Modularizing Transformations

A goal-oriented design tool of a modular four-bar linkage mechanism

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Abstract

Recent advances in materials science and manufacturing technology have not only provided promising opportunities for industrial and product design but have also catalyzed the emerging areas of transformable material design. This field of transformable material design is a multidisciplinary subject that provokes and inspires researchers to innovate. In the field of human-computer interaction (HCI), in particular, research has been looking beyond static, rigid physical interfaces to explore the rich transformability of input/output devices using transformable materials.

However, most transformable materials require a unique mechanism or structure, making them suitable for specific tasks, but difficult to implement broadly. Moreover, due to the techniques used, most are not reconfigurable. So, is there a reconfigurable transformable material mechanism that can include multiple functions in its structure and can switch easily between functions autonomously? If yes, the design space for it would be incredibly large and the challenge is - how to design with this reconfigurable transformable material mechanism?

As a response to this question, this thesis proposes a modularized mechanism for designing transformable materials, as well as a design tool to help the designer make reconfigurable transformable material structures. With the design tool, designers can easily explore the huge design space made possible by the mechanism by simply inputting their design goal represented as curves. The tool will automatically generate the desired transformable structures.

Thesis Co-advisor - Terry Knight
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- Sen Dai

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1. Introduction

Recent advances in materials science and manufacturing technology have not only provided promising opportunities for industrial and product design but have also catalyzed the emerging areas of transformable material design. This field of transformable material design is a multidisciplinary subject that provokes and inspires researchers to innovate. In the field of human-computer interaction (HCI), in particular, research has been looking beyond static, rigid physical interfaces to explore the rich transformability of input/output devices using transformable materials. [1].

However, most transformable materials require a unique mechanism or structure, making them suitable for specific tasks, but difficult to implement broadly. Moreover, due to the techniques used, most are not reconfigurable. So, **is there a reconfigurable transformable material mechanism that can include multiple functions in its structure and can switch easily between functions autonomously?** If yes, the design space for it would be incredibly large and the challenge is - **how to design with this reconfigurable transformable material mechanism?**

As a response to this question, this thesis proposes a modularized mechanism for designing transformable materials, as well as a design tool to help the designer make reconfigurable transformable material structures.

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[1] *Tangible Media Group in MIT Media Lab has many fascinating and famous projects about transformable interfaces. For for Information: https://tangible.media.mit.edu/*

The basic transformation mechanism comes from my former research - KinetiX. KinetiX is a four-bar linkage system that allows output structure to bend, fold, shrink and twist. In this thesis, I extend the ability of KinetiX to change shape from one state to another, as well as a modularized way of fabricating KinetiX, making it reconfigurable.

In order to be able to design with this mechanism and make the transformable structure a reality, a goal-oriented design tool in Rhino3D/grasshopper platform is created to link creative design space exploration with material reality. With the design tool, designers can easily explore the huge design space made possible by the mechanism by simply input the design goal that is represented as curves. The tool will automatically generate the desired transformable structures. To further prove the feasibility of this design tool, I include several design demos to show how the design tool can assist designers to create desired transformable structures

2. Background

This chapter discusses the related topics which are the background of this thesis. By going through this information, the motivation and reasoning behind the thesis topic are further explained.

2.1. Transformable material

Materials are a fundamental part of how we interact with the world. Recent advances in fabrication technology have enabled a new field of tunable materials with tailored properties. Recently, within the domains of Human-Computer Interaction (HCI) and Computer Graphics (CG), there has been a growing interest in designing tunable material systems that allow deformable physical shapes/structures [1–3]. In addition, novel transformation mechanisms [4–7] and applying responsive materials [8–10] open up wide design space for researchers to prototype shape-changing materials for design. These works investigate how to integrate energy sources (heat, air pressure, humidity, etc.) and transformation mechanisms into an interactive system.

Transformable material utilizes different material properties to achieve transformability. Based on the properties or techniques they have, I classify transformable materials into four types - Anisotropic, Composite, Metamaterial and Linkage system.

- Anisotropy means direction dependent. It is the heterogeneous distribution of material. Leveraging material anisotropic, we can build materials that have dramatic and scalable transformation. [Figure 1 (1-4)]
- The composite material is much more versatile than can be realized with conventional materials. In the field of transformable material design, combining materials with different properties can be widely seen to create material deformation. [Figure 1 (5-8)]
- Metamaterial is a type of transformable materials mechanism whose behavior is governed by structure, rather than composition. Through careful design of the material's architecture, new material properties have been demonstrated, including the negative index of refraction, negative Poisson's ratio, high stiffness-to-weight ratio, and optical and mechanical cloaking. [Figure 1 (9-12)]
- Linkage-based structures have a long history in mechanical engineering. Previous work shows a linkage structure can be used to design transformable toys and buildings. Many of configurations similar to this have been widely presented in the design practice. [Figure 1 (13-16)]

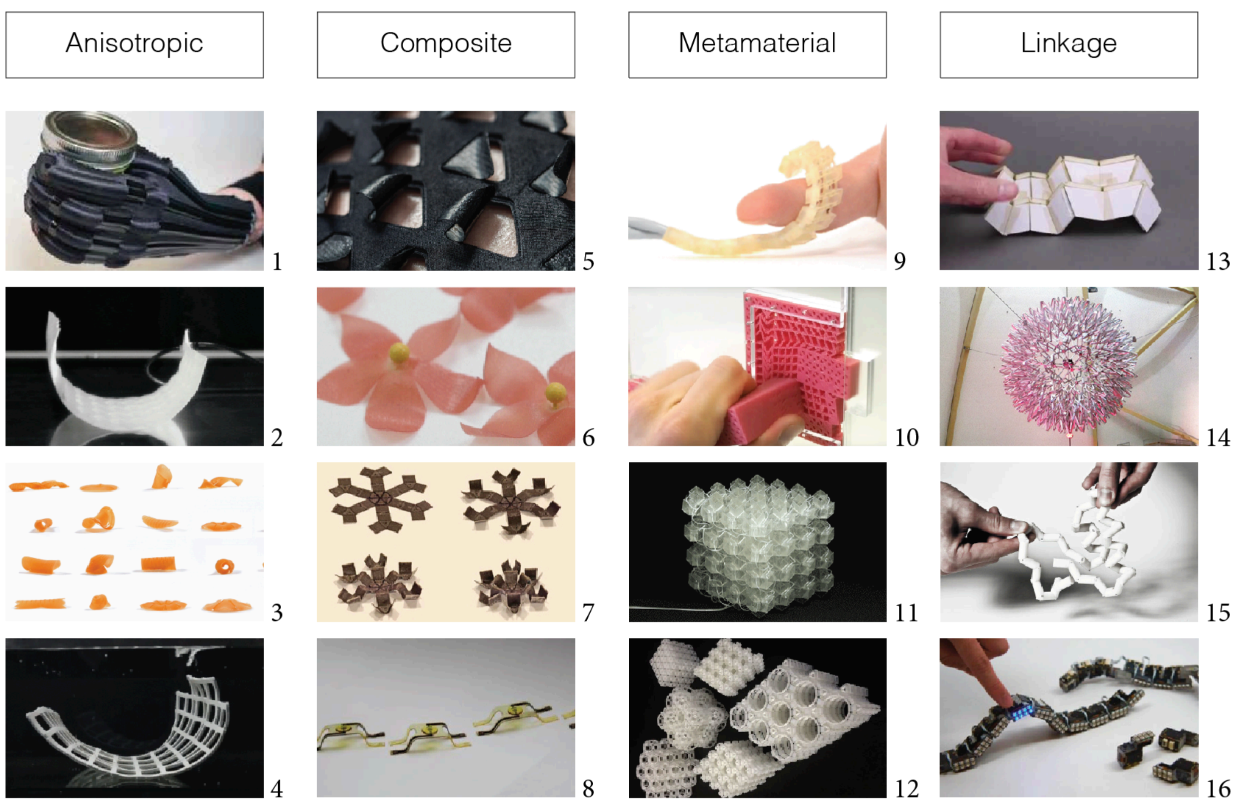

Figure 1. Classify transformable materials based on material properties

As we have seen from all of these transformable materials, they all require a unique mechanism or structure to some extent, making them ideal for specific tasks, but difficult to implement broadly. Moreover, most of them are not reconfigurable. Therefore, this thesis tries to find a versatile transformable material mechanism.

2.2.Programmable materials

Recent research in CG and HCI has been investigating how to digitally manipulate material composition and structures to create predictable shape-changes or property changes [11-13] . This includes both how to adapt responsive materials in an interactive system [8] , and material composition strategies to create programmable material transformations [5,6].

Former research from Rasumssen, et al., presented an overview of the types of change in shape [14]. As showed in [Figure 2], some shape changes are topological equivalent, meaning shapes that can pass from one form to another through continuous deformation. While other shape changes are not topological equivalent because shapes are being split, united or perforated.

We can achieve each of these shape changes with programmed material constraints. By combining modules with different transformability, this thesis suggests that we can create more complex deformable material structures.

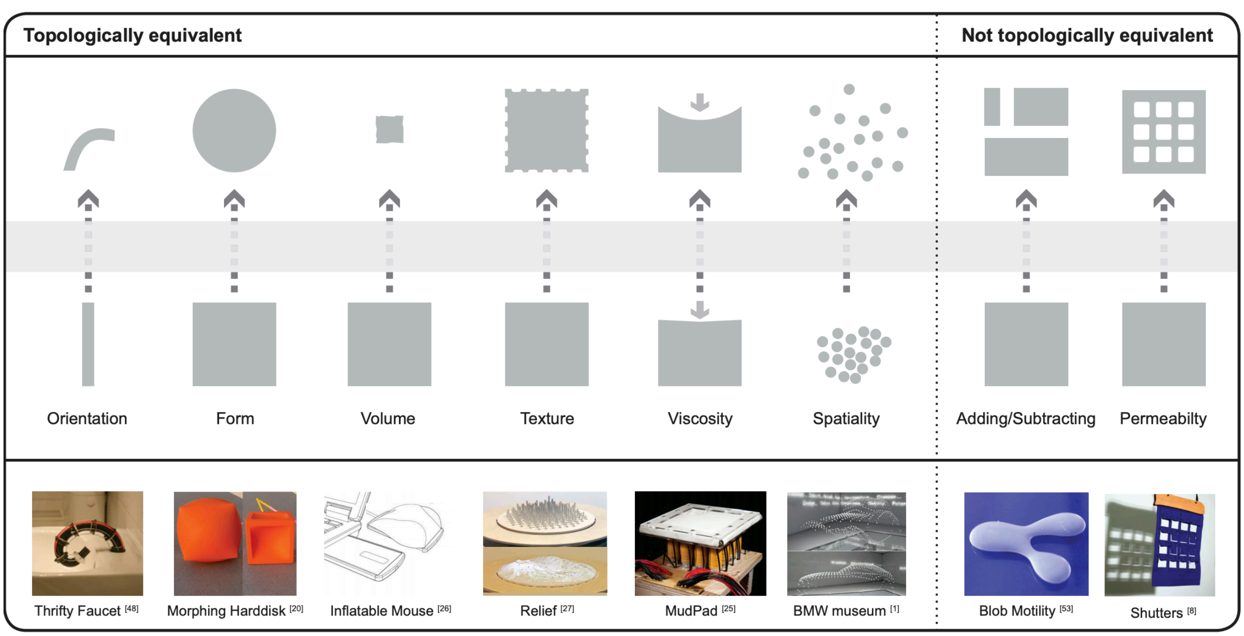

Figure 2. An overview of the types of change in shape from a research by Rasumssen, et al.

