# KIT-OF-MOTION
## Complex motion through simple structures

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**Abstract:** Kinematic systems and the theory of kinematics have been used extensively within the realm of architecture and design. Rather than focusing on the efficiency and functionality of kinematic systems, as seen in various built architecture projects around the world, we focused on the elegance of motion that kinetic architecture brings through the complexity of kinematic systems built by a kit of simple mechanisms, created via the passive actuations of environmental features such as wind, gravity and water. We examined a variety of installations that make use of kinematic systems focused on performance and aesthetics, breaking down each installation into simple movements of rotation and sliding actions, the basics of kinematics. Through drawings and model-making tests, we examined various simple mechanisms and ways to control their movement paths, which we then developed a catalogue of different parts and mechanisms that we found to be important. This catalogue of the different kit of parts informed the design and fabrication of a variety of iterative prototype models at various scales to create complex motion through the layering of simple mechanisms. These different iterative prototypes led to the design of three 3'x2' installations that show the aesthetic of complex kinematic systems activated via passive environmental inputs. Finally, from these installations, we developed 3 different speculative applications in which these mechanisms could be seen as a pavilion typology.

**Keywords:** Kinematics, environmental/human interaction, kit of parts, simulation, prototype, conceptual design

## 1. Introduction

Kinematic systems, the study of the motion of objects or a system of mechanisms, have been a recent focus of efficient and functional facades within the realm of architecture and design. Over the past 20 years, developments in active building systems have led to the usage of kinematic systems as kinetic architecture facades that act as efficient and functional environmental and climate control systems for buildings, from sun shading devices to ventilation systems (Sharaidin, 2014). This can be seen in the development of contemporary projects such as the Al Bahr Towers, Shanghai Art Center, and Institut du Monde Arabe, as shown in Figure 1 (Shakeri, 2025).

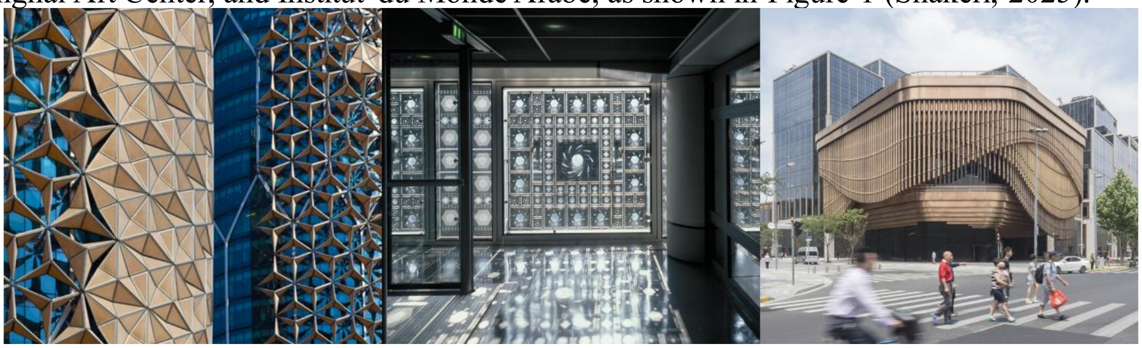


*Figure 1: From left to right- Al Bahr Towers; Institut du Monde Arabe; Kolding University*

However, while these buildings and kinetic architecture emphasize efficiency and functionality (whether successful or not in the case of the Institut du Monde Arabe) to control environmental features using simple motions of single-layered mechanisms, kinematic design has the potential to be more successful through the multi-layering of mechanisms to create complex motions. Rather than creating efficient and functional kinetic architecture that controls environmental features through shading or ventilation systems, we focused on the elegance of motion that kinematic design brings through the complexity of kinematic systems built by a kit of simple mechanisms in combination with the passive actuations of environmental features.

### 1.1 KINEMATIC FUNDAMENTALS & CASE STUDIES

Kinematic mechanisms are made up of simple motions of rotation and sliding (*Chapter 2. Mechanisms and Simple Machines*, n.d.). These two motions are the foundation of various simple mechanisms such as levers, slider cranks, pulleys and more, which in turn can be layered to create vastly complex systems. When examining various art installations and conceptual designs with varying levels of complexity, such as Jean Tinguely's *Hannibal II* (*Collection of Work of Jean Tinguely | Museum Tinguely Basel*, n.d.) or Arthur Ganson's *Machine With Oil* (Arthur Ganson, 2009), each project can be broken down into a variety of simple mechanisms that use combinations of sliding and rotational movement to create complexity, as shown in Figure 2.

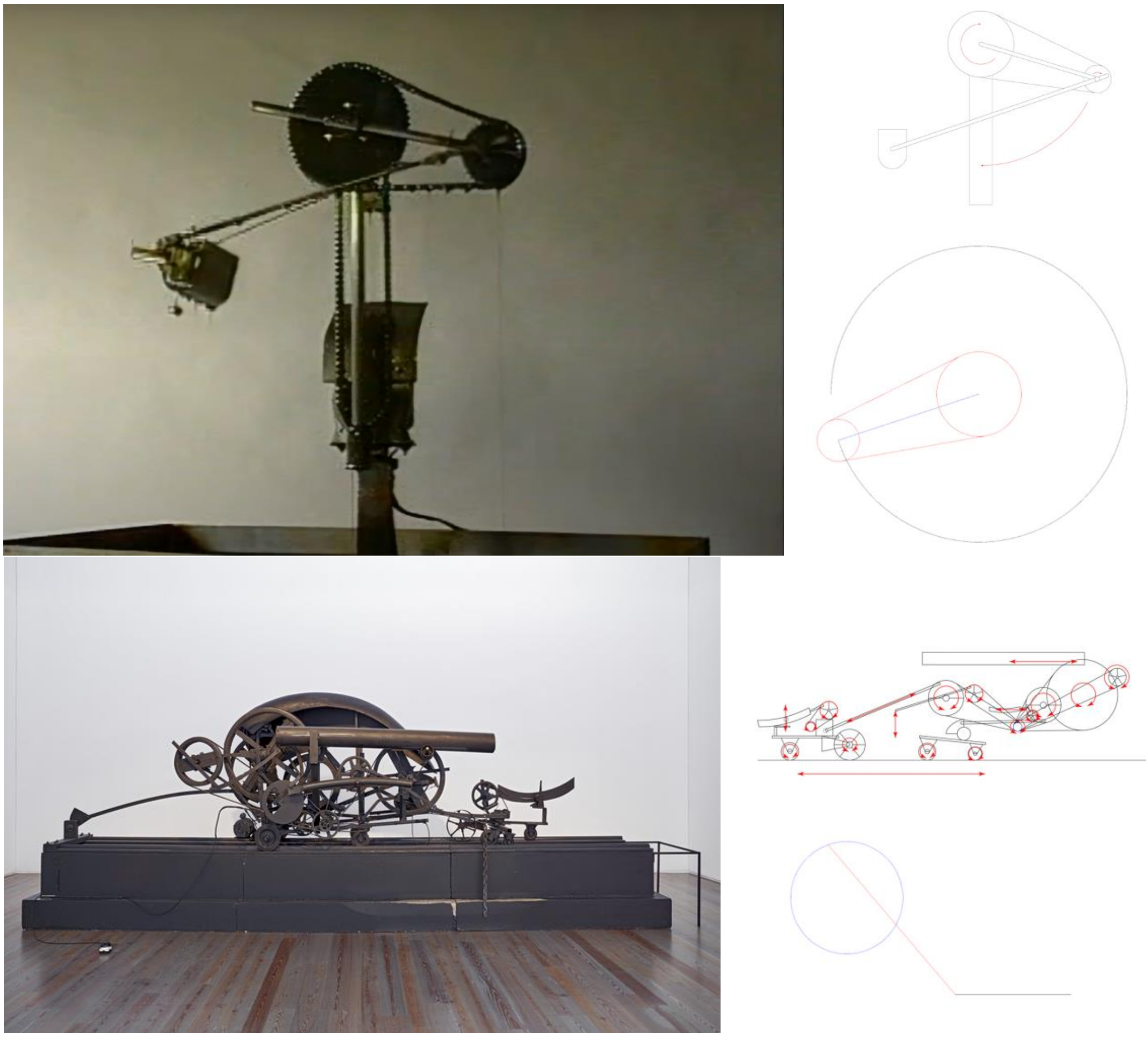


*Figure 2: Examples of how installations like Arthur Ganson's "Machine with Oil" (Top) and Jean Tinguely's "Hannibal II" (Bottom), while highly complex on first glance, can be broken down into 1-2 simple mechanisms that are just layered together to create.*

