Development of Design Workflows for Kinetic Structures Using Fuzzy Logic

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Kinetic structures offer the means to significantly expand the functional and performance features of traditionally static architectural solutions. However, the added element of motion creates considerable challenges during conceptualization and introduction into existing design workflows. Rigidly foldable shells offer tremendous potential for developing kinetic architectural structures. They require few support points, eliminate sliding overlaps and are relatively easy to mock up as initial concepts.

Achieving the desired motion range, however, requires a significant design effort. If performed manually, the motion optimization is tedious and unpredictable. This paper examines possible optimization algorithmic strategies with the use of fuzzy logic. Specifically the paper focuses on the application of fuzzy logic as a tool for effectively negotiating modifications of complex linked geometries while using intuitive, high level statements and directives. Highlighted is the potential of fuzzy logic-based algorithms as tools that can help the transition of existing design workflows into environments that can handle extended challenges involving kinetic geometries.

INTRODUCTION

The unprecedented technological, economic, and demographic dynamics of mankind are putting traditional building codes and construction standards to the test. The question is can building structures better address the increasingly more complex requirements of the modern world. Can they offer increased comfort under adverse climatic conditions? Can they afford functional advantages in densely populated areas? Can they mitigate the ecological footprint of new construction? Most importantly, can they provide better protection under extreme circumstances like natural or man induced disasters? Can they assure the means of easily deployable, robust, and adaptable sheltering under emergency conditions? In the end, can they more effectively serve and save human lives?

During the last decades, architects and engineers showed increasing interest in the application of kinetic elements in buildings as a means of more effectively addressing the extended set of contemporary requirements. The purposes of such structures are to adjust easily to changing functional needs and weather conditions, and facilitate transportation and deployment. Utilizing computer programs, advances in engineering and materials technology, designers have shown that motion need not be antithetical to our understanding of architecture and that it may actually make architecture more functional and exciting for its users.

KINETIC STRUCTURES–BENEFITS AND CHALLENGES

Kinetic structures can facilitate efficient integrations of existing building volumes with additional functions, for example commercial, institutional, and even residential use. They can also provide means of flexible expansion and improve comfort and safety for the occupants by adding zoned and controlled protection during extreme weather conditions. A variety of free standing, easily deployable kinetic structures can serve as adaptable, on-demand exhibitions, markets, exploration stations and public events facilities. More importantly, they are well suited to be developed into quick deployment shelters to aid in emergency situations.

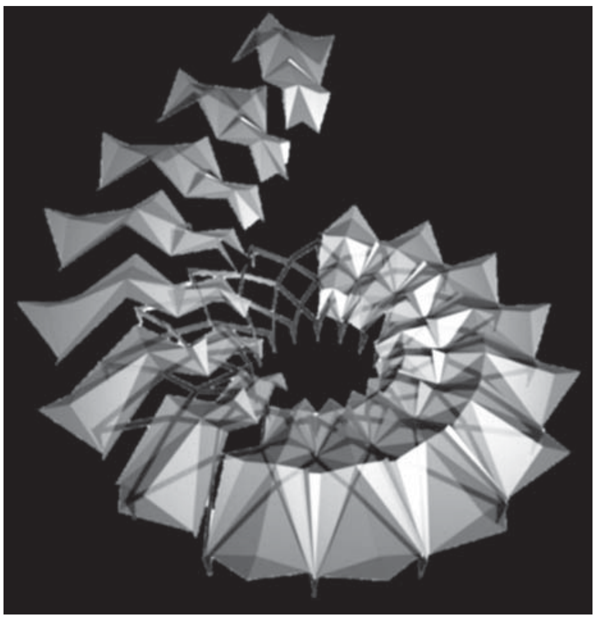


FIGURE 1 An illustration of the concept of kinetic structure

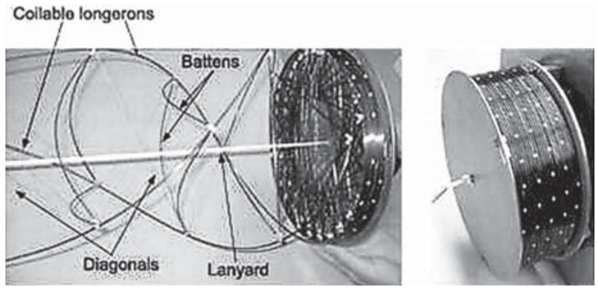


FIGURE 2 NASA coilable mast

Advances in design tools, actuation, controls and material engineering have opened possibilities for structures that implement novel folding geometries and automation technologies to pursue significantly expanded functional programs. The essential feature of such "performative" structures is a kinetic component that allows the spatial geometry to be adapted according to changing needs (Figure 1). This kinetic aspect is also the most challenging element during the design development as it exceeds the capacity of traditional standards, formulas, workflows, and design tools. Consequently, it poses planning and management difficulties typical for pioneering and trend setting work like increased effort and budgetary uncertainties and lack of readily available expertise.