2.3. Goal-oriented design

The concept of Goal-oriented Design (or Goal-directed Design) is first introduced in the field of UX design. It is a user-centered methodology developed by Alan Cooper[2] to address situations where different users of a proposed product express a desire for different things. These desires accumulated by different users lead to more complex features in the software, which leaves users with a product that is increasingly hard to use—and with growing frustration as they try to use it. Therefore, a way to simplify the design process is very important to product design.

In this thesis, the Goal-oriented Design method empowers designers to focus on the design goal rather than unrelated details that are too complicated to work on. The method can simplify the design process by addressing three of its main challenges, 1) the large design space, 2) the interdependence of design subcomponents and 3) the design fabrication. This subsection exhibits two examples that are highly related to Goal-oriented Design methods from computer science. Both of the two projects are from MIT CSAIL Computational Fabrication Group.

<u>Interactive Robogami</u>

The first example is Interactive Robogami [15], an End-To-End system for ground locomotion robots design. It has a tool for composition-based design of ground robots that can be fabricated as flat sheets and then folded into 3D structures. This rapid prototyping process allows users to create lightweight, affordable, and substantially versatile robots with short turnaround time [Figure50]. Using Interactive Robogami, designers can compose new robot designs from a database of print and fold parts. The designs are tested for the users' functional specifications via simulation and fabricated upon user satisfaction.

This project aimed to democratize the design and fabrication of robots, enabling people of all skill levels to make robots without needing expert domain knowledge. On the one hand, the end-to-end system interpreted the design process by guiding designers through the large design space. The instant visual feedback and the simulation allow the designer to interactively alter the model. This interactiveness created an efficient feedback loop between concepts and objects, making the process more effective and intuitive. On the other hand, the modularized approach for designers to modify model is encouraging. It eliminates difficulties in both design and fabrication.

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[2] *H. Deubberly, "Alan Cooper and the goal directed Design Process", San Francisco, 2001.*

Interactive Exploration Of Design Trade-Offs

The second example introduces a computational approach to discover the design spaces, allowing designers to navigate the landscape of compromises efficiently [16]. This design space exploration strategy is very inspiring for my thesis, as it greatly simplifies the design process and enables designers to concentrate on the functionality of design outcomes.

Traditionally, design for manufacturing applications requires simultaneous optimization of conflicting performance objectives: Design variations that improve one performance metric may decrease another performance metric. In these scenarios, there is no unique optimal design but rather a set of designs that are optimal for different performance. In this project, the proposed method creates a way to effectively explore the design space for different performances. Moreover, according to different performance trade-offs, the entire design performance space is represented as a high-quality and segmented smooth patches to promote the designer's intuitive exploration [Figure 4].

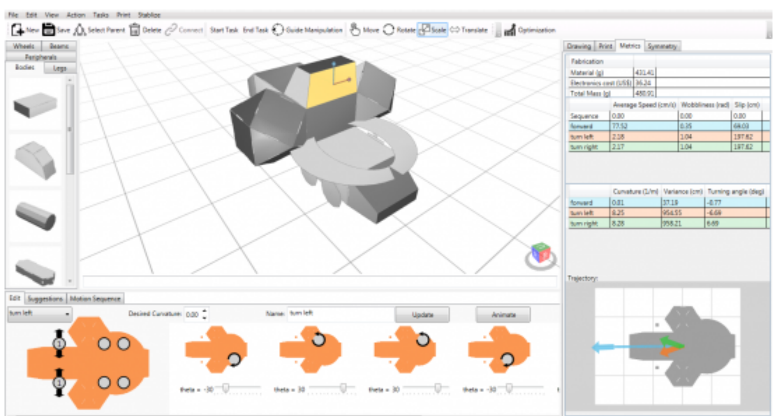

Figure 3. The interface of the design tool of Interactive Robogami.

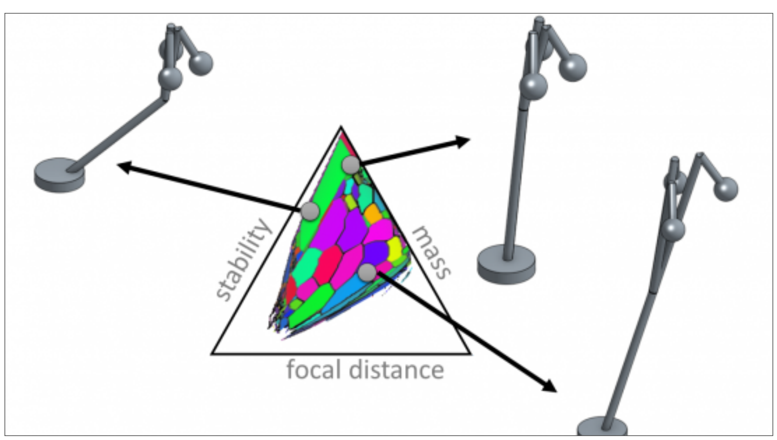

Figure 4. The design spaces and tradeoffs mapping into different patches.

3. The modular four-bar linkage mechanism

Figure 5. A 1D tessellation of spatial transformation that performs bending and twisting behavior.

This section of my thesis responds to the first question asked in the introduction part - **is there a reconfigurable transformable material mechanism that can include multiple functions in its structure and can easily switch between them autonomously?** The answer is yes. I believe that the linkage-based structures have the most potential. To be specific, this thesis is based on a four-bar linkage mechanism from former research - KinetiX [17]. KinetiX is research on transformable materials led by professor Hiroshi Ishii and Jifei Ou. I participated in it and my role is to design and fabricate the transformable structures.

KinetiX describes a group of auxetic-inspired material structures that can transform into various shapes upon compression. We developed four cellular-based material structure units composed of rigid plates and elastic/rotary hinges. Different compositions of these units lead to a variety of tunable shape-changing possibilities, such as uniform scaling, shearing, bending and rotating [Figure 5]. By tessellating those transformations together, we can create various higher level transformations for product design.

Transformable materials designed by KinetiX can transform between different shapes, where the shape change is precisely programmed with the settings of a group of geometric parameters. KinetiX has the potential to accommodate multiple functions, yet it still needs improvements to achieve versatility. The following two parts will first introduce the former research of KinetiX and then attest my improvements to KinetiX which make it a reconfigurable transformable material mechanism for designing transformable materials.

3.1.KinetiX

KinetiX is a transformable material mechanism stemmed from auxetic material. As illustrated in [Figure 6], an auxetic material is a material that exhibits a Negative Poisson's Ratio (NPR). Unlike conventional materials, when an auxetic material is stretched in one direction, instead of becoming thinner, it becomes thicker in perpendicular directions. While the majority of the studies of auxetic materials focus on their mechanical properties and topological variations, KinetiX proposed a parametric design approach that gives auxetic structures the ability to deform beyond shrinking or expanding.

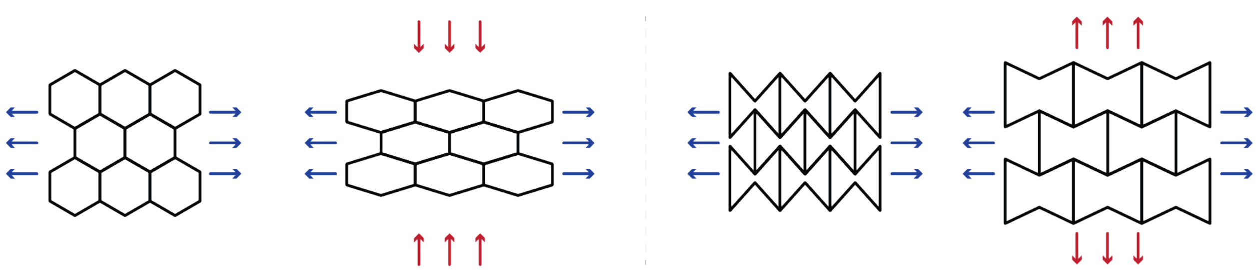

Figure 6. Left: conventional material becomes thinner when stretched; Right: auxetic material exhibits a Negative Poisson's Ratio (NPR), it becomes fatter when stretched.

KinetiX has a cell configuration by extending an auxetic mechanism to a parametric four-bar linkage system [Figure 7]. Each cell module consists of rigid plates or rods and elastic hinges. The following two segments will present the features of this cell configuration.

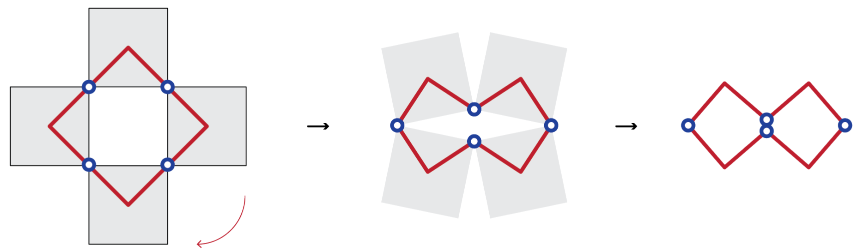

Figure 7. Rotating polygon type auxetic material simplified as a four-bar linkage structure.

3.1.1. Unit cell transformation

The basic mechanism of KinetiX material is based on a four-bar linkage connected by four rotary joints (hinges). By parametrically placing four hinges on the four sides of a rigid square unit respectively, we are able to transform the rigid unit in designated ways, both planar and spatially. Based on their transformation ability, KinetiX's units can be classified into five basic types [Figure 8].

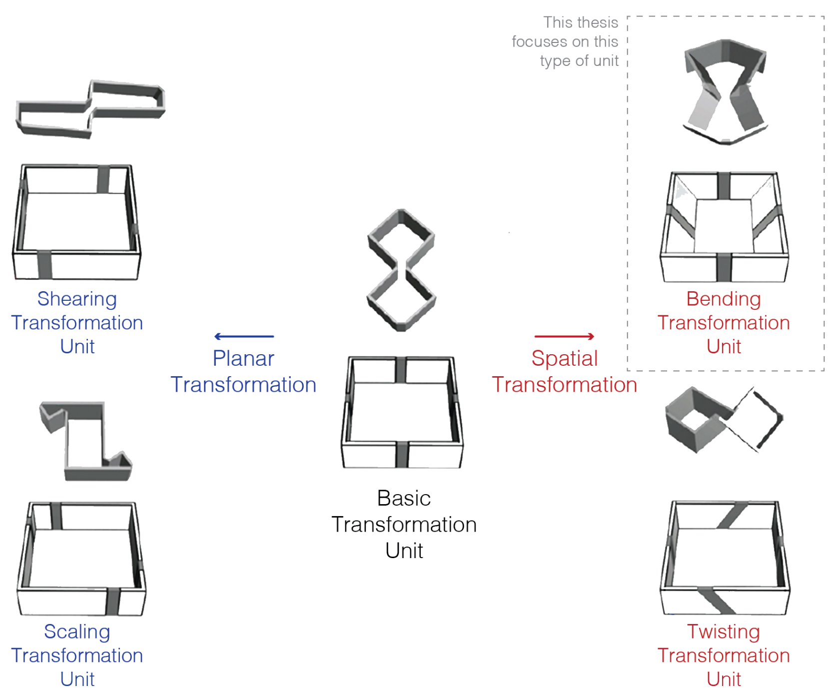

Figure 8. From the basic unit, a planar and spatial transformation can be created. Parametrically shifting the position of the hinge creates uniform scaling and shearing; rotating the hinge in or out the bar plane creates twisting and bending.

3.1.2. Unit cells tessellation

A single transformation unit can be combined with either identical ones or different ones. Combination of Identical units can produce scaling or shearing transformations while maintaining a one degree of freedom. When one hinge in this combination is deformed, the whole system will transform accordingly.