This is especially important when it comes to considering the activation method of each system, often starting with the push, pull or rotating method to move the kinematic system from a mode of stasis to a mode of action, creating a chain reaction of elegant complex motion. While most kinematic designs are often started via human input, the actuation of a system via an environmental condition (wind, water, falling sand, etc.) as seen with Ned Kahn's *Moving Goalposts* (*Wind – NED KAHN*, n.d.), Figure 3, can create similar or more elegant and organic complex motion.

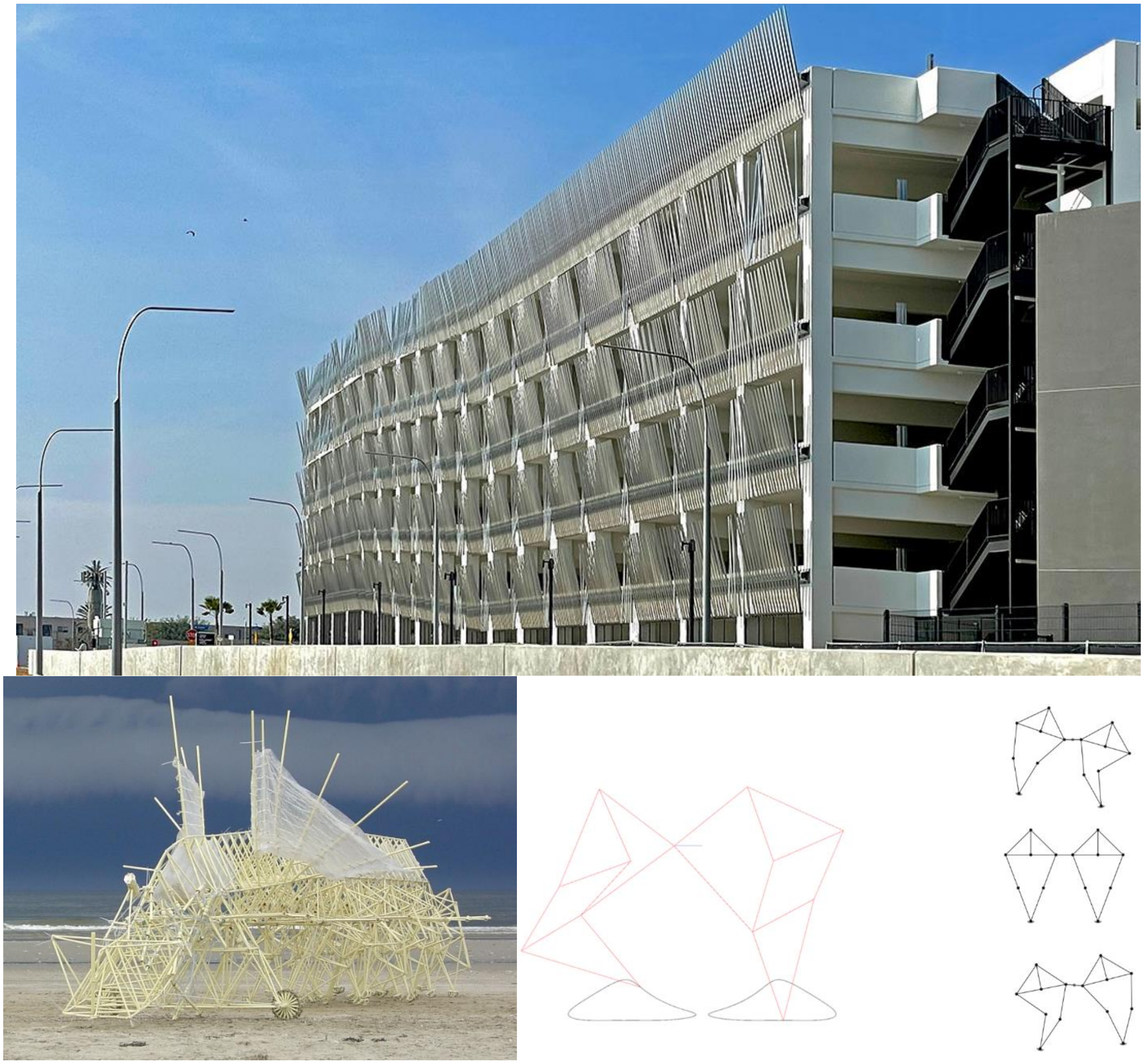


*Figure 3: (Top) Ned Kahns "Moving Goalposts" and (bottom left) Theo Jansen's StrandBeest, with a diagram (bottom right) breaking down the complexity of Teo Jansen's popular work into another simple system, with the linkage (red) moving in a bipedal manner.*

While Kahn's work focuses on the combination of many singular elements arrayed over a vast scale, this simple actuation movement can still cause multi-layered mechanisms to create multiple chain reactions, as seen with Theo Jansen's *StrandBeest* installations (*Home - Strandbeest*, n.d.), Figure 3. From first glances the *StrandBeest* highlights the intricacy of multi-layered systems that creates a very complex machine moving in an elegant, human-like bipedal manner. However, when examined more thoroughly, the installation can be broken down into simple mechanisms, that in turn can further be broken down into the two fundamental movements of rotation and sliding.

## 1.2 PRELIMINARY DESIGN EXPERIMENTS

Through our research into the kinematic fundamentals and the analyzation of a variety of case studies that create complex motion through the multi-layering of mechanisms, we analyzed how a simple environmental actuator could create a transitional chain reaction from simple to complex movement. From this analyzation, we sought to recreate these simple mechanisms by combining the two fundamental motions to understand each movement as well as figure out ways to control/restrict the movement of each mechanism.

As shown in Figure 4, a variety of mediums were used to perform these design experiments, from simulations using the program Linkage (Linkage Mechanism Designer and Simulator – Dave's Blog, n.d.), drawing out the motion paths by hand, and physically modeling out the mechanisms using simple materials. Through these series of experiments, we were able to determine how different connection types (pinned connections to allow rotation around a node and fixed to create restrictions in the mechanism to "ground" the system) could enable and/or restrict the movement of a mechanism.