OVERVIEW OF CONCEPTS AND TECHNOLOGIES

Not surprisingly, space exploration is the locus of many ingenious inventions. However, it is important to keep in mind the very different environment and applications such devices are designed for. Orbiting structures operate in a microgravity environment which is ideal for folding, kinetic, and actuated mechanisms as there are no gravity induced loads or frictional forces. Ultra-light and ultra-compact structures are the dominant design criteria. Added advantages are the absence of wind loads, rain blasts, freezing rain, wet-snow perils, and lesser nuisances like dust and moisture.

As an example, a coiled mast springs out of a compact spool into an extended and self-supporting position but only in a gravity free environment (Figure 2). Although, a

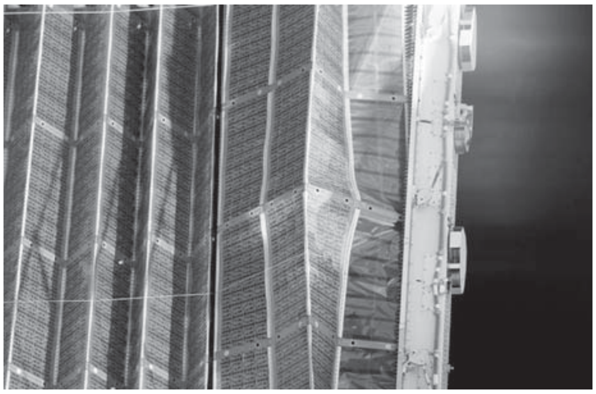


FIGURE 3 NASA solar panel

thin capton-film mounted solar array may demonstrate its precarious nature even under gravity free conditions (Figure 3). Figure 4 is an impressive example of how much of a controlled structure can be ejected from a compact box (Figure 4). This ultra-light structure deploys a precise parabolic skin as an antenna, yet it is only able to do so in a weightless environment. In essence, the applicability of such structures in architectural solutions is not realistic in ground-based applications. In Figure 5, a tessellation of hexagons and triangles supported by two cables with adjustable lengths is shown. The structure can become kinematically determinate simply by the adjustment of the two supporting cables. The top layer can be used to support a reflective wire mesh. It can also serve as a tension grid for theatre walkways. Here there is an obvious focus on lightweight, pre-stressed structures that offer self-deployment characteristics for space applications, for example an array of over-constrained mechanical linkages forming an expandable space frame that can be folded into a compact bundle. Another example is shown in Figure 6. Structures of this kind are being developed to deploy large, controlled surfaces in space where the key requirement is a single deployment path that takes the structure uniquely from folded to the fully deployed state (Pellegrino and Gan 2006). A spherical, diaphragm-like roof (Figure 7) is one example of very few attempts at building these structures (Jensen and Pellegrino 2002). However, besides partially open and fully closed positions, it does not offer much of an adjustability advantage.

This overview of kinetic technologies establishes the context of the research which is discussed further in this paper. Large, folding, adjustable, and functionally sound architectural structures do not have much conceptual or manufacturing precedence within the boundaries of the mainstream construction industry. The premise of this paper is that the provision of viable design tools and methods is as vital for the emergence of novel kinetic architectural solutions as conceiving of new ideas themselves.

DEVELOPMENT OF FOLDING SHELLS

In our earlier research, a concept of a folding structure was introduced based on the fusion of a folding structural frame with a rigidly foldable enclosing shell coupled to it (Figure 8). In order to complement a folding frame with a shell, a geometrical interface between these forms needed to be established. The connecting points of this interface form the controlling grid and the resulting mechanical connection. Such a grid is the consequence of the selection and configuration of a particular folding-frame geometry; it establishes the defining and parametrizing geometry for the purpose of designing a matching folding shell.

Rigidly foldable shells are advantageous for kinetic structures as they eliminate sliding overlaps and fold without buckling or warping stresses. A static, conceptual mock-up of a loosely arranged, free form set of facets can be easily appended to the underlying controlling structure (Figure 9). The resulting geometry outlines the desired target shape in an assumed functional configuration.

