KNOWLEDGE-BASED ARCHITECTURAL DECISION MAKING OF KINETIC STRUCTURES

by

Madalina Nicoleta Wierzbicki

M. Arch. Faculty of Architecture and Urban Planning, Bucharest, Romania
B. Arch. Faculty of Architecture and Urban Planning, Bucharest, Romania

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

In

THE FACULTY OF GRADUATE STUDIES

Mechanical Engineering

The University of British Columbia

2007

Abstract

This thesis concerns kinetic engineering structures, which can be quickly resized and adjusted to conform to frequently changing needs, folded for transportation or storage and be easily deployed by means of unfolding. Unprecedented technological, economic and demographic growth is subjecting the traditional building codes and construction standards to test. The questions underlying this thesis are whether kinetic building structures could better address the demanding requirements of the modern world; importantly, could they provide better protection when exposed to extreme circumstances like natural or man-induced disasters; could they provide means of rapidly deployable, robust and adaptable sheltering for the population that has been affected by catastrophic events; and in the end, could they effectively contribute in saving more human lives?

Advances in design tools and materials engineering open up possibilities for kinetic structures, which may offer unprecedented functional performance and adaptability to changing conditions. Such structures may respond better to the demands of increasingly dense urban development, better space management and reduced environmental impact. Foremost, they may be very well suited for rapid, on-demand deployment in emergency situations. The essential feature of such structures is a kinetic component that allows the spatial geometry to be adapted according to changing needs. Kinematic chain geometries borrowed from traditional mechanics and robotics can be developed into a variety of topologies suitable for architectural structures. Modular deformable grids can provide the functionality of expanding and collapsing as well as the ability to be infinitely arrayed. The thesis investigates these aspects. The demands of the design process that is needed to develop kinetic structures will expand the traditional

architectural workflow to include the parametric modeling tools, motion analysis tools and fuzzy logic-based optimization algorithms that are common in mechanical engineering. The thesis explores these issues as well.

In particular, the thesis focuses on conceptualizing kinetic structures that employ rigidly foldable shells and frames derived from kinematic chains. It studies the application of human knowledge through fuzzy logic for the process of designing and automatically manipulating the kinematic properties of a kinematic structure. It implements the fuzzy logic formalism to develop a design optimization tool that can form the foundation for design workflows that target kinetic structures. Folding structures that provide adjustable, on-demand configurations can be effectively conceptualized if appropriate interdisciplinary expertise including engineering, architecture, and knowledge-based decision making is brought together, as highlighted in the thesis.

Table of Contents

List of Tables

List of Figures

Nomenclature

A	Angle of the segment
a_1	Angle of the controlling grid
a_2	Angle of the controlling grid
d0	Sketch parameter
d1	Sketch parameter
d2	Sketch parameter
dA	Adjustment
D_A	Pivot distance of the outer linkage
D_B	Pivot distance of the inner linkage
dN	Relative node movement
F	Degree of folding
fx	Sketch parameter expressed as a formula
g	Vector of inequality constraints
h	Vector of equality constraints
h_1	Offset height
h_2	Offset height
h_3	Offset height
$\boldsymbol{J}$	Objective of optimization
L	Total length of the segments
L_1	Span of the controlling grid
L_2	Span of the controlling grid

L_A	Length of the outer linkage
L_B	Length of the inner linkage
N	Neutral point; node; end node; vertex
$\boldsymbol{N_1}$	Relative node movement
$\boldsymbol{N_2}$	Relative node movement
O	Pivot point
P_1	Point
P_2	Point
Q	Singularity
r	Radius of the inner segment
R	Radius of the outer segment
$\mathbf{x}$	Vector of the design variables
$\mathbf{x}_{lb}$	Lower bounds of the design variables
$\mathbf{x}_{ub}$	Upper bounds of the design variables

Abbreviations

2d	Two-dimensional
3d	Three-dimensional
CAD	Computer-Aided Design
FEA	Finite Element Analysis
FIS	Fuzzy Inference System
Glulam	Laminated wood
I/O	Input/Output
MDO	Multidisciplinary Design Optimization
SOM	Smallest of Maximum

Acknowledgments

I would like to express my sincere gratitude and appreciation to my supervisor, Prof. Clarence W. de Silva for agreeing to supervise me and for his proactive attitude toward innovative ideas. His support and guidance, his fine teaching and invaluable advice were of utmost importance in bringing this thesis to completion. I thank him for taking an active interest in my research, for his patience in reading and editing my latest publications, for his consistent encouragement regarding my professional and academic goals and for providing part of the financial support (through his NSERC grant) for my research and for conference attendance.

I would also like to thank Prof. Elizabeth Croft, and Prof. Don Krug for encouraging this research from the beginning up to the present and for the valuable comments and suggestions, Prof. N. Rajapakse for accepting me in the M.A.Sc. program, Prof. Farrokh Sasani and Prof. Mu Chiao for their advice, and Prof. Lalith Gamage for his comments during my presentations.

Thanks go to all my colleagues in the Industrial Automation Laboratory of UBC, under the directorship of Prof. Clarence de Silva for making the lab a great and friendly place.

On a personal note I would like to thank my husband for his patience and support, my son for coming up with concepts that defy the restrictions of convention, and fate for my father being a mechanical engineer.

Dedication

In a memory of my parents

Chapter 1 – Introduction

This introductory chapter sets the stage for the research that is presented in the thesis. Objectives of the research are given and the rationale for these objectives is outlined. Pertinent literature is surveyed starting with a historical overview of kinetic elements and experiments in architecture. As well, a brief analysis of the potential benefits of adjustable structures is presented.

1.1 Objectives

This thesis concerns kinetic engineering structures, which can be quickly resized and adjusted to conform to frequently changing needs, folded for transportation or storage and be easily deployed by means of unfolding. In particular, the dissertation introduces novel concepts and methodologies aimed at developing feasible implementations of large-scale kinetic structures. Designed as modular and on-demand reconfigurable systems, such structures are intended to become the key element of a class of buildings, enclosures and shelters. This type of structures has not been developed yet; however, recent advances in design tools, materials and manufacturing methods, and technological know-how, particularly in the field of robotics, provide fertile ground for initiating interdisciplinary projects targeting novel concepts of folding structures as well as viable methodologies for developing a knowledge-base and assisting design-related decision making.

First, the thesis provides an overview of the concepts and significance of kinetic structures and theoretical concepts and classifications necessary for developing kinetic architectural elements. Within this context, the thesis proposes and investigates novel topologies for folding structures. The applicability and limitations of available design tools is examined to present a practical workflow scenario. The difficulties encountered in designing foldable geometry are analyzed. This thesis proposes a knowledge-based decision making solution which incorporates the knowledge the designers gain while observing the kinematic properties of folding structures. The use and application of fuzzy logic to harness such a knowledge base and make decisions using that knowledge base is demonstrated.

1.2 Scope and Motivation

Foldable structures can offer features that are beneficial in responding to the extended set of contemporary requirements of rapid-deployment buildings. These requirements call for better safety when faced with natural and man-induced disasters. They encourage meaningful environmental responsibility and material use. Cost and speed of building and operation, and the functional flexibility are important as well. Foremost, they define the relevant functional and comfort expectations of societies that are becoming more dynamic, complex, and cost conscious. Kinetic structures prefabricated as modular components can be assembled on site at lower cost and with less environmental impact than buildings constructed by traditional methods. Furthermore, the inherent ease of disassembly and reuse of modular kinetic components facilitates lifecycles based on adjustment and relocation rather than demolition and new construction, which can have adverse environmental implications in addition to other obvious disadvantages. Functionally, kinetic systems have the capability to play an important role in forming reactive environments, spaces that can intelligently, cost-effectively and rapidly respond to changing conditions such as occupancy dynamics, environmental conditions and emergencies. Undoubtedly, an added element of kinematics will introduce new challenges for designers. This thesis pursues critical thinking in this direction and proposes a novel folding topology for structures and discusses the design process. In particular, it focuses on difficulties encountered while testing the folding performance of the geometry, and develops an approach of knowledge-based decision making, through fuzzy logic, to overcome the difficulties.