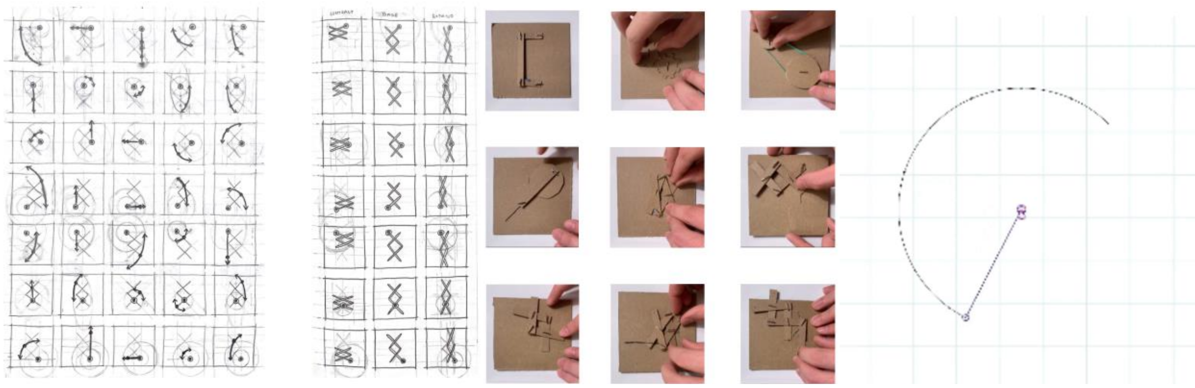


*Figure 4: The different methods and mediums of testing we accomplished to build the catalogue of systems we found to be interesting and ideal for layering together.*

## 1.3 KINEMATICS BOOKLET

From our experimentations with different mechanisms, testing out movements and trying to understand how to enable and/or restrict different movements based on the different pinning and/or fixing of different nodes within the system, we began to catalogue our different tests into a kinematics booklet, developing our own library of different kinematic designs that served as basis for many of our different experiments. This booklet, as seen in Figure 5, expresses the kit of parts design for all our future linkage designs, where the stick and node fundamentals of kinematics focused on a designed linkage holding a bearing wheel, which could relate to other linkages through the two different connection points to create a simple mechanism. By cataloguing our efforts and designing our own kinematic system through the use of the booklet, we can easily fabricate and modulate the linkage designs regardless of material used, easily layering different simple mechanisms we experimented with previously, which in turn can be layered onto one another to create complexity and more organic, performative and elegant motion that is significant to the exploration of kinematic design.

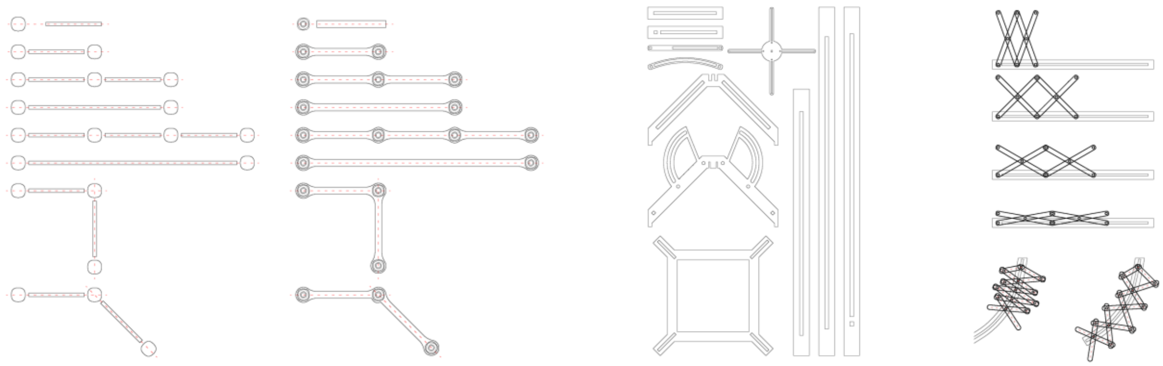


*Figure 5: Examples of different mechanisms, tracks and joints catalogued in the booklet*

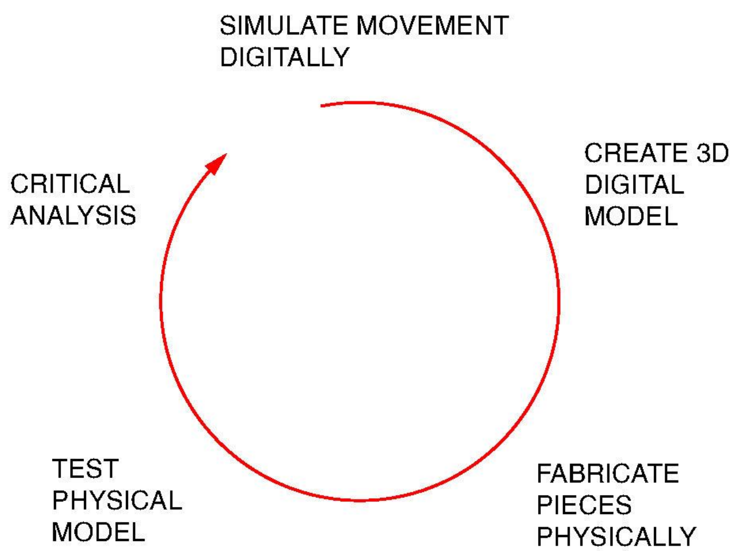
This booklet became the foundations for our future work into developing prototype installation models that could physically simulate the motions we had experimented with, as well as creating speculative applications in the form of pavilions, where these kinematic designs could transition into an architectural building model, being constructed in a variety of different locations with different environmental activations to express the adaptive design of the kit of parts system.

## 2. Research Methodology

This paper seeks to investigate the project KIT-OF-MOTION, which explores kinematic design as performative/interactive architecture by creating elegant, complex motion through the layering of simple mechanisms activated by environmental forces. This paper documents various physical prototype iterations that were made to physically create complex motion based on the layering of different mechanisms, connections and linkages documented in our kit-of-parts booklet. Each physical iterative prototype was made using a cyclical design thinking method (Figure 6):

1. Simulating the movement via analog sketches and/or using computer simulations such as Linkage and/or Grasshopper
2. Creating a digital model of the system using Rhinoceros 3D
3. Fabricating the pieces using laser cutters, 3D Printers, etc.
4. Testing the model
5. Critical analysis – documenting successes and failures
6. Repeat cycle

With the 1$^{st}$ iterative prototypes, test models were completed using laser cut 2-3 ply chipboard with screw joints. Further iterative test models were completed using laser cut 1/8" black plexiglass with screw or bearing joints. From the prototype designs we created 3 speculative applications to understand kinematic systems as an architecture pavilion, exploring design factors such as location, setting, representation, aesthetics, materiality, and more. The findings from our final 3 installations and speculative applications will be discussed in the Results/Discission section

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## 3. Iterative Prototype Design and Fabrication Process

During the development and documentation of our kit-of-parts booklet, we engaged in a series of rigorous design, building, and testing of different iterative prototypes. These prototypes made use of the different mechanisms, joint connections, and linkage types that we had identified. The goal of this iterative design process was to physically create our previous research and early study-models on the complex and elegant motion of multi-layered kinematic systems actuated through the simple engagement of a simple mechanism in either a sliding or rotational movement.

### 3.1 1ST ITERATIVE PROTOTYPE

Our first iterative prototypes began by examining how actuation through human movements (push, pull, crank, rotate) could engage in a complex motion. As seen in Figure 7, these models expanded upon our previous research by exploring different ways to control and engage complexity by either altering different lengths of linkages, different patterns, or different combinations of mechanisms. These early test models were successful in showing the possibilities of motions that could be created via different restraints and minimal changes to the parameters of each linkage and joint.