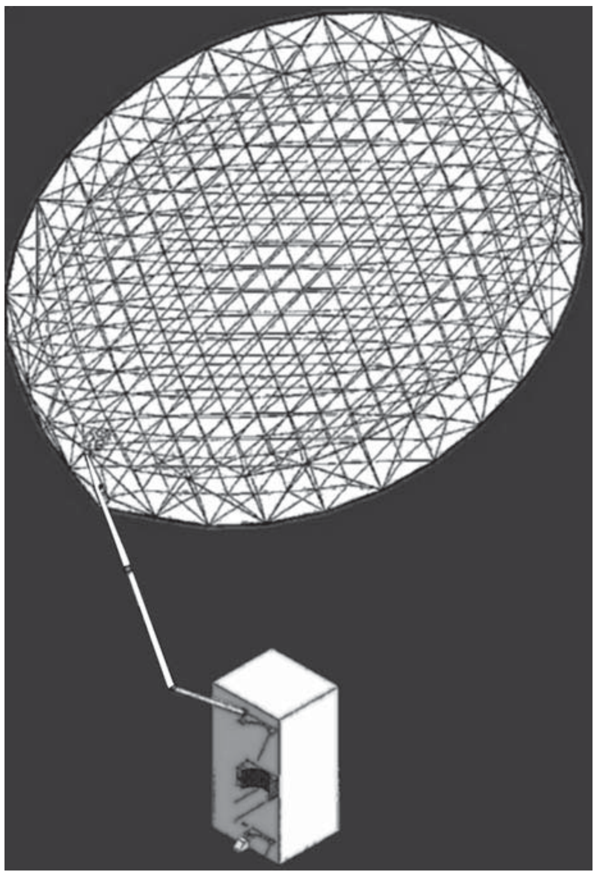


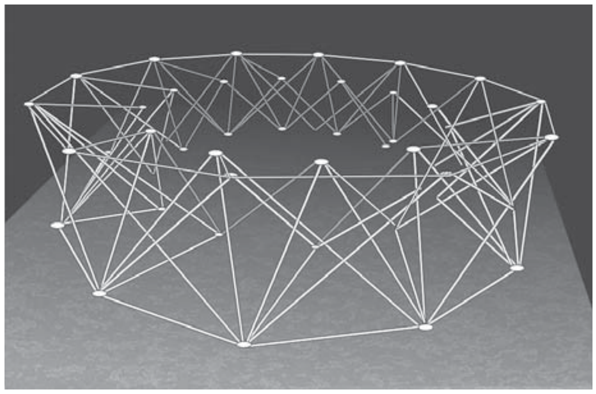
FIGURE 4 Astro-aerospace mesh reflector

DESIGN CHALLENGES

The challenges become apparent when attempting to fold a complex mesh such as the one illustrated in Figure 10. In this example, a singular configuration as well as a collision would occur while folding. A singularity denotes a fully stretched or flat folded state that results in indeterminate output motion states for a given input motion. In practice, singular configurations will require theoretically infinite forces for further actuation, and also may result in loss of static stability. The next design step is obvious: adjustments to the sizing of mesh facets need to be applied until the shell can fold as intended. This is, in general terms, an optimization process that attempts to eliminate kinematic errors within the useful folding range.

The optimized geometry folds without the previously encountered problems (Figure 11). Notable is the minimal impact of the optimization on the unfolded states of both shells. Interestingly, the differences between the initial and the optimized geometries are very subtle. This is one of the optimization challenges. Very minute adjustments result in significant dynamic behavior changes while folding. Consequently, the remedial changes that need to be applied are not obvious from the original shape of the shell. They can only be deduced while observing the kinematic behavior: that is, the folding of the geometry. In this case, the shell has been optimized manually through a tedious and time-consuming process of trial and error.

While designing folding structures, the geometry optimization is a key step to achieve the desired motion targets. Without efficient, automated methods, a designer must resort to a laborious, lengthy, and unpredictable process of manually tweaking the sizing of the shell's facets. This is the key question of the present paper: specifically, how can one optimize shells in an effective way. A logical step is to investigate available computational methods that could be adapted for this purpose. Algebraic formalism of controlled transformations of deformable three- dimensional (3-D) meshes is analogous to that of parallel robots (Figure 12). In a mesh, any node is simultaneously supported by three or more parent nodes acting through connecting ridges. The topology is that of an array of closed kinematic chains. If these parent nodes become the driving, controlling points of the mesh, then the motion of the driven node is a complex output that represents the intersection of all input geometries. The motion of the end node is the result of simultaneous actuation by multiple connecting ridges. A number of characteristics of parallel topologies are advantageous for kinetic structural building elements. Since any end node is simultaneously supported by multiple connecting ridges, the carried loads are effectively distributed across the structure which results in high payload-to-weight ratio. If compared to serial linkage arrangements, parallel topologies exhibit much higher inherent rigidity. Also, motion accuracy is better since joint errors are shared rather than accumulated.



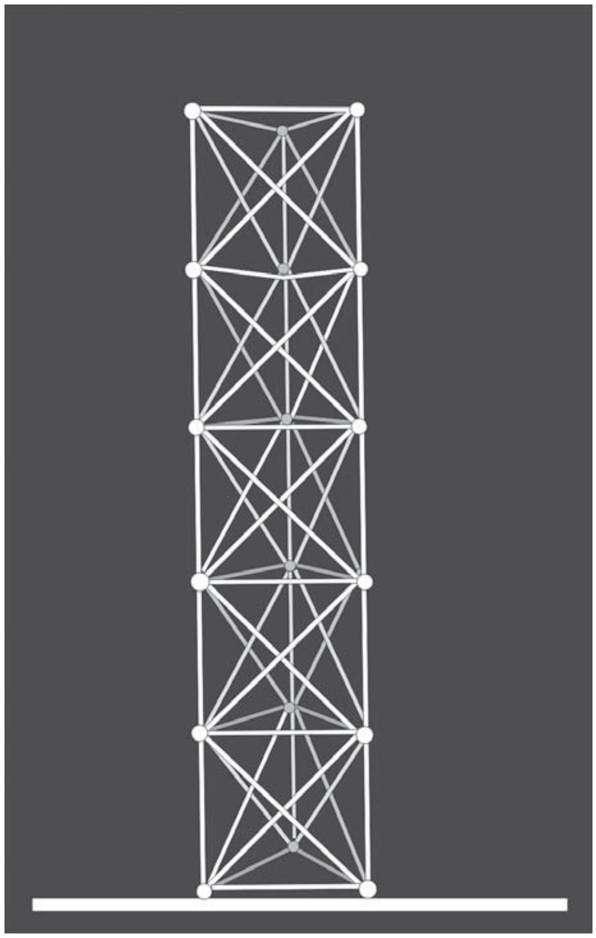


FIGURE 5 (top) Deployable ring structure, University of Cambridge
FIGURE 6 (bottom) Pantographic mast, University of Cambridge