For the combination of different units, we utilize both planar and spatial transformations to create large linear and surface tessellations. As guidance of the experiment, we created a table of potential two units tessellation. This table aids designers to preliminarily assign two different units into the grid system to get different transformations at desired locations [Figure 9].

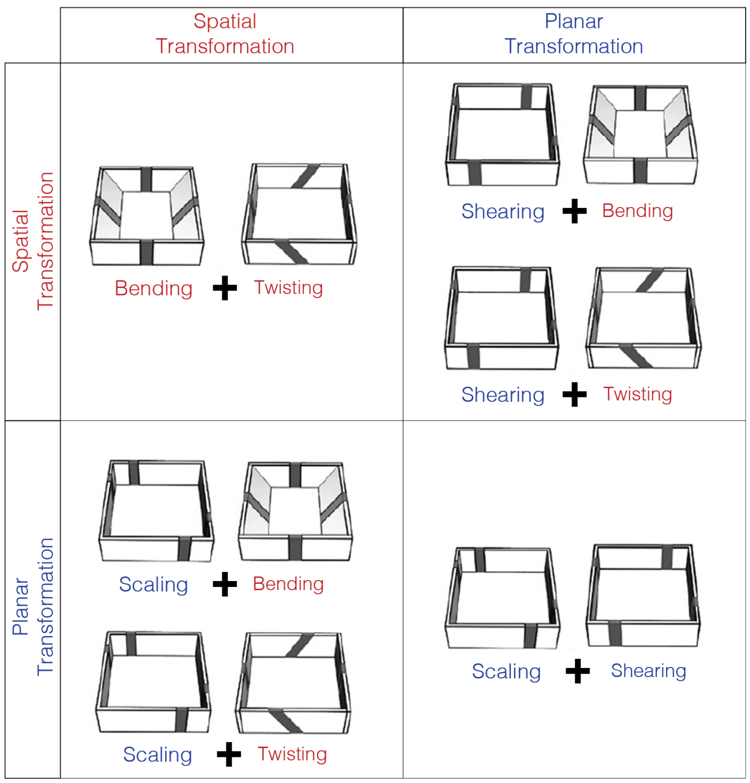

Figure 9. KinetiX transformable unit composite table. Spatial transformation includes bending and twisting. Planar transformation includes uniform scaling and shearing.

In this thesis, I mainly discuss the transformation of the bending units for the following reasons. First, the planar transformation units are easy to conceptualize and design with, so it is repetitive to make a design tool solely for that. Second, as mentioned in the KinetiX paper [17], the twisting transformation unit is plausible in the physical model but not in geometric analysis. Therefore, computation and simulation are not accurate. Even worse, it will incrementally raise the error when we try to combine different units.

The combination of KinetiX units can be 1D tessellation (linear) or 2D tessellation [Figure 10]. In this thesis, I largely work on the linear tessellation and extend its ability to form complex transformable structures.

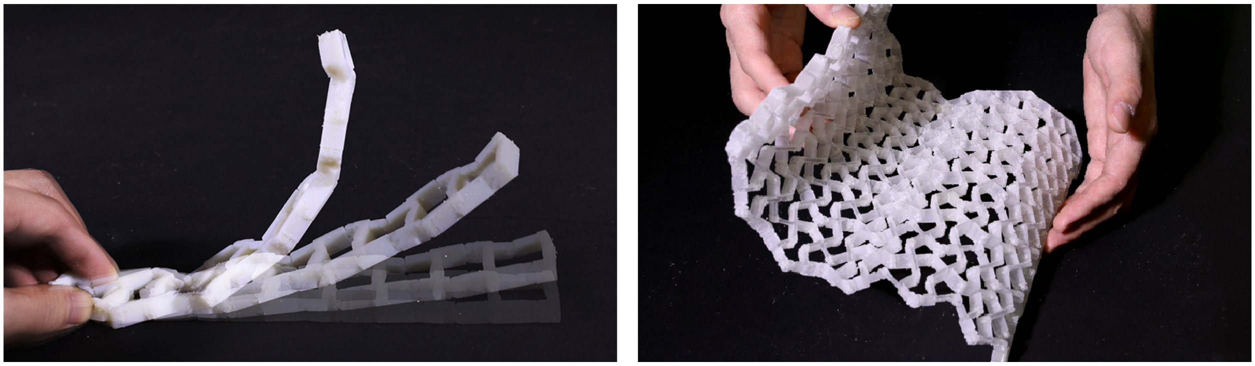

Figure 10. Example of 1D tessellation on the left and example of 2D on the right.

3.1.3. Physics-based simulation tool

The former KinetiX research also developed an interactive simulation tool to designers visualize and validate the designed structures. This simulation tool can preview the shape-changing process by dragging/pushing the given input 3d model. [Figure 11]

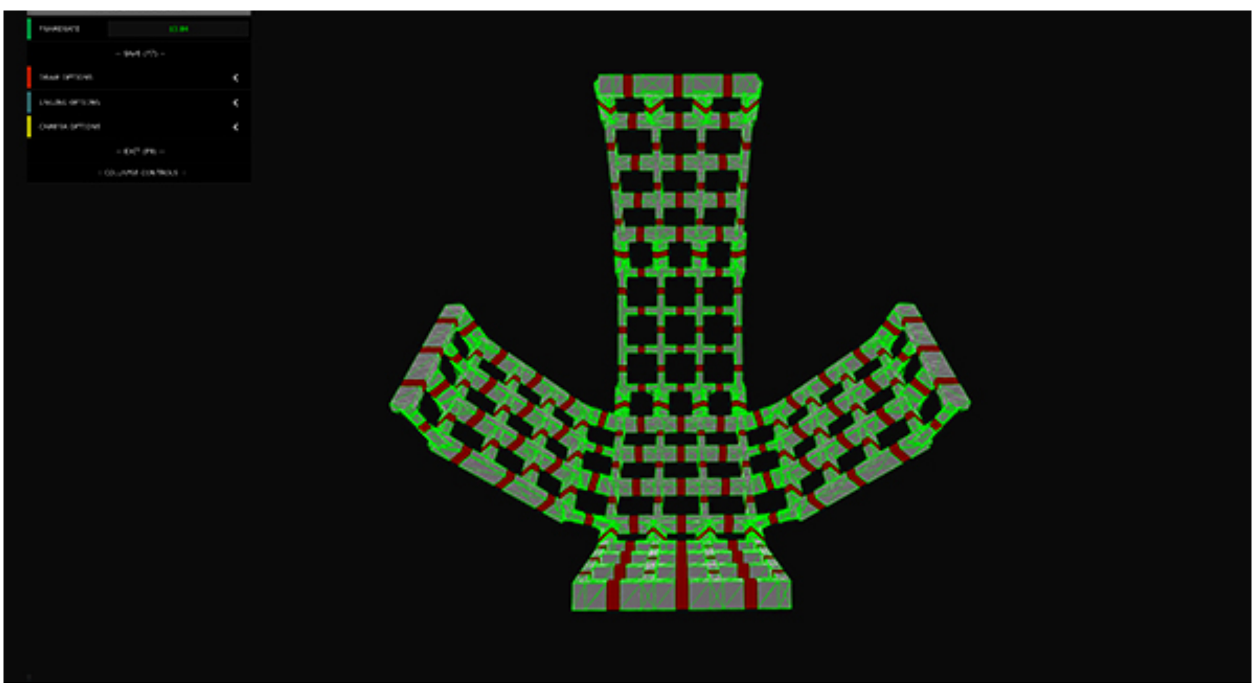

Figure 11. The interface of the simulation tool in the KinetiX project.

3.2. Modular KinetiX

Based on the KinetiX research described in the former section, this thesis improves and extends the KinetiX into a modularized and reconfigurable mechanism - the Modular KinetiX.

Considering the effectiveness and time constraints, Modular KinetiX will have particular focuses.

- This thesis only discusses the bending transformation units. As we mentioned in section 3.1.1, the bending units are mathematically representable as well as spatially transformable. In addition, I do not consider the asymmetrical configuration of the bending units due to its experientially increasing complexity (3.2.1 gives a detailed description of this).
- This thesis concentrates on 1D tessellation (linear). For 2D tessellations (planar), the shape change of single curved surface shares the same basic structure with 1D tessellation, so it considers to be the same as 1D tessellation. The double/multiple curved 2D tessellations are an excellent research topic but require different approaches. Therefore, I will leave it in future work.

The improvements of the Modular KinetiX are briefly outlined below. The next three subsections elaborate and demonstrate how these improvements work.

- The new Modular KinetiX exhibits a geometric representation system to reduce the effort in designing this four-bar linkage transformable mechanism. By enabling a promising mapping between the shape change and the numerical parameters, this method provides the groundwork for the goal-oriented design tool.
- Theoretically, structures designed with KinetiX mechanism are able to transform between distinct shapes. However, the original KinetiX research only shows the transformation within symmetrical shapes. While the Modular KinetiX is upgraded in this respect. It allows a transformable structure to switch between multiple completely different shapes.
- The Modular KinetiX is modularized, both physically and digitally. In this thesis, I designed 9 primitive modules for assembly based on the bending units. Designers can join these modules into desired shape-change structures with the instructions from the design tool. Besides, they can also use them to freely create deformable structures.

3.2.1. Geometric representation

Modular KinetiX has a geometric representation system that maps the structures and shape changes to a series of numerical lists. Each structure has a **parameter list** to specify the structure, and a **state list** to represent the current shape. In addition, the computation leverages a 3x8 matrix as a mathematical representation, which benefits the understanding and calculation of a KinetiX transformable material. We will begin with the single bending unit and generalize it to linear tessellation.

<u>Single unit representation</u>

Parameter list - Each unit has 6 parameters and can be presented in the form of

$$[L, W, H, \alpha, \beta, t]$$

L, W, H is the unit's length, width, and height respectively. α, β means the rotation angle of the bar. In this thesis, we only consider the symmetry situation, suggests that the unit is symmetric along the x-direction and y-direction. [Figure 12]

State list - When a unit changes shape, it can be described as a list like

$$[\theta, \gamma]$$

θ is the rotation angle of the α hinge divided by 2 (for a computation convenience), and γ is the bending angle of this unit at this shape. γ can be derived with θ and the parameter list. [Figure 13]

3x8 matrix - A unit can be represented as a 3x8 matrix. The first four columns of this matrix are the spatial position of the hinges' center point, and the last four columns give the direction vector of each rotated bar.

$$\begin{bmatrix} Xpt1 & Xpt2 & Xpt3 & Xpt4 & Xvec1 & Xvec2 & Xvec3 & Xvec4 \\ Ypt1 & Ypt2 & Ypt3 & Ypt4 & Yvec1 & Yvec2 & Yvec3 & Yvec4 \\ Zpt1 & Zpt2 & Zpt3 & Zpt4 & Zvec1 & Zvec2 & Zvec3 & Zvec4 \end{bmatrix}$$

With <u>Rodrigues Rotation Formula</u>, we can calculate every shape state of the unit. [Figure 14]

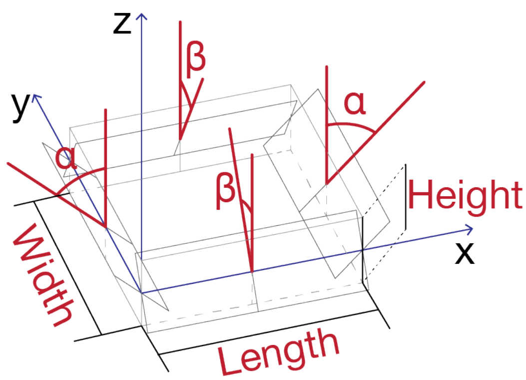

Figure 12. Parameters of a unit (bending transformation unit)

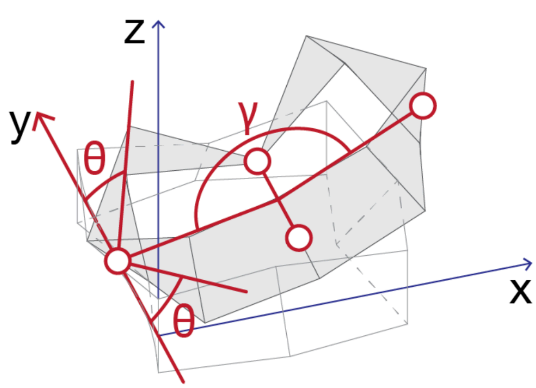

Figure 13. Representation of a shape stage

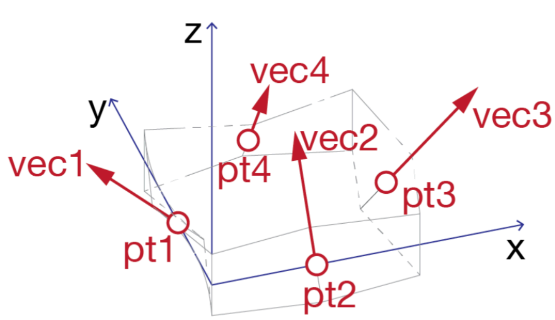

Figure 14. Mathematical representation

Linear tessellation representation

A single bending transformation unit can be combined with either identical ones or different ones. As mentioned before, this thesis will focus on the 1D Linear tessellation.