1.3 Related Work

1.3.1 Historical Context

The idea of configurable, kinetic elements in architecture is as old as architecture itself. Doors, windows, blinds, gates, trap-floors, draw bridges and other simple-in-concept devices have been known for ages. They have been traditionally used to control ingress and manage light penetration and air flow. Simple sliding or pivot mechanism concepts gave way over the years to countless examples of ingenious engineering solutions and craftsmanship, as exemplified by elaborate stage and background mechanisms in opera houses that could transform the interior to dazzle audiences.

During the last forty years, architects and engineers have shown increasing interest in the application of kinetic elements in buildings as means to more effectively address the complex requirements of the rapidly developing world. Utilizing computer software, engineering science and technology, and materials advances, 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, while adding benefits of flexibility, speed of deployment, and cost effectiveness. Professor Zuk pioneered the modern philosophy of kinetic design in the late 1960's with the publication of a visionary and detailed overview of kinetic concepts (Zuk & Clark, 1970). He made an interesting remark: According to Zuk,

> *" Architecture has often been called frozen music. Others have referred to it as a permanent expression of an age-the freezing of an era; the petrification of an idea; the recording in stone of an isolated fragment of history. The purpose of this book is to describe and discuss an emerging approach to architecture which significantly rejects these typical descriptions of architecture. What is presented is not architecture of fantasy, but a prediction for the future based upon a natural evolution, a reasoned and reasonable extension of accelerated trends, and need to satisfy a dynamically changing society. What will be discussed is an architecture that is not static, as has traditionally been the case, but one that has the capability of adapting to change through kinetics." (Zuk & Clark, 1970).*

Thirty five years later, Prof. Ataman provides an interesting update:

> *Even though, most technological innovations hold the promise to transform the building industry and the architecture within, and although, there have been some limited attempts in this area recently; to date architecture has failed to utilize the vast amount of accumulated technological knowledge and innovations to significantly transform the industry. (Ataman, 2005).*

1.3.2 Modern Examples

Recent decades have seen the advent of large, retractable roofs over stadiums and stages, elaborate partition systems in conference centers, configurable floor installations in concert halls, revolving floor stages, anti-sway devices in high-rise towers and automatically adjustable columns that compensate for ground settling. Elevators and escalators allow cross-connection to areas that would otherwise be, in geometrical topology terms, isolated. However, these kinetic elements have mostly a limited, localized function of controlling egress, subdividing space and adjusting some aspects of the exterior shell. The most innovative are experiments with kinematic arrangements and novel forms and applications. Chuck Hoberman's Iris Dome is a retractable roof that opens or closes like an iris, composed of sliding and overlapping heavy-gauge metal plates supported by a circular linkage array, as shown in Figure 1.1.

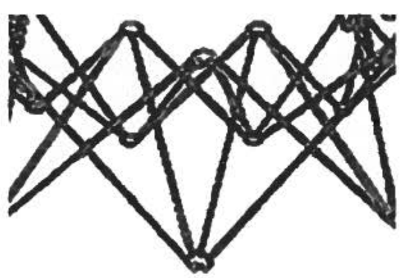

Figure 1.1. Iris Dome by Chuck Hoberman.

Renzo Piano's IBM Pavilion is an array of pivoting frames that allows partial or complete enclosure of the space, as shown in Figure 1.2. The Macro Mod tent designed by Michael Fox is based on a module composed of a scissor-like, folding frame and a bi-folding roof element. An array of these modules forms a non-continuous, vented enclosure, as shown in Figure 1.3.

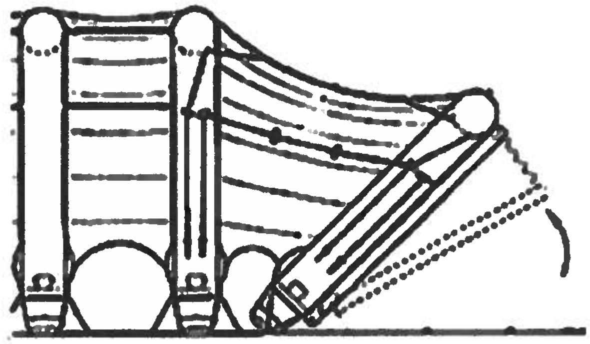

Figure 1.2. IBM Pavilion by Renzo Piano.

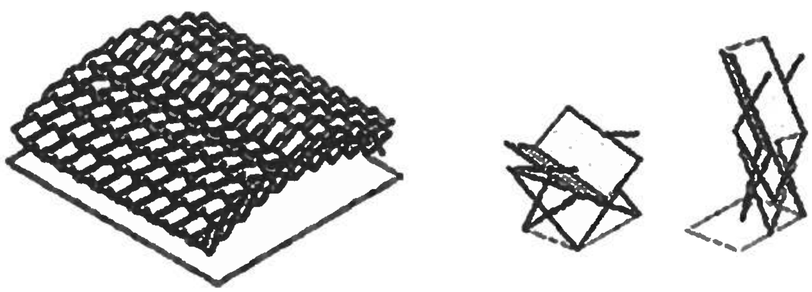

Figure 1.3. Macro Mod Tent by Michael Fox.

The concept of a deployable mast targeted at telecommunication and space applications is shown in Figure 1.4.

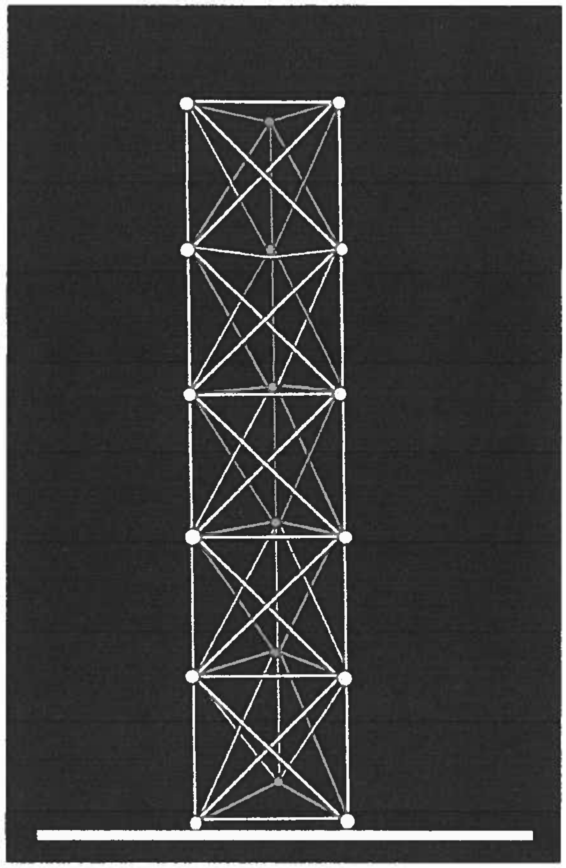

Figure 1.4. Pantographic mast, University of Cambridge.

The spherical, diaphragm-like roof shown in Figure 1.5 is one of the very few conceptual structures that can be continuously adjusted (Jensen and Pellegrino, 2002). However, besides partially open and fully closed positions, it does not offer much of a functional advantage.

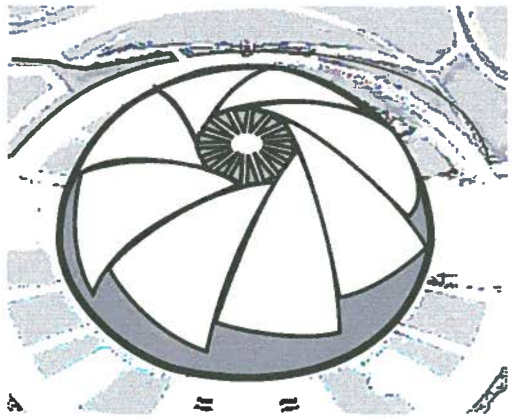

Figure 1.5. Spherical roof concept, University of Cambridge.

The conceptual nature of these ideas with little operating experience indicates that the concept of a 'foldable' building or reconfigurable-on-demand functional layout is not quite here yet. Researchers and designers continue experimenting with kinetic designs and foldable set-ups. In these prototypes, the difficulty of integrating a kinematic structure with a foldable, adjustable shell becomes apparent. Frequently, the improvised, tent-like patches of external shell do not match the grace and ingenuity of the underlying structural skeleton.

