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Humanizing Architecture: A Polymorphic Space

Nada Abbara

HUMANIZING ARCHITECTURE
A POLYMORPHIC SPACE

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CONTENTS

CONTENTS

ACKNOWLEDGMENTS

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ABSTRACT

The built environments in which our communities thrive constitute an integral part of human experience and evolution. Yet, many places are detached from the way we experience them due to mass-production, which often produces standardized environments, and due to the tendency of modern architecture to delineate spaces as static objects rather than dynamic interactions. Thus, there is an emerging need to humanize architecture through an interdisciplinary approach that engages nature's behavioral patterns. The project proposes a transformable polyhedral structure that interacts with human emotion through a three-dimensional morphing space that contracts and expands. This spatial interaction is achieved through a comprehensive process of employing the principles of interactive design and by applying mechanical construction techniques of transformable polyhedrons inspired by Buckminster Fuller's *Jitterbug*.

Fig. 1. A scene from *Playtime* (1967): Monsieur Hulot navigating the space around him.

INTRODUCTION

Monsieur Hulot, a character in Jacques Tati's 1967 film *Playtime*, is trapped in the new modernity of Paris where buildings are derivative and predominantly gray. He desperately navigates a built environment that is mundanely homogeneous, spatially confusing, and paradoxically detached from human scale. *PlayTime* shows how industrialization and mass-production have produced dehumanized spaces that are static and monotonous, standardized and repetitive. These spaces are almost impossible to navigate, decode, or establish any meaningful relationship with. In such spaces, we become alienated from our surroundings and inclined to perceive and utilize spaces passively. Hence, our sense of space is diminished over time, for our architecture is mute.

This profound sense of spatial silence originates from the modern architectural tendency to regard spaces as materialized entities rather than dynamic interactions and interrelations.[1] In fact, our recollection of a space is shaped by the depth of our interaction with its various components as well as the quality of our experience with its constituents, whether tangible or intangible. These experiences are primarily formed by factors beyond the spatial periphery; they are the product of our psychological and sociological interpretations of a space.[2] John Welwood clarifies in *The Journal of Transpersonal Psychology* that our physical and psychological space belongs to one and the same space; they reflect each other. Our psychological space is not measurable yet undeniably experienceable.[3]

Pallasmaa's *The Eyes of the Skin* speaks of the timeless task of architecture where one's self should be "in [a] constant dialogue and interaction with the environment, to a degree that it is impossible to detach the image of the self from its spatial and situational existence. "'I am my body,' but 'I am the space, where I am."[4] To achieve such a holistic sensational experience and establish a more dynamic relationship with the spaces we inhabit, we need to "search for ways out from the stagnation of the architectural scene."[5] Architectural spaces should not be perceived or treated as passive autonomous enclosures where human activities unfold, but rather interact with and be part of them. I believe they should not be "encountered" as Pallasmaa suggests, but rather *interacted with*; not merely "lived" but *alive*.

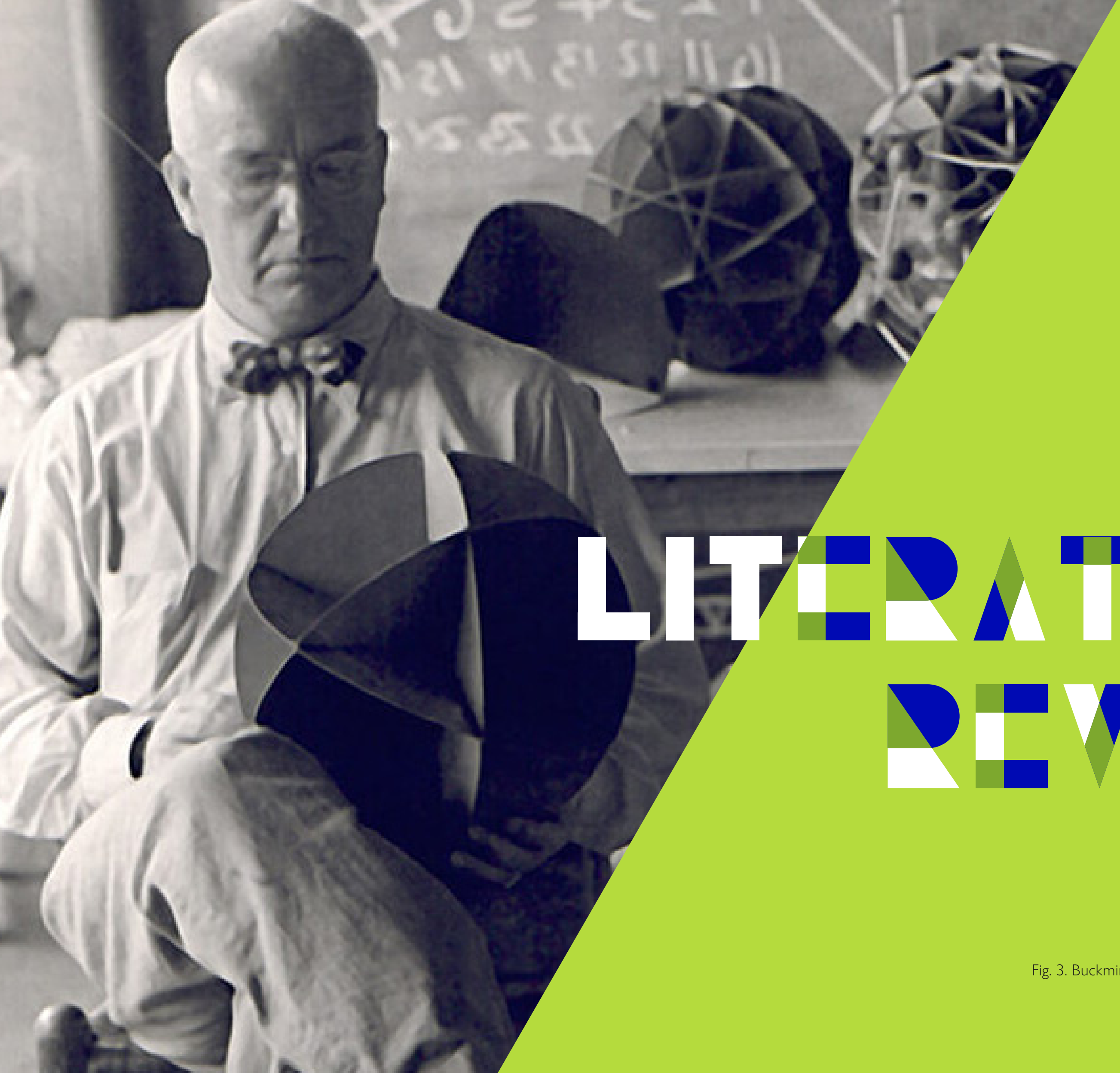
The emergence of interactive technologies has infused spaces with capabilities associated with the living realm. Such spaces reveal advanced dimensions when equipped with smart technologies, amplifying the "dialogue" with inhabitants through a multisensorial experience.[6] Interactive structures or installations respond and adapt to environmental changes and users' activities through the convergence of two complementary systems: an embedded computational system (intelligence), and a physical mechanical system (kinetics).[7] An example of installations composed of humanized mechanical components and computational systems is Omar Khan's *Open Columns* (2007). It is an interactive installation that consists of deployable columns made of polyurethane elastomers connected to a smart system in the ceiling. The system regulates CO_2 levels in the environment by reducing occupant capacity. When CO_2 concentration is high, the columns expand to alter people's circulations and propel them to disperse (Fig. 2).[8]

Fig. 2. *Open Columns* by Omar Khan (2007).

Interactive architecture creates a triangular relationship between nature, architecture, and humans; it reaches deep into the relationship between humans and their built environment and draws it back into the conversation. This approach provides a new agenda where spaces are humanized through interactivity, where motion and metamorphosis replace stasis, and where evolution and mobility become the program.[9] Transformation is the key characteristic that renders our spaces as living mechanisms. Humans are drawn to, and influenced by, dynamic spaces because there is a psychological correlation between spatial transformation and life.[10, 11] Hoberman indicates that "when one sees this spatial behavior [of transformation], one feels it in one's body—perhaps a physiological connection, because there is a sensation, a physical sensation and a mental and a perceptual sensation."[12]

To design spaces that transform the way they transform in nature, designers must bridge the gap between the digital and the physical design worlds. This gap is often bridged through mechanical systems.[13] Chuck Hoberman and Buckminster Fuller utilized geometry as a design tool since it is inherently highly symmetrical and modular, and therefore offered myriad transformable possibilities. The use of polyhedrons in spatial design allows architecture to shift from a two-dimensional, planner thinking style, to a three-dimensional, volumetric thinking style. However, geometry functions not only from a practical standpoint, but also from a symbolic one, as it resonates with nature and brings us in touch with the edge between the tangible and the intangible.[14, 15]

In the pursuit of humanizing architecture, my research investigates the human perception and experience of spatial environments and explores the triangular relationship between human psychology, spatial transformation, and nature. This project assumes an interdisciplinary design approach by combining Fuller's study of geometry and Hoberman's concept of transformation, coupled with interactive computational technology, to produce an immersive and interactive spatial experience. The project proposes a metamorphic polyhedral structure that interacts with human emotion through a three-dimensional spatial transformation of contraction and expansion. This renders the space as a pulsating, *living organism* that possesses the ability to *feel* its inhabitant.



LITERATURE REVIEW

Fig. 3. Buckminster Fuller, Black Mountain College (1948).

World War II (1939 – 1945) demonstrated an unprecedented dispensability of human life; around 85 million people perished.[16] In a world that witnessed so much destruction, restoring human life had never been more crucial. The atrocities of the war sparked a persistent desire to recoup human dignity by placing humankind at the center of scientific development and artistic experimentation. Post-war philosophical literature reflected this pursuit to revive the value of humankind and illustrated a renewed focus on 'humanism.' The concept of 'humanism' also took root in post-war architectural discourse on an urban and architectural scale. Although the phrase "Humanization of Space" was first coined by the architect Alfred Neumann in 1952, he was not the first to introduce this concept.[17] The humanization of space is a recurring concept that is constantly observed and reinterpreted. It is not a style or a group of predefined expressions or principles, but rather an experience of a space.

It was through the study and theories of proportions and measurements that 'humanism' as a design principle was first established in the architectural field. Two of the most influential essays that introduced theories of proportions in postwar architectural discourse were Rudolf Wittkower's "Architectural Principles in the Age of Humanism" (1949) and Le Corbusier's "The Modulor" (1950). The latter explored how the dimensions derived from different human postures can comply with the golden ratio to provide a scale or measurements for the design of buildings. Le Corbusier's incorporation of the golden ratio overlaps with Alfred Neumann's theory of proportions: 'the em-phi theory' (1953). It was believed that since the golden ratio is found abundantly in nature, it should therefore appear in architecture. Geometry was the tool to reveal and translate such ratios into built environments.[18] All of these theories promoted distinctive approaches, yet they shared the same purpose of humanizing architecture through proportions.

Buildings or structures were revolutionized significantly as a result of technological advancements in the military, which progressed quickly due to the pressures of the war. These wartime inventions were slowly appropriated into other areas of daily life. The American architect and inventor Buckminster Fuller applied these advances to architecture.[19] Fuller believed that buildings should be highly efficient and that this could be achieved through technological advances: to "build more with less until eventually you can do everything with nothing," a concept that he called "Ephemeralization."[20, 21]

Fuller focused on two aspects in his work: performance and geometry, the latter of which he developed through an exploratory approach to mathematics and three-dimensional investigations. For Fuller, geometry was lines of force and resistance that provided a powerful problem-solving tool.[22] The study of transformation of polyhedrons was first proposed by Fuller in 1963 after he developed a transformable polyhedron which he called "Jitterbug Transformation" (see page 30). Although he believed in the importance of the physical implementation of such transformable polyhedrons, it was not technologically feasible to build the *Jitterbug*. Ultimately, his geometrical discoveries led him to develop his most renowned invention, the *Geodesic Dome* (Fig. 4 & 5).[23]

Fig. 4. *Geodesic Dome,* United States pavilion for Expo 67, Montréal.

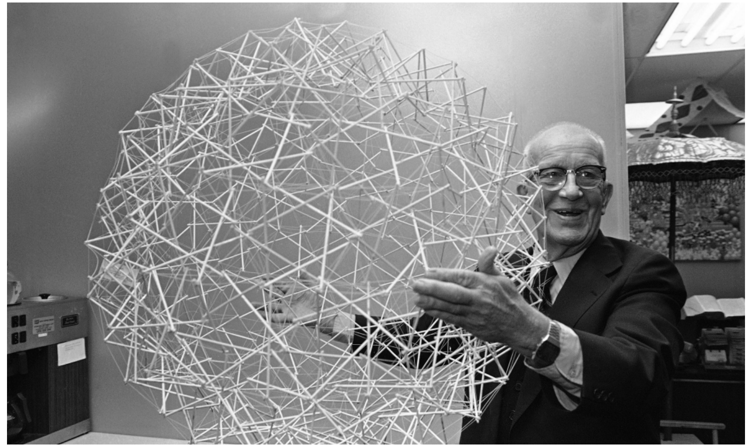


Fig. 5. *Tensegrity Sphere* by Buckminster Fuller.

Geometry is the medium through which architectural abstraction becomes real. Although geometry is used thematically by most architects, Fuller and Naumann worked with geometry in its purest state.[24] (Fig. 6 & 7) Their design approaches varied significantly yet shared the conception that geometry is the quintessence of the universe. Their approach to design is non-planar and utilizes unconventional orthogonal axes through space-filling tessellation (three-dimensional tessellation of polyhedrons). Indeed, geometry allowed Fuller to do "more with less." He insisted that the social and environmental challenges facing humankind required a break from the past by ignoring the conventional boundaries between disciplines. His unique discoveries effectively took place in the space between disciplines, which laid a path to revolutionize architectural thinking.[25]

Nonetheless, the humanization of space as we know it today was influenced considerably by factors extraneous to architecture: the technological advances of the industrial revolution, modern science, and psychology.[26, 27] These factors induced a dramatic shift towards humanizing spaces by moving from a form-oriented to a behavior-oriented approach. It evolved into a concept that emphasized interacting with the built environment and utilizing technological innovations that became less reliant on traditional architectural precedents.[28] This architectural approach is interdisciplinary by nature and is characterized by mobility and performance where space is humanized through the interaction with its inhabitants and context. In such an interactive environment, the third dimension—space—is a variable constituent, and the fourth dimension—time—is a newly integrated constituent: thus, a space-time architecture.

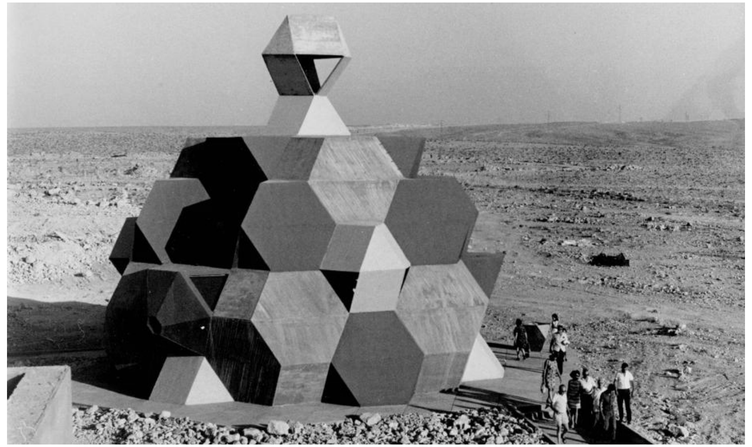


Fig. 6. Synagogue at the Officers School Training Base I, Israel.

Fig. 7. Interior view of the Synagogue at the Officers School Training Base I, Israel.