Most of the typical disadvantages of parallel arrangements for robotic applications, like limited-motion envelope, low dexterity, and more frequent singularities are irrelevant for architectural structures. However, well-known computational difficulties related to forward kinematics solutions pose a considerable challenge (Bonev and Ryu 2000). 3-D meshes, even in simple arrangements, tend to be much more complex, from a kinematics point of view, than typical parallel robotic arrangements. The computational difficulties of modeling of parallel topologies are best exemplified by the fact that a parallel robot devised 60 years ago called a Gough Platform (Gough 1956) still does not have a formulated solution for its forward kinematics algorithm. To fulfill the expectations of 3-D foldable meshes entering the design mainstream, reliable and manageable design tools must be provided to tackle the issues of kinematics. It seems that, at present, the traditional forward kinematics formalism cannot provide such tools.

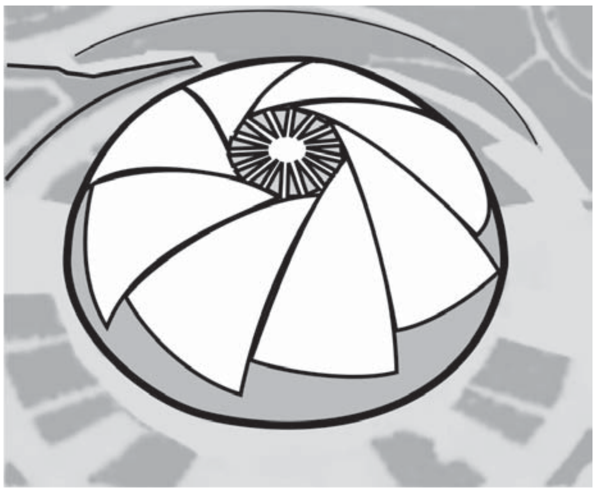


FIGURE 7 Spherical roof concept developed at University of Cambridge

APPLICATION OF FUZZY LOGIC

To expand the possibility of automating the kinetic design of architectural structures, we have explored the application of fuzzy logic. Numerous examples of architects and engineers adapting various non-formulaic and non-linear problem-solving approaches like fuzzy logic and genetic programming provide encouraging context (Karray and de Silva 2004). The applications include functional programming optimization and structural bracing optimization (Baldock and Shea 2006). Fuzzy logic has been devised to reason with human logic and to provide robust decision and control strategies while emulating a mix of intuitive and learned behaviors of an expert human operator. The strength of human approach when solving a problem lies in the ability to improvise and act while little initial information or experience is available. The main advantage of fuzzy logic is its ability to interpret, compile, and use vague and intuitive human reasoning in an automated fashion. While doing so, it handles the incomplete information, ambiguities, and contradictions that this approach encounters very well.

Human reasoning is captured as a set of *If-Then* statements that allows linguistically simple and intuitive directions to be easily compiled. An example of a fuzzy rule is: "IF the left ridge of the node that collides is longer than the right ridge THEN shorten it a little." A collection of such statements forms the so-called *Knowledge Base* of the fuzzy logic decision-making process. Another important feature of fuzzy logic is its ability to effectively negotiate a collection of such statements regardless of the fact that they are frequently ambiguous, redundant, or incomplete. This is achieved by using the hallmark logical operations that are based on the notion that besides the standard, discrete values of TRUE and FALSE there are also possible all values in between--hence the term fuzzy. In the case of shell opti-

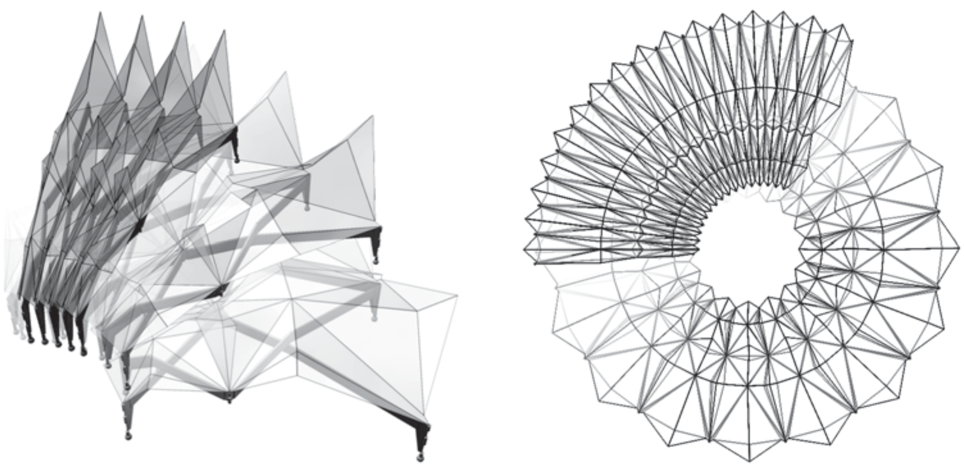


FIGURE 8 A folding structural frame with a rigidly foldable enclosing shell

mization, we have considered a set of typical steps one would perform while adjusting a real life prototype of a folding structure. Based on readily observable parameters like collisions or slopes and intuitive remedial actions like shortening or lengthening of linkages, they form the knowledge base of the algorithm.