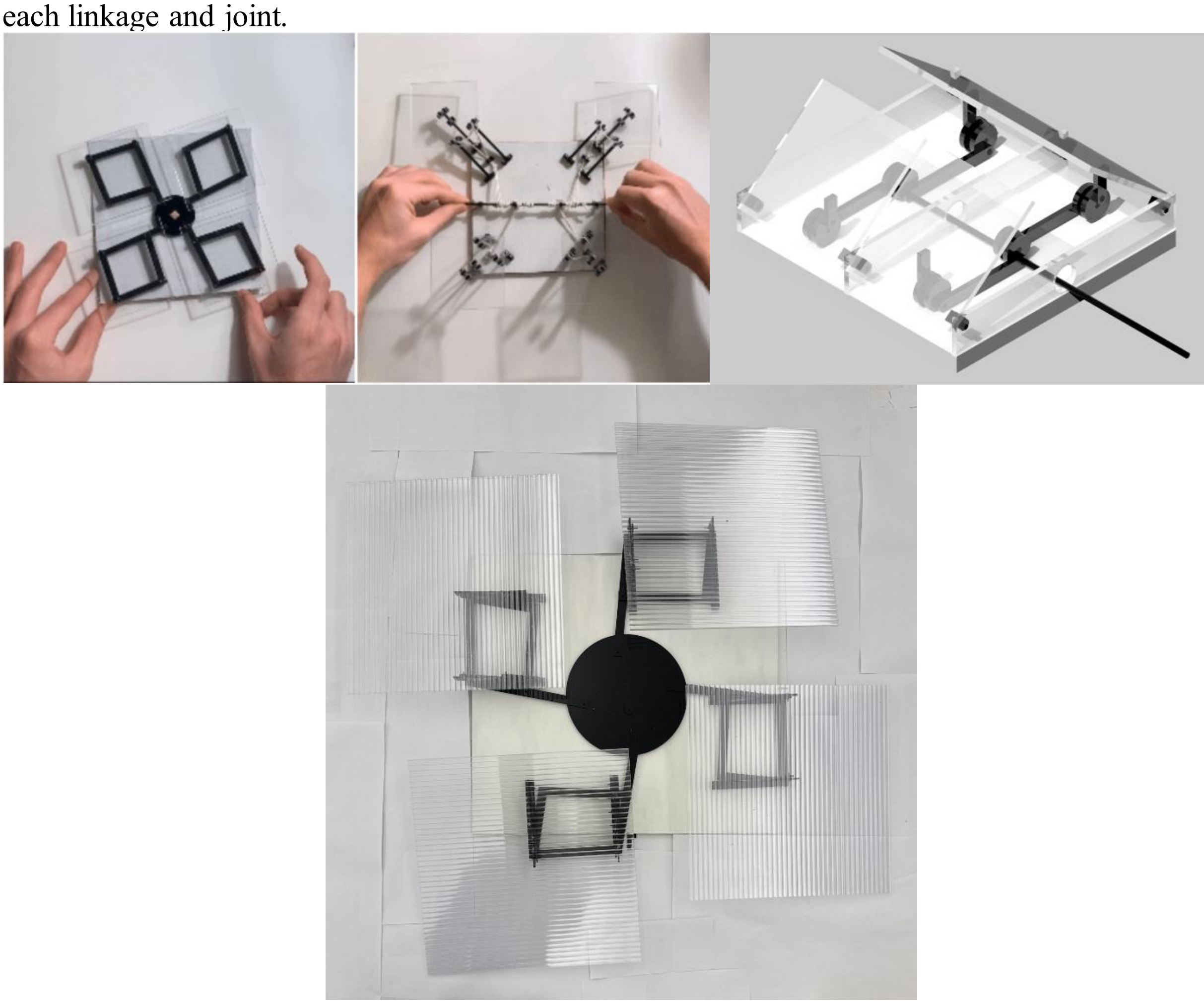

*Figure 7: (Top) the three first iterative prototypes, with our final large-scale installation (bottom) shown.*

However, there were some notable problems with the movement of the physical models regarding tension and rotational abilities, as well as the craft of the models. When it came to operating two of the physical models that dealt with rotational actuation, the build-up of multiple systems created high amounts of stress and torsion. This caused problems in the movement of the system, such as creating the motion through manual movement of the mechanism, or the complete breakdown of the entire system resulting in no movement whatsoever. Also, when trying to achieve light and thin in the design, the link parts became too fragile, either breaking in the process of movement, or causing other pieces to break off as well.

These first iterative prototypes were used to create the design of our first large scale iterative prototype model. This 3ft x 3ft model combined and scaled up the parts and systems of the models in hopes to create a complex system that would flower and bloom upon the turn of a rod in the middle of the system from a human hand. Upon immediate testing, the design was ultimately unsuccessful, where full mechanical motion could only be achieved through significant manual control and support. We learned that the design failed due to three key reasons:

1) By scaling up the mechanisms and linkages while keeping the same thickness, this led to floppy and unstable connections that distorted from the weight of polycarbonate panels.

2) Lack of account for gravitational force in the digital models and simulations meant the model, while successful in the digital realm, would not succeed in the physical world; and

3) Because we did not design at the proper scale, each layer of mechanisms was too spread apart, creating long thin connection links that were very unstable.

### 3.2 2ND ITERATIVE PROTOTYPE

From the analysis of the 1st iterative prototypes and large-scale model, we moved into developing our 2nd iterative prototypes. This time, we focused on creating test models using chipboard to understand the movement before building with laser cut 1/8” black plexiglass for the final models. Each of our final 2nd iterative models (Figure 8) focused on again creating complex movement through human activation.