These factors played an active role in shaping the theoretical foundation of interactive environments, which can be classified into mainly two fields of study: anthropology and cybernetics. The anthropological literature of architecture influenced the discussion of spatial thinking whereby the terms space, place, and placelessness were distinctively defined yet inextricably related. Space is amorphous and intangible, it cannot be simply defined or analyzed, but generally, space provides a context for place. The knowledge of space is essentially in the experience of it, thus it is more defined by the meanings assigned to it and less by location or landscape. We don't only experience a space through our senses; "space is not just perceived, it is lived."[29] Through this lens, architectural anthropology explores the reciprocal relationship between humans and their inhabited space.[30]

The emerging field of cybernetics, which originates from a Greek word meaning "the art of steering," is the study of systems that have a purpose or goal in both animals and machines. According to cybernetic principles, all types of systems—social, biological, and technological —have goals. Each system, biological and non-biological, is a loop of action and feedback (or cause and effect), which embodies characteristics of self-management and self-correction through communication.[31]

The period between the 1960s and 1980s witnessed a groundswell of theoretical and conceptual work that found its way into architecture. Postwar thinkers and architects developed theories that are named differently yet lie within the same context of humanizing spaces. Gordon Pask, a cybernetician, developed a 'conversation theory,' which serves as the basis of the architectural developments in interactive architecture.[32] The theory postulates that the inhabitant and the environment learn from each other and develop a constructive relationship through a conversation comprising of impacts, modifications, and reactions. The "Paskian," environment, as it were, is an interactive environment where the inhabitant is a participant rather than merely a user. It is important to point out that a Paskian environment is ideally not a preprogrammed system for a predefined set of actions, but more accurately a system that learns the behavior of its inhabitant, reprograms itself, and reacts accordingly.[33] Around the same period, Reyner Banham and others reimagined architecture through the lens of technology and introduced the 'anticipatory theory,' which is about flexible, adaptable technologies that anticipate and respond physically to changing environmental conditions.[34]

Cedric Price was one of the most influential early architects to adopt the theoretical framework outlined by cyberneticians and synthesize it with architectural theory, which is illustrated in his unbuilt projects. One of these projects was the *Fun Palace* in 1961, a responsive, flexible building that reacted to the changeable needs of the users and context. Yet these early theoretical works failed to establish a foothold due to the lack of adequate computational developments and physically-built prototypes.[35]

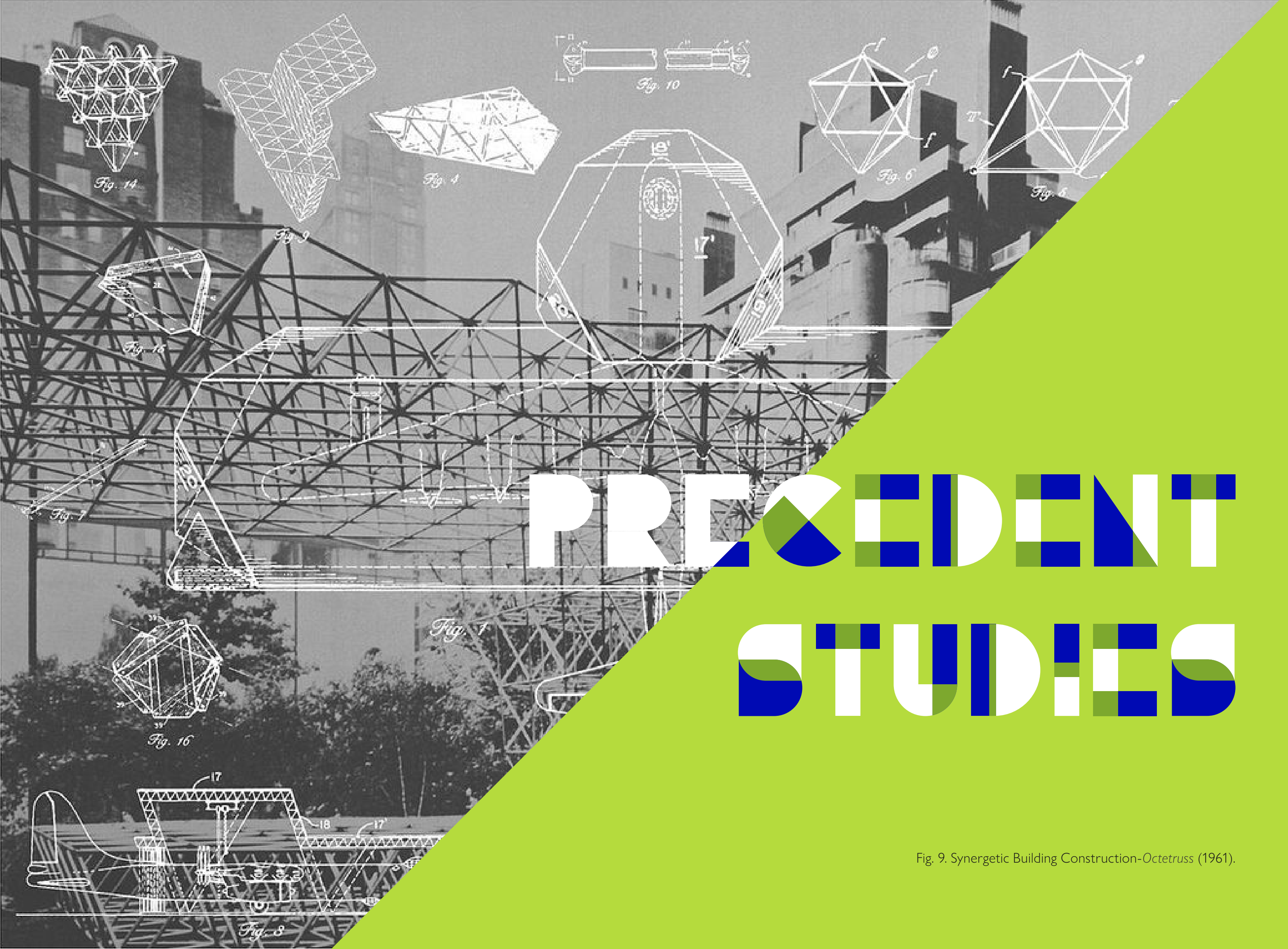
It wasn't until the late 1990s that technological advances became feasible to implement, which fueled the exploration and experimentation of these early architects' theories.[36] The advances in computer science and technology influenced the production methods and materials that brought about fundamental changes in traditional ways of building. Computer-aided design software offered a valuable tool to the study of transformable structures. It was a tool that not only allowed designers to generate a three-dimensional representation of an object before constructing it, but it could also simulate the movements of its mechanism.[37] Architects such as Chuck Hoberman, "the Buckminster Fuller of the 1990s,"[38] began to explore mechanisms where the notions of motion and transformation were challenged and redefined by the new possibilities that computational technology offered. Although Hoberman's concept of morphing structures is a digital inspiration, it stems from nature as well where transformation occurs at all scales (Fig. 8).[39]

In recent times, human-like-behavior (humanized) technology has altered the system reference for design conception, from the machine theory to the prevalent organic theory, which forms the contemporary basis for interactive architecture. The 'organic theory' (also named biomimicry) emerges from nature; an environment that possesses evolutionary patterns are continually reforming in response to environmental fluxes and rhythms. The change in a mechanical system is cyclical, but not developmental; the same factors are continually repeated. The organic system is also cyclical, yet it is evolutionary and reciprocal; "it emulates life."[40]

Fig. 8. Expansion of triangulated geodesic dome from angulated units designed by Chuck Hoberman.

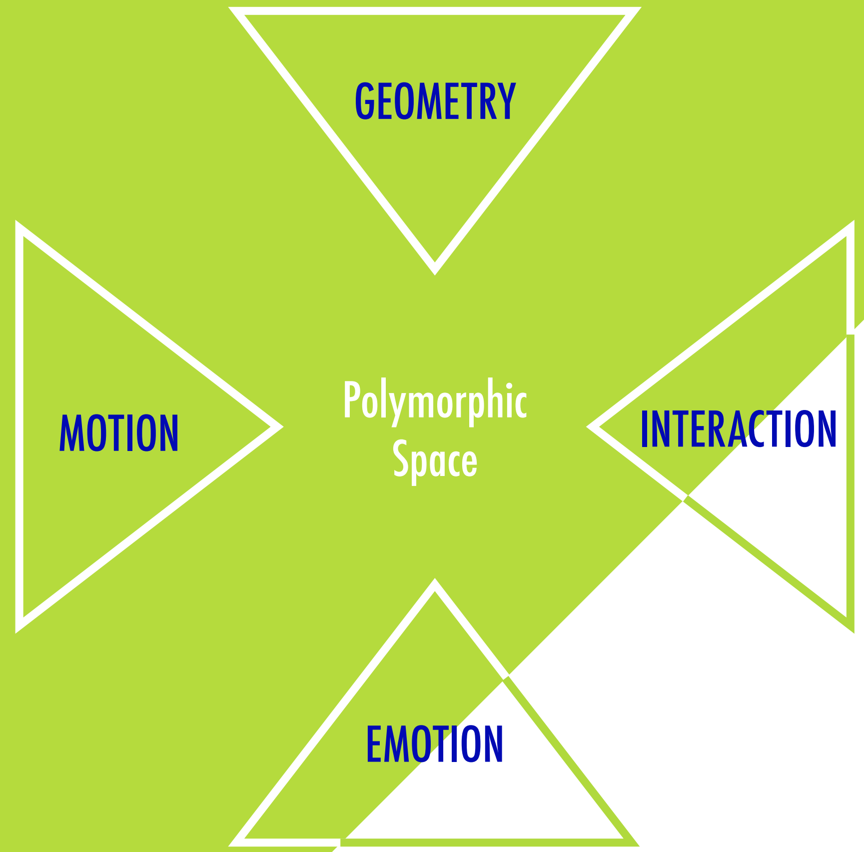
Perhaps it is only fair to conclude with what Michael Fox and Miles Kemp state in their book, *Interactive Architecture*:

> “[O]ur present task is to unfreeze architecture, to make it a fluid, vibrating, changeable backdrop for the varied and constantly changing modes of life. An expanding, contracting, pulsating, changing architecture would reflect life as it is today and therefore be part of it.[41]”



PRECEDENT STUDIES

Fig. 9. Synergetic Building Construction-*Octetruss* (1961).



THE FANTASY END OF THINGS

Howl's Moving Castle

Director	Hayao Miyazaki
Type	Animated fantasy film
Date	2004
Language	Japanese
Production Company	Studio Ghibli
Based on	*Howl's Moving Castle, by Diana Wynne Jones*

Fig. 10. *Howl's Moving Castle.*

Howl's Moving Castle

His heart is a flame that is the heart of his castle. The walls cave in for his sorrow, expand for his joy, branch and shrink into interlocking pathways when he feels lost, and retreat to a tranquil warm home when he feels hopeful. His space is literally a physical extension of his emotional states. A unique portrait of the intimate and delicate relationship between space and its inhabitant is illustrated in Hayao Miyazaki's film—*Howl's Moving Castle* (Fig. 11a & b).

The main character, a wizard called Howl, lives in a castle of his own creation that is operated magically by a personified flame. Both are bound together by a curse that unfolds through the events of the story, and towards the end, his lost heart is found in the flame. The castle has a steampunk aesthetic, and moves on four legs like a living creature. It walks, settles, and alters locations and modes according to its master's needs and desires. It is an idealistic and artistic conceptual metaphor of 'humanized architecture' (Fig. 10).

In the real world, most spaces are passively designed because almost everything is standardized, including people's needs, which produces objectified places. In contrast, in the fantasy realm of films, storytellers must construct an immersive world where the story takes place, a process called 'world building'. The mise-en-scène is constructed with active and specific considerations of motion, spatial configuration, props, sound, light, and color to convey a character's personality, mood, and interests. All come together to produce a *subjectified* space explicitly designed to narrate a visual story. Within the confines of the screen, every frame is a painting, thus every detail matters. Such an active and holistic design approach demonstrates the substantial relationship between people and their places. Films, like *Howl's Moving Castle*, exaggerate and bring this relationship to the foreground where spaces play an active role in everyday life, and so they should.

The castle becomes a literal representation of Howl's emotions and creates a unique interactive relationship, providing a conceptual foundation and idealized inspiration for this project. Hoberman explains: "In developing ideas like mine, it makes the most sense to start on the fantasy end of things and work toward the reality end."[42] *Howl's Moving Castle* is the fantasy end of this thesis research.

Fig. 11a. A sequence of scenes from *Howl's Moving Castle*: Howl feels optimistic and magically transforms his place into a warm home

Fig. 11b. Howl is in his monster form, feeling lost and distant from his human nature; his place became a chaotic maze.

ON GEOMETRY

VECTOR EQUILIBRIUM

Jitterbug Transformation

Architect/ Designer	Buckminster Fuller
Building Type	Transformable Polyhedral Structure
Date	1948

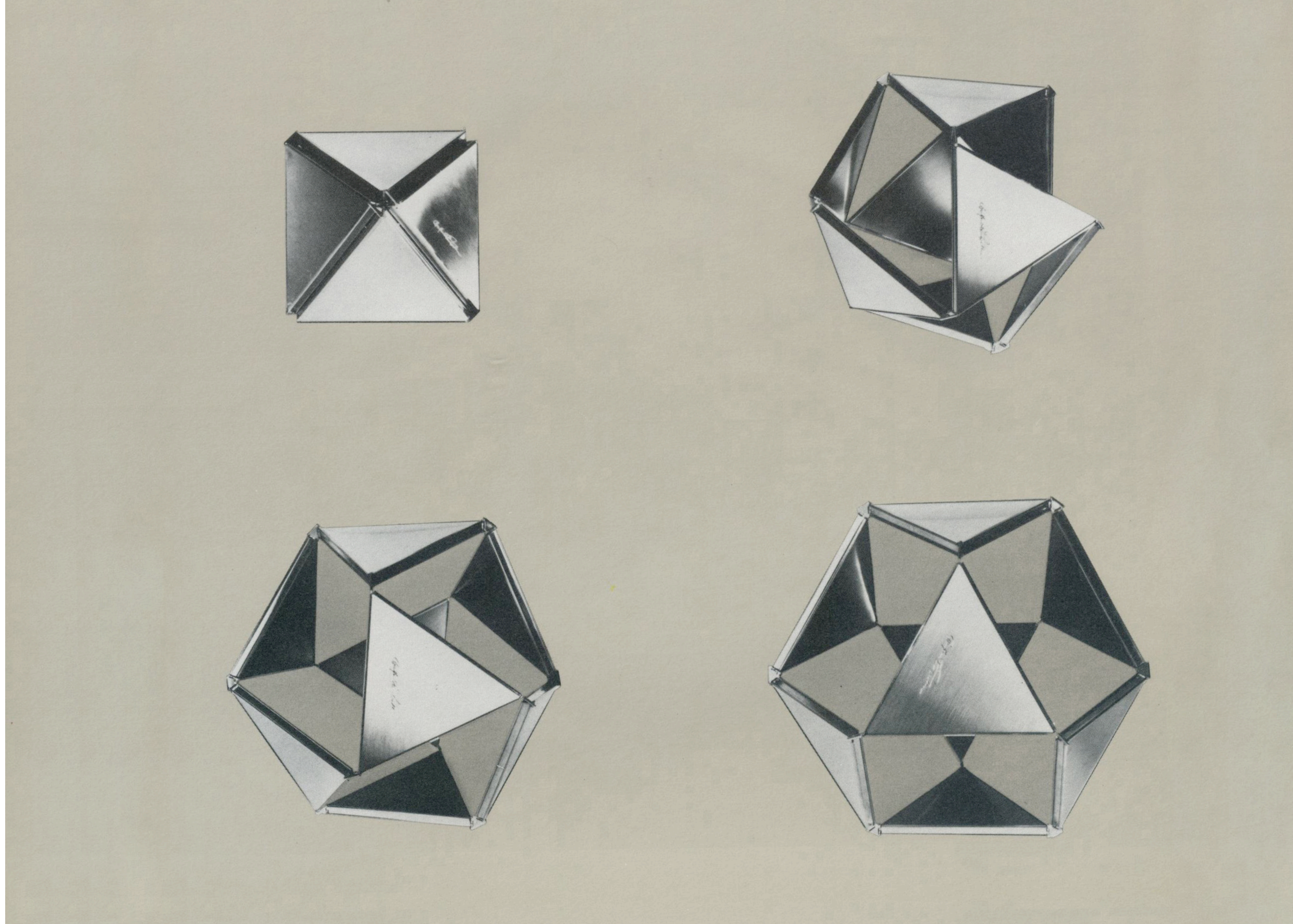


Fig. 12. Single-cell *Jitterbug*.