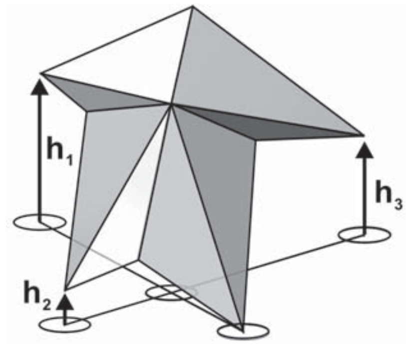
The purpose of implementing fuzzy logic for the design of kinetic structures is to avoid the prohibitively difficult forward kinematics modeling of complex parallel kinematic assemblies like the foldable 3-D meshes. Instead, designers would devise a sketchy initial geometry and use an optimization process implementing fuzzy logic-based decisions to fine-tune the linkage sizing. Such application of fuzzy logic incorporates a fuzzy inference system or FIS. The cornerstone of FIS is a set of simple, intuitive, empirically derived adjustment instructions compiled in the knowledge base.

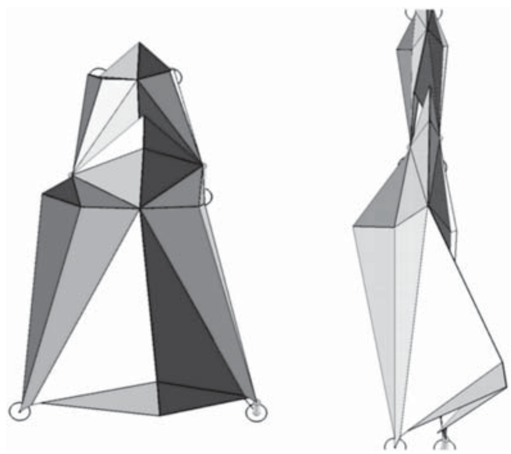
The strategy is to be able to achieve the optimization of larger geometries by iterating through localized corrective actions on geometry fragments. Consequently, the modular nature of such an algorithm facilitates scalability and application for optimization of geometries of any size.

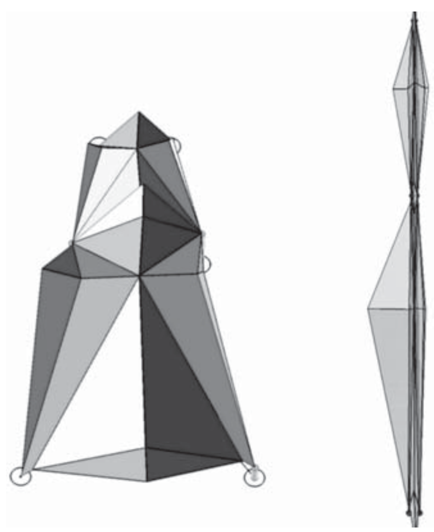
DEVELOPMENT OF FUZZY LOGIC ALGORITHM

Folding or collapsing of articulated meshes quickly reveals typical behaviors and exception conditions. Mesh facets can reach singular positions, and can collide or incline at negative slopes. Any of these occurrences will prevent the geometry from further folding. In the development of the optimization algorithm, we have taken advantage of the fact that a single parameter can be used to monitor all of the adverse conditions, particularly the slope. Therefore, the measure of the slope forms the primary test-condition to avoid folding errors. Once any of the facets reaches the critical, predefined angle while folding, the "Optimization Engine" is triggered to generate a corrective action (Figure 13). The corrective action involves adjusting the lengths of linkages that formed the undesired angle. Two contextual parameters have to be taken into consideration while adjusting the lengths. The degree of folding that has been reached at the moment of triggering the excessive slope error affects the magnitude of adjustments. Based on empirical observations, the higher the degree of folding achieved, the smaller the additional adjustments should be.

The relative height of the subject node in relation to neighboring nodes affects the ratio of shortening and lengthening of sibling linkages. The purpose is to avoid a systematic vertical drift of the subject node while performing multiple adjustments. This also helps in preserving of the initial layout intent.