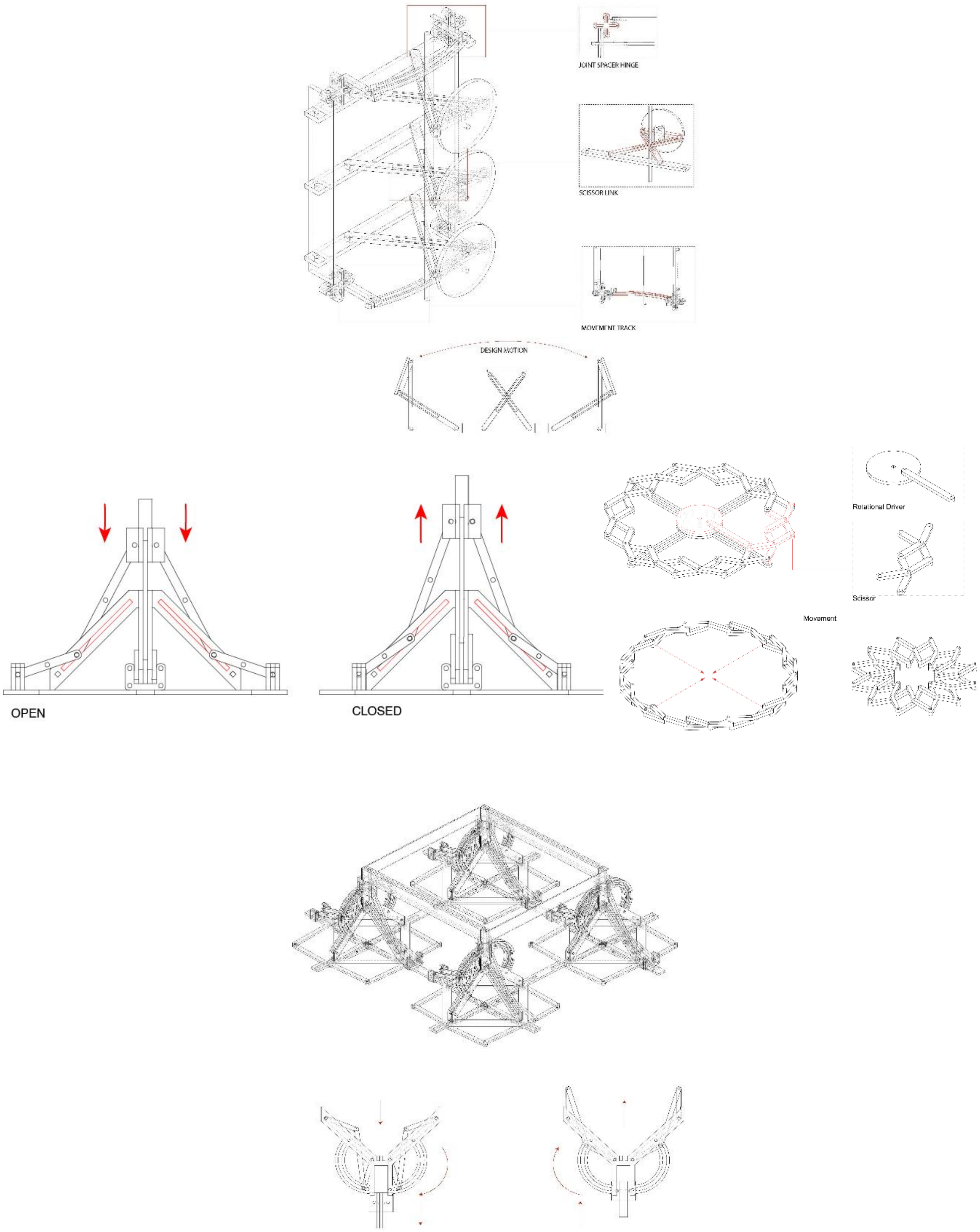


*Figure 8: (Top in descending order) The first, second and third prototype designs in the 2nd iteration with the diagrammatic movements of each one displayed. (Bottom) the design of the 2nd large-scale installation, with the (unbuilt) push mechanism to control all systems at once.*

The first model, when pushed on the back, would move linkages on tracks to spread open a polygonal scissor linkage, causing four panels at the front to rotate outwards, creating a blooming-like effect. At the same time, a linkage member would be thrust outwards through the gap created by the expanding scissor linkage. This model successfully demonstrated movement in

2 different axes through the design of a custom universal joint. The model also emphasized the smooth mechanics plexiglass created. The only problem again came from the screw joints, which after a few uses would come undone.

The second model focused on combining a rotational and flipping movement. A rod placed between two arcing slide tracks would operate three individual mechanisms that would cause 3 panels to flip. This model was successful in demonstrating individual vs. group movement, whereby sliding the rod at certain angles could control how much each flipping mechanism would move. This model also demonstrated the minimum thickness of the linkages at such a scale, emphasizing light and elegant motion that expressed a complex system.

The third model combined the slider crank movement with a radial scissor linkage design, where the radial scissor linkage would expand and contract on four sliding rails as the single linkage rotates around the circular linkage that is being turned. This model was unsuccessful due to the design and actuation of the model, where too much torsion/stress on the central wheel from holding the fixed scissor linkage caused it to buckle. At the same time, the friction from the screw joints caused significant drooping of the scissor links, which would bind and be unable to expand and contract properly, before eventually causing the mechanism to fall apart.

These 3 different models helped inform us of the more successful designs that we then used to build our second large scale prototype installation. This 3ft x 3ft model, as seen in Figure 9, focused on combining the systems of the first and second model into one kinematic system. This design would fit in all four corners of the model, held by a wooden plate frame attached to a 2x4 wooden frame. The idea of the installation was to be activated by a push-pull mechanism, which would cause the mechanism to operate like the first model, pushing four panels attached to a scissor-linkage mechanism outwards, exposing a gap in between. At the same time, a flipping panel would push out in the gap created by the sliding panels as a combination between the first and second model mechanisms.

Unfortunately, this 2$^{nd}$ large-scale installation was only partially successful. The entire system was able to open through a significant amount of force, however it could not contract via the pull mechanism, thus needing manual movement to set each mechanism back in place. From this testing we were able to determine a couple of different reasons why this model was unable to move properly:

1) Similar to the first iteration, instead of designing at the scale of the physical model, we scaled up the mechanisms to fit within the dimensions of the frame. This caused many linkages to be large and heavy, adding extra weight that detracted from the design and functionality of the system.

2) Too much material and too many mechanisms were compacted into a small area, leading to an overly complex design with an actuation type that was insufficient to provide enough force to move the system.

3) The design, while being highly complex in structure, was too uniform and ended up creating very simple motions due to the limited range it could realistically move, going against what we had been trying to achieve.

## 3.3 3$^{RD}$ ITERATIVE PROTOTYPE

Taking what we had learned from our previous prototype attempts to physically simulate complex elegant motion via the layering of mechanisms, we changed the starting actuation from human interaction to environmental forces. By focusing on such factors, we hoped that it would negate the problems of the 2$^{nd}$ large-scale installation from having tightly compacted, overly complex mechanisms into a much lighter and looser design, but not too loose so that it would be floppy and deformed as seen in the 1st large scale installation. Thus, the environmental factors would add necessary controls to the design scheme that could lead to physically functional models.

The 3rd large-scale installation (Figure 9) is split into 3 different kinematic modules at a scale of 3ft x 2ft. Each kinematic module is designed based on the environmental force that activates each system. This was done to show the range for which our kinematic kit-of-parts library that we had documented in our booklet could be used to create systems of elegant complex motion, as well as to express the range of forces that could be designed to create complexity.