Jitterbug Transformation

Buckminster Fuller is known as an inventor, engineer, mathematician and futurist, but was not initially an architect.[43, 44] Yet, he revolutionized architectural thinking and uncovered remarkable discoveries precisely by not being an architect. His geometric inventions were a result of his exploratory and experimental approach to mathematics through the construction of three-dimensional models.[45]

Through his geometrical investigations, Fuller was introduced to the remarkable geometrical and structural properties of the cuboctahedron: the faces of the cuboctahedron are squares and equilateral triangles, all edges of the solid are of the same length. Exceptionally, if the center of the cuboctahedron is joined to each of its vertices, the twelve radii produced have the same length as the edges. This unique property led Fuller to call the cuboctahedron a "vector equilibrium."[46]

When the vertices of a cuboctahedron are joined to the center, it produces a structure of enormous stability. However, without connecting these vertices to the center, the cuboctahedron is an unstable structure. This instability is what Fuller was interested in exploring. In the late 1940s, he made a model of cuboctahedron with flexible rubber nodes that transformed in a twisting motion through distinct transition phases: cuboctahedron, icosahedron, octahedron, and tetrahedron.[47] In such a transformation, the octahedron becomes not a solid body anymore, but a fluid rotational motion in which one body dissolves into another, as if the structure is dancing. Fuller dubbed this transformation "Jitterbug," in reference to the *Jitterbug Dance* that was popular in the 1940's. Currently, the term "Jitterbug" is used to describe the rotational transformation of polyhedrons (Fig.12 & 13).[48]

The *Jitterbug* transformation is inspired by quantum physics. It is believed to be a tangible display that explains some of the invisible atomic behavior that happens all around us.[49] The study of the transformable polyhedrons is essential to this project in order to produce a transformable space that has the ability to stably expand and contract.

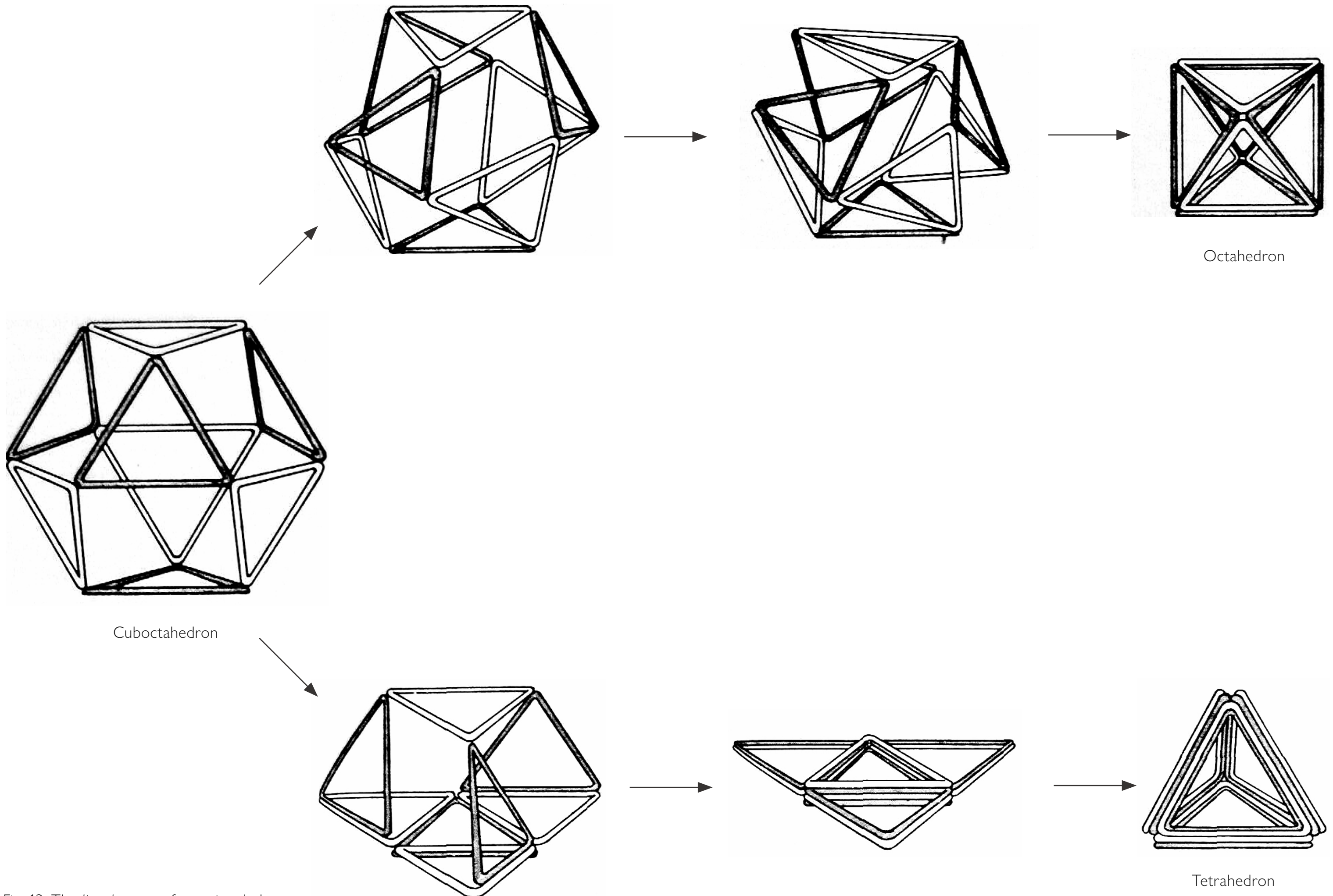


Fig. 13. The *Jitterbug* transformational phases.

NATURE'S LANGUAGE

Strandbeests *Animaris Rhinoceros Transport*

Architect/ Designer	Theo Jansen
Building Type	Kinetic sculptures
Date	2003 – 2005
Project site	Ypenburg, Netherlands
Area/size	*Animaris Rhinoceros Transport* is 6 x 5 x 4.7 m
Status	It was moved to the Osdrop Business Park, Ookmeerweg, Amsterdam New-West

Fig. 14. *Animaris Rhinoceros Transport* (2004).

Strandbeests

Strandbeests, meaning "beach animals" in Dutch, are wind-powered moving sculptures made by the Dutch artist Theo Jansen. He developed a series of kinetic sculptures that are skeletal in structure and mechanical in nature. These sculptures are built with simple materials: yellow PVC pipes joined by heat welding (Fig.15 & 16).[50, 51]

Their movement is powered by the wind and generated by a complex proportional mechanical system without the use of any computational technology. They walk on the sandy ground using mechanical legs that generate a natural movement, rather than wheels that imply a machine aesthetic. While treading, they appear as life-like forms that roam on the beach.[52] One of these beach animals/ beasts is *Animaris Rhinoceros Transport*, the largest sculpture in the series. Unlike the other structures, it was built with a steel skeleton covered by a polyester skin and weighed 3.2 tons, yet it can be moved by a relatively small external force (Fig.14).[53]

These kinetic structures provide studies of mechanical systems where motion is generated through the transfer of forces. Understanding the basic mechanics of these structures assists in developing mechanical solutions for this project. On a conceptual level, Jansen's beach animals express life through motion, which is a simple yet fundamental aspect of 'humanization' that can also be found in *Howl's Moving Castle*, Fuller's *Jitterbug*, and *Hoberman's Sphere*. These projects verify that the humanization of space is not achieved through a superficial application of form or aesthetic, but merely through the basic behavior of all living creatures, *motion*. They translate motion into life, "and life itself is motion; when motion ceases, life ceases."[54]

Fig. 15. *Strandbeests* on the beach with the artist, Theo Jansen.
Top: *Plaudens Vela* (2013). Bottom: *Suspendisse* (2014).

Fig. 16. *Strandbeests* on the beach. Top: *Percipiere Primus* (2006). Bottom: *Siamesis* (2009).

EMOTION A.I.

Ada

Architect/ Designer	Jenny Sabin & Microsoft Research
Building Type	Interactive pavilion
Date	2019
Project site	Microsoft's Building 99
Area/size	Two-stories high, and weighs around 816 kg (1800 pounds)
Status	Existing currently at its designated location

Fig. 17. *Ada's* interaction with the audience.

Ada

Ada project is a partnership between architectural designer Jenny Sabin and Microsoft Research. *Ada* is an architectural interactive pavilion that employs artificial intelligence to create a human-centric responsive environment. The pavilion senses people's emotions, analyzes them, and responds by changing light intensity and color, which creates "a choreographed dance of color and light" (Fig. 17).[55]

The pavilion's skeleton is an ellipsoid form, which consists of a hexagonal web made of 890 3D-printed nodes that connect fiberglass rods. The skin of the structure is a web made of a fabric that is digitally knit with photoluminescent yarn (these photoluminescent fibers absorb, collect, and emit light). At its center sits a large tensegrity cone composed of fiber optical cables.[56, 57] A network of sensors located around the building enables *Ada* to collect data on the audience's facial expressions, voice tone, and body gestures that are processed by A.I. algorithms and then decrypted into sentiments (Fig. 18-20).[58, 59]

This unique interactive installation comes to life by connecting with people and thriving on their emotions. It bridges architecture, technology, and psychology and offers a peek into the great potential of embedded computational technology on an architectural scale. Although *Ada's* responses are limited to changes in light and color, it provides an example of emotion-recognition technologies that could be implemented in this design project.

Fig. 18. *Ada* pavilion in Microsoft's Building 99.

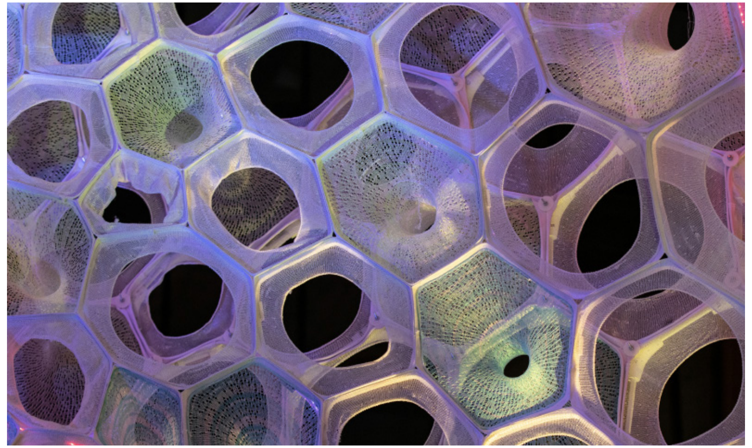


Fig. 19. A close-up of *Ada's* hexagonal web and structural components.

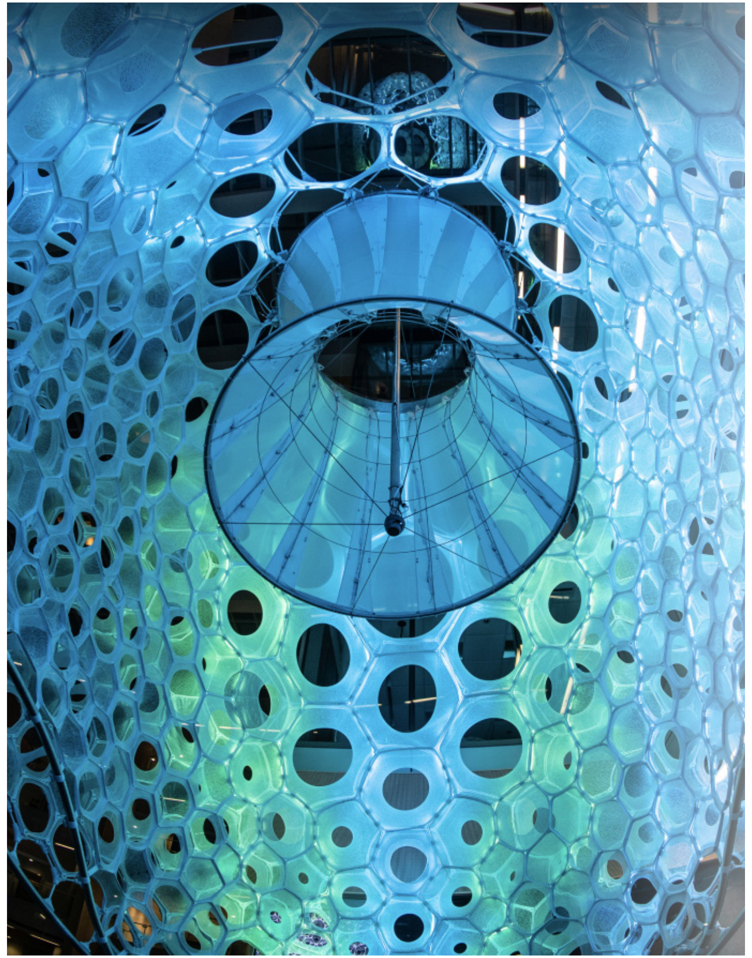


Fig. 20. The tensegrity cone of fiber optical cables in the center of *Ada*.

INVESTIGATIONS AND OUTCOMES

My thesis investigates deployable structures because I believe they have the potential to truly create transformative, dynamic experiences. Deployable structures are structures capable of configurational changes, often in an expansion and contraction motion, due to their geometrical and mechanical properties.[60] They are also referred to as transformable or kinetic structures and can be classified into four main categories: spatial bar structures, foldable plate structures, tensegrity structures, and membrane structures.[61]

Transformable structures have been studied extensively in scientific fields but few have made their way into architectural applications. Most of these applications are two-dimensional and deal with one architectural element rather than the whole space, such as transformable facades, or contractible roofs. The objective of this investigative process is to create an inhabitable morphing structure where the whole spatial volume transforms rather than a planar part.

Accordingly, three variables were considered:

- *The enclosed volume (the interior space) of the structure*
- *Three-dimensional transformation of expansion and contraction*
- *The stability of the transformational states*

GEOMETRIC EXPLORATIONS

Transformable structures are based on geometric and symmetric principles that are mostly bi-dimensional, hence their transformations are planar (in horizontal or vertical directions). Yet, some of these geometric studies can be developed to perform tri-dimensional transformation like *Hoberman's Sphere* (Fig. 21 & 22).

In geometry, polyhedrons are three-dimensional shapes with highly symmetrical configurations which offer the greatest potential for exploring tri-directional transformation. There are two main classes of convex* polyhedrons consisting of regular polygonal faces: the platonic and Archimedean solids. Platonic solids have only one type of polygonal faces and include five polyhedrons, whereas the Archimedean solids are composed of more than one type of polygonal faces and include thirteen polyhedrons (Fig. 23).[62]

*A convex polyhedron is one in which its faces never intersect and when joined together form a convex interior.

Fig. 21. Angulated scissors mechanism capable of two-dimensional expansion.