From top to bottom:
FIGURE 9 A controlling structure
FIGURE 10 Folding of a complex mesh
FIGURE 11 The optimized geometry

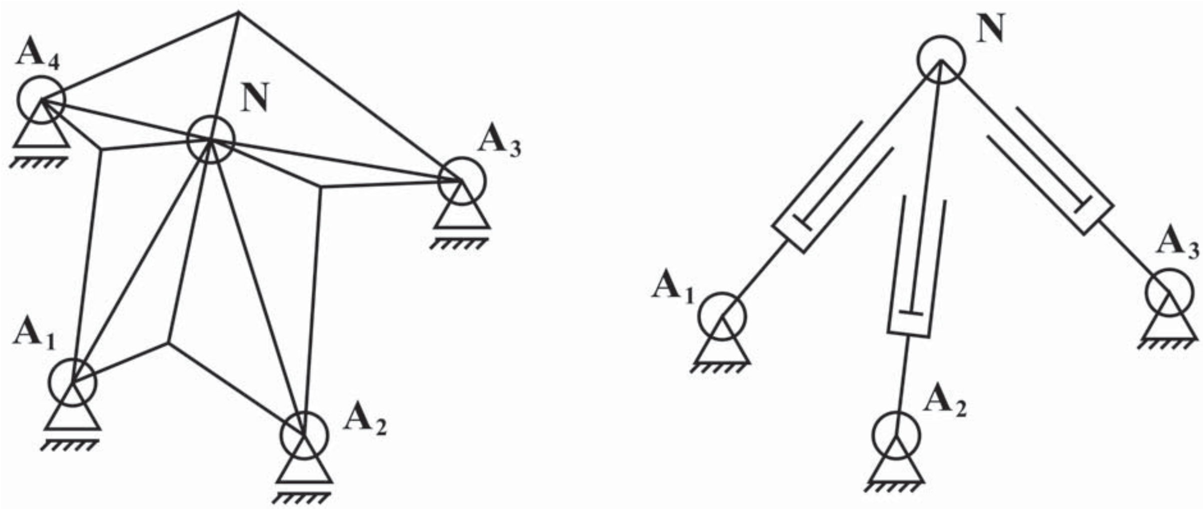


FIGURE 12 Deformable 3-D meshes

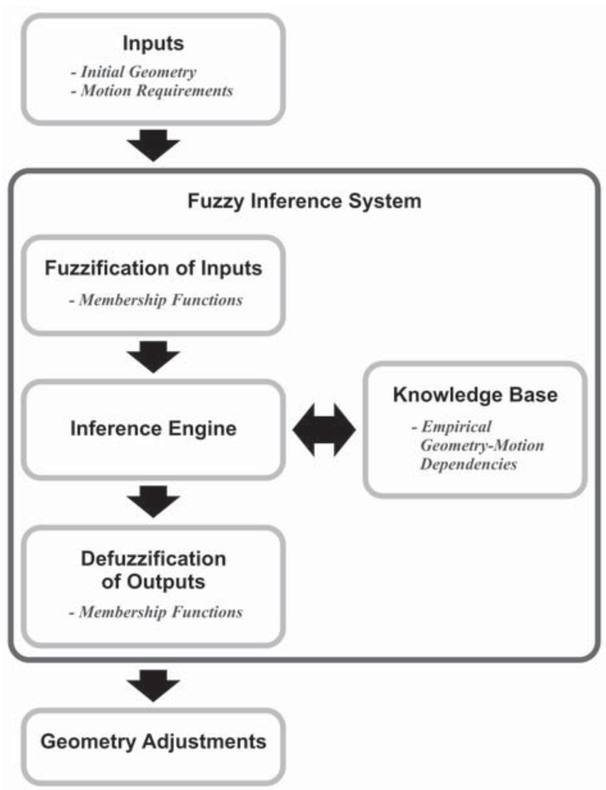


FIGURE 13 Flow-chart of the fuzzy decision making system

All of these conditions can be gauged numerically and supplied as inputs to Fuzzy Inference System where they undergo "fuzzification." Membership functions that are used for the purpose of input "fuzzification" reflect empirical, intuitive interpretations of the test conditions:

- Slope: quite steep.
- Degree of folding: barely folded, halfway folded, almost fully folded.
- Relative node position: lower, equal, and higher.

Empirical observations of articulated geometries being animated yield intuitive, synthesized conclusions that capture dependencies between the geometry and performance:

- Linkage lengths must be adjusted to increase the degree of folding.
- Length adjustments of sibling links must be coordinated to avoid excessive node drift.
- The magnitude of necessary length adjustments is highly non-linear and dependent upon the achieved degree of folding.

The Knowledge Base is used to derive detailed adjustment instructions in response to sets of concrete circumstances, as given in Figure 14.

The optimization process flow has been based on a typical design iteration where a design or adjustment action is performed and then followed by a qualifying test step (Figure 15). Depending upon the results of the test, either further verification is continued or modification steps are initiated. Hence, two distinct process-flow loops are clearly defined: verification and optimization. The Fuzzy Inference System plays a key role in the optimization loop.

