or Freeform Origami Simulator [158, 159], to virtually fold the crease patterns instead of folding by hand. The design steps can be used as a random idea generation method or as a more directed bioinspired design tool where designers begin with a specified need for their engineering system. For example, the Tortoise shell/Pangolin scales case study is an example of the random idea generation method because it begins with no specified design need. Random biological examples are extracted and evaluated to create origami with no preconceived purpose for the developed crease patterns, resulting in an unclear application to engineering solutions. The Woodlouse case study is an example of a more directed approach because it begins with the design need of an unspecified engineering application. Therefore, the passages FoldSearch retrieves are evaluated based on biological behaviors (i.e., functions) and the application to engineering solutions is apparent after the crease pattern is developed.

6.6. Summary

The utility of FoldSearch using design abstraction is demonstrated through the two case studies, which has led to the development of novel bioinspired origami and potential engineering design solutions. The case studies also confirm that there are more biological sources for origami design inspiration than simply insect wings and the physical properties of plants. The design abstraction process implemented in both case studies is formalized and provided as an additional research contribution. Designers may achieve outcomes similar to the results of the case studies by following the suggested design abstraction process steps.

7. RESEARCH CONTRIBUTIONS AND FUTURE WORK

This section completes the dissertation with a discussion of contributions in Section 7.1, challenges and future research directions in Section 7.2, and concluding remarks in Section 7.3.

7.1. Research Contributions

This dissertation work contributes to the fields of bioinspired design and origami engineering. Specifically, a text-based search algorithm, called FoldSearch, is developed to provide biological solutions for foldable engineering applications. While other search tools exist to facilitate general bioinspired design, this dissertation work is specifically focused on the retrieval of biological solutions for the design of foldable engineering systems. A search algorithm designed for this distinct purpose did not exist in the literature prior to this dissertation work. Therefore, FoldSearch provides designers with a directed method for discovery of biological patterns, structures, and behaviors related to folding.

Further, design abstractions of the biological solutions retrieved by FoldSearch are created in two separate case studies to provide novel bioinspired folding patterns and analogical design solutions for foldable engineering applications. The design abstraction process implemented in both case studies is formalized and provided as an additional research contribution. Designers may achieve outcomes similar to the results of the case studies by following the suggested design abstraction process steps.

7.2. Future Work

While the primary objective of the search algorithm development is to provide designers with nature’s wealth of untapped, foldable design solutions, the efficiency and readability of

FoldSearch can be improved to more effectively mine the biological domain. Combining the strengths of the Descriptive Search mode and the Ignore Search mode into one inclusive search mode may yield even greater performance metrics. Currently, the Descriptive Search and Ignore Search modes employ a universal list of descriptive words and stop words that are applied to all biological keywords. Despite the high performance metrics of FoldSearch using universal descriptive and stop words, this "cookie-cutter" filtering approach may be a limitation of the current FoldSearch algorithm. The search modes may be independently refined by creating a unique set of descriptive words and stop words for each individual biological keyword.

Other FoldSearch improvements include integration of advanced filtering techniques, such as the bioinspired design classifier developed by Glier et al. [139]. The classifier may be adopted to discard a greater number of irrelevant results and improve overall efficiency of the keyword search algorithm. Integrating machine translation techniques, such as the lexical substitution method proposed by Lee et al. [140], may also increase readability of the search results for designers with non-biology backgrounds.

The design abstraction process proposed in Section 6.5 can be further evaluated through completion of Step 6, where the structural properties and functionality of the bioinspired origami are applied to engineering applications. The second case study proposes ideas for foldable engineering applications of the bioinspired origami. However, prototyping and fabrication does not occur, as these additional tasks lie outside the scope of this dissertation.

7.3. Conclusions

FoldSearch provides designers with a useful, directed methodology to extract examples of folding in nature. These extracted folding examples can serve as design inspiration for bioinspired origami and foldable engineering applications. FoldSearch integrates a curated list of biologically meaningful keywords and filtering methods to increase performance and enhance user-friendliness. Passages are retrieved from an extensive corpus with content related to different fields of biology.

FoldSearch is evaluated using inter-rater reliability analysis and information retrieval statistical measures. The performance metrics of FoldSearch demonstrate the usefulness and strengths of the algorithm. The inherent limitations of conventional keyword search tools for bioinspired design, such as curated databases and limited search function, are not present in FoldSearch. FoldSearch can be used on various forms of biological literature, from leisure books to textbooks to academic publications, and across a broad spectrum of biological research fields, from zoology to materials.

Prior research related to bioinspired origami isolates insect wings and the physical properties of plants as the primary sources for origami design inspiration. However, the outcomes of the case studies clearly confirms that there are more biological sources for origami design inspiration than simply insect wings and the physical properties of plants. Indeed, many folding patterns, structures, and behaviors exist in nature that may provide useful design inspiration for origami crease patters and their application to novel foldable engineering problems.

Interestingly, over 75% of origami-based products were developed in the last five years [11]. Therefore, integrating origami principles into product design is an emerging design methodology. The bioinspired design process presented in this dissertation work has the potential to provide additional design solutions to support and advance the growing interest in origami engineering.