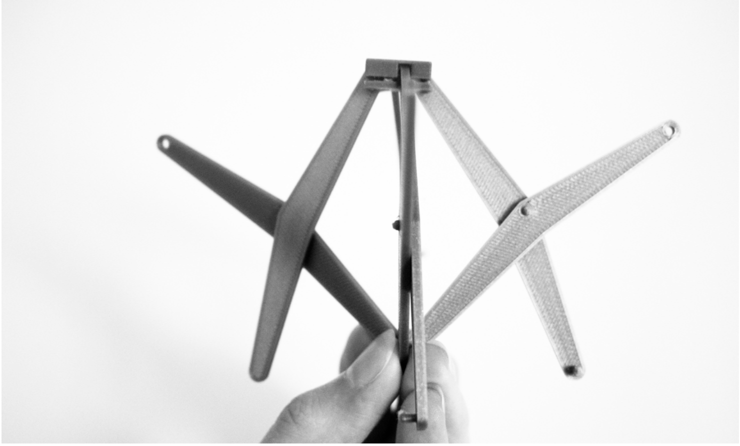


Fig. 22. The building unit of *Hoberman Sphere*: connector and scissors assemblies (4-sided).

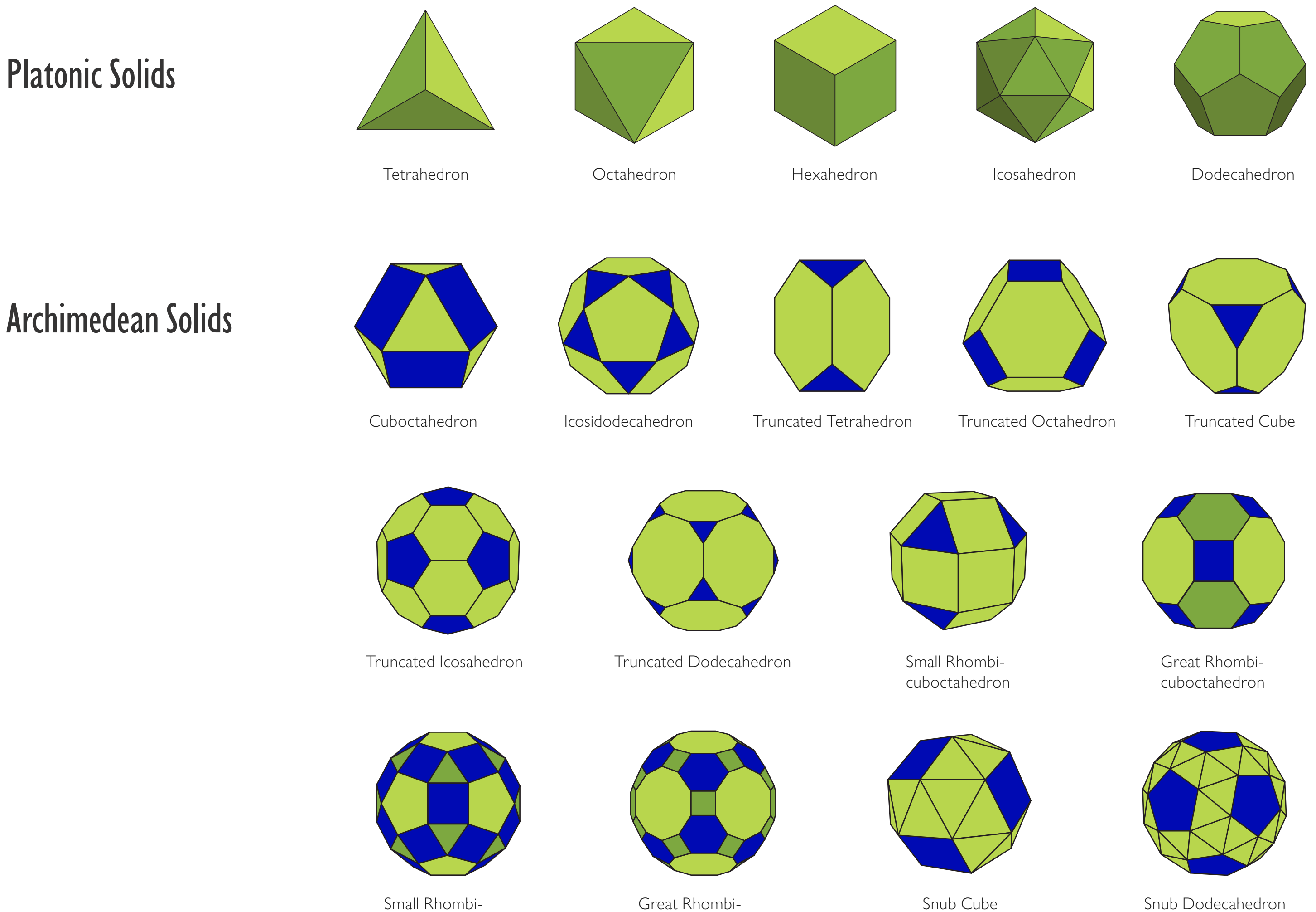


Fig. 23. Platonic and Archimedean solids.

DIRECTION 1

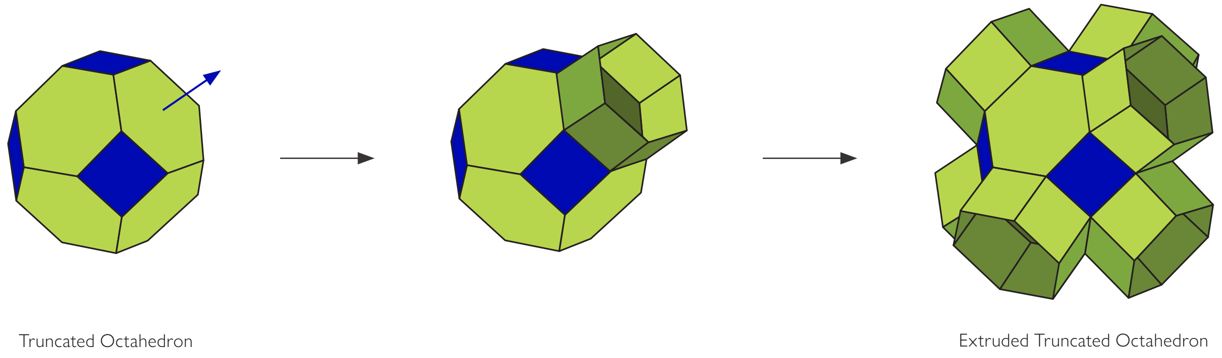
In the early stages of investigation, the art of origami provided a rich introduction to the design of reconfigurable forms. This structural study was adapted from the Snapology origami technique that constitutes prismatic geometry (extruded polyhedrons) to create three-dimensional reconfigurable structures.[63]

They are made through extruding the edges of regular polyhedrons in the direction normal* to their faces to construct the extruded unit (Fig. 24 & 25). The flexibility of the resulting structures was greatly reduced by their connectivity: the more extruded edges there are, the less flexible the structure is. To overcome these limitations, the design strategy was to reduce the connectivity of the materials by selectively extruding some of the faces while keeping the remaining faces rigid.[64]

This technique revealed a great variety of interesting modular structures capable of three-dimensional transformations. However, this approach does not satisfy the purpose of designing a habitable space because these structures have complex volumetric forms, are mechanically challenging to construct, and their transformational states generate unresolved surfaces (the extruded units have a branched configurational nature) (Fig. 26-28).

*In geometry, a normal is the axis perpendicular to a given object.

Fig. 24. Extruding the edges of a truncated octahedron in the direction normal to its faces.



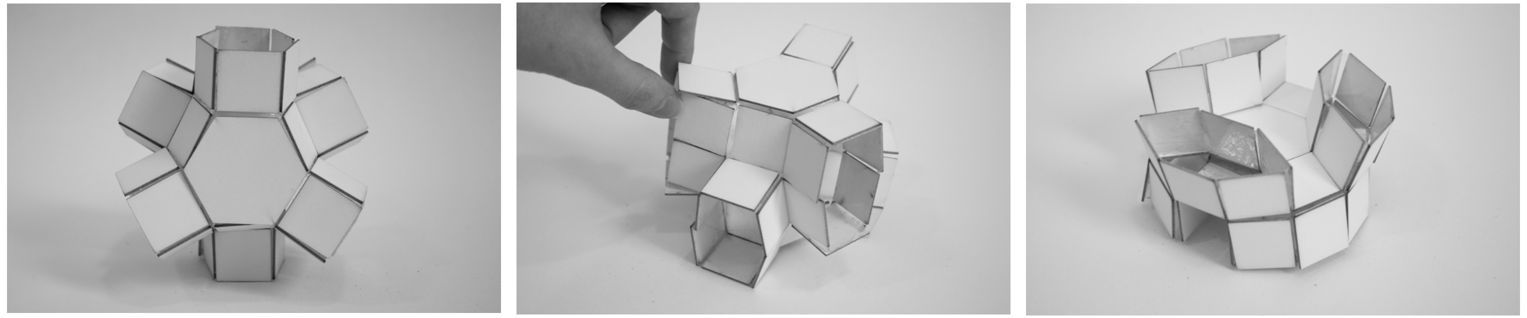


Fig. 25. Transformational phases of the extruded truncated octahedron.

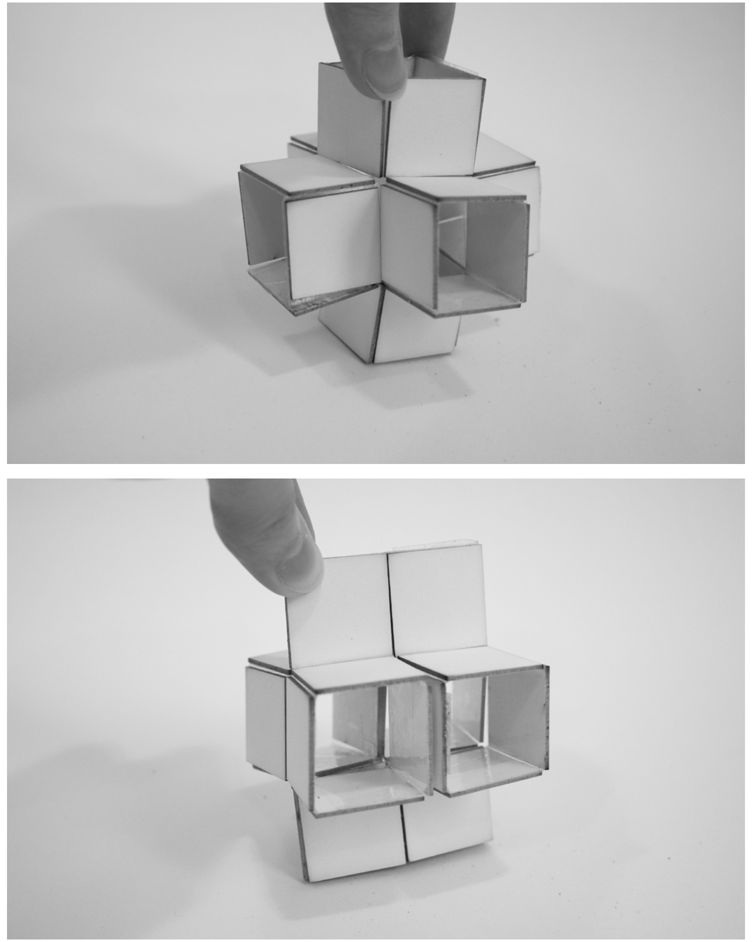


Fig. 26. Extruded cube.

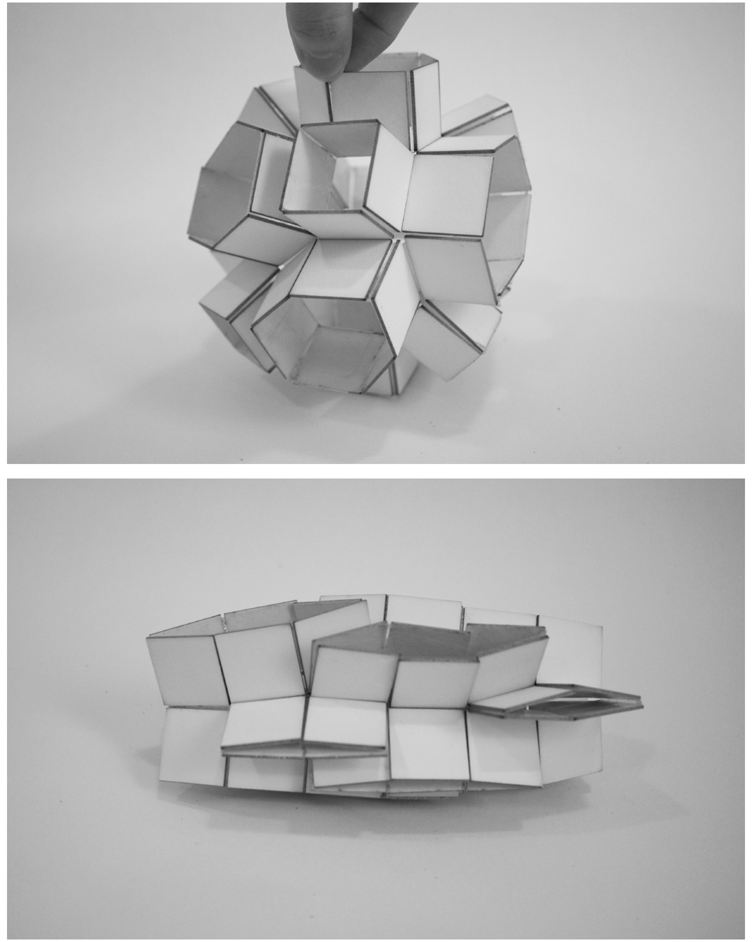


Fig. 27. Fully extruded truncated octahedron.

Fig. 28. Collection of extruded polyhedrons.

DIRECTION 2

This direction explores transformable polyhedrons that were first introduced by Fuller through the *Jitterbug* (see precedent study page 30). Polyhedrons that are *Jitterbug*-like transformers can accomplish a symmetrical expansion and contraction motion that allows for a large volumetric ratio.

In this approach, polyhedrons from the two families of Platonic and Archimedean solids can transform from one to the other if the two polyhedrons have the same number of identical-type polygonal faces. For instance, an octahedron can transform into a cuboctahedron since they have the same number of triangular faces. Such transformation involves the rotation of the identical faces around their normal at the center. These identical faces remain rigid during the transformation while the other faces vanish (Fig. 29).[65]

Type 1

In some paired polyhedrons, the rigid faces remain connected at the vertices during transformation, like an octahedron that transforms into a cuboctahedron. (Fig. 29) The faces of the polyhedral model are connected at the vertices by revolute joints that have one degree of freedom (DOF). Mechanically, the number of degrees of freedom (DOF) refers to the number of directions (axes) a body can move (Fig. 30) Transformable polyhedrons require the number of DOF to be low, thus the transformation can be easily controlled and prevent the structure from collapsing.[66]

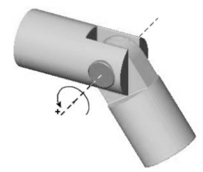
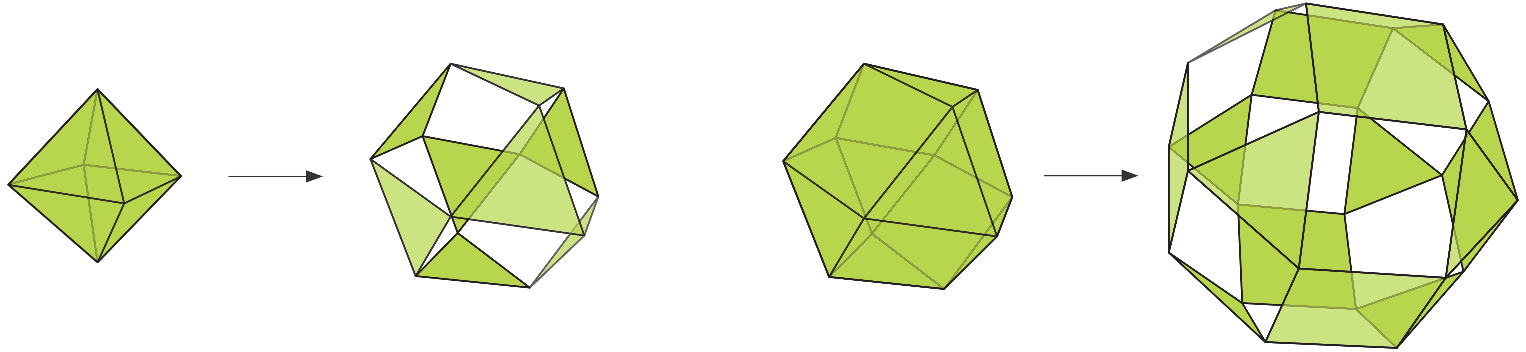


Fig. 30. Revolute joint: one degree of freedom.