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 gravity-induced frictional forces. Ultra-light and ultra-compact structures are the dominant design criteria. Adverse atmospheric conditions such as wind loads, rain, ice, snow, dust and moisture are typically absent in these environments. The coiled mast shown in Figure 1.6 springs out of a compact spool into an extended and self-supporting position, but it can do so only in a gravity-free environment. A foldable, capton-film mounted solar array reveals its fragile, optimized-for-weight nature even under gravity-free conditions in Figure 1.7.

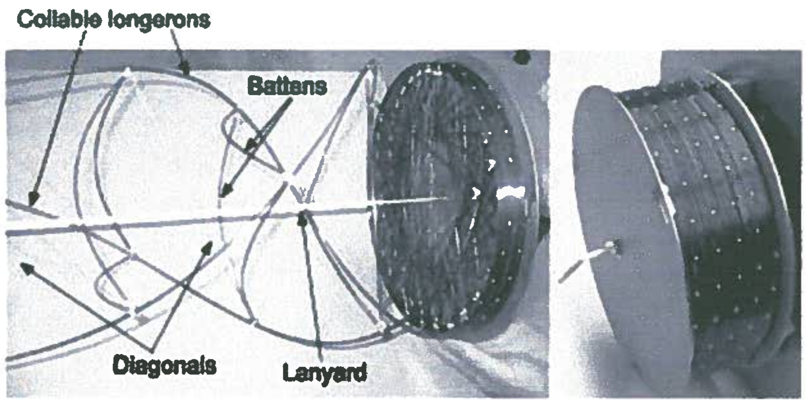

Figure 1.6. Coilable mast, NASA.

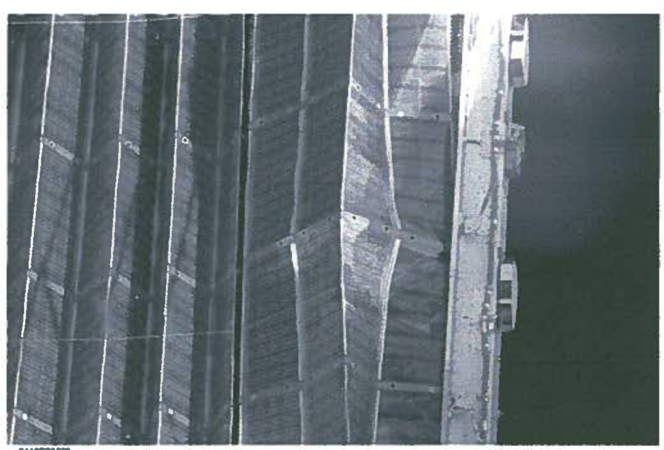

Figure 1.7. Foldable solar panel, NASA.

Figure 1.8 shows an impressive example of how much of a controlled structure can be ejected from a compact box. This ultra-light structure deploys a precise parabolic skin as an antenna; however, it is only able to do so in a weightless environment.

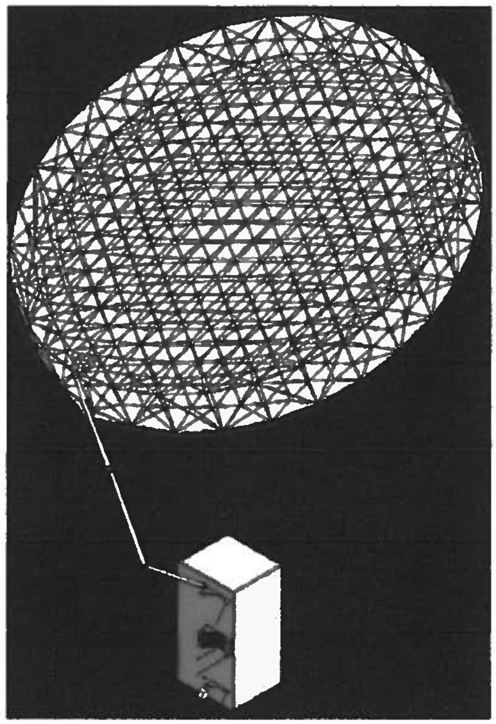

Figure 1.8. Deployable mesh reflector, Astro-Aerospace.

Figure 1.9 shows a deployable ring constructed from hexagonal and triangular linkage chains that are controlled by two adjustable-length cables.

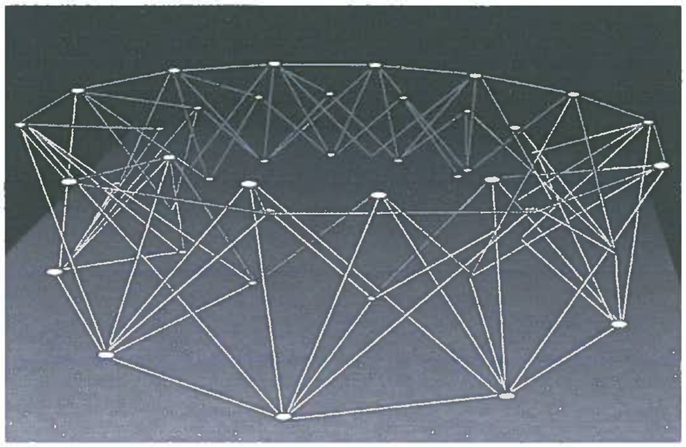

Figure 1.9. Deployable ring structure, University of Cambridge.

These examples focus on lightweight, pre-stressed structures that offer self-deployable, kinematically determinate characteristics that are valuable for space-oriented applications. Such structures are two-state devices: they are either folded into a compact, space-saving shape for transportation or fully deployed into their functional configurations. They are not designed to be adjusted or re-shaped adaptively during use. More important, the pre-stressed and overconstrained concepts shown here, which can self-deploy in a kinematically determinate fashion, have a very limited load capacity and can operate only under the gravity-free conditions of space. Structures of this kind are being developed for the purpose of installing large, controlled surfaces in space where the key requirement is a single deployment path that takes the structure predictably from folded to the fully deployed state (Pellegrino and Gan, 2006). The use of such structures in architectural, ground-based solutions is not realistic.

1.4 Future Trends and Applications

Traditional architectural methodologies hold that building forms are static, non-adaptable civil engineering infrastructures developed to support social processes. Decisions regarding function, aesthetics and lifecycles of buildings and the resulting urban grid are considered to be part of the initial planning and design process. Once buildings are erected, they form a permanent and unchangeable manifestation of these decisions. From that moment on, inhabitants and authorities have to conform their needs to such fixed civil infrastructure. The inertia with which these systems can respond to changing social demands or functional conflicts and exclusions, is obvious. Short of demolishing and rebuilding the infrastructure to fit the optimal compromise, the logistical conflicts can only be mitigated by regulatory means such us usage and access restrictions. There are many examples of urban fabric stratification into functionally unsustainable, fragmented nodes as a result of the limited effectiveness of managing an infrastructure whose original functional specifications have become obsolete yet demolition and rebuilding of the structure is infeasible. In this context, the potential benefits of structures that offer aspects of kinematics and adaptability are apparent.

Kinetic structures prefabricated as modular components can be rapidly assembled on site with reduced cost and less environmental impact than buildings constructed with traditional methods. Furthermore, the inherent ease of disassembly and re-use of modular kinetic components facilitates structural lifecycles based on adjustment and relocation rather than on demolition and all-out new construction, the latter having obvious disadvantages with regard to environmental impact, efficiency, and convenience of utilization.