1: **IF** (*Degree-of-Folding* **IS** *Unfolded*) **AND** (*Relative-Crown-Node-Height* **IS** *Lower*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Significantly*)

2: **IF** (*Degree-of-Folding* **IS** *Unfolded*) **AND** (*Relative-Crown-Node-Height* **IS** *Equal*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Significantly*) **AND** (*Shorten-Sibling-Linkage* **IS** *Significantly*)

3: **IF** (*Degree-of-Folding* **IS** *Unfolded*) **AND** (*Relative-Crown-Node-Height* **IS** *Higher*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Moderately*) **AND** (*Shorten-Sibling-Linkage* **IS** *Significantly*)

4: **IF** (*Degree-of-Folding* **IS** *Half-Way*) **AND** (*Relative-Crown-Node-Height* **IS** *Lower*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Moderately*)

5: **IF** (*Degree-of-Folding* **IS** *Half-Way*) **AND** (*Relative-Crown-Node-Height* **IS** *Equal*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Moderately*) **AND** (*Shorten-Sibling-Linkage* **IS** *Moderately*)

6: **IF** (*Degree-of-Folding* **IS** *Half-Way*) **AND** (*Relative-Crown-Node-Height* **IS** *Higher*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Minimally*) **AND** (*Shorten-Sibling-Linkage* **IS** *Moderately*)

7: **IF** (*Degree-of-Folding* **IS** *Fully-Folded*) **AND** (*Relative-Crown-Node-Height* **IS** *Lower*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Minimally*)

8: **IF** (*Degree-of-Folding* **IS** *Fully-Folded*) **AND** (*Relative-Crown-Node-Height* **IS** *Equal*)
THEN
(*Lengthen-Subject-Linkage* **IS** *Minimally*) **AND** (*Shorten-Sibling-Linkage* **IS** *Minimally*)

9: **IF** (*Degree-of-Folding* **IS** *Fully-Folded*) **AND** (*Relative-Crown-Node-Height* **IS** *Higher*)
THEN
(*Shorten-Sibling-Linkage* **IS** *Minimally*)

FIGURE 14 The knowledge base of FIS

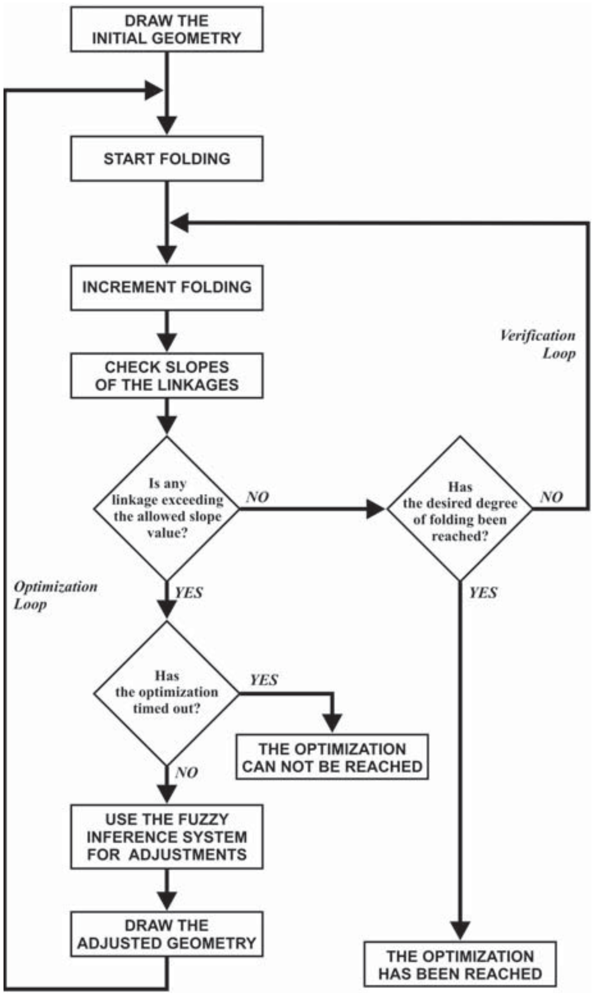


FIGURE 15 The optimization process flow

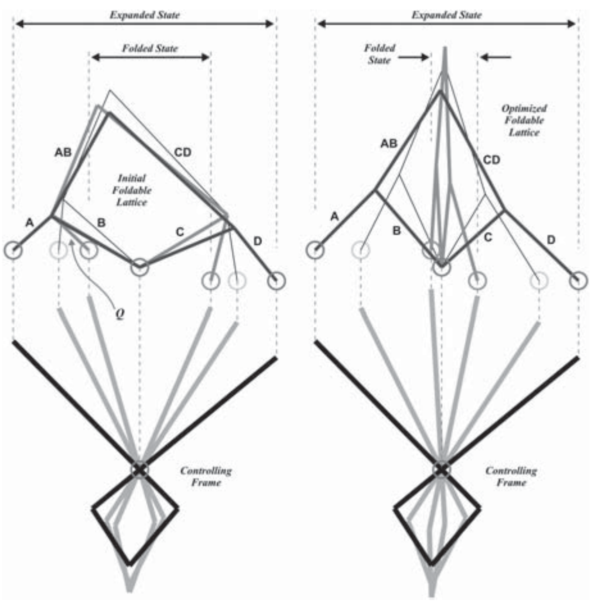


FIGURE 16 Example of a 2-D lattice

EVALUATION OF FUZZY LOGIC ALGORITHM

The most important question pertains to the efficacy of FIS based algorithm. Can it possibly replace complex mathematical modeling with intuitive tweaking based on simple modifications like 'shorten a bit here' and 'lengthen more there'? The potential benefits of effective fuzzy logic based algorithms for optimization of parallel geometries may play a significant role in overcoming the traditional computational challenges that tend to keep parallel kinematic concepts out of the design mainstream. The example presented now takes a rough, sketchy parallel geometry and implements a Fuzzy Inference System to optimize it for folding. The intended output is a geometry that fulfills the assumed kinematic performance criteria and can be used for product development.