Octahedron   Cuboctahedron   Cuboctahedron   Small Rhombi-cuboctahedron

Fig. 29. Transformable polyhedrons of Type 1.

Type 2

This approach can be extended to other paired polyhedrons, but the number of DOF would be high. In some pairs of polyhedrons, like the tetrahedron and truncated tetrahedron (Fig. 31), the joints (spherical joints) have two DOFs and the connection at the vertices between the rigid faces disappear through the transformation (Fig. 32). The process of making this transformation mechanically work requires a complex joinery system that would take up the inner volume (in this context: would reduce the interior space of the structure), hence this type of transformable polyhedrons was excluded.[67]

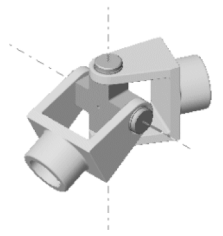


Fig. 32. Spherical joint: two degrees of freedom.

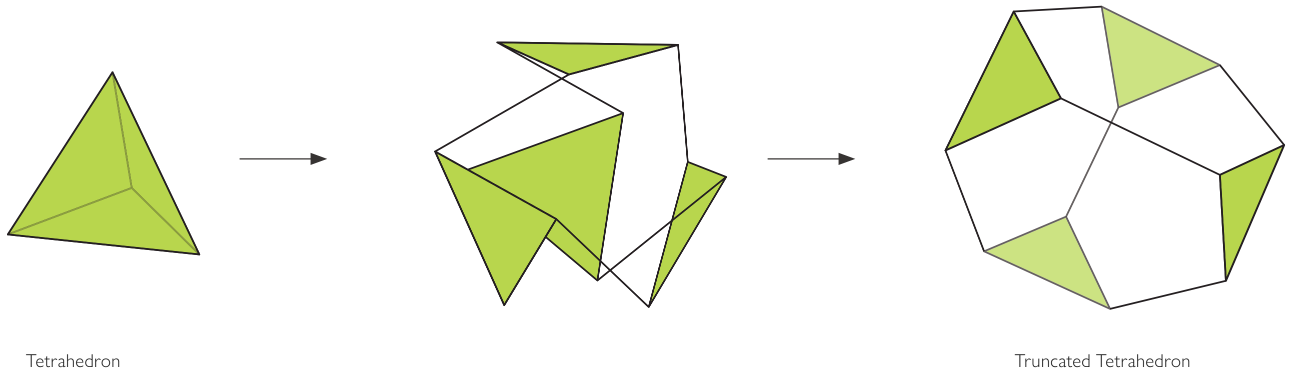


Fig. 31. Transformable polyhedron of Type 2.

FORM MODIFICATION

I prototyped and observed two transformable polyhedrons of type 1: (a) an octahedron and a cuboctahedron, and (b) a cuboctahedron and a rhombicuboctahedron. The transformation processes of these structures demonstrated a stable rotational motion of the polygonal faces. The following observations were noted: (1) a large volumetric ratio of one to five between the contracted and expanded states; (2) the rotational motion can occur in both directions (clockwise or anticlockwise); (3) the motion of a single polygonal face can actuate transformation of the entire structure; (4) lastly, the polygonal base is static throughout the transformation (Fig. 33-37).

Although there is a large volumetric ratio in both models, the area of the polygonal base stays the same.* This poses a limitation since there is no dimensional change where the horizontal circulation would take place in an inhabitable space. Nonetheless, the maximum planar change occurs in the mid-section of the polyhedral models. I explored removing some of the polygonal faces of the two models to have the central plane as the base of the structure. This led to narrowing the investigation to the cuboctahedron since it offered more structural stability than the octahedron. The cuboctahedron was divided as follows: the top square with four adjacent triangles, the four lateral squares, and the bottom square with four adjacent triangles. Then, I subtracted the bottom square and the four adjacent triangular faces (Fig. 38).

The altered polyhedron has five squares and four equilateral triangles connected by revolute joints. In a closed state, it forms a cuboctahedron minus the bottom square with the adjacent triangles. When it is expanded, the form is a half rhombicuboctahedron with an octagonal base. The resulting shape satisfies the structural parameters that were considered through the investigative process: It transforms three-dimensionally while maintaining its stability (one to five volumetric ratio), with a base that extends radially almost five times its original size. These spatial attributes demonstrated a significant potential for developing an inhabitable transformable structure. The next step was to plan the real scale of the structure and design an operational system (Fig. 39 & 40).

*The area of the base is the area of the rigid polygonal face on which the structure rests.

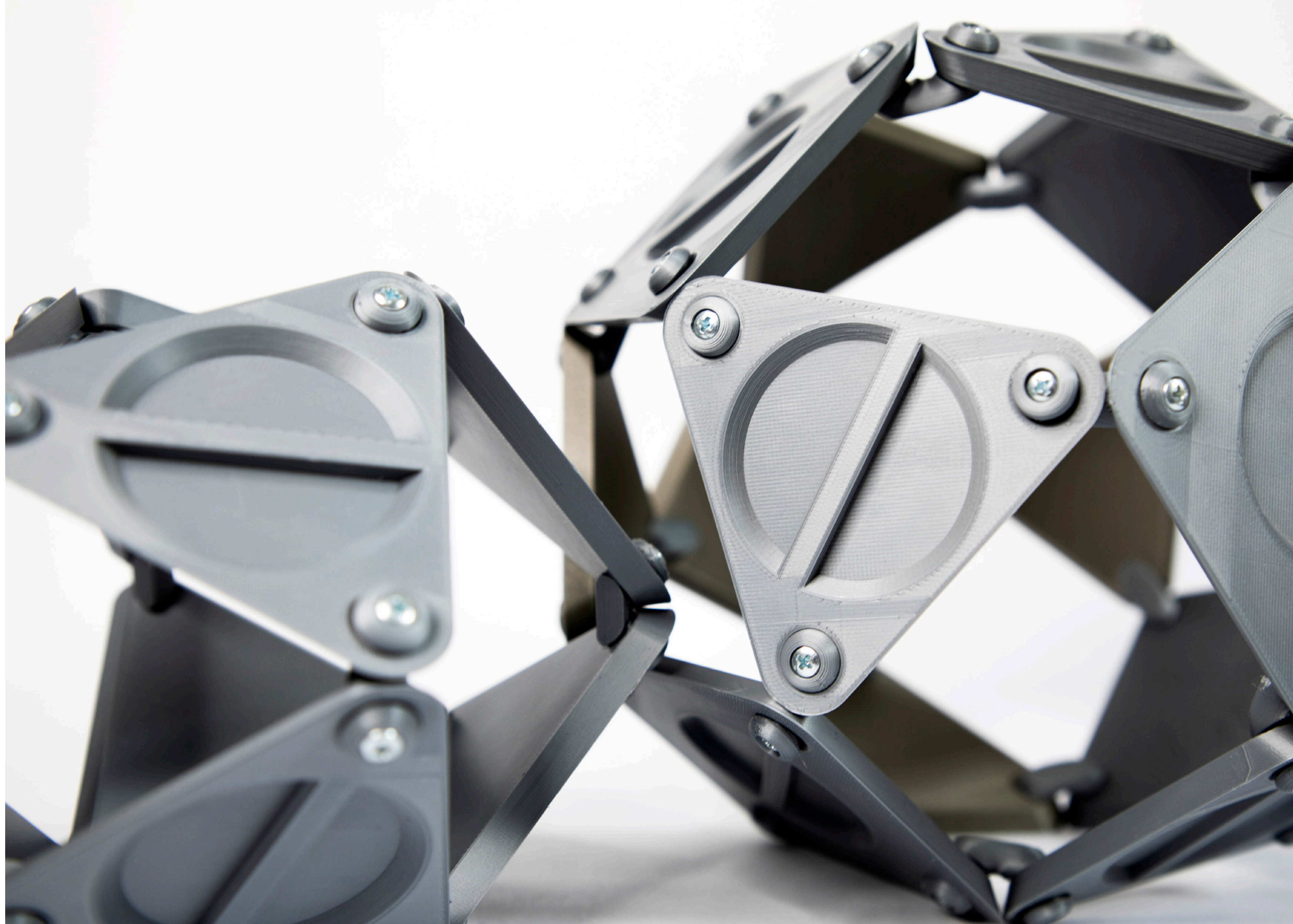


Fig. 33. A close-up of the polyhedral models.

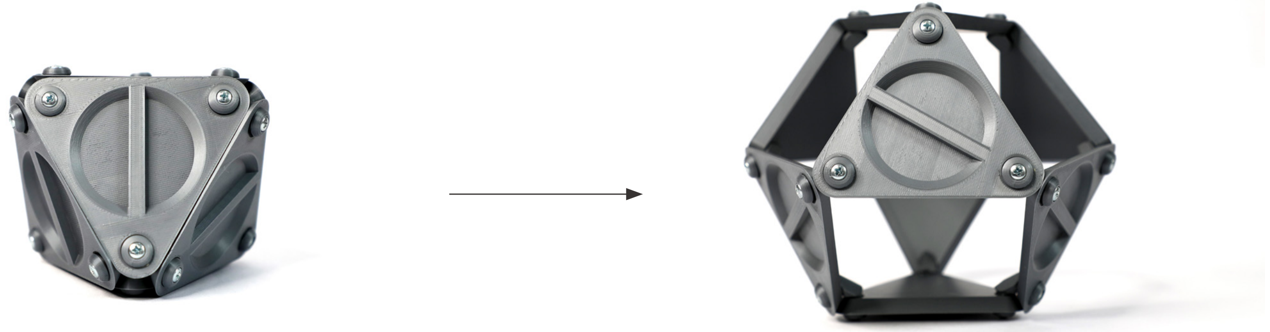


Fig 34. An octahedron that transforms into a cuboctahedron.

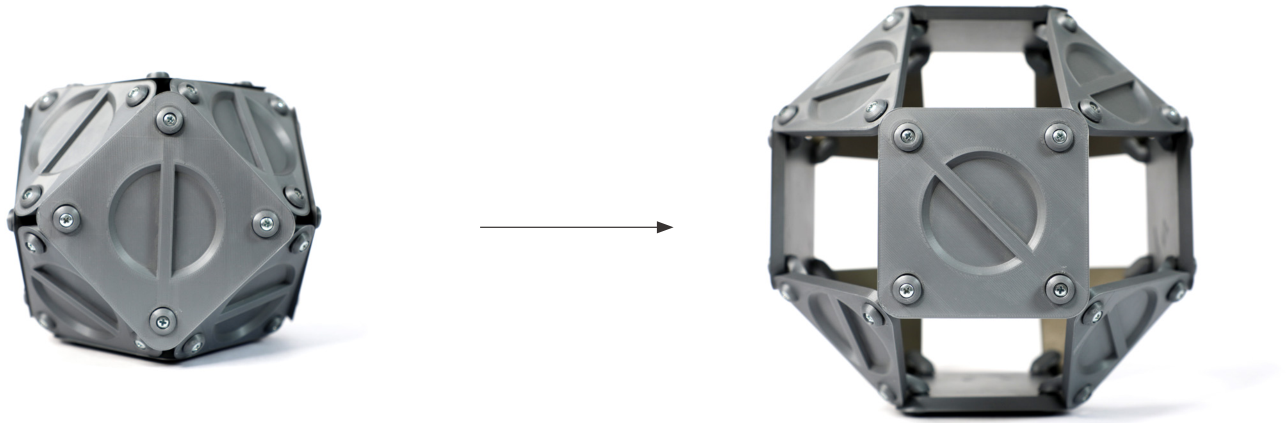


Fig 35. A cuboctahedron that transforms into a rhombicuboctahedron.

Fig. 36. The transformation of the polyhedral models can be actuated by moving a single polygonal face.

Fig. 37. The transformation of the polyhedral models can occur in both directions.

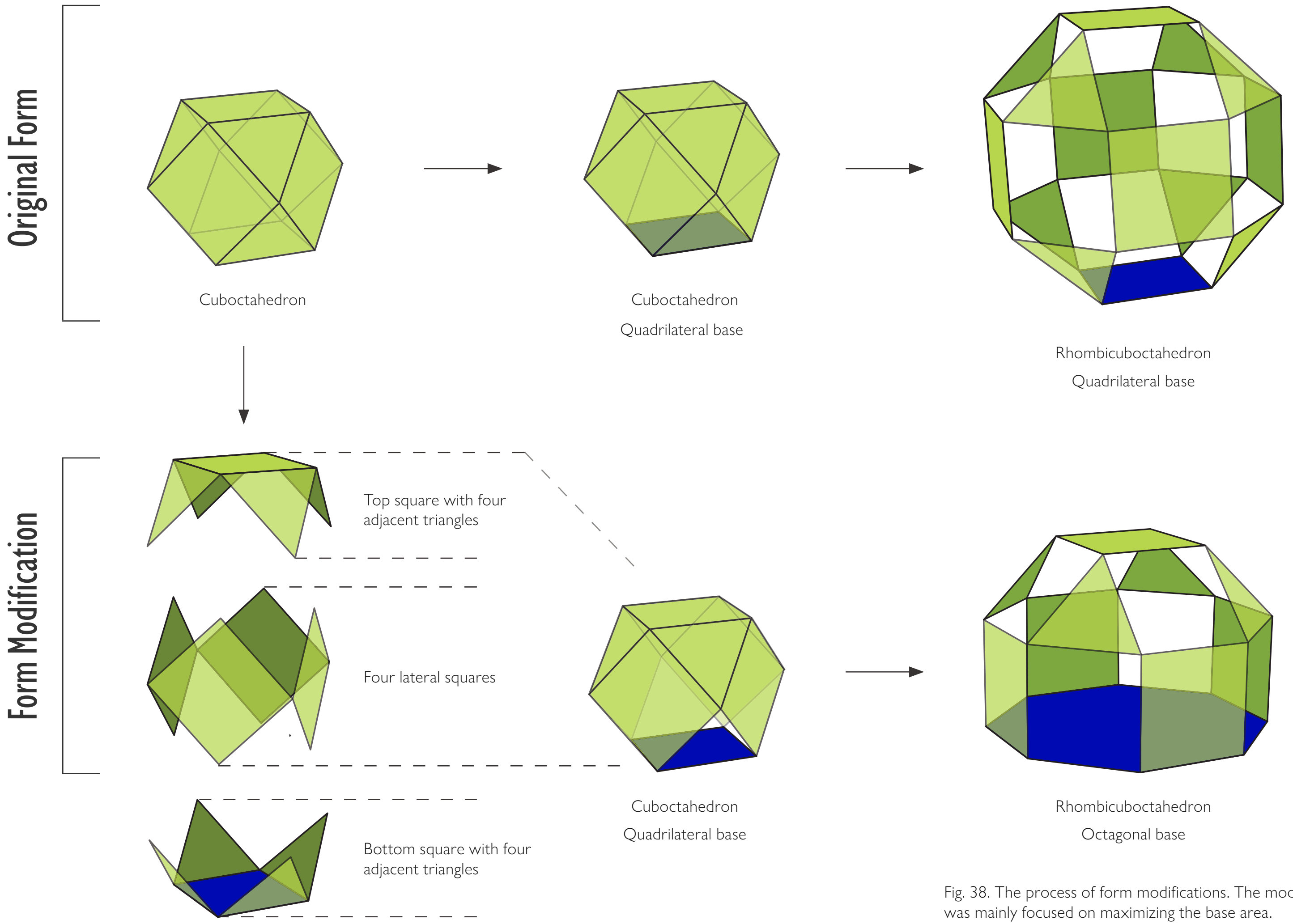


Fig. 38. The process of form modifications. The modification was mainly focused on maximizing the base area.