Professor Kibert, the pioneer of ecologically viable construction methods, points out the importance of managing the ecological footprint of the construction industry:

> *. . . the construction sector consumes 40% of all extracted materials, produces one-third of the total landfill waste stream, and accounts for 30% of national energy consumption . . . (Kibert, Sendzimir & Bradley, 2002, p. 1).*

Kilbert also provides a systemic classification of the technical lifecycle aspects of various construction elements:

Buildings are assembled from a wide array of components that can be generally divided into five general categories:

> *1 manufactured, site-installed commodity products, systems, and components with little or no site processing (boilers, valves, electrical transformers, doors, windows, lighting, bricks);*
> *2 engineered, off-site fabricated, site assembled components (structural steel, precast concrete elements, glulam beams, engineered wood products, wood or metal trusses);*
> *3 off-site processed, site-finished products (cast-in-place concrete, asphalt, aggregates, soil);*
> *4 manufactured, site-processed products (dimensional lumber, drywall, plywood, electrical wiring, insulation, metal and plastic piping, ductwork);*
> *5 manufactured, site-installed, low mass products (paints, sealers, varnishes, glues, mastics).*
> *. . . Category 1 components, because they are manufactured as complete systems, can be more easily designed for remanufacturing, reuse, and disassembly, and thus have an excellent potential for being placed into a closed materials loop. Category 2 products also have this potential . . . (Kibert et al., 2002, p. 9-10).*

This classification indicates the potential advantages of modular kinetic components. Such components fulfill the structural tasks of those listed in Category 2 while their ecological lifecycles match the efficiency of the components listed in Category 1. The unique features of foldable structures may change traditional building deployment, maintenance and lifecycle models and offer reconfiguration as an alternative to demolition and rebuilding, particularly in urban environments with high population densities. Configurable structures, being better suited for re-use, modification and re-location, can be expected to have less environmental impact than traditional technologies. In this context, the field of kinetic structures introduces a "mechanical engineering flavor" to an area that is traditionally dominated by architects and civil engineers.

1.5 Contributions and Thesis Organization

This thesis presents original contributions in the conceptualization of new topologies for kinetic structures, analysis of design workflows, research of potential problems and application of fuzzy logic for developing automated, empirical knowledge based design tools capable of modeling the kinematic behavior of foldable geometries. An novel concept of folding structures is introduced based on integration of two innovative ideas: a rigidly folding shell modeled as a general case of an under-constrained 3d mesh, and a folding structural frame based on a pantographic kinematic linkage. The proposed solution uses the folding frame to support the shell, engage its available degrees of freedom, and control its motion.

The design challenges are identified related to achieving a desired, error-free degree of folding and linked them to the topological characteristics of foldable shells. An original analysis of the design workflow aimed at kinetic structures based on a matrix of applicable computer-assisted design (CAD) tools and a typical design processes is introduced. The analysis identifies the areas that require development of additional, customized tools.

The thesis also introduces a novel method of emulating the forward kinematics behavior of complex parallel geometries using a two-dimensional construct for the purpose of developing efficient test simulations. Finally, a novel application of fuzzy logic is developed for the purpose of constructing automated design algorithms, which make design decisions that employ the accrued knowledge-based design information.

Chapter 1 outlines and justifies, by presenting the potential benefits of adjustable structures, the objectives and contributions of the thesis against a historical overview of kinetic elements and experiments in architecture.

Chapter 2 provides an overview of the historical developments in geometry and kinematics relevant to designing kinetic structures, and explains the conceptualization process. The initial layout of controlling geometry, modularization scheme and development of a linked foldable shell are detailed. The original research on folding shapes is presented as a comprehensive classification of transformable geometries that are applicable to kinetic structures. The design stages of a novel concept of a folding structure are detailed and the kinematics illustrated. Possible applications, lifecycle specifics and potential benefits are analyzed.

Chapter 3 discusses the overall design methodology with special attention paid to efficient and productive workflows. The interdisciplinary context as the key element in projects that pursue novel solutions is detailed. The available design tools, their suitability for integrated design workflows and the areas requiring new design algorithms are reviewed. The kinematics of the developed folding structure are explained and the performance validation process is outlined.

Chapter 4 investigates the design challenges stemming from the topological characteristics of foldable shells. The history and current status of algorithmic and computational methods developed for analogous geometries in robotics are presented. The limitations of these methods for designing folding shells and achieving the desired kinematic performance are discussed; in particular, error-free folding. A novel approach toward optimizing the geometry in order to achieve the desired folding range is introduced. The optimization technique proposed here utilizes the knowledge-based methods originating from human designers. Fuzzy logic is used to develop algorithms that are capable of implementing a knowledge-based approach to decision making associated with design and deployment of a kinetic structure. The structure of the developed fuzzy logic system together with its knowledge base and the decision making module are detailed, as well as the programmatic structure of the developed algorithm.

Chapter 5 details the testing and evaluation process of the developed optimization algorithm. The strategies involved in modeling the behavior of a foldable shell and in developing the testing simulation environment are explained, and the structure and the interface of the testing program are described. Test results are presented and discussed and the behavior and performance of the algorithm are evaluated. Main contributions of the thesis and the planned future research directions are outlined in Chapter 6.

Chapter 2 – Concept Development

This chapter provides a review of the geometric concept and past developments in geometry and kinematics relevant to designing kinetic structures. It presents the associated conceptualization process. The initial layout of controlling geometry, modularization scheme and development of a linked foldable shell are detailed. The original research on folding shapes is presented as a comprehensive classification of transformable geometries that are applicable to kinetic structures. The design stages of a novel concept of a folding structure are detailed and the kinematics illustrated. Possible applications, lifecycle specifics and potential benefits are analyzed.

2.1 The Geometrical Concept

A pantograph like geometrical construct forms the basic concept for a folding structural frame. Inscribed into a rectangle or a symmetrical trapezium to enable modular arraying, it can fold into a narrow, elongated shape or expand to increase the coverage, as shown in Figure 2.1.

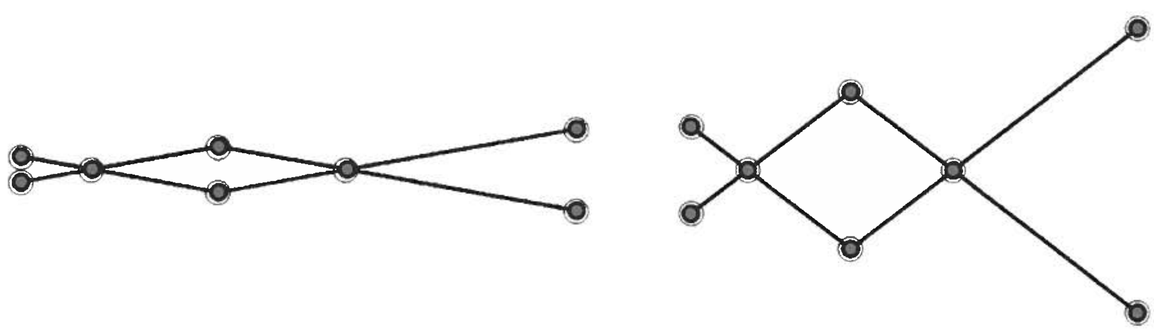

Figure 2.1. Geometrical concept.

It can therefore be adapted for kinetic structures that need to be folded for storage or transportation or need to be adjusted during use. Next section discusses the historical roots of this construct.

2.1.1 Historical Overview

German mathematician Christoph Scheiner devised the geometrical construct of pantograph in 1630 (see Figure 2.2). It is, in simple mechanical terms, a linkage of pivoting arms. It is a variation of the four bar linkage that employs the geometry of a parallelogram. Its original purpose was to help with making scaled copies of 2-dimensional shapes, patterns and drawings. Certainly, it deserves to be termed as an archetype of a reprographic device.

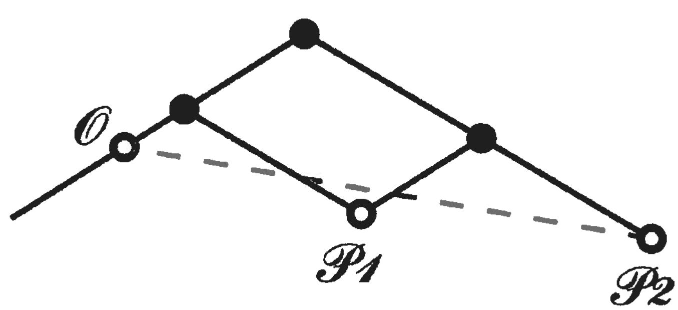

Figure 2.2. Scheiner's geometrical construct.

Such translatable, or in other words: deformable geometrical constructs, if executed as mechanical devices, form kinematic chains. The most common, practical purpose of kinematic chains is to convert one kind of motion into another. For instance, circular, or rotational motion into linear motion.