Parameter list - Units in a linear tessellation have simplified parameter list. First, the thickness of all the units in a structure is the same. The thickness usually depends on fabrication methods. Second, the Width and Length of each unit on the same line are the same. The height also usually stays the same. For example, the 4 units single line structure in [Figure 15] is represented as:

$$[[W, H, t], [L1, \alpha1, \beta1], [L2, \alpha2, \beta2], [L3, \alpha3, \beta3], [L4, \alpha4, \beta4]]$$

If we set the unit be all square, then we can further simplify the parameter list to be:

$$[[\alpha1, \beta1], [\alpha2, \beta2], [\alpha3, \beta3], [\alpha4, \beta4]]$$

Usually, due to the symmetry of each unit, the α has the pattern of (1,-1,1,-1,1,…). So we can simplify one more step as [[α, β1], [-α, β2], [α, β3], [-α, β4]]. In this thesis, I will not go for the aforementioned detailed representation because it will be very complicated when we have multiple line structures.

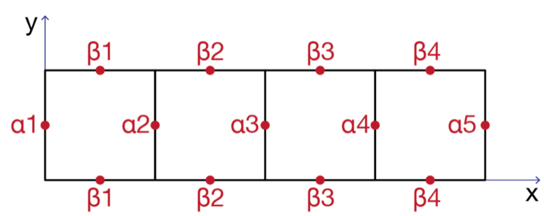

Figure 15. A single line tessellation example with the parameter list of [[α, β1], [-α, β2], [α, β3], [-α, β4]]

State list - When a linear tessellation structure changes shape, we can use a state list to show the state of shape change. Similar to the state list of single unit, a linear tessellation structure has the [θ,γ(i)] to display the shape change state. θ is the rotation angle of the first unit's hinge divided by 2 (for a computation convenience), while γ(i) is the bending angle of each unit in the structure. γ(i) can be computed with θ and the parameter list. [Figure 16]

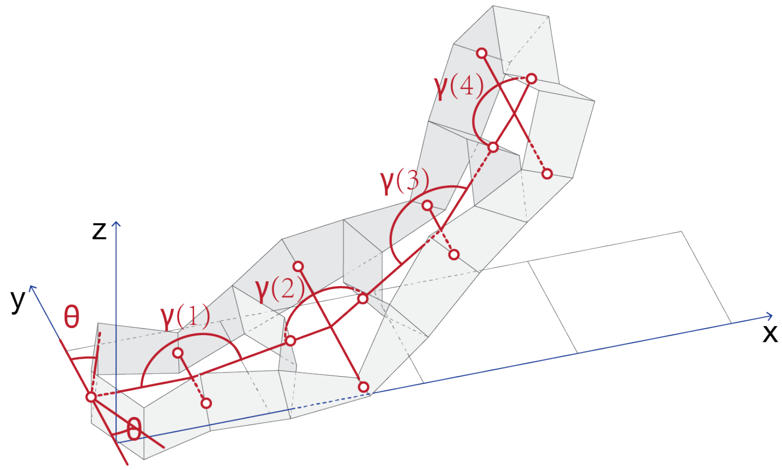

Figure 16. A single line tessellation example with the state list of [θ, γ(1), γ(2), γ(3), γ(4)]

<u>Multiple linear tessellation representation</u>

In a single line tessellation structure, if one of the units has 3 connected neighbors or it changes the line's direction, then we have a multiple linear tessellation structure. If the structures form a loop, then it is a simplified version of 2D tessellation. The state list is identical with single line tessellation.

Parameter list - For multiple linear tessellation structure, the parameter list is a stack of every single line's list (x-axis first) and an appendix list at the end. The appendix list gives information on the intersecting units position. For example, in [Figure 17], the parameter list will be as follows:

[[[α1, β1], [α2, β2], [α3, β3], [α4, β4], [α5, β5]], - x-direction

[[α6, β6], [α7, β7], [α8, β8]], - y-direction column 1

[[α9, β9], [α10, β10], [α11, β11]], [[α12, β12], [α13, β13]], - y-direction column 2,3

[[1, 3, 5], [[2], [2], [1]]]] - appendix

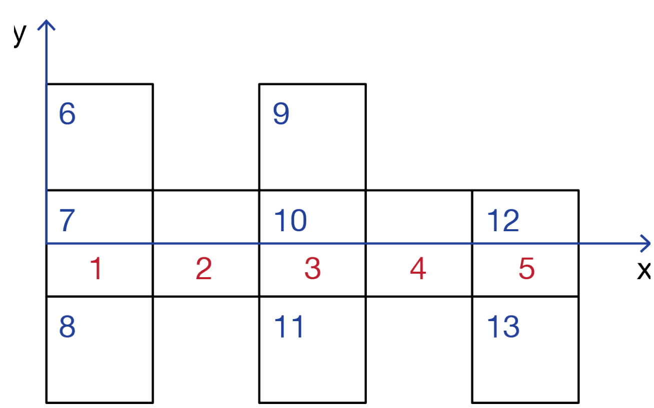

Figure 17. multiple line structures example

3.2.2. The shape change

Theoretically, KinetiX structures are able to transform within distinct shapes. Nonetheless, the original KinetiX research only shows the transformation connecting symmetrical shapes (named Mirrored structure). The Modular KinetiX is upgraded in this respect. It can switch within multiple completely different shapes (named Unmirrored structure).

<u>Single unit's shape</u>

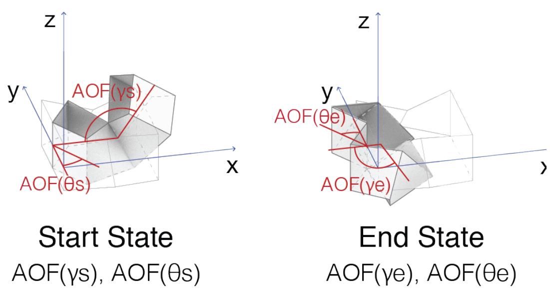

Figure 18. The start state and final state of a single KinetiX unit due to the collision of hinges.

Each unit's distinctive parameter list not only leads to the difference in shape change, which is represented as the state list (section 3.2.1), but also determines the limit shape change which I called the **start state** and the **end state**. To be specific, the state list value of θ,γ is constrained into a certain domain because the two hinges collide each other when the unit continues to deform. Therefore, each configuration of the unit has a final bending shape, the state of this shape is described as the start/end state, and the angle value of θ,γ are called the

Angle of Fold (AOF(γ), AOF(θ)) [Figure 18]

In physical reality, α, β usually has a value domain of [-60°, 60°] due to the fabrication material rigidity. This leads to an AOF(γ) boundary below 90°.

<u>Transformation within different shapes</u>

The shape of each KinetiX structure has three Indicative states. In addition to the start/end states mentioned above, we have a middle state, which is the intermediate state of the start/end states. In the original KinetiX, the middle state is flat and the two limit states are symmetrical to each other. It is called the Mirrored structure [Figure 19]. However, this kind of structure is very limited in the diversity of morphological changes.

This prompted us to imagine that if the intermediate state is not flat, the shapes of start and end state are not symmetrically similar.

To make the middle state a curved shape, I introduce a prebend process. This process allows the KinetiX structure to deform within completely different shapes and leads to the Unmirrored transformable KinetiX structure [Figure 20].

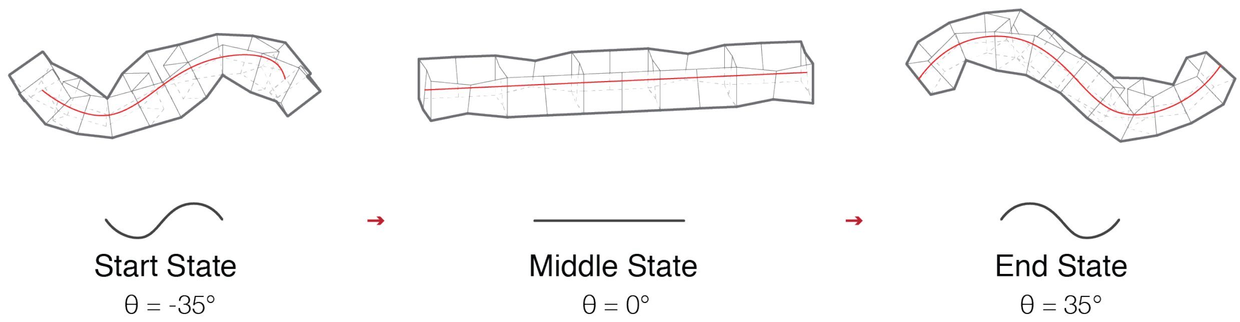

Figure 19. The three states of a Mirrored structure

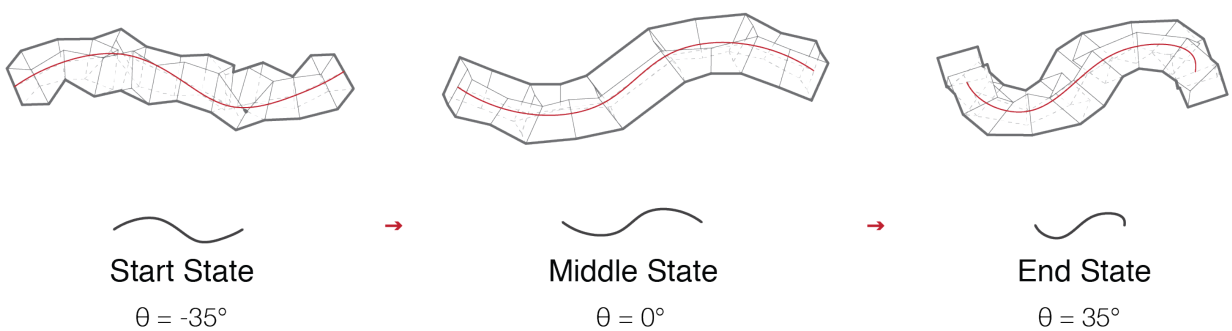

Figure 20. The three states of an Unmirrored structure

A prebend means that, in the middle flat state, some of the units of the structures are rotated along the α hinge bar's y-direction [Figure 21]. After prebend, the start state and end state changes shape accordingly.