The initial, sketchy geometry as well as the degree of the target folded state is pre-defined by the designer. The verification loop performs gradual folding of the geometry in an attempt to reach the fully folded state. If slope errors are encountered, the geometry is modified and the verifying folding is repeated from the beginning. Programmatic limiting of optimization iterations is implemented in order to avoid run-away code execution if the given geometry fails to get optimized within a preset number of steps.

However, to answer the initial question, a virtual testing experiment is set up entirely in Matlab utilizing its Fuzzy Logic Toolbox. Since the primary focus is to test the efficacy of the algorithm while optimizing assemblies based on parallel kinematic chains, it is important, from the efficiency and clarity view-points, to set up the input geometry that can illustrate all the behaviors of parallel systems while avoiding unnecessary complexity that does not qualitatively contribute to the final results. To address the issues described above, a 2-D lattice is implemented as the subject geometry (Figure 16). The 2-D lattice in topological terms is a continuous projection of a 3-D mesh onto a 2-D space (plane). As such, it preserves all the kinetic phenomena of a 3-D mesh. It can collide and reach singular states. Also, its forward kinematics representation becomes prohibitively complex as the nesting levels increase.

As illustrated in Figure 17, the main components of the optimization set-up interface are:

- The lattice plot window where the folding is shown in real time.
- The trigger condition plot window which displays, in real time, all slope values imposed over the slope membership function.
- FIS type selection and review buttons.
- Optimization progress plot and statistics.

The results indicate that the algorithm works prop-

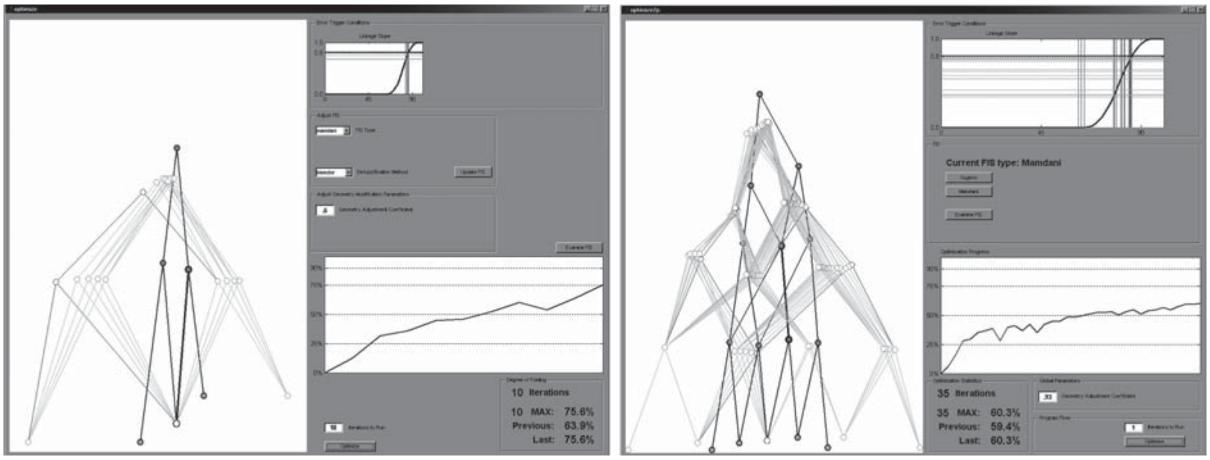


FIGURE 17 Main components of the optimization set-up interface

erly. Always, the geometry ended up folding significantly more (from initial 12% to in excess of 70%) within a reasonable amount of iterations (15 to 40). Further work will focus on performance improvements (speed and achieved degree of folding), reliability for border condition geometries and effective preservation of the initial layout intent.

CONCLUSION

As the last few decades indicate, kinetic phenomenon does not quite possess the dynamics of a revolution. Its gradual progress is evolutionary in the most literary sense. The contextual complexity surrounding kinetic architecture is evident. The development of feasible applications as well as assessment of benefits and marketability must adequately support the design effort. Safety and performance tests need to be conducted and appropriate changes to building codes need to take place. Different models of space usage and sharing may encounter social acceptance issues. Not surprisingly, it is difficult to imagine that urban landscapes would be swept overnight with kinetic extravaganza. However, pioneering effort of designers will certainly popularize the potential capabilities of kinetic structures. The unique features of foldable structures may change the traditional building maintenance and lifecycle models and offer reconfiguration as an option to demolition. In general, configurable structures will make less of an environmental impact than traditional technologies as they are better suited for re-use, modification, and relocation. Inherently modular, they facilitate the assembly of infinite variations from a limited set of prefabricated components. They may offer functional advantages over traditional solutions while constructing configurable habitable spaces in densely populated areas. In fact they may become the mainstream of tomorrow.

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