Interestingly, Scheiner's geometrical model was preceded, some 40 years earlier, by the concept of a kinematic chain that introduced elements of similar, pantograph like geometry. The mechanism, devised by da Vinci, is depicted in his Codex Madrid, as indicated in Figure 2.3. This document dates back to the 1490s. Da Vinci complemented his concept with a screw type actuator. Even by today's standards, da Vinci's Codex Madrid is a treasure chest of various, sometimes very elaborate, actuation mechanisms.

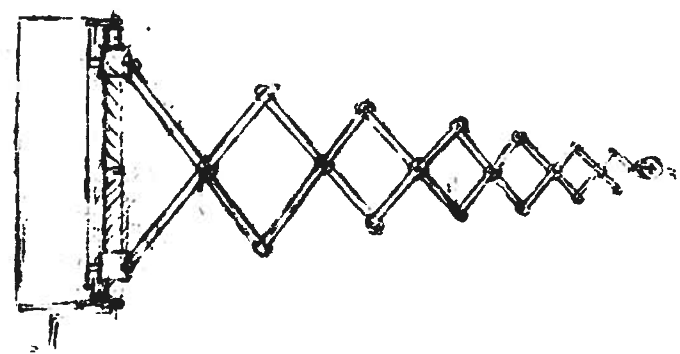

Figure 2.3. da Vinci's mechanism.

More than three centuries later, in the late 19th century, a German engineer named Franz Reuleaux formed a systemic mathematical methodology for designing kinematic devices. He used physical, functional models of mechanisms to illustrate the theoretical concepts and demonstrate the motion effects. It is fair to acknowledge this as the first use of conceptual motion simulation. His research resulted in a vast collection, some 800, of functional models of mechanisms that illustrated his ideas, as exemplified in Figure 2.4.

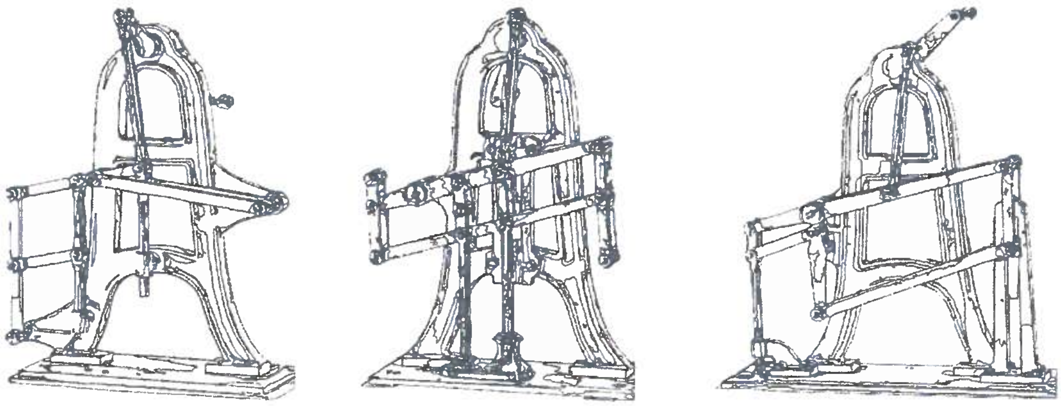

Figure 2.4. Franz Reuleaux, Models of Mechanisms.

2.1.2 Kinematic Chains

Four bar linkages are examples of the simplest closed loop kinematic chains. Despite their simplicity, they can execute complex motion patterns of great variety. Some popular four bar linkage configurations are, as shown in Figure 2.5: drag-link, crank-rocker, double-rocker and crank slider.

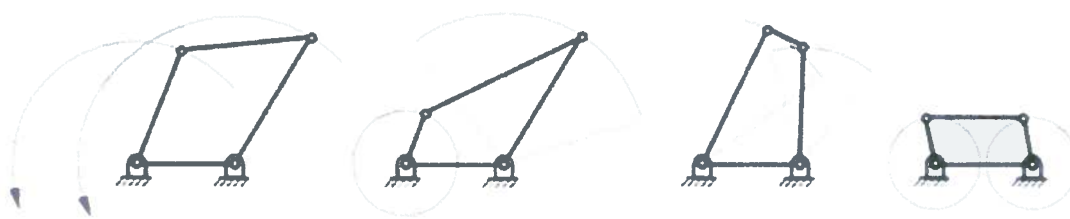

Figure 2.5. Four bar linkages

Many kinematic chain geometries borrowed from traditional mechanics may provide inspiration for developing concepts for kinetic architectural structures. One of the prerequisites is the ability to be assembled into larger, repeatable grids.

2.1.3 Rectilinear Grid Development

Rectilinear deformable grids can provide the functionality of expanding and collapsing.

A simple geometrical construct based on the original Scheiner's concept can be developed into a rectilinear kinematic chain and arrayed to create a variety of configurations, as shown in Figure 2.6.

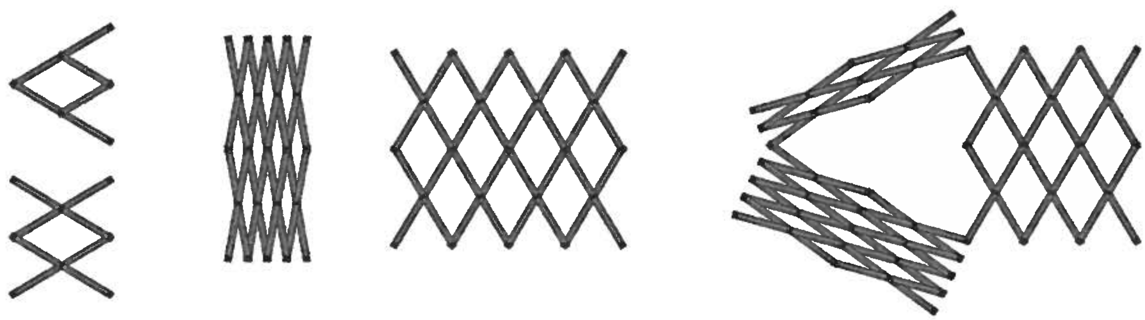

Figure 2.6. Arraying of rectilinear kinematic chains.

2.1.4 Converging Grid Development

Converging grids allow for circular arrays and fan like folding, as illustrated in Figure 2.7. However they add the challenge of retaining a coordinated angular envelope, as shown in Figure 2.8.

.

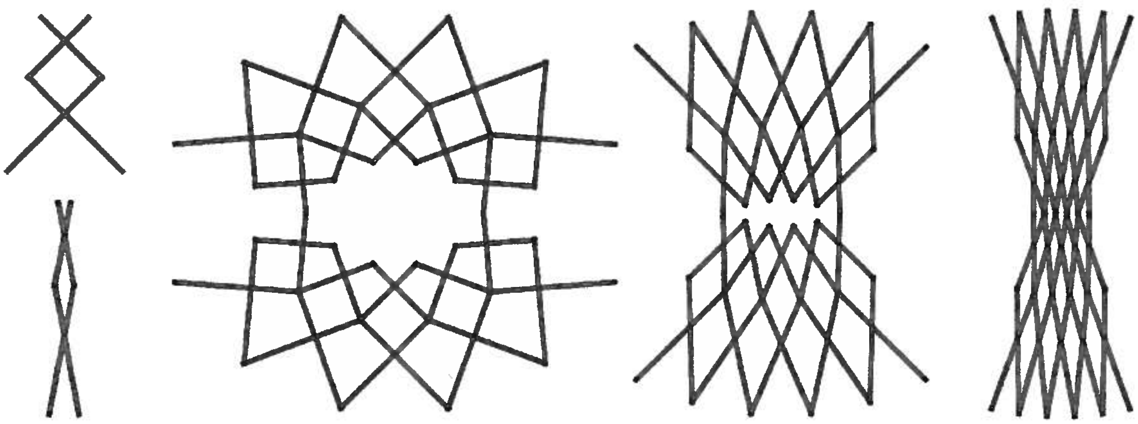

Figure 2.7. Arraying of converging kinematic chains.