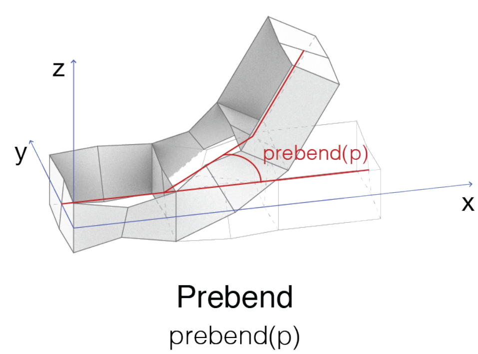

Figure 21. The prebend process

New design spaces

With the rich combination of parameters and this new prebend process, the new Modular KinetiX mechanism is considerably improved in the breadth of the design application. It creates a larger design space and makes this four-bar linkage mechanism more beneficial. The two structures with the same parameter list but different prebends can represent completely different shape change phases [Figure 22].

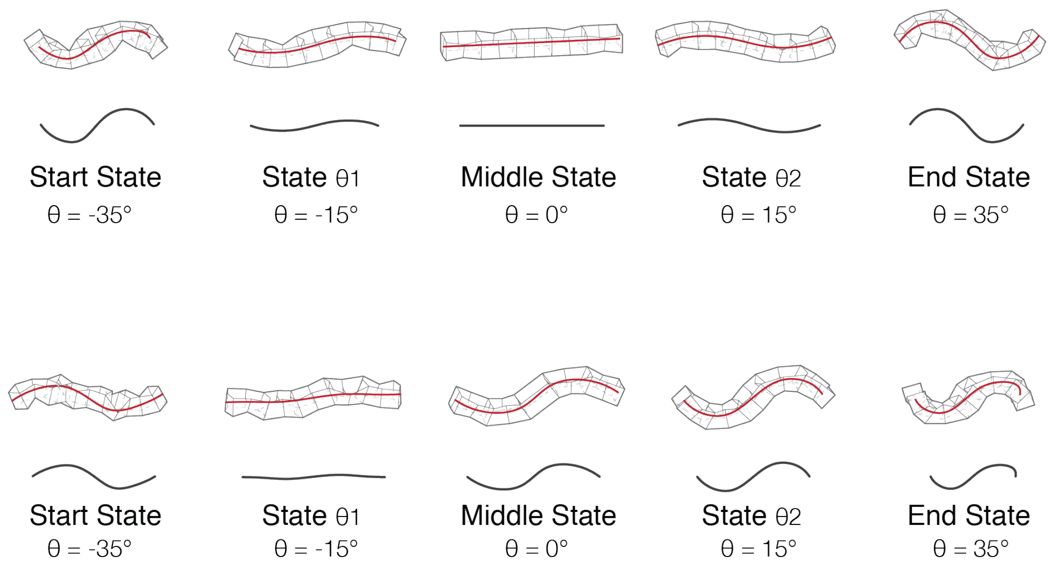

Figure 22. Same parameter list may have different shape changes at same θ

To think a further step, we could have two structure that have same final states but different middle shapes. This allows the possibility of designing customized transformable products for different users [Figure 23].

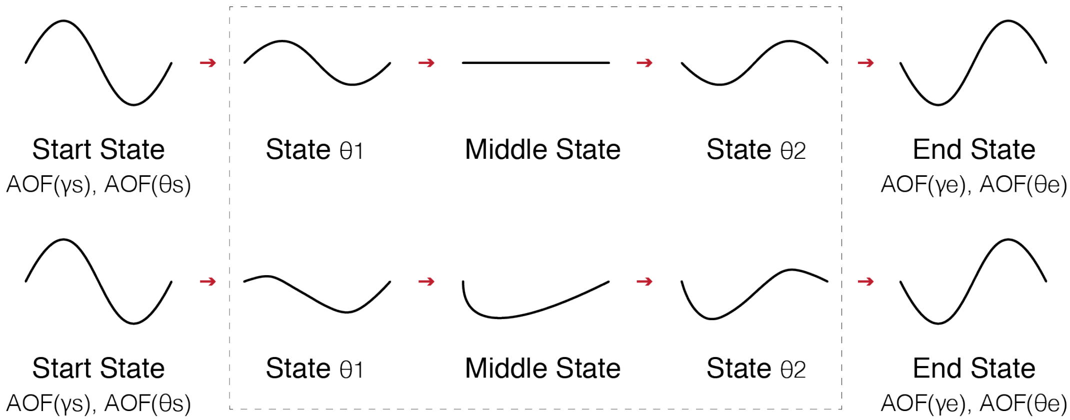

Figure 23. Same final states but different middle shapes

3.2.3. Fabrication of standard modules

The Modular KinetiX is modularized, both physically and digitally. In this thesis, I design and fabricate 9 primitive standard modules [Figure 24]. Designers can assemble these modules into desired shape-change structures by following the instructions from the design tool. Moreover, in this modularizing way of design transformable material, designers can also use modules to randomly assemble deformable structures.

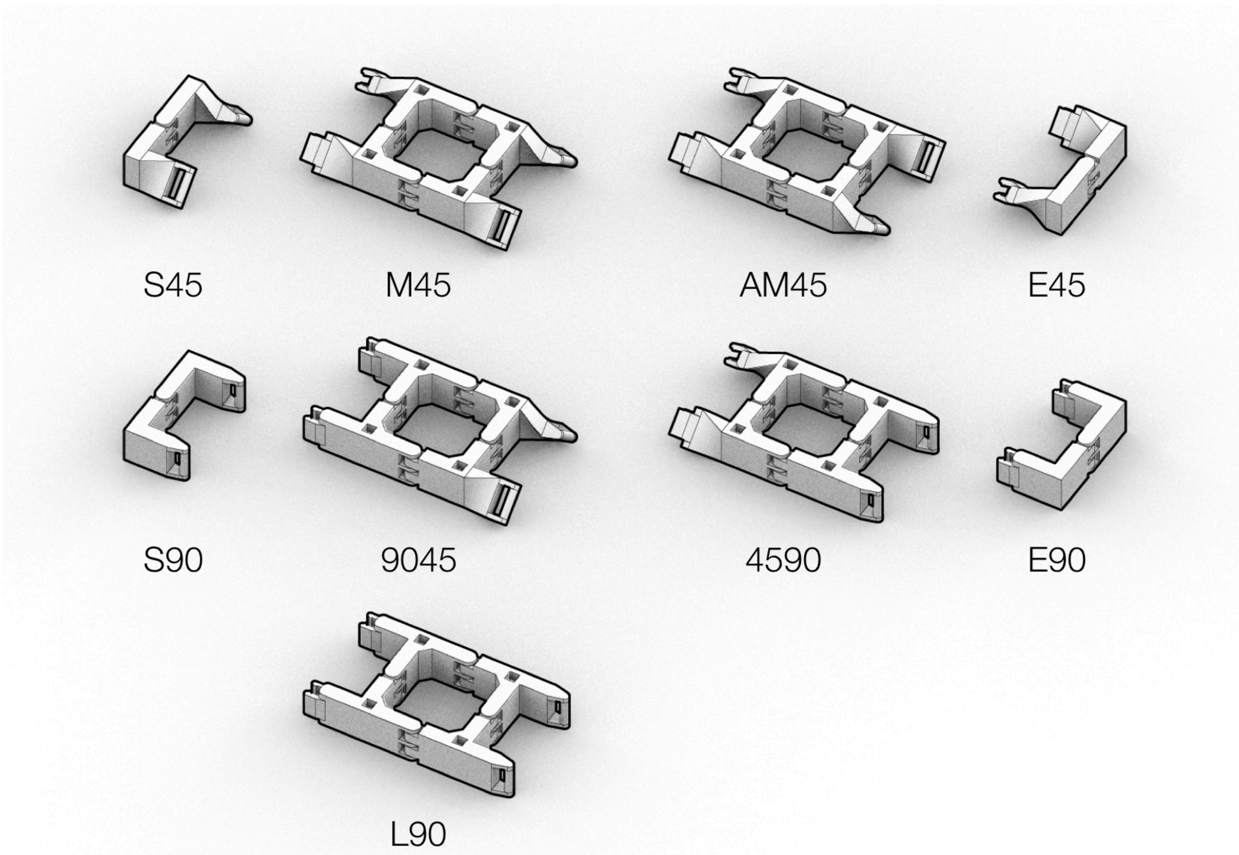

Figure 24. The 9 standard primitive modules.

The 9 primitive modules are carefully designed under a set of rules and constraints. First, the fewer the number of modules, the better. Because too many modules make the system more complicated and each module is difficult to locate. Second, the modules should be able to describe as many different shape changes as possible. Third, the structure should be easily reconfigured. Besides, the result structures should be able to form the 2D Tessellation. Considering all the rules above, the 9 primitive modules in this thesis has the β angle of either 90° or 45°, and all the α angles are 0°.

There are limitations when using these modules to tradeoff the fabrication time. The prebend structure is not possible with standard modules. The accuracy of the resulting structure is degraded, some intricate structure is not possible with these standard modules.

The 9 standard modules are marked with a letter and number, where the letter is the short for its function and number means the angle of joints. A structure usually starts with an S90/S45 module, and end with E90/E45 module. The rest of the structure is composed of modules which provide the main shape changing feature. In addition, the connection modules are stackable, enabling a more complex intersected structure of KinetiX transformable material [Figure 25].

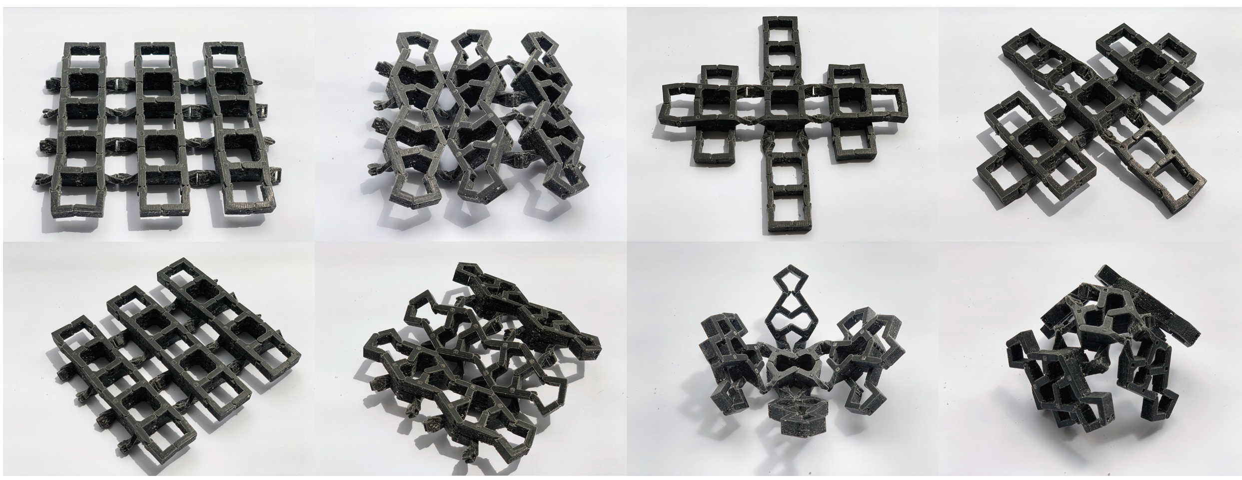

Figure 25. Examples of the freely assembles KinetiX transformable material.