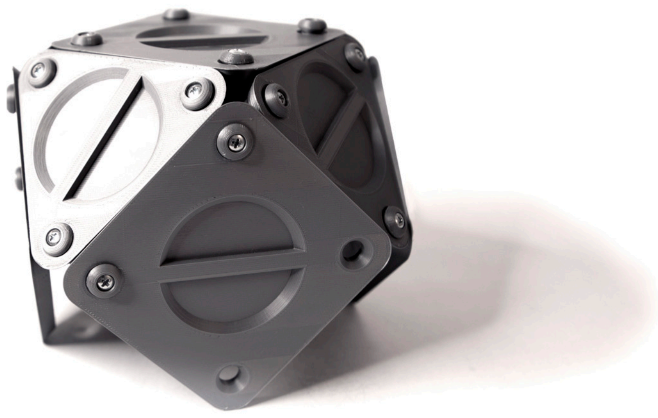


Fig. 39. The closed state of the form after modifications

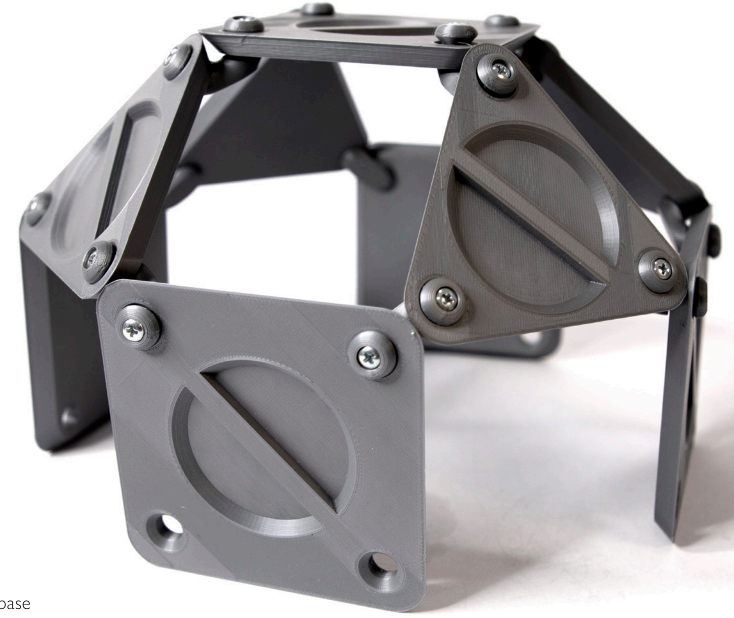


Fig. 40. The expanded state of the form after modifications. The ratio of the volume and the base area between the transformational states are 1:5.

MECHANIZATION & AUTOMATION

Since it is an architectural project, the experience of the space geometry is facilitated through a full-scale static structure that represents the expanded form of the model. The full-size skeletal structure is composed of polygonal faces with edge length that equals 1.8 m (the average human height) and is made of PVC pipes, 3D printed joints, and stretched fabric. For the scope of this thesis, the real scale of the transformable structure was scaled down to a one to eleven scale for testing and production feasibility (Fig. 49 & 50).

The downscaled structure is a conceptual model that represents an interactive transformable space. Through analyzing and tracing the motion of the polygonal faces, I noticed that the four vertical squares simultaneously move in radial directions while each rotates around its vertex that meets the horizontal plane (or base). These four vertices remain on the same plane throughout the transformation, and thus are used as points of actuation (Fig. 41). To automate the structure's transformation, I designed an operational base that houses the mechanical and the electronic system (Fig. 42).

The opening and closing process is operated by a simple rack and pinion mechanism with a central large gear that is connected to a stepper motor. When the central gear rotates, it actuates the rotation of the four smaller gears, which is converted into a linear motion through four racks placed at the edges of the base. Each rack is connected to the vertical squares at a single vertex with a special joint designed to allow the squares to rotate around these points as they move outward (Fig. 43 & 43).

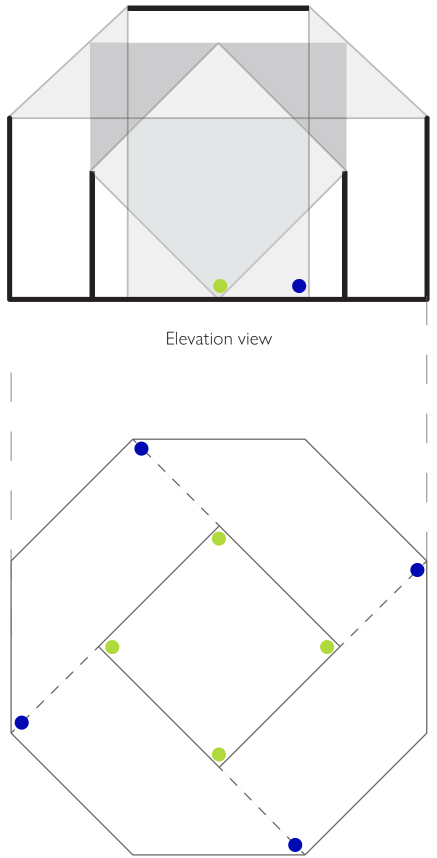


Fig. 41. The diagram shows the movement path of the squares. The dots indicate the corners that stay on the base through the transformation. Green dots: closed state, quadrilateral base. Blue dots: expanded states, octagonal base.

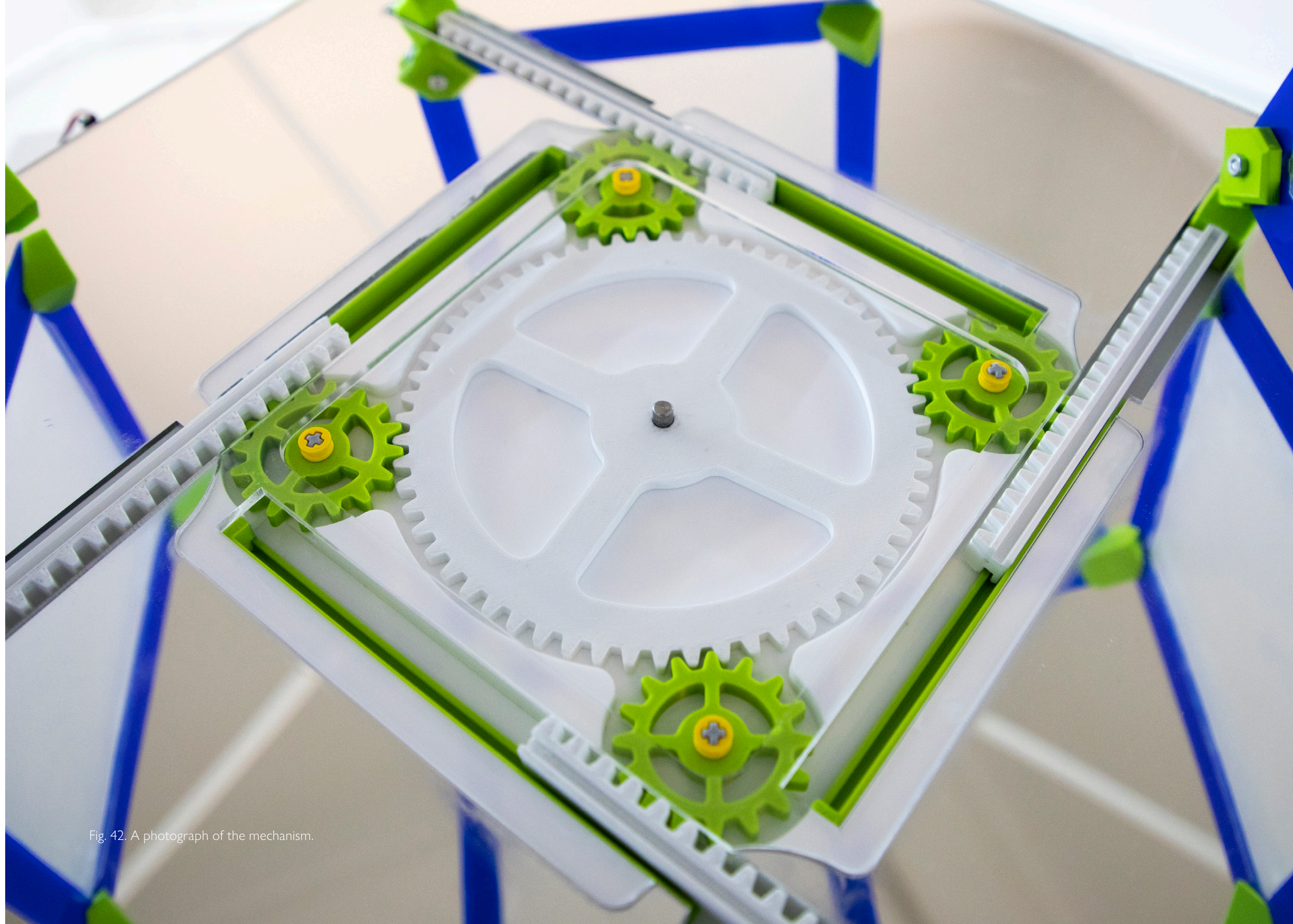


Fig. 42. A photograph of the mechanism.

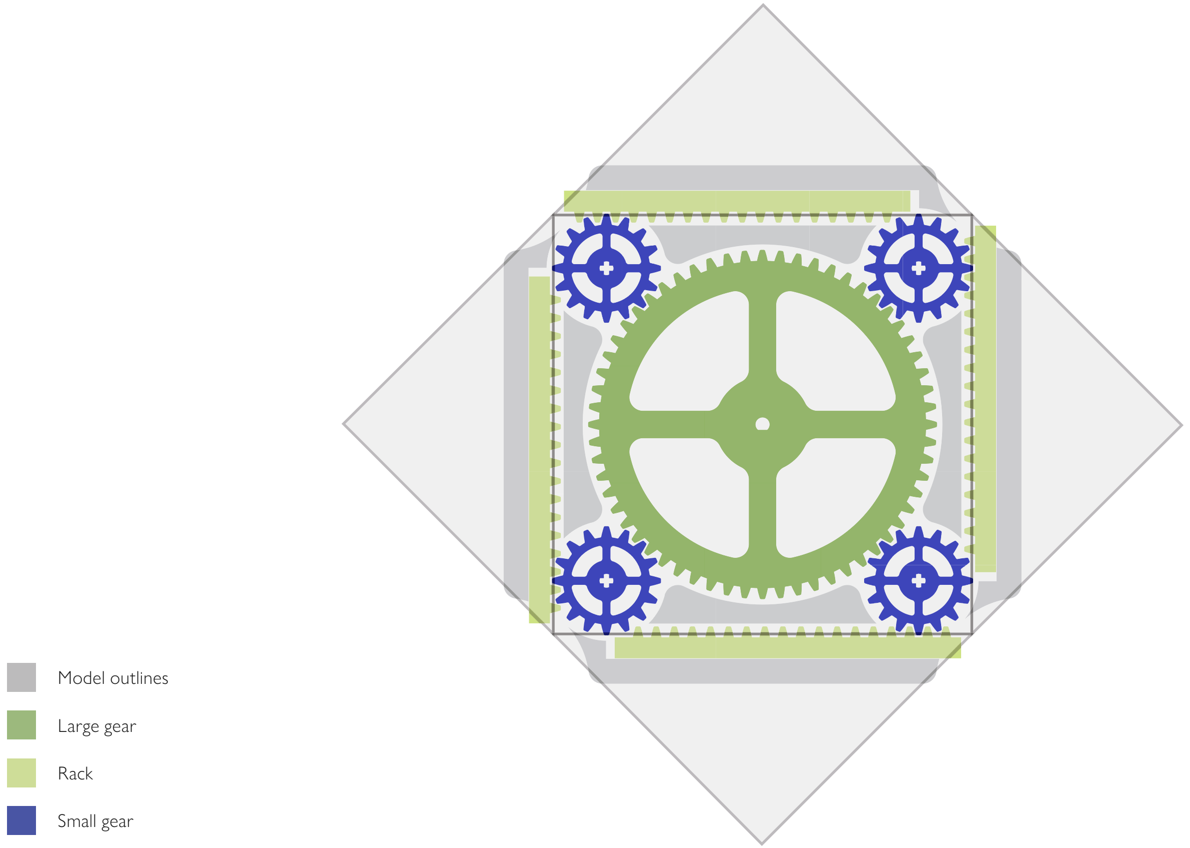


Fig. 43. Top view of the mechanism in the closed state.

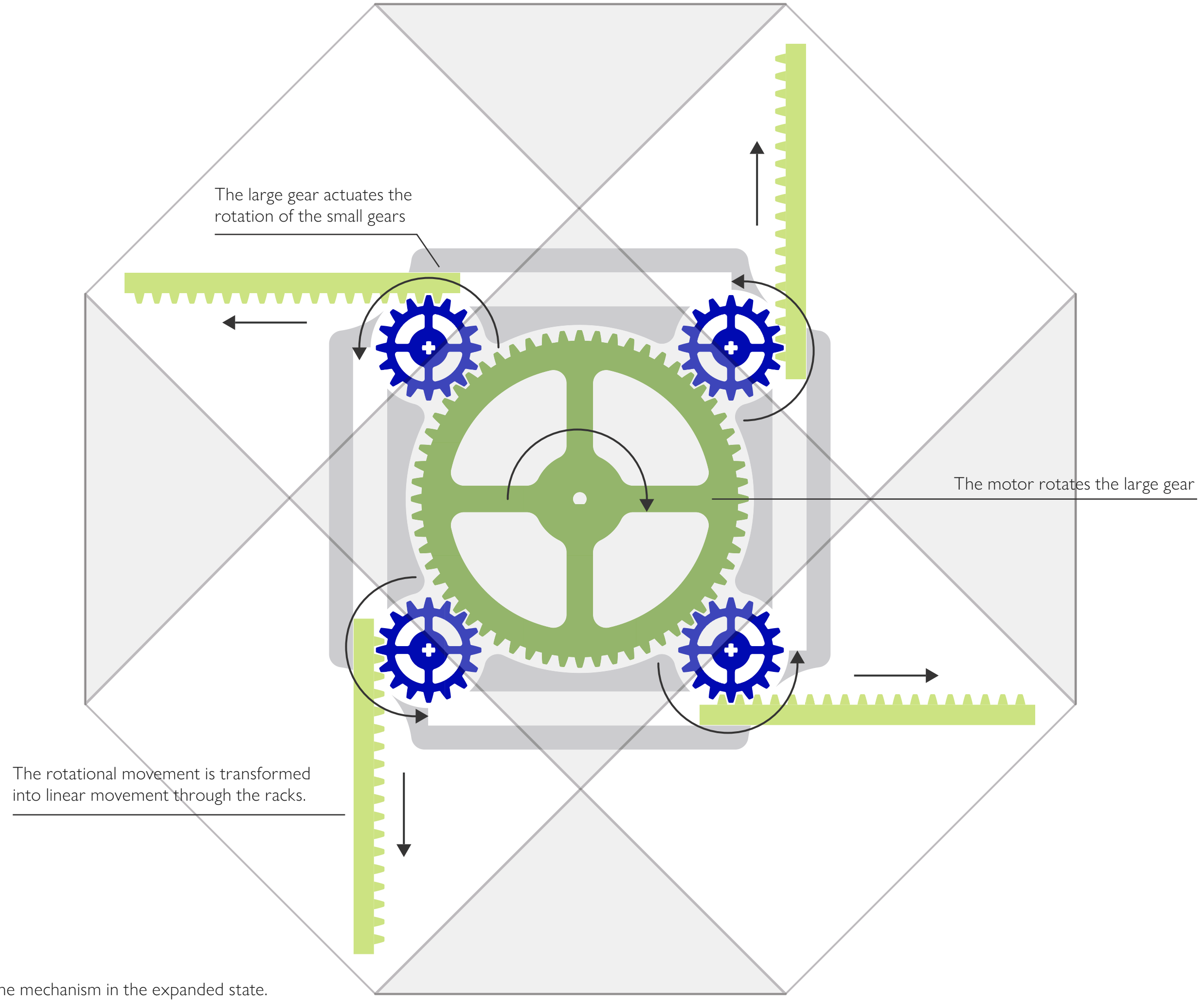


Fig. 44. Top view of the mechanism in the expanded state.