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APPENDIX A: FOLDSEARCH ALGORITHM

```
#!/usr/bin/python

import nltk.data
import os
import re
import textwrap

from nltk.tokenize.punkt import PunktSentenceTokenizer, PunktParameters
punkt_param = PunktParameters()
punkt_param.abbrev_types = set(['dr', 'vs', 'mr', 'mrs', 'prof', 'inc', 'fig'])
sentence_splitter = PunktSentenceTokenizer(punkt_param)


class color:
   PURPLE = '\033[95m'
   CYAN = '\033[96m'
   DARKCYAN = '\033[36m'
   BLUE = '\033[94m'
   GREEN = '\033[92m'
   YELLOW = '\033[93m'
   RED = '\033[91m'
   BOLD = '\033[1m'
   UNDERLINE = '\033[4m'
   END = '\033[0m'


def scan(database, mode):
        RAW = 1
        DESCRIBE = 2
        IGNORE = 3

        descriptive_words = ['pattern', 'patterns', 'tiles', 'mosaic', 'rotational', 'rotate',
 'rotates', 'lattice', 'array', 'grid', 'tessellation', 'packing', 'vertex', 'vertices', 'symm
etry', 'translation', 'reflection', 'divide', 'division', 'network', 'geometry', 'angle', 'ang
les', 'profile', 'arrangement', 'behind', 'under', 'over', 'below', 'above', 'forward', 'forwa
rds', 'backward', 'backwards', 'inward', 'inwards', 'outward', 'outwards', ' up', 'upward', 'u
pwards', 'down', 'downward', 'downwards', 'towards', 'beneath', 'against', 'structure', 'struc
tures', 'its', 'it', 'itself', 'their', 'his', 'her', 'origami', 'leaf', 'leaves', 'seedling',
 'seedlings', 'plant', 'plants', 'stem', 'stems', 'flower', 'flowers', 'petal', 'petals', 'win
g', 'wings', 'proboscis', 'proboscises', 'tail', 'tails', 'antennae', 'fin', 'fins', 'back', '
web', 'webs', 'muscle', 'muscles', 'tissue', 'scales', 'denticles', 'tendrils', 'shape', 'shap
es', 'form', 'forms', 'body', 'size', 'rigid', 'rigidity', 'oblate', 'jointed', 'flat', 'flatt
ened', 'thickness', 'spherical', 'sphere', 'spheres', 'square', 'squares', 'hexagon', 'hexagon
s', 'hexagonal', 'octagon', 'octagons', 'pentagon', 'pentagons', 'pentagonal', 'triangle', 'tr
iangles', 'triangular', 'cylinder', 'cylindrical', 'cylinders', 'round', 'circle', 'cirlces',
'circular', 'shell', 'ball', 'balls', 'interlock', 'interlocks', 'mesh', 'architecture', 'barb
', 'surface', 'ridge', 'movement', 'movements', ' crease', 'flex', 'flexible', 'flexibility']

        stop_words = ("protein","amino acid", "molecule", "polypeptide", "proteins", "DNA", "R
NA", "mRNA", "molecules", "molecular", " gene ", " ion ", " ions", "wild type", "wild-
type", "bond", "bonds", "bonding", "dimer", "syndrome", "nano", "in-", "de-
", "change", "difference", "increase", "decrease", "higher", " lower ", " more ", "genome", "c
hain", "hairpin", "jelly roll", "chromatid", "chromatids", "chromosome", "chromosomes", "helix
", "helices", "helical", "bind", "binding", "domain", "domains", "mR", "sequence", "sequences"
```

```
, "topology", "jelly-roll", "cytoplasm", "periplasm", "cofactor", "co-
factor", "reductase", " domain", " protein", "substrate", "kinase", "in vivo", "putative", "li
pid", "substrates", "strand", "-strands", "strands", "-
strand", "mutant", "septin", "monomer", "antibodies", "antibody", "actin", "tubulin", "tubule"
, "residue", "thread", "collagen", "procollagen", "VPS", "mitotic", "chromatin", "cells", "cel
l")

        journals = os.listdir(database)
        os.chdir(database)
        kword_re = chooseword()
        count = 0

        rows,columns=24,40
        cols = int(columns) - 1

        for journal in journals:
                print(color.BOLD+journal+color.END)
                with open(journal, 'r') as j:
                        journal = j.read()
                if not quicksearch(journal, kword_re):
                        print("skipping")
                        continue
                sentences = sentence_splitter.tokenize(journal)

                for sentence in sentences:
                        found = []
                        found_descriptive_words = []

        #Raw Search Mode: Returns all passages containing any form of the selected keyword
                        if mode==RAW:
                            thissentences = textwrap.wrap(sentence, width=cols, break_long_wor
ds=False)
                            counted=False

                            for kw in kword_re:
                                    found += kw.findall(' '+sentence)
                                    found = [ a.strip().rstrip('.?!"\')]') for a in found ]

                            for thissentence in thissentences:
                                if (found):

                                        for hit in found:
                                                thissentence = thissentence.replace(hit, color
.RED+hit+color.END)
                                        print(thissentence)
                                        if not counted:
                                            counted=True
                                            count += 1
                            if counted:
                                print()

                #Descriptive Search Mode: Returns only passages containing any form of the sel
ected keyword AND the descriptive words
                        if mode==DESCRIBE:
                            thissentences = textwrap.wrap(sentence, width=cols, break_long_wor
ds=False)
                            counted=False

                            for kw in kword_re:
```

```
                                    found += kw.findall(' '+sentence)
                                    found = [a.strip().rstrip('.?!"\')]') for a in found]

                            for dsc in descriptive_words:
                                    found_descriptive_words += re.findall('\\b'+dsc+'\\b', sen
tence)

                            for thissentence in thissentences:
                                if (found) and (found_descriptive_words):

                                        for hit in found:
                                                thissentence = thissentence.replace(hit, color
.RED+hit+color.END)

                                        for dsc in found_descriptive_words:
                                                thissentence = thissentence.replace(dsc, color
.DARKCYAN+dsc+color.END)
                                        print(thissentence)
                                        if not counted:
                                            counted=True
                                            count += 1
                            if counted:
                                print()

               #Ignore Search Mode: Returns passages containing any form of the selected keywo
rd AND NOT the stop words
                        if mode==IGNORE:
                            thissentences = textwrap.wrap(sentence, width=cols, break_long_wor
ds=False)
                            counted=False

                            for kw in kword_re:
                                found += kw.findall(' '+sentence)
                                found = [ a.strip().rstrip('.?!"\')]') for a in found ]

                            for stop in stop_words:
                                t=sentence.find(stop)
                                if t!=-1:
                                    found=[]

                            if (found):
                                for thissentence in thissentences:
                                    for hit in found:
                                        thissentence = thissentence.replace(hit,color.RED+hit+
color.END)
                                    print(thissentence)
                                    if not counted:
                                        counted=True
                                        count += 1
                                if counted:
                                         print()

        return count


def chooseword():
        kwords = [('Bend', 'Bending', 'Bends', 'Bended', 'Bent',),
                 ('Coil', 'Coiled', 'Coils', 'Uncoil', 'Uncoiled', 'Uncoils',),
                 ('Compact', 'Compacts', 'Compacted',),
```

```
                 ('Curl', 'Curls', 'Curling', 'Curled', 'Uncurl', 'Uncurls', 'Uncurled', 'Curvature'),
                 ('Curve', 'Curves', 'Curved', 'Curving', 'Curvature'),
                 ('Elongate', 'Elongation', 'Elongated', 'Elongates',),
                 ('Expand', 'Expands', 'Expanded', 'Expandable', 'Expanding',),
                 ('Extend', 'Extends', 'Extended', 'Extending',),
                 ('Flex', 'Flexes', 'Flexing', 'Flexed', 'Flexure',),
                 ('Fold', 'Folds', 'Folded', 'Folding', 'Foldable', 'Unfold', 'Unfolds', 'Unfolded', 'Unfolding',),
                 ('Inflate', 'Inflates', 'Inflated', 'Inflating', 'Inflatable',),
                 ('Retract', 'Retracts', 'Retracting', 'Retracted', 'Retractable',),
                 ('Roll', 'Rolled', 'Rolls', 'Rolling', 'Unroll', 'Unrolled', 'Unrolls', 'Unrolling',),
                 ('Shape change', 'Shape-change', 'Shape-changing', 'Shape changing', 'Changes shape', 'Changed shape', 'Changing shape', 'Change shape', 'Change its shape', 'Change their shape',),
                 ('Snap', 'Snaps', 'Snapped', 'Snapping',),
                 ('Stack', 'Stacks', 'Stackable', 'Stacking', 'Stacked',),
                 ('Stretch', 'Stretchable', 'Stretches', 'Stretching', 'Stretched',),
                 ('Tuck', 'Tucks', 'Tucked', 'Tucking',),
                 ('Twist', 'Twists', 'Twisting', 'Twisted',),
                 ('Wrap', 'Wrapping', 'Wraps', 'Wrapped',)]

        print()

        for a in range(0, len(kwords)):
                print(str(a+1)+") "+kwords[a][0])
        choice = int(input("Enter a number: "))
        kword =  [ a.lower() for a in kwords[choice-1] ]
        return [re.compile('[^a-zA-Z0-9-]'+kw+'\\b') for kw in kword ]


def quicksearch(journal, kword_re):
        found = []
        for word in kword_re:
                if (word.search(journal)):
                        return True
        return False


if __name__ == '__main__':
        mode = int(input(("\nSearch Mode:\n1) Raw Search Mode\n2) Descriptive Search Mode\n3) Ignore Search Mode\n> ")))
        while (mode not in range(1,4)): mode = int(input("> "))
        count = scan('TextFiles',mode)
        print("\nFOUND "+color.PURPLE+color.BOLD+str(count)+color.END+" Occurences\n")
```