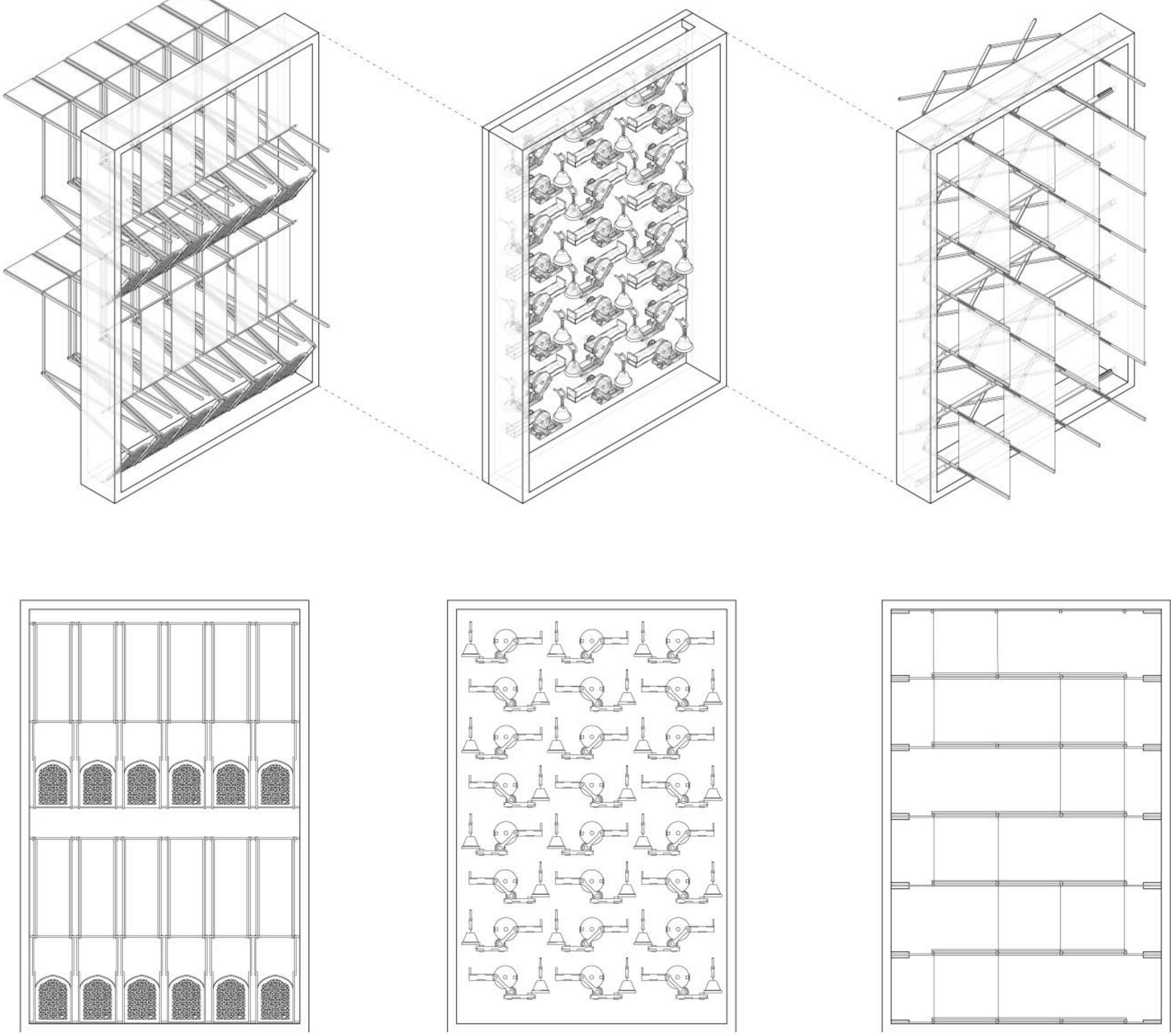

*Figure 9: Final large-scale installation made up of (3) 3ft x 2ft panels. Each panel mechanism is activated by 3 different environmental factors: Sand (left); Water (center); Wind (right).*

Wind, water, and sand were chosen as the three different environmental forces that would activate each module separately due to the range of force each environmental actuation would generate. Each kinematic system would be built with thin plexiglass linkages and having M3 screw joint connections. The systems will be attached to the frame via thin metal rods to further push the elegant, light feel as well as create a strong structure. The frames themselves are made of thin plywood material. These modules can be connected to create a larger installation or separated into 3 modules.

## 4. Speculative Applications

While the final prototype installation focused on the actual movement of each kinematic system through the activation of an environmental phenomenon, the module designs helped to influence 3 speculative applications that explored kinematic systems through pavilion architecture to further emphasize our creation of a kit-of-parts as being an adaptable façade design. These speculative applications take the form of 3 different pavilion designs that explore the dynamic between the user, the façade, and the environment through different performative kinematic systems.

### 4.1 DANCING FINS

DANCING FINS seeks dynamic complexity through the movement of simplicity. An oxymoronic design, the park pavilion (Figure 10) focuses on 2 contrasting, orchestral-like experiences of wind. When approaching the pavilion, viewers will be able to experience the wonderous spectacle as it dances, flutters and blooms in the wind as if controlled via a puppeteer's hands. Each individual thin member floats like a cloud, emphasizing this elegant arching and flexing motion of the wind as moving air controls and billows through the fabric fins. This smooth and slow-motion of the exterior contrasts deeply with the harsh, chaotic and whipping gestures in the interior, as spindly arms twist and writhe like tree branches in a gale. DANCING FINS emphasizes the two faces of wind in interaction with; A smooth dancer that effortlessly cascades beautiful, simple gestures while moving to Tchaikovsky's *Waltz of the Flowers,* to a violent, wriggling, twisting spectacle as if driven by the Vivaldi's "Summer" from *The Four Seasons*.

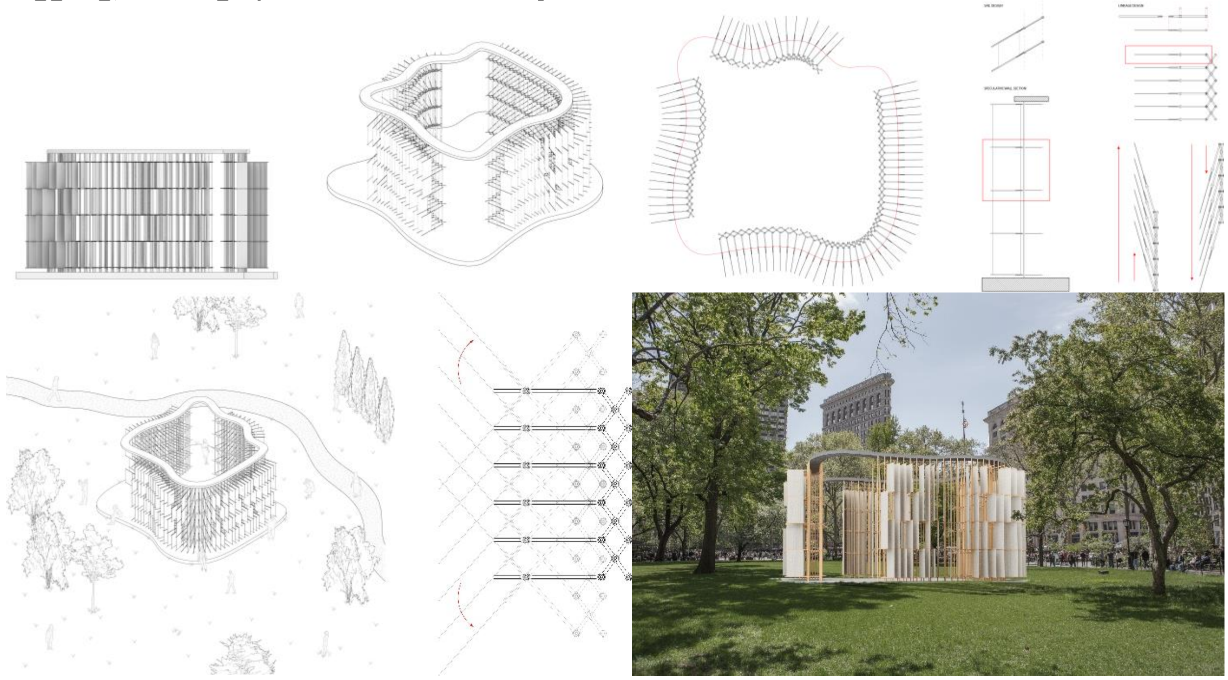

*Figure 10: In descending order from left to right - (1) Diagrams breaking down the kinematic system and operation; (2) Axonometric of the project; (3) North-facing elevation; (4) Conceptual render of the pavilion.*

### 4.2 FALLING MUSIC

FALLING MUSIC expresses the poetic nature of falling water as both a beautiful expression and as a powerful force. During a clear day the pavilion (Figure 11) remains inactive, reflecting the monotonous yet peaceful-like stillness of the pond as an element that supports the surrounding active landscape. However, when rain begins to fall, and visitors seek shelter under the comfort of the solid roof above, the pavilion and the pond begin to create music. Water rushes down the gentle slope of the roof into gutters that send the water into the panels, where thin paddles begin to flip and rotate as the water falls onto them. These paddles trigger a chain reaction of movement that causes small mallets to hit onto metal plates, ringing out sweet and light sounds in tandem with the individual raindrops falling into the pond. However, as the rain becomes more torrential, these light sounds exponentially built upon another to create a cacophony of powerful, overbearing, forceful music as more mechanisms activate, acting in cue with the violent, heavy, explosive splashes on the pond's surface. The garden becomes filled with this overbearing roar and crash of water until the storm finally breaks, and the orchestra dies down into individual touches of sound, before finally coming to a standstill as the pavilion and the pond stops moving, once again becoming like follies until the next rainstorm.