The mechanical system is activated by a central motor connected to an Arduino board (Fig. 48). Originally, the transformation of the structure interacts with the emotional state of the inhabitant. This would be achieved through a galvanic skin response (GSR) sensor to calculate the electrodermal activities in human skin. These bio data indicate physiological and psychological arousal that would be translated into human emotional states of relaxation or activeness. Nevertheless, because of the unusual circumstances of Covid-19 the system was simplified to interaction with human presence through an ultrasonic sensor that detects movement through emitting ultrasonic sound waves and receiving reflected waves by an object/human in its field of view (Fig. 47).

In an ideal situation, the space senses the inhabitant's emotional states and responds through spatial transformation of expansion and contraction that dissolves the geometry of the space into a fluid pulsating motion. This polymorphic space accommodates these emotions and enables the inhabitant to be aware of them, eventually nurturing an empathetic relationship with its inhabitant.

Fig. 45. A close-up of the joint that connects the model to the rack.

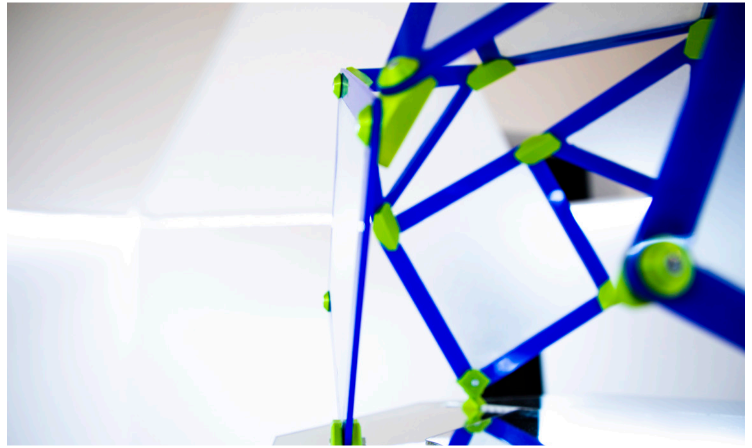


Fig. 46. Details of the model.

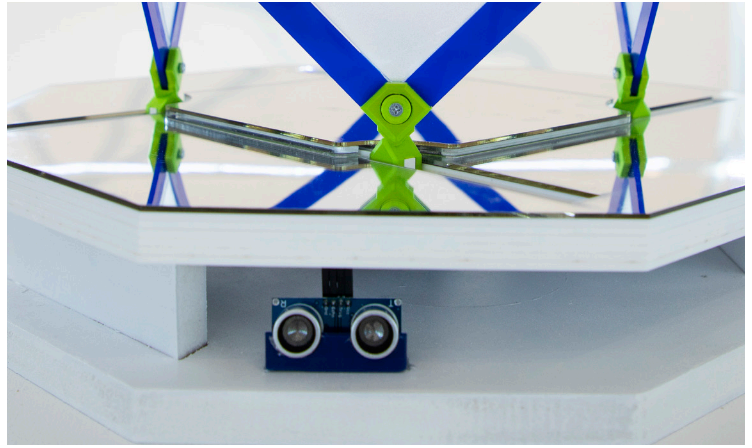


Fig. 47. Ultrasonic sensor.

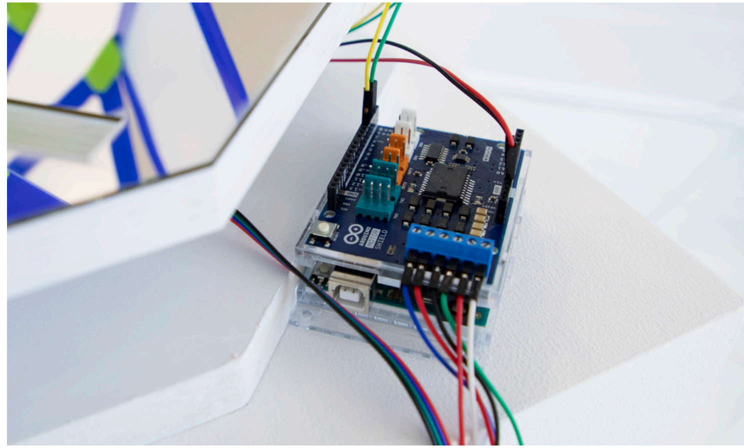


Fig. 48. Arduino board.

Fig. 49. Long shot of the exhibition. The full-scale structure resonates the opened state of the model.

Fig. 50. A close-up of the 3D printed joints.

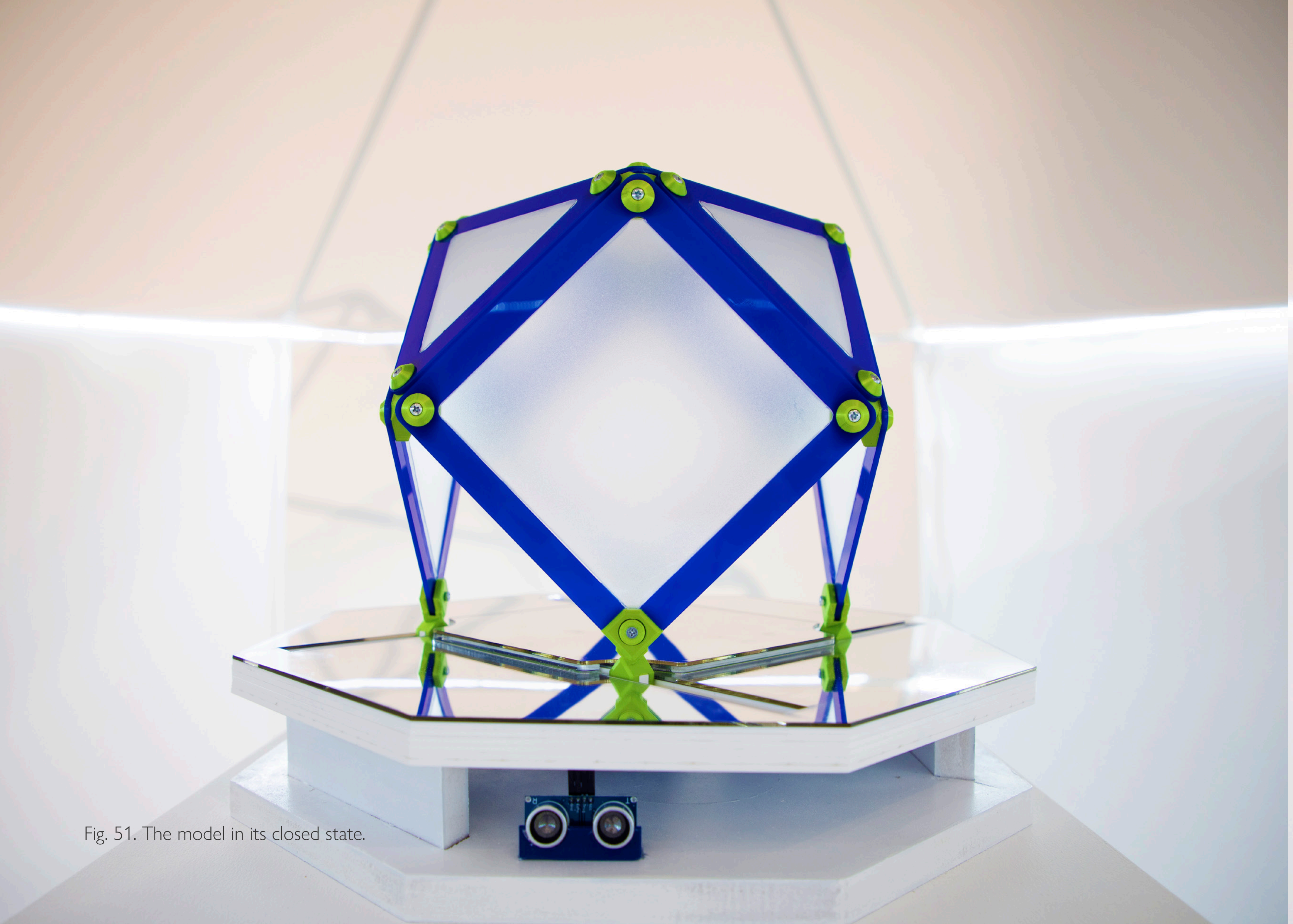


Fig. 51. The model in its closed state.

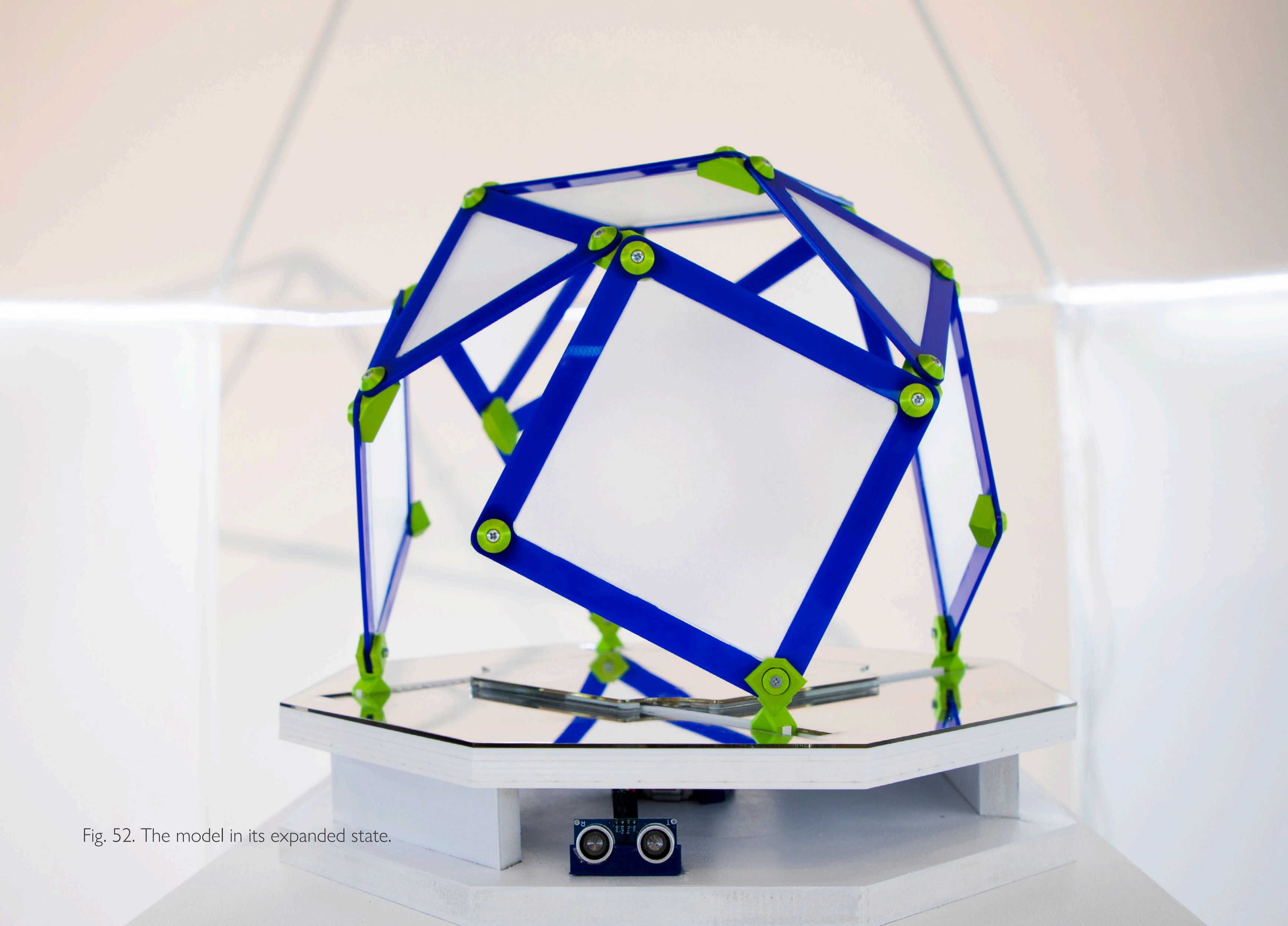


Fig. 52. The model in its expanded state.

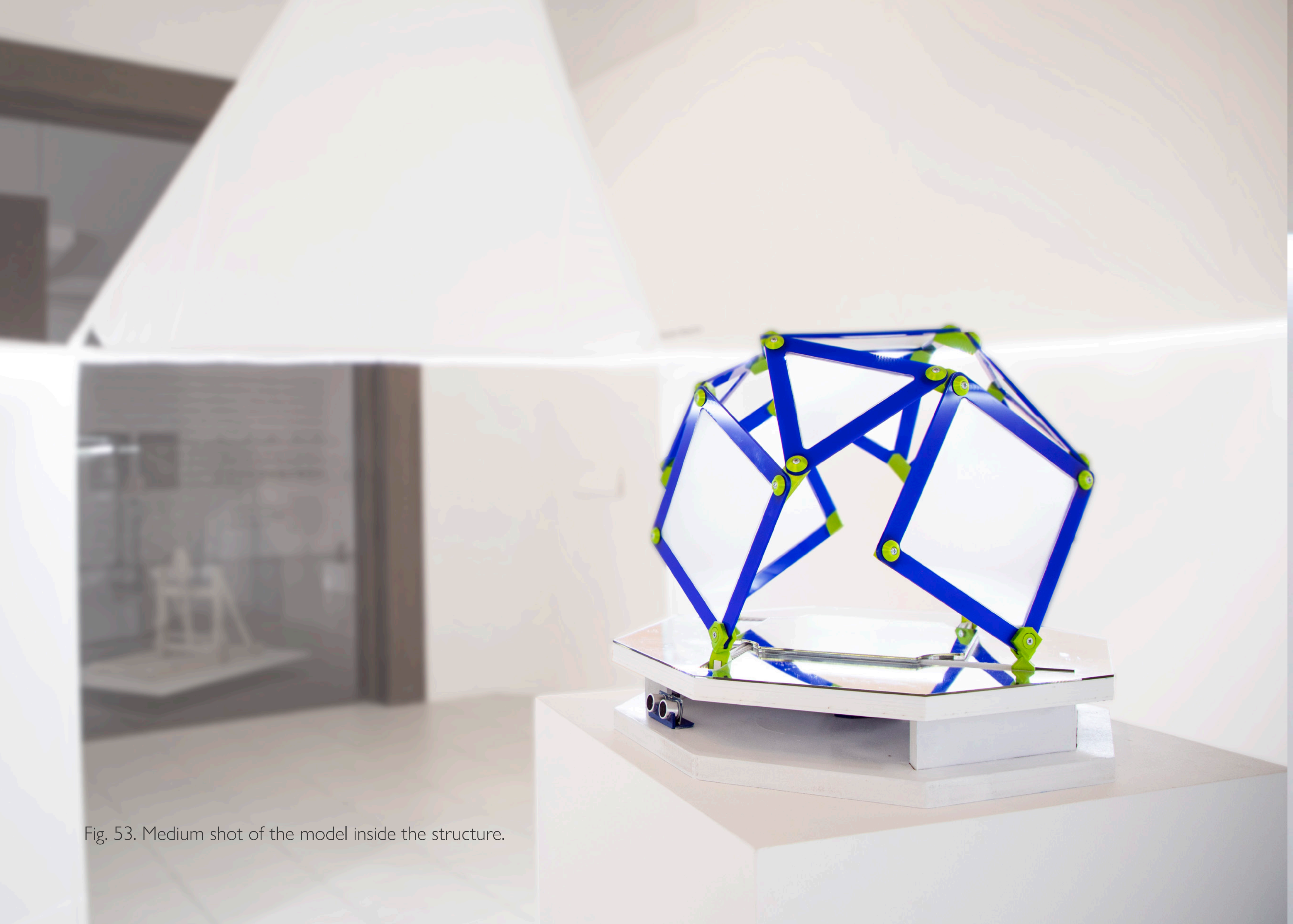


Fig. 53. Medium shot of the model inside the structure.