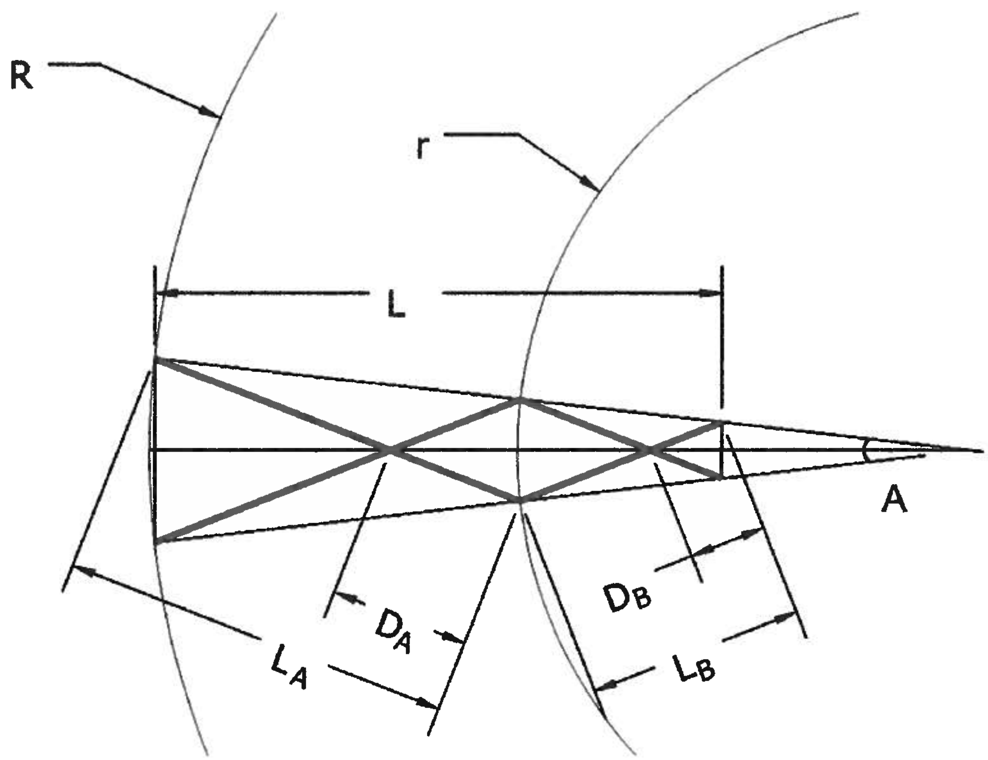

Figure 2.8. Converging iso-angular module.

2.2 Development of Kinetic Structures

2.2.1 Foldable Frames

The challenge of developing two-dimensional geometrical concepts into viable folding frames is the cornerstone of designing kinetic structures. In mechanics, kinematic chains are, most of the time, a part of much larger assembly context that provides anchors, support and constraints therefore they can be easily modeled as two-dimensional devices. Since architectural structures bear a combination of static loads of construction materials and dynamic loads induced by use, operation and elements, they need to be self-supporting and statically stable. Therefore the two-dimensional concept chains need to be transformed into a three-dimensional system of interleaved frames and off-set joints to assure load bearing capacity and static integrity. This process is more difficult for converging grids as the architectural structures do not scale as easily as simplified mechanical chains.

2.2.2 Arrays

To realize the full potential of modular flexibility, the folding frames must incorporate features that facilitate arraying into large assemblies. This requirement places additional demands on detailing of the interlocking elements and analyzing the geometry of motion within the context of a complete assembly, as shown in Figure 2.9.

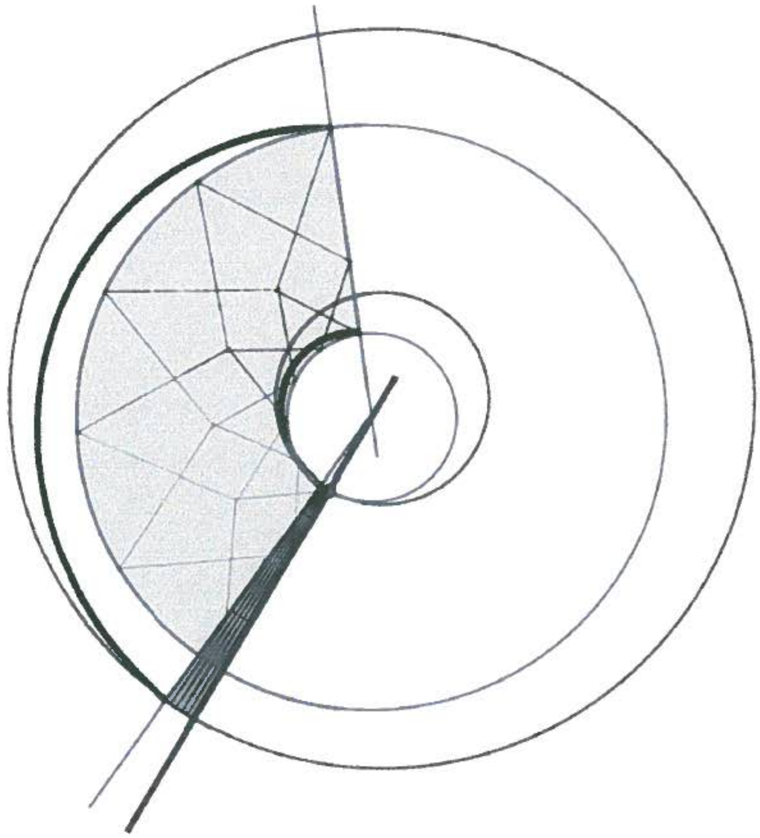

Figure 2.9. Swept trajectories of a folding structure.

2.3 Development of Shells

Kinematic chains provide a good conceptual basis for the design of articulated skeletal structures. However, a different method is needed to develop foldable shell assemblies that can complement kinetic structures and form a finished, functional architectural solution. Size and shape change can be achieved by either sliding over or folding the selected facets of the exterior. Folding is the desirable method since it results in more rigid and easier to seal assemblies.

2.3.1 The Controlling Grid

In order to be able to complement a folding frame with a folding shell, a geometrical interface between these entities needs to be established. The points of mechanical and geometrical interface form the controlling grid. Such a grid is the consequence of selection and configuration of a particular folding frame geometry. It forms the defining and parameterizing geometry for the purpose of designing a matching folding shell.

2.3.2 Rigid Folding

Commonly, transformations of folding are associated with flat sheets and play a key role in sheet metal fabrication, packaging industry and art of origami. A more generalized approach is to consider folding as the manipulation of the degrees of freedom available in an under-constrained mesh. This mesh may be, in a special case, a tessellated flat sheet. Generally, however, any 3d mesh can be subjected to folding. A flat pattern and a flat fold define the extreme states of a foldable mesh. Only a flat sheet can form the flat pattern while the state of a flat fold can be applied as well to some non-flat meshes.

Foldable structures do not reach the extremes of a flat pattern or a flat fold. Physical dimensions of components as well as assembly offsets limit the range of transformation. The purpose of the folded state for a foldable structure is to achieve a certain practical level of compactness. The deployed state forms the functional configuration that satisfies the design requirements. Geometrical constraints required to satisfy the full range of folding from the flat pattern to the flat fold are most restrictive. Since they do not apply to practical folding structures, significant freedom of possible configurations is available to the designer. The only requirement that a foldable mesh must satisfy is the condition of rigid folding, which means that mesh facets cannot be bent or twisted. Figure 2.10 illustrates various types of folding and their corresponding states.