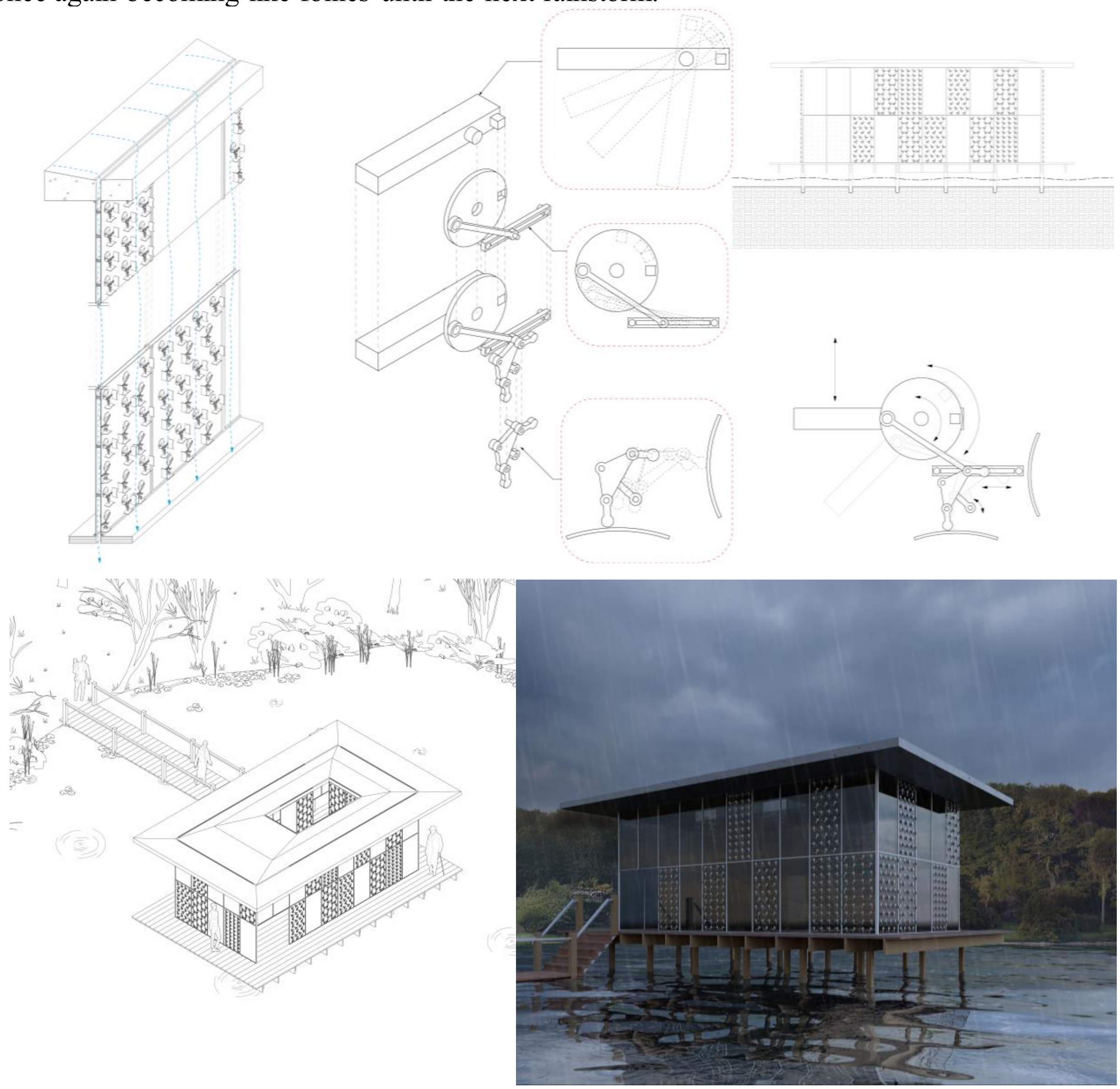

*Figure 11: In descending order from left to right - (1) Diagrams of the musical mechanism showing the different layers of movement happening and of the panelized kinematic system; (3) Speculative axonometric exploring the location of the pavilion; (4) Conceptual render showcasing materiality and atmosphere with the pavilion in conjunction to the surrounding scene.*

4.3 WHISPERING DUNES

Designed specifically for desert and sand prone environments, WHISPERING DUNES leverages a carefully balanced counterweight linkage system triggered by sand accumulation (Figure 12). As sand collects within fabric pockets, its weight activates the linkage mechanism, opening the fabric pockets and simultaneously lifting shading panels upward. Visitors experience both visual and acoustic interactions as sand audibly cascades from pocket to pocket, highlighting the pavilion’s responsiveness to environmental changes. Once the sand disperses and the pockets empty, the weighted panels at the rear counterbalance the structure, returning the fabric pockets to their original position and lowering the shading panels. This cyclical motion demonstrates a dynamic and sustainable architecture solution uniquely adapted to its desert context. WHISPERING DUNES also emphasizes the slow yet constant changing landscape of sand dunes, building into giant waves that eventually break and collapse over vast spans of time as the surrounding environment flows and counterbalances around it.