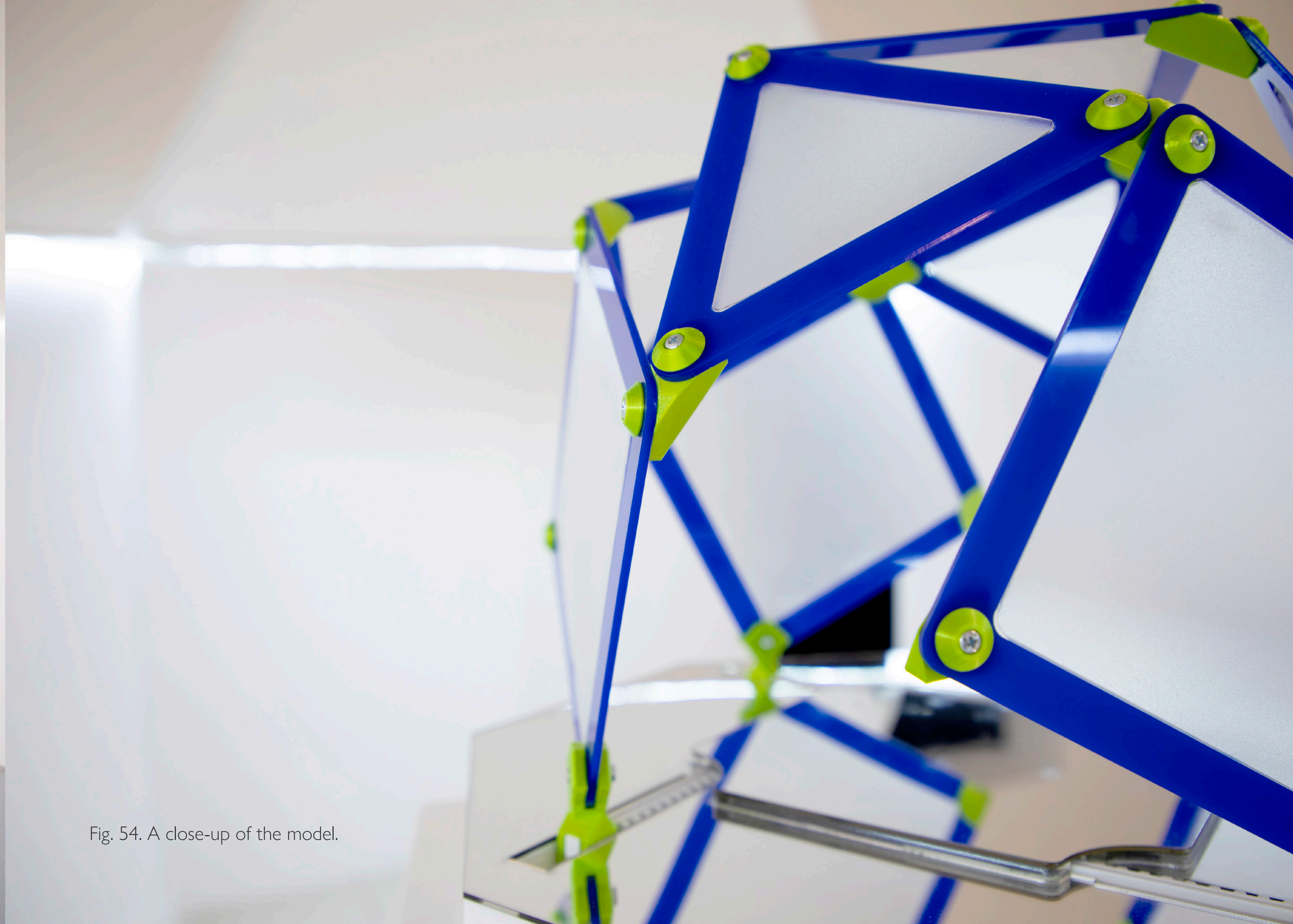


Fig. 54. A close-up of the model.

Fig. 55 & 56. Interior views of the model.

Fig. 57. Top plate that covers the mechanism.

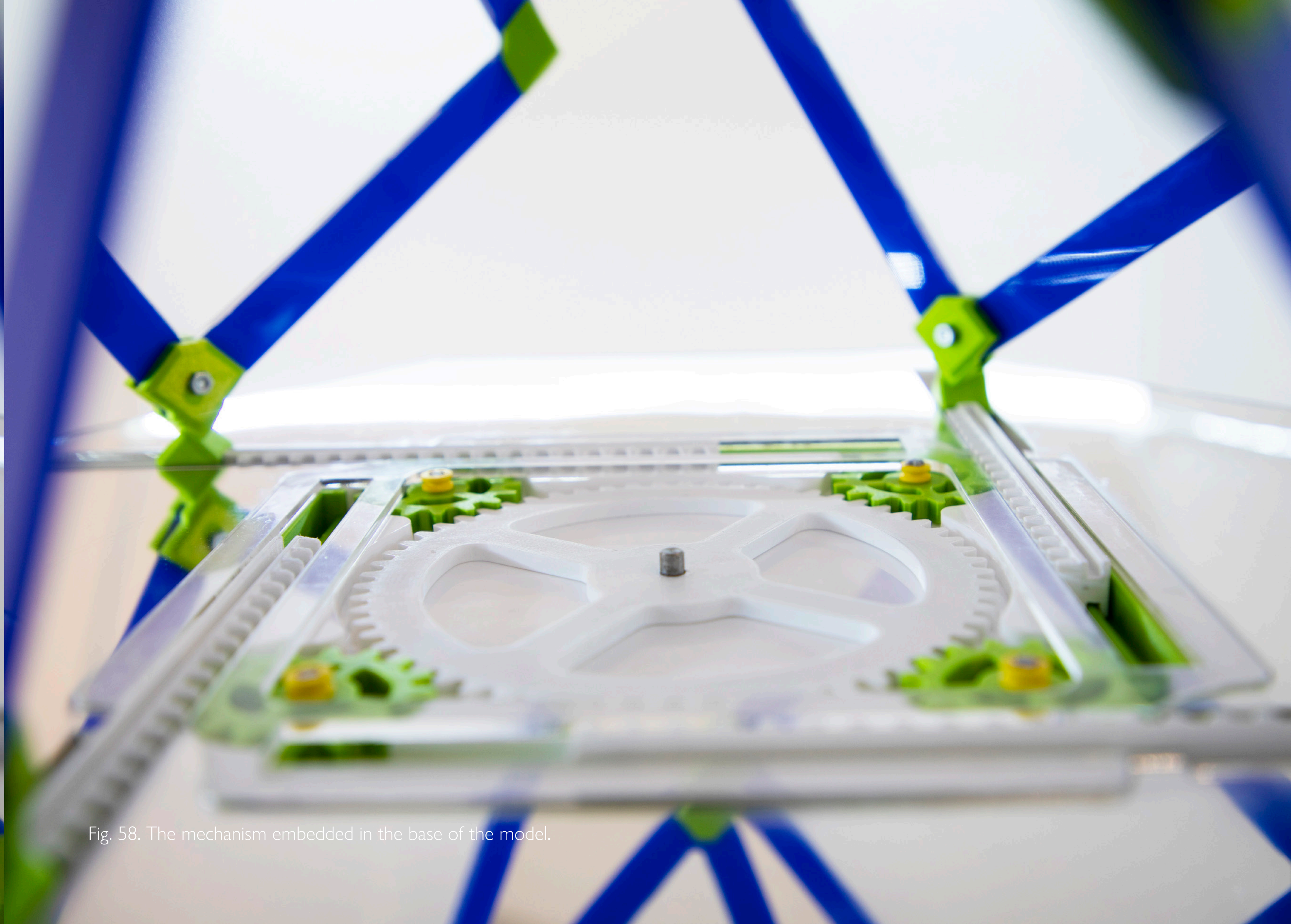


Fig. 58. The mechanism embedded in the base of the model.

CONCLUSION

The modular coordination of mass production has generated an architectural industry of mass repetition and generalized individual needs. In the attempt to produce buildings efficiently, the design of spaces eventually shifted to planar thinking and buildings turned into kit-of-parts (object-oriented buildings).[68] Consequently, our spaces have become increasingly passive and emotionally flat. This has created a growing demand to humanize architectural experiences by reexamining our relationship with the built environment. Konnenburg states "that because of the way in which the world is changing technologically, socially, economically, and culturally, it is probable that flexible, transformable, transportable design is as important now as it was when, in the past millennia, the nomadic way of life was the dominant one across the planet."[69]

In my thesis, I explored design theories and nature principles to bring our architecture to life. I was inspired by various, seemingly isolated, aspects: Fuller's geometric studies, Hoberman's transformable structures, and nature's behavior, in an attempt to build a space as alive as *Howl's Moving Castle*. The built model that emerged from this thesis is a conceptual representation of a polyhedral space that reacts to the inhabitant's emotions through three-dimensional spatial transformation based on Buckminster Fuller's *Jitterbug*.

From a structural perspective, the model can be easily developed into a functioning space through engineering processes. On the other hand, the computational system needs more research and improvement, especially since it relies on the emerging field of artificial intelligence. An interactive space that senses human emotions can adjust the space accordingly to promote relaxation or social interaction and form a relationship with its inhabitant. The general implications of transformable architecture that responds to contextual stimuli include but not limited to: spatial optimization, multifunctionality, and contextual adaptability (e.g. adapting to climate patterns).

Since this thesis investigates humanizing our spaces through transformable polyhedral spaces that are equipped with sensing abilities, one might suggest that such pure geometric shapes are unassociated with nature because they are not human, soft, flawed. However, it is crucial to elucidate that the humanization of spaces is not through architecture that mimic nature's forms, but through *interactive behavior*, which is evident in the precedent studies (see pages 24-41). In fact, geometry is the building block of nature's creations and such polyhedral transformations occur in nature on a microscopic scale. Geometry was utilized as a problem-solving tool that permits the developing of deployable structures that are capable of tri-dimensional transformations, which otherwise would be impossible to achieve.

FUTURE DIRECTON

ARCHITECTURE WITH FEELINGS

In my research, I have reflected on the current advancements in interactive architecture. I have reached two conclusions concerning the future of humanizing architecture:

FORM AND PERFORMANCE

The humanization of architecture has taken diverse routes and forms, but the dominant theory is biomimicry. There have been juxtaposed tendencies to either mimic nature's forms, which are mostly what I believe to be superficial implementations of natural creations, or to replicate nature's behaviors in interactive architecture where the emphasis has been on interactive technologies with less regard to the form that these spaces take on. This doesn't provide a sustainable solution to our architectural predicament because it marginalizes the need for a deeper insight into the comprehensive concept of synergy. Buckminster Fuller introduced synergy in his book, *Synergetics: Explorations in the Geometry of Thinking*, which he defined as the "behavior of whole systems unpredicted by the behavior of their parts taken separately."[70] Fuller states that to understand nature we need to understand synergy, "[b]ecause synergy alone explains the eternally regenerative integrity of Universe."[71]

Nature's forms and performances are intrinsically linked in unity; they are in a constant reciprocal interaction, hence, they behave efficiently. In biological systems "… unity is not uniformity, but is coherence and diversity admixed in collusion."[72] Therefore, I believe that the form and the transformational behavior of that form in an interactive architectural environment are equally fundamental. We need a deeper understanding of the logic behind nature's morphological processes in order to create holistic architectural analogies of nature's formative processes and information systems.

E*MOTIONAL SPACES

The core of architecture has always been the experiences that we feel through our senses. In fact, according to Fox and Kemp, "we do not inhabit architectural space for shelter; we do because we need the experience of space."[73] and "in many instances, a building that adapts to our desires can shape our experience." When our interaction with the built environment, become more like human-human interaction, it generates an increased sense of attachment.[74] But it seems that architecture has forgotten the centrality of human emotions, because architecture has mostly been a manifestation of ideas and less about an experience of emotions.[75]

To emancipate our architecture from its stagnation, we need to design emotive interactive experiences that foster a sustainable relationship with our spaces. I argue that anthropomorphizing our spaces requires more than just interactive technologies (evolution) or transformable structures (motion). Certainly, they are a crucial part of the equation, but what is missing is *emotere* "energy in motion"; internal energy through our senses stimulated by external energy of spaces.

What distinguishes *Howl's Moving Castle* from other countless smart architectural machines in films is not its miraculous transformations or creaky movement, but its ability to *feel* and make *you feel*. Spaces that can feel us and transform in response to our emotions are the true embodiment of humanized architecture because it augments interactive architectural systems and makes it more relatable, natural, and simply *human.*

E*motional spaces = interaction + motion + emotion

To the future designers, I quote:

> “Good design is a renaissance attitude that combines technology, cognitive science, human need, and beauty to produce something that the world didn’t know it was missing [76]”

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Fig. 1. Screenshots from film. Tati, Jacques. Released 1967; France: Bernard Maurice René Silvera. Film. https://www.moma.org/media/W1siZiIsIjQ3MjQzNSJdLFsicC IsImNvbnZlcnQiLCItcXVhbGl0eSA5MCAtcmVzaXplIDIwMDB4MTQ 0MFx1MDAzZSJdXQ.jpg?sha=b84107f734fdb96e .

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Fig. 4. “Richard Buckminster Fuller.” A Tribute to Buckminster Fuller. https://c1.staticflickr.com/8/7157/26806373786_03b16622c5_b.jpg .

Fig. 5. “Buckminster Fuller.” Highlike. https://highlike.org/media/2014/04/Buckminster-Fuller-Tensegrity-Sphere.jpg .

Fig. 6. Photograph by Archive of Zvi Hecker. “A Prague exhibition celebrates the life and work of an unsung hero of Israeli architecture.” Wallpaper, September 13, 2017. https://cdn.wallpaper.com/main/styles/fp_922x565/s3/2_10.jpg .

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Fig. 8. Hoberman Sphere in 4 progressive stages of expansion, 1993. Chuck Hoberman fonds, Canadian Centre for Architecture, Hoberman Associates. https://i.pinimg.com/originals/11/82/3e/11823e408bab497cdcdb0f766ca8870c.jpg .

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Fig. 14. “Strandbeest: Theo Jansen.” Arch20. https://www.arch2o.com/wp-content/uploads/2015/09/Arch2O-strandbeest-theo-jansen-5-scaled.jpg .

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Fig. 32. https://www.researchgate.net/profile/Luis-Sandino-2/publication/262282922/figure/fig1/AS:613919160807446@1523381142424/Universal-joint-at-point-P-H.png .

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