4. The goal-oriented design tool

Due to the incredibly large design space, the modular KinetiX have an effective computational tool to help the designer explore it. This chapter introduces the goal-oriented design tool which allows the designer to upgrade the original design process to an efficient interactive design process. Design demos are provided to showcase the usage of the design tool.

4.1. Original design process of KinetiX

The original design process of KinetiX structures is empirical and heuristic. Designers need to understand KinetiX's mechanism well and try many times to get the desired result. In addition, it is just a tremendously laborious task if a designer wants to design a larger and more complex transformable structure with many units.

As [Figure 26] shows, the original design process is divided into a computation part and a fabrication part. The process starts with a concept and the designer makes the first-round digital model empirically. Then, the model is tested in the simulation tool. If the test works, we can refine the model and make it ready for fabrication; if it does not, the designer has to empirically modify the model and sent it to a simulation tool to test again. This trial-and-error process usually happens 3-4 times until the designer gets the desired structure. After the computation part, even if we have the model for fabrication, there is still a chance of failure. Because the simulation tool is physics-based, it is not mathematically correct. This may cause a big discrepancy between the simulation and the actual fabricated structure. Therefore, designers often need to return to the computation part and iterate the design several times. In summary, the original design process has serious problems in design efficiency and accuracy.

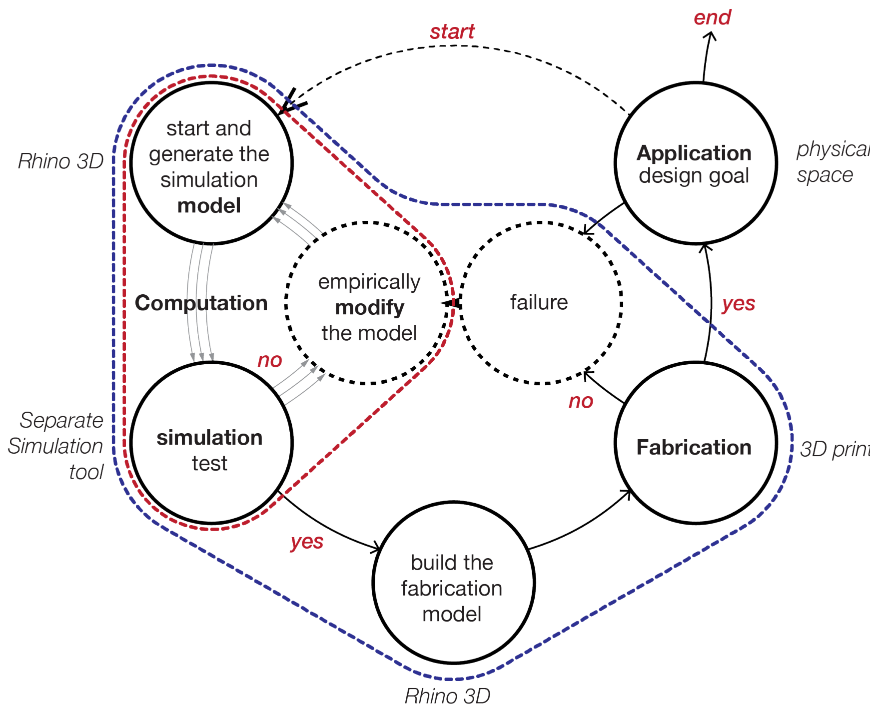

Figure 26. The original design process. The red curves includes the computation process, and the blue contains the possible fabrication process. The figure id the snapshot of a helmet design.

To improve the design process, we need to optimize both computation and fabrication parts. The looping process in the computation parts should be eliminated. The design process should generate a correct and desired digital model directly. In the meantime, the designer should be able to get instant feedback on the design so as to interactively adjust the design. Consequently, since the computation generated model is mathematically correct, there is no place for failure in the fabrication process. Furthermore, with the new Modular KinetiX, we can make the fabricated structure modularized and reconfigurable. [Figure 27]

Therefore, we need a computational design tool to assist designers. The tool allows designers to input their design goal and get the bug-free KinetiX structures as desired.

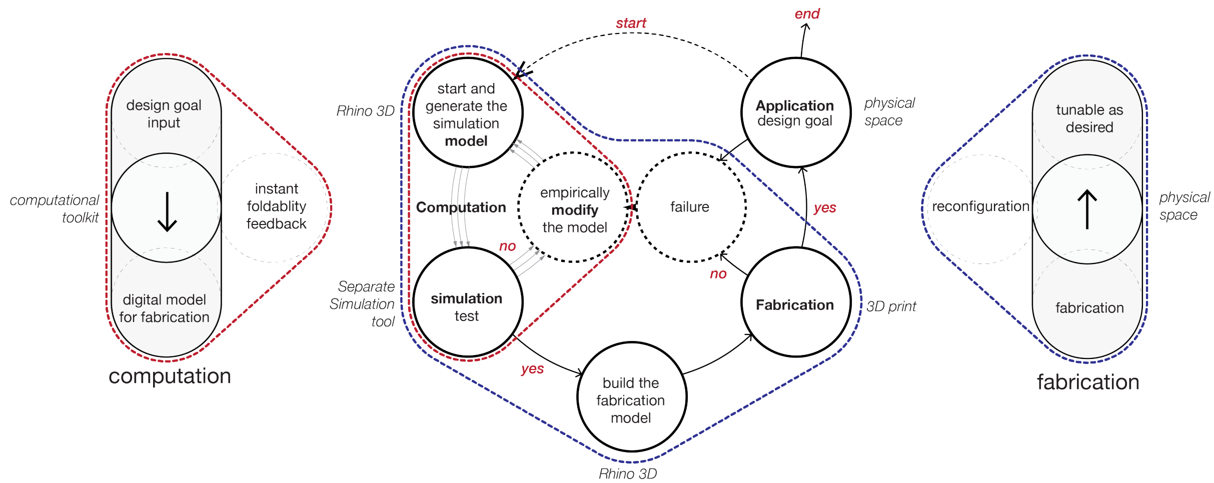

Figure 27. The improvement of the original design process.

4.2. The goal-oriented design tool

Input	→	Computation	→	Output
Design goal		Shape analysis Calculations Instant visuals		Fabrication file Assemble instructions

Figure 28. Goal-oriented design methods

Borrowing the concept from the area of UX design, I develop a goal-oriented design tool to help designers create transformable materials with Modular KinetiX. The goal-oriented design method will eliminate the trial-and-error process and allow designers to focus on the shape change and its functionality. This goal-oriented design process is composed of input, computation, and output. It starts with a design goal as input and outputs the desired instructions for modules assemblage or a fabrication file. The computation part solves all the difficult calculations in order to create more space for the designer to think about the design of the transformation itself [Figure 28].

The design tool is implemented in the 3D modeling software Rhinoceros 3D and its parameter plugin Grasshopper. The prerequisites for designers being able to use this tool are first, to get the entry-level knowledge of Rhino/Grasshopper, and second, to properly describe their design goals in the form of curves. Once the designer is familiar with the design tool, he/she might come up with creative designs and applications. For the design tool, I only implemented the mirrored structure. The unmirrored structure will be left to future work.

The design tool has 4 parts. Each part contains one or more customized components in grasshopper which designers can use directly. The following 4 sessions are the detailed introduction and instruction of these components. [Figure 29]

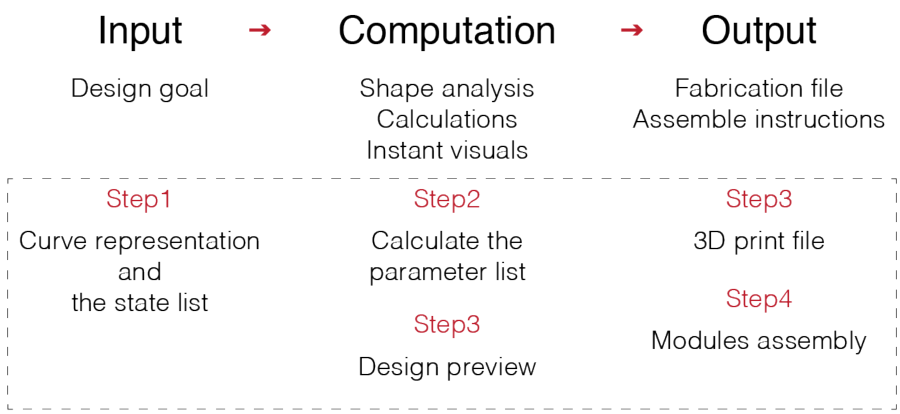

Figure 29. The 4 parts of the design tool.

4.2.1. Step1 - Curve representation and the state list

A natural way to represent a KinetiX structure is through the curve. Based on section 3.2.2, the design goal can be translated into a set of two curves, where one of it describes the start shape state and the other for the end shape state. For complicated design shapes, we can use multiple intersected curves to represent the design goal. Next, by analyzing the curve/curves, we can get **the list of AOF(γ)** of each unit in this structure, which is used for parameter calculation in the next step.

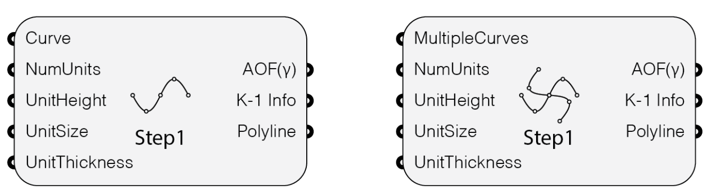

Figure 30. Step1 - Curve analysis

Step1 has two customized curve analysis grasshopper components [Figure 30].

Inputs:

- Curve(s): The curve/curves that represent the start(end) state of the structure. The green circle is the relative position of the center of each unit. A red cross will show up if the γ angle exceeds the bound value. The designer can adjust the shape of the curve/curves by dragging the green circle (red cross)

- NumUnit: The number of units in this structure. Increasing the amounts is an effective way to prevent a red cross.
- UnitHeight: The height of each unit.
- UnitSize: These two components treat all units as square ones. UnitSize is the length of the square.
- UnitThickness: The thickness of the bar in each unit.

Outputs:

- AOF(γ): The list of finals bending angle of units in this structure.
- K-1 Info: Information to passed to the step2 components.
- Polyline: The calculated shape of the structure in the form of a polyline.

4.2.2.Step2 - Calculate the parameter list

With the AOF(γ) list from step1, we can calculate the **AOF(θ)** as well as **the parameter list** of the structure. The calculation is a gradient descent process in which an optimal combination of the parameter is found.

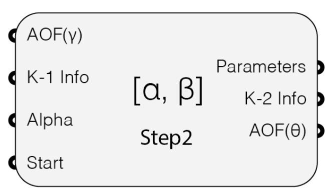

Figure 31. Step2 - Calculate parameters

Step2 has customized components. [Figure 31]

Inputs:

- AOF(γ): From step1, the list of finals bending angle of units in this structure.
- K-1 Info: Information from the step1 components.
- Alpha: Since the structure is linear, it is more convenient it gives out control of α. Set α to 0 if the designer wants only to consider β in the calculation.
- Start: The computation of these components eats computational memory quickly. The start toggle (true/false) is a switch to turn on/off the computation.

Outputs:

- Parameters: The calculated α and β.
- K-2 Info: Information to passed to the step3 components.
- AOF(θ): The θ of finals bending state of this structure.

4.2.3. Step3 - Design Preview and 3DP

When we have the parameter list, it means we know the structure thoroughly. We can rebuild the structure and preview the model for the designer to interactively adjust the design. In addition, we can also prepare the fabrication files for designers to prototype their design.