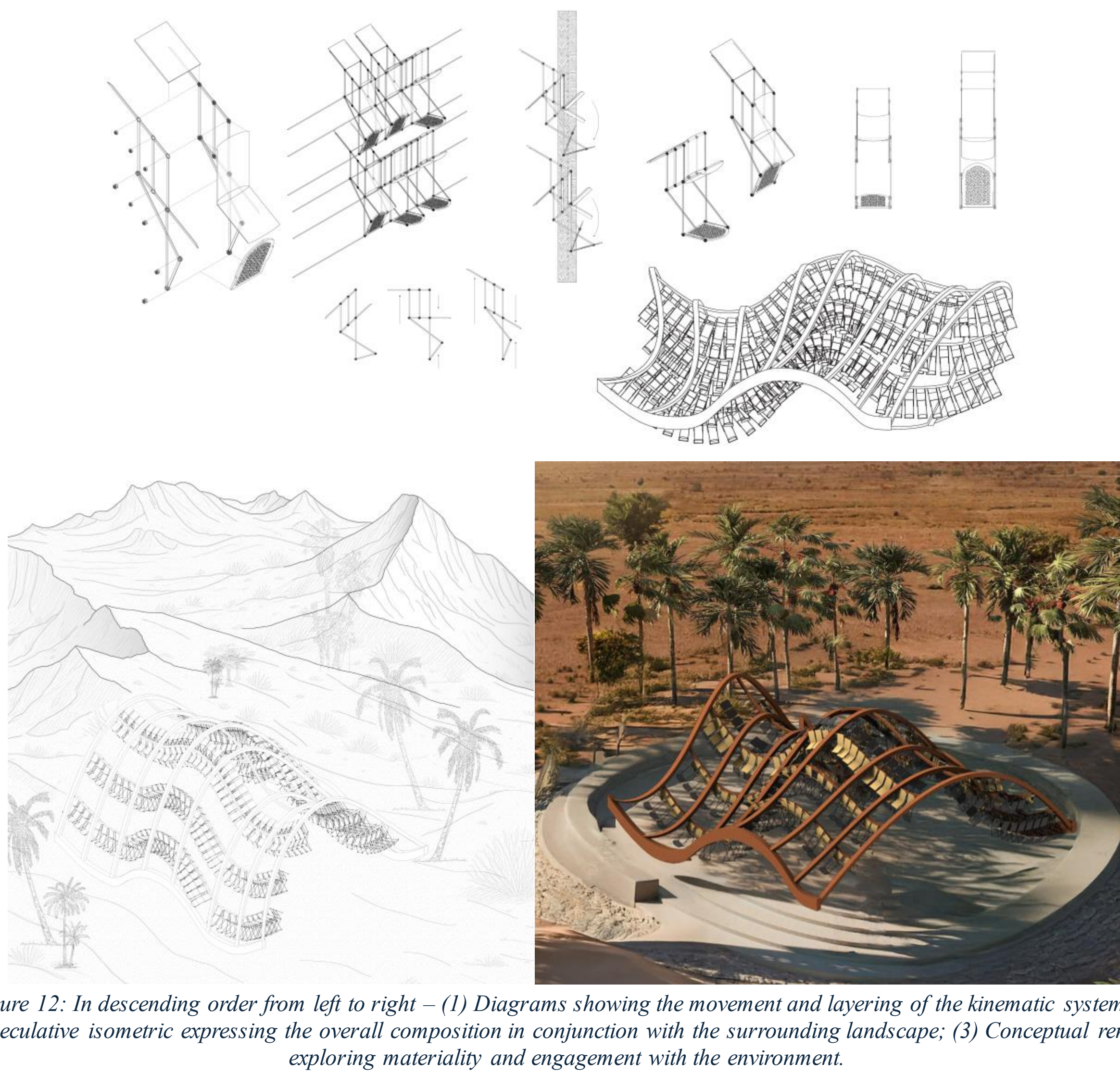

*Figure 12: In descending order from left to right – (1) Diagrams showing the movement and layering of the kinematic system; (2) Speculative isometric expressing the overall composition in conjunction with the surrounding landscape; (3) Conceptual render exploring materiality and engagement with the environment.*

## 5. Results/Discussion

When it came to creating complex motion from simple actuation of kinematic systems by environmental forces, both the final installation model and the speculative applications were highly successful in demonstrating the variety of configurations the project could take on using the kit-of-parts linkage library detailed in the booklet.

The final model installation was successful in expressing the connection between lightweight and thin mechanism designs to the simple activation of each environmental phenomenon, where the plexiglass linkages could flutter, wave, flap or dance from the slightest of triggers of motion due to moving wind, falling water, or cascading sand particles. By transitioning from human activations as seen in our previous iterative prototypes to environmental factors activating each panelized kinematic system, we were able to successfully create the complexity of motions that we had set out to achieve. Likewise, by fabricating each mechanism plexiglass linkages using laser cutting machines, we were easily able to reconfigure and redesign each panelized system within the construction process as we tested out different designs to dial in the correct movements to create effortless complex motion. These simple fabrication techniques successfully demonstrated the flexibility and modularity of the kit-of-parts library, where active design and construction methods could be used to change kinematic mechanisms on the fly without compromising the final movements or overall design scheme as we had seen in our previous iterations.

Like the final installation model, each speculative application was intricately designed to create congruency with their specific environmental factors, as seen through their materiality and adaptability. All three pavilion designs express the static and dynamic nature of the mechanisms, transitioning from decorative background ornamentation to a more active role within the design. DANCING FINS makes use of wooden linkages paired with thin fabric sheets that build exponentially together, imitating the surrounding trees in the layering of limbs, stems and leaves that express the otherwise unseen movements of wind. In contrast, both FALLING MUSIC and WHISPERING DUNES make use of thin metal mechanisms to actively demonstrate how individual elements such as rain drops/sand particles can have as much an effect on the kinematic pavilions as torrential falling water or cascading sand. In the case of FALLING MUSIC, the mechanisms become an overwhelming sensual spectacle that dominates the entire area with its constant metallic ringing of tuneless music during storms. However, for WHISPERING DUNES, the pavilion demonstrates the constant, slow-changing, cyclical motion of the desert, where sand particles build onto the pavilion's fabric bags before being released when overburdened. All three speculative pavilions successfully expressed a philosophical relationship between the environments they inhabited and the creative motions that were created by specific environmental phenomena.

Despite these successes, both the final installation model and the speculative applications demonstrated key drawbacks, most notably in the longevity of the kinematic systems. While the installation model and conceptual pavilions make use of modular kit-of-parts designs, we were unable to fully test out and document the longevity and degradation of the systems, particularly when exposed to harsh environmental factors. This is especially important when considering the choice of such environmental actuators such as falling water and sand, where erosion and rusting of metal parts and connections would lead to limitations and difficulty in the movement.

Another notable drawback is the limitations of project scale. As we experienced in the creation of the iterative prototypes, scale is a huge factor in the design and choice of mechanisms, especially when it comes to the layering of different systems together to create even more complex movement. These different mechanisms can be impacted by factors such as joint connections, materiality, and orientation conditions. While we were successful in demonstrating a variety of scales for different kinematic systems using certain materials like laser-cut plexiglass, we were unable to test a variety of different materials. As such we can only speculate from our final model installation that pavilion structures would be the only applicable scale for our kinematic systems, otherwise these systems would either become too heavy and rigid or too light and spindly, thus reducing the consistent performance of the entire moving design.

On the note of scale, another limitation we found within the project that highlights both a success and challenge of kinematic systems in general is the appropriate number of layered mechanisms. We found that 2-3 different mechanisms worked best, for achieving complex movement when activated by environmental phenomena. When trying to add more layers, issues came about from too many moving parts, increased resistances such as linkage weight, and unnecessary complexity that reduced the overall movement of the design. While it might be possible to achieve more complex movement across larger areas, this again runs into issues of scale that was previously mentioned, as well as the overall life cycle of the entire kinematic systems, before general degradation of moving connections would require repairs or new replacements of entire systems.

## 6. Conclusion

This paper documents the research, process and findings of KIT-OF-MOTION, a kinematics project that aims to perform complex motion from a design booklet kit of simple mechanisms, created via the passive actuations of environmental features such as wind, gravity and water. Through self-analysis of the final installation model and speculative applications, the paper finds that the project was successful in the overall goal to create complex motion started by the activation of simple mechanisms from environmental phenomena. The project was also successful in achieving simple fabrication and modular construction through the kit-of-parts design booklet, which was also used to create architecturally compelling pavilion designs that were uniquely adapted to 3 different environmental locations. This paper does note that despite these successes, key drawbacks were found within the project, such as limitations in scale, lack of testing in material diversity for the mechanisms, general constraints in the layered complexity of mechanical systems, and lack of testing regarding the overall longevity and life cycle of the kinematic systems due degradation from environmental factors and frictional wear and tear. To address these key drawbacks, future testing of full-scale mock-up designs could seek to incorporate different materiality studies for the kinematic systems, exploring how basic building materials such as wood and metal could create more varied and configurable systems that explore different varying levels of complexity. Further on, the incorporation of automatic systems such as light sensors, motors, pistons, hydraulics and more could help achieve better diversity in environmental actuators, possibly increasing the adaptability potential for the entire project.

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