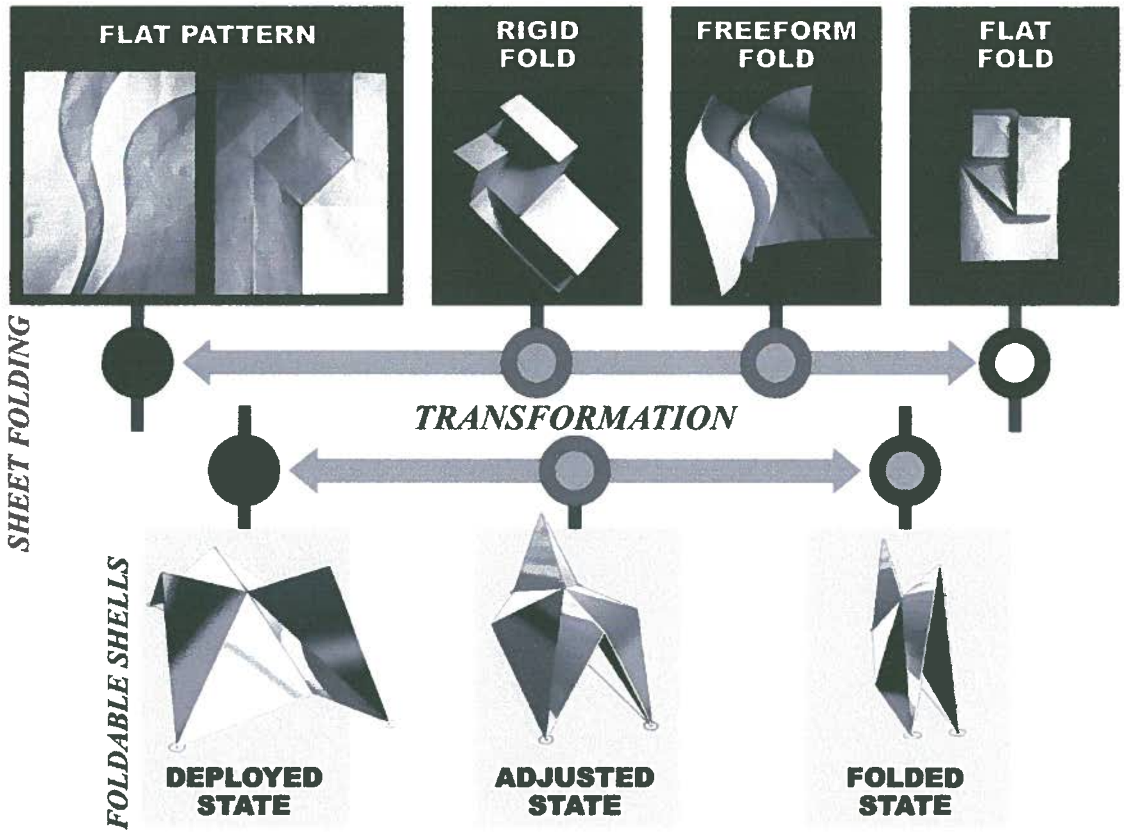

Figure 2.10. Folding of flat sheets and foldable shells.

2.3.3 Conceptualization of Rigid Foldable Shells

3d meshes provide seemingly unlimited design possibilities which may increase the difficulty of initial conceptualizing. This thesis proposes a simple method for developing the primary concepts of folding geometries. A basic geometrical configuration of the eight crease sheet fold provides a good introduction to the kinematics of folding.

Figure 2.11 illustrates the process of controlled folding of a flat sheet. A controlling grid comprised of two pairs of pivoting points is imposed over a pattern of creases. If the sheet is folded by bringing in the corners to coincide with the points of the controlling grid, the result is a three-dimensional, fully constrained and rigid shell. The shape of the shell can be varied by adjusting the parameters of the controlling grid, as shown in Figure 2.12. In a practical applications, usually only the angle '*a*' of the pivoting grid provides means of adjustment.

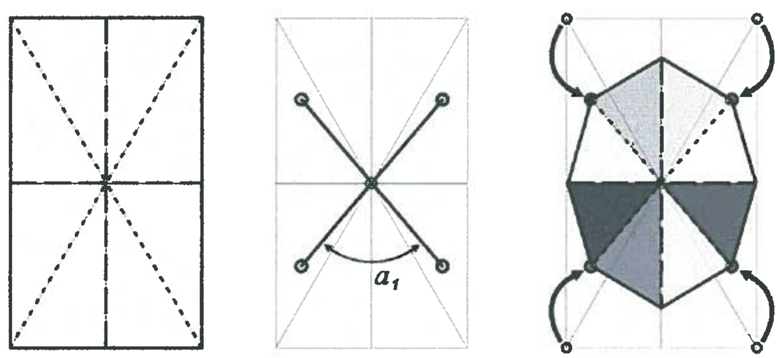

Figure 2.11. Controlled folding of a flat sheet.

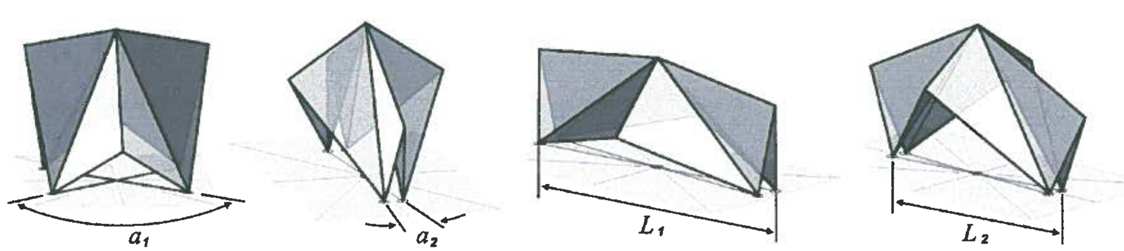

Figure 2.12. Adjustment of folding parameters.

Non-flat folding meshes can be easily developed by constructing individual facets directly over the controlling geometry, as shown in Figure 2.13. The controlling grid is transformed into a network of 3d controlling edges by means of offsetting a neutral point N off the plane of the grid to define a construction vertex. In this case, four sectors are formed. They can be independently populated with facets that follow local geometrical confines. The stretched sector requires that the sum of the vertex angles of the facets is larger than the angle between the controlling edges, in order to avoid a singularity of a fully stretched state.

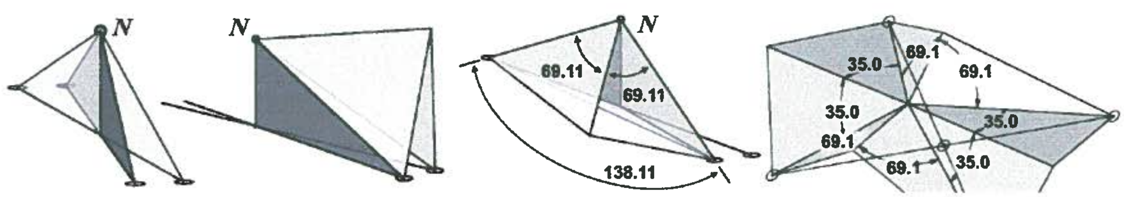

Figure 2.13. Constructing a 3d mesh.

The requirement for all the facets to form a flat pattern is irrelevant since the assumed controlling geometry as well as the practical motion range were not intended to reach either fully stretched or fully folded state. In this example, the total of the vertex angles is greater than 360 degrees and the facets form a saddle type compound surface. The pivoting angle '*a*' is the parameter that controls the folding of the finished shell. Figure 2.14 shows the range of transformation.

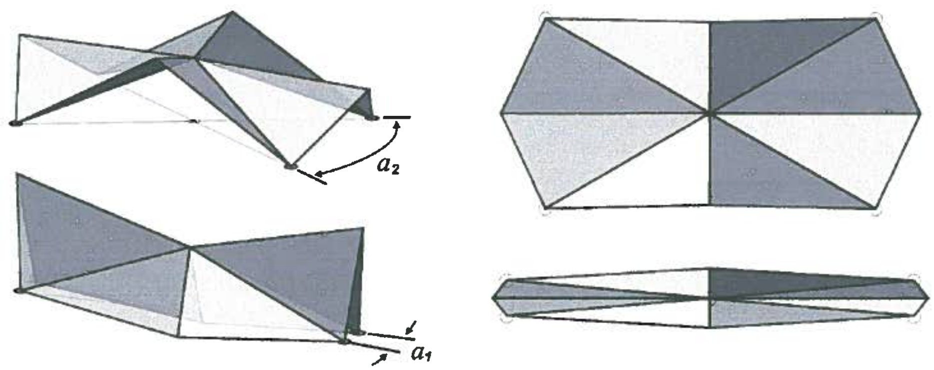

Figure 2.14. Range of transformation.