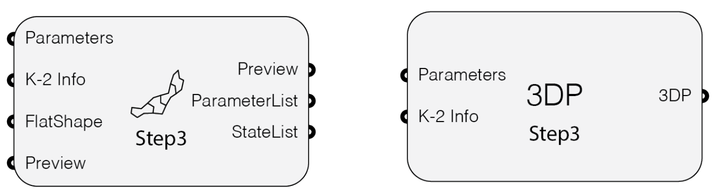

Figure 32. Step3 - Preview shape change and prepare 3DP model

Step3 has two customized grasshopper components, one previews the shape change, the other prepares the 3D-print-ready files. [Figure 32]

Preview Inputs:

- Parameters: The calculated α and β form step2.
- K-2 Info: Information from the step2 components.
- Flat Shape: Preview the structure as flat.
- Preview: The designer can drag the slider to interactively see the shape change of the output structure.

Preview Outputs:

- Preview: To bake the simplified structure.
- Parameter list: The parameter list of the structure.
- State list: The state list of the previewing shape.

3DP Inputs:

- Parameters: The calculated α and β form step2.
- K-2 Info: Information from the step2 components.

3DP Outputs:

- 3DP: The 3D-print-ready files to bake.

4.2.4. Step4 - Modules assembly

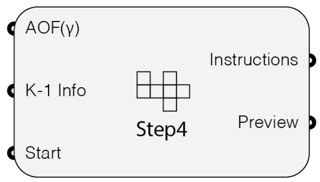

Figure 33. Step4 - mudular assemblage

Step4 gives an alternative way of getting the structures by assembling with the 9 standard primitive modules. This step has one component that can give the designer a detailed instruction of how to assemble the structure with modules. [Figure 33]

Inputs:

- AOF(γ): From step1, the list of finals bending angle of units in this structure.
- K-1 Info: Information from the step1 components.
- Start: The computation of these components eats computational memory quickly. The start toggle (true/false) is a switch to turn on/off the computation.

Outputs:

- Instructions: The calculated α and β.
- Preview: To bake the simplified structure.

4.3.Design demo

This section presents a design demo that shows the use of this tool step bu step. The goal of this design demo is to create a transformable structure that can be deformed from flat shape to double-spiral shape, detailing the workflow of the design tool. The design process is described in 4 steps.

Step1: I draw a curve in Rhino3D to represent the final shape change state of the wanted structure, and reference it in the Grasshopper Step1 Component. Then, I use the recommended unit settings to provide the height, length, and thickness of the unit. Two red cross shows up, so I adjust the curve in Rhino and also increase the numUnit to 10. [Figure 34]

Step2: Adding the Step2 component and toggle true for the start input, I successfully get the parameters. I use the default 0 for the alpha input. [Figure 35]

Step3: Utilizing the Step3 preview component, I build a simple visualization for my KinetiX structure. By sliding the numerical slider, I can see the shape change to decide and make the final modification to the initial curve interactively [Figure 36]. Next, I want to 3d print this structure so I use the Step3 3DP component to generate the models [Figure 37].

Step4: When the structure is printing, I also want to assemble with standard modules to understand how it works. The Step4 component gives me instructions on which modules I need and how to connect them [Figure 38]. [Figure 39] shows the 3DP and assembly results.

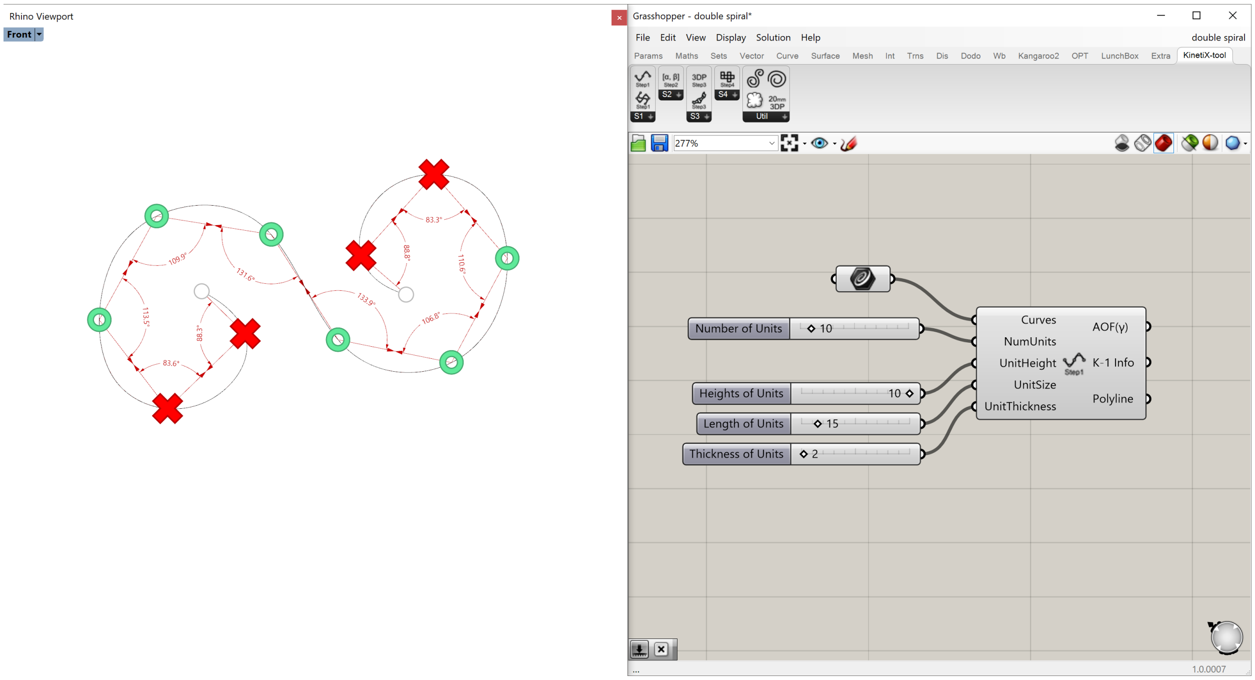

Figure 34. Step1

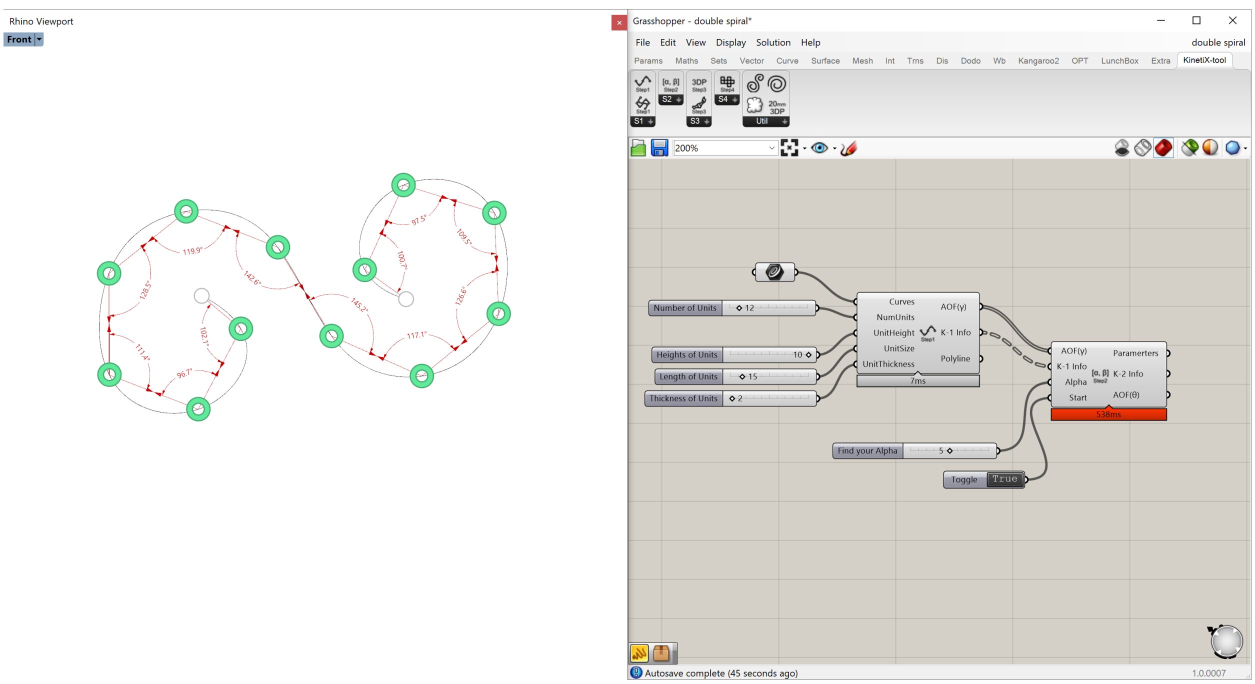

Figure 35. Step2

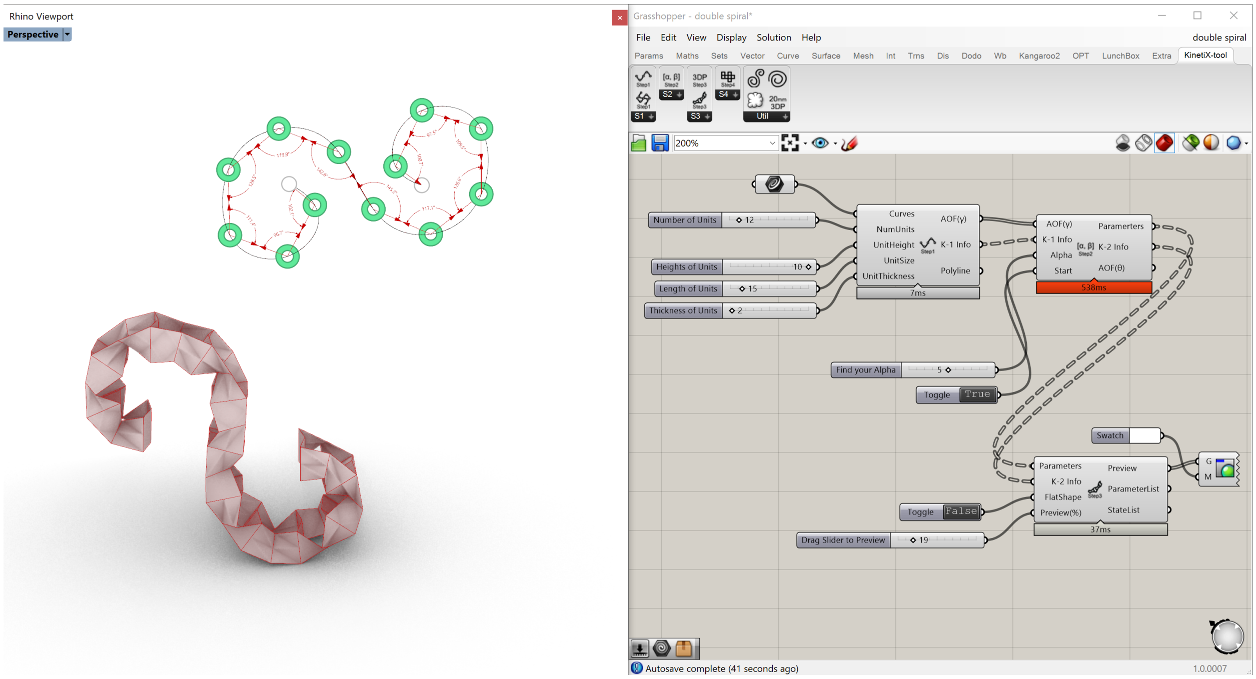

Figure 36. Step3 - preview the structure

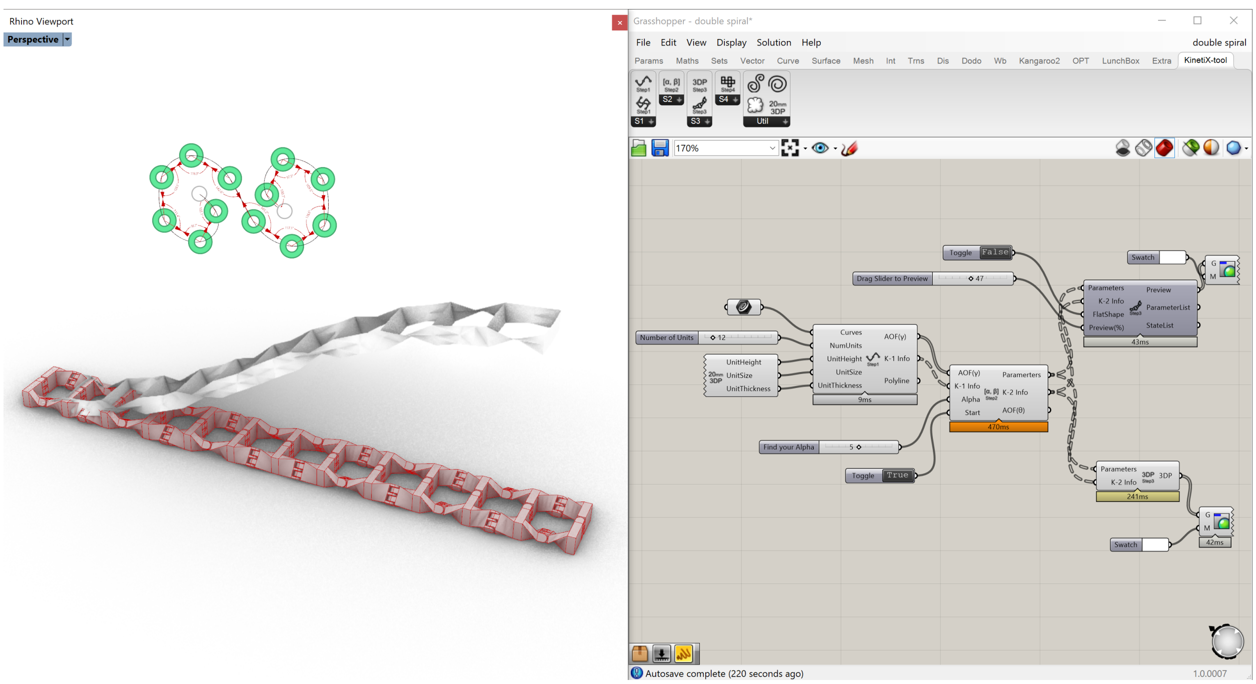

Figure 37. Step3 - generate the 3DP model

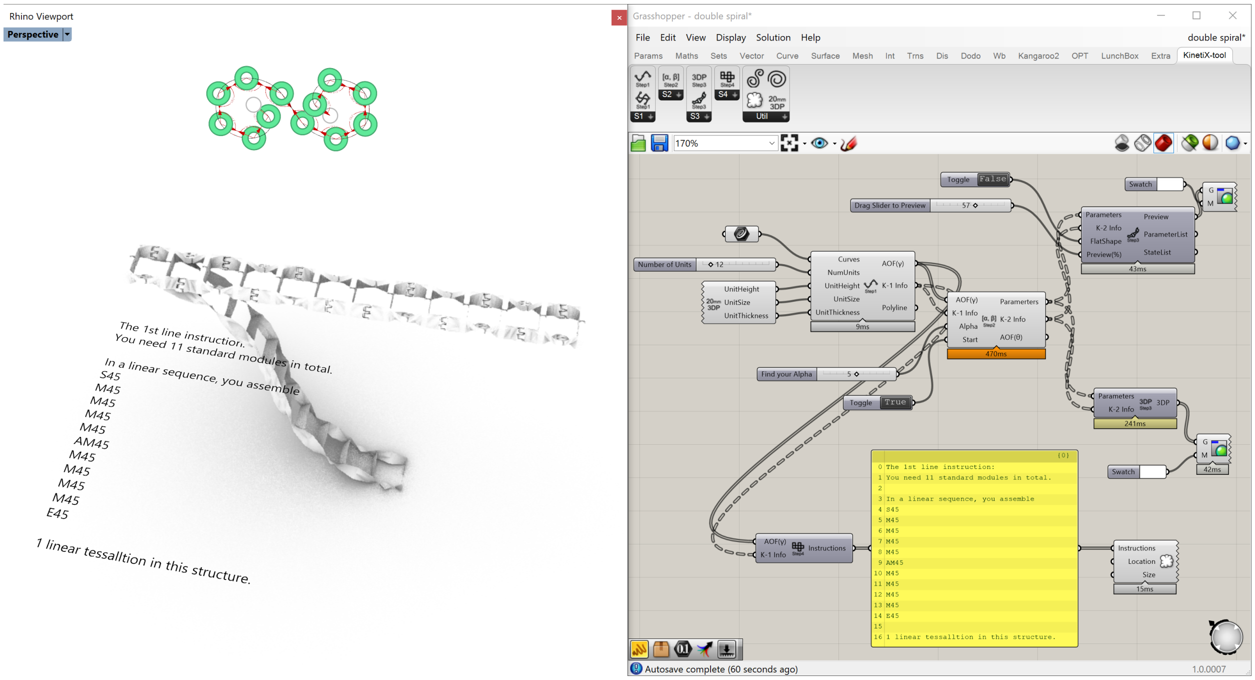

Figure 38. Step4 - the instructions for assembly

Figure 39. The top two images are the 3DP result, the bottom two images shows the assemble result.

5. Conclusion

5.1. Contribution

In this thesis, I have proposed a modular reconfigurable transformable material mechanism, the Modular KinetiX, as well as its design tool for the designer to make reconfigurable transformable material structures. Evolving from former research of KinetiX, this improved version is able to contain multiple functions in its structure and can easily switch within them upon compressing.

Specifically, I introduced a geometric representation of KinetiX and proved that KinetiX structure can be switched in completely different shapes. Through this geometric representation system, this mechanism becomes manageable.

To further extends, I implemented a design tool for Modular KinetiX. Utilizing the geometric representation method and some optimization algorithms, the design tool is empowered to achieve a goal-oriented design process. This tool relieves the designer from the trial-and-error design process and greatly improves the efficiency and the accuracy of the design results.

In addition, I designed 9 standard modules. With the instructions from the design tool, the designer can quickly obtain the desired transformable structure by assembling the modules. This modular approach allows each transformable structure to be reconfigurable and the designer can modify it after fabrication.

5.2. Future work

Implementation of the prebend process

The implementation of the design tool contains only the Mirrored structure and does not involve the asymmetric Unmirrored structure brought about by the prebend process. The Mirrored structure verifies the feasibility of this goal-oriented design approach. However, in order to ultimately achieve the use of KinetiX to make a variety of transformable materials, it is necessary to implement prebend calculations in the design tool. Only such improvements can really improve this four-bar linkage mechanism.

2D tessellation research with a data-driven approach

As described in Section 3.2, 2D tessellation is a good research topic. 2D tessellation can achieve a transferable structure like a curved surface, which will greatly expand the scope that KinetiX can be applied. However, since the complexity of 2D tessellation increases exponentially with the number of units, the study of 2D tessellation requires expensive computation. Perhaps the best research method is the data-driven approach. By randomly generating and creating transformable KinetiX structures, we can collect their data and then use that data to continually approximate the results we need.

Across scale fabrication

The modular KinetiX mechanism is independent of scale, and we can design around this transformable material mechanism for cross-scale applications. On a small scale, this material mechanism can help design micro-robots. The shape memory material can act as an actuator here. In large structures, because any location of the KinetiX structure can cause deformation of the entire structure, the mechanism can be used for foldable satellite solar panels driven by a single actuation. In addition, considering aesthetics, this mechanism can make attractive shape changeable art installations.

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7. List of figures

Figure 1. Classify transformable materials based on material properties. Image by the author. The reference of the projects are as follows:

(1) Connolly, Fionnuala, Diana A. Wagner, Conor J. Walsh, and Katia Bertoldi. "Sew-Free Anisotropic Textile Composites for Rapid Design and Manufacturing of Soft Wearable Robots." *Extreme Mechanics Letters* 27 (February 1, 2019): 52–58. https://doi.org/10.1016/j.eml.2019.01.007.

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Figure 2. An overview of the types of change in shape from a research by Rasumssen, et al. From “Rasmussen, Majken K., Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornb\a ek. “Shape-Changing Interfaces: A Review of the Design Space and Open Research Questions.” In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 735–744. CHI ’12. New York, NY, USA: ACM, 2012. https://doi.org/10.1145/2207676.2207781 ”.

Figure 3. The interface of the design tool of Interactive Robogami. This is a project from MIT Computational Fabrication Group. Image from URL: http://cfg.mit.edu/content/interactive-robogami-end-end-system-design-robots-ground-locomotion.

Figure 4. The design spaces and tradeoffs mapping into different patches. This is a project from MIT Computational Fabrication Group. Image from URL: http://cfg.mit.edu/content/interactive-exploration-design-trade-offs.

Figure 5. A 1D tessellation of spatial transformation that performs bending and twisting behavior. This is a project from MIT Media Lab Tangible Media Group. Image from URL: https://tangible.media.mit.edu/project/kinetix--designing-auxeticinspired-deformable-mate/.

Figure 6. Left: conventional material becomes thinner when stretched; Right: auxetic material exhibits a Negative Poisson's Ratio (NPR), it becomes fatter when stretched.

Figure 7. Rotating polygon type auxetic material simplified as a four-bar linkage structure.

Figure 8. From the basic unit, a planar and spatial transformation can be created. Parametrically shifting the position of the hinge creates uniform scaling and shearing; rotating the hinge in or out-of-plane creates twisting and bending.

Figure 9. KinetiX transformable unit composite table. Spatial transformation includes bending and twisting. Planar transformation includes uniform scaling and shearing.

*Figure 6-9. Reprint from "Ou, Jifei, Zhao Ma, Jannik Peters, Sen Dai, Nikolaos Vlavianos, and Hiroshi Ishii. "KinetiX - Designing Auxetic-Inspired Deformable Material Structures." *Computers & Graphics* 75 (October 1, 2018): 72–81. https://doi.org/10.1016/j.cag.2018.06.003".

Figure 10. Example of 1D tessellation on the left and example of 2D on the right.

Figure 11. The interface of the simulation tool in the KinetiX project.

*Figure 10,11. This is a project from MIT Media Lab Tangible Media Group. Image from URL: https://tangible.media.mit.edu/project/kinetix--designing-auxeticinspired-deformable-mate/.

Figure 12. Parameters of a unit (bending transformation unit). Image by the author.

Figure 13. Representation of a shape stage. Image by the author.

Figure 14. Mathematical representation. Image by the author.

Figure 15. A single line tessellation example with the parameter list of $[[\alpha, \beta 1], [-\alpha, \beta 2], [\alpha, \beta 3], [-\alpha, \beta 4]]$. Image by the author.

Figure 16. A single line tessellation example with the state list of $[\theta, \gamma(1), \gamma(2), \gamma(3), \gamma(4)]$. Image by the author.

Figure 17. Multiple line structures example. Image by the author.

Figure 18. The start state and final state of a single KinetiX unit due to the collision of hinges. Image by the author.

Figure 19. The three states of a Mirrored structure. Image by the author.

Figure 20. The three states of an Unmirrored structure. Image by the author.

Figure 21. The prebend process. Image by the author.

Figure 22. Same parameter list may have different shape change. Image by the author.

Figure 23. Same final states but different middle shapes. Image by the author.