To gain more freedom in forming a foldable mesh, selected corner points of the controlling grid can be offset off the construction plane. Figure 2.15 shows the placement of offset points over a converging controlling grid. The asymmetrically lifted edges allow for shell overlapping in arrayed configurations.

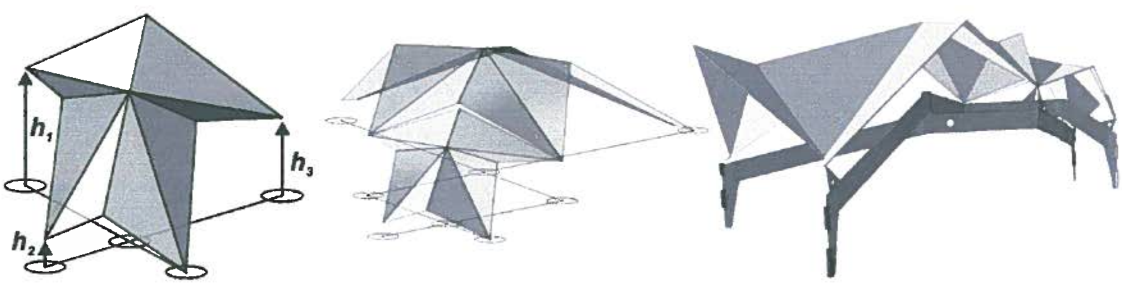

Figure 2.15. Development of a foldable module.

The design decisions made while constructing the folding mesh define its functional folding range. Figure 2.16 shows the deployed and folded states of the finished module. The compactness of the folded form can be further optimized if needed by adjusting the controlling grid and refining the mesh facets. A more compact shape may be beneficial for the ease of transportation if a mobile solution is required.

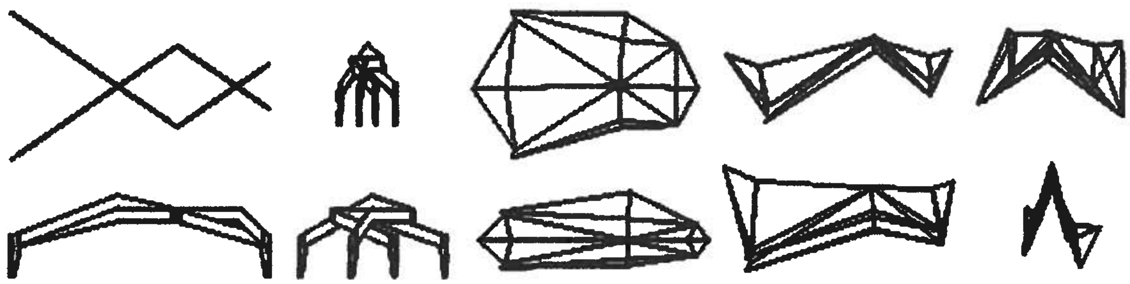

Figure 2.16. Details of a foldable module.

2.3.4 Development of Freeform Shells

This section explores the question whether more flexible design concepts that employ non-stretchable and rigid, non-fabric media can be developed for folding structures. The cumulative effect of constraints and kinematic dependencies described in the previous section restricts design flexibility. Final adjustments of the shell geometry can be tedious and usually involve many trial-and-error iterations. Most importantly, the topology of the final shape is predefined by the controlling grid, thus limiting the variety of expressive forms that can be generated.

This thesis suggests that the physics of crumpling can be considered as a logical extension of research on rigid folding and that it may be beneficial in developing freeform foldable structures. Crumpling is the logical direction for exploring deformations of sheets and meshes once all the possibilities of rigid folding are exhausted. In fact, rigid folding is a large scale and orderly application of the kinematics of crumpling. What sets crumpling apart is the build-up of stresses in a crumpled object. Freeform folding of a flat sheet along pre-defined curved paths does induce stresses as well and can be considered as a transitional process between orderly, stress-free rigid folding and stochastic, stress accumulating crumpling.

The pattern of ridges and crescents in a crumpled sheet is random and unpredictable. However, a crumpled sheet of paper (or a sheet of metal) can be still straightened out into the original rectangle. Therefore the effects of crumpling do not necessarily involve non-reversible stretching or other non-elastic effects.

Crumpling has gained a surge of attention recently in circles of physicists. The question of interest is why a physically insubstantial leaf of tissue or sheer foil, if crumpled, gains a more enduring shape that can gradually build up a sizable resistance against the deforming force. Crumpling is a result of elastic folding and buckling. The build-up of elastic deformations in a sheet is analogous to cocking a spring. It results in a pre-stressed, pre-loaded state that stores static (potential) energy. This energy resists further deformation and lends to a much more robust form of a crumpled sheet.

The ridges of a crumpled sheet act as springs whereas the ridges of rigidly folded objects perform the role of pivoting hinges. Crumpling may be considered as a generalized case of mesh folding where the conditions for explicitly defined, sharp bend lines are relaxed to allow for gradual bend radii and the line intersection point nodes are replaced with stretched crescents. In other words, the loosely abbreviated fold patterns of crumpled meshes can be expressed as geometries of higher entropy to reflect the aspect of perceivable unpredictability and disorder of patterns.

This thesis highlights the following characteristics of crumpled bodies as having a potential significance for architectural structures. The underlying fractal character of crumple patterns is advantageous for developing freeform shaped shells and pursuing expressive and dramatic architectural forms. Crumpling assures the highest rigidity for a given thickness of the material. Therefore application of crumpled geometries may result in more efficient and economic structures that also offer ecological benefits in terms of reduced embedded energy and reduced material waste. Most importantly, crumpled geometries exhibit properties that are crucial for safety. Crumpled bodies gain resistance as the deforming forces increase, which is beneficial for developing structural systems that collapse gracefully under catastrophic conditions.

This thesis lays out a practical design methodology for developing concepts based on crumpled geometries. The features that contribute toward the resilience of crumpled sheets are also quite difficult to incorporate into standardized manufacturing processes. It is virtually impossible to algorithmically model the networks of randomly distributed crescents and ridges. However, if an elementary geometrical primitive of the crumpled topology is abstracted, then such a construct can be replicated in controlled and predictable patterns as shown in Figure 2.17.

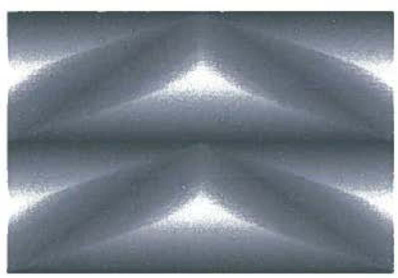

Figure 2.17. Ridge and crescent primitive coded as a height map.

Such a ridge-crescent can be tiled over larger areas and interleaved with other, large scale, folding patterns to model desired shapes. A concept application of this method is shown in Figure 2.18.

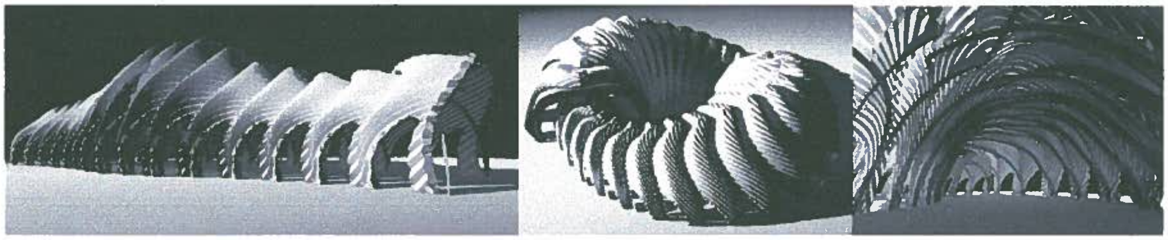

Figure 2.18. Concept structure utilizing a crumpled shell.

2.4 Functional Structure Development

The following sections will focus explicitly on rigidly foldable shells. The purpose of the discussion of crumpling in the previous section is to provide a better understanding of constraints that rigid folding imposes and explore venues for developing solutions beyond these constrains.

2.4.1 Modular Segment

The controlling grid and the derived folding frame, Figure 2.19 outline a modular segment of the foldable structure, as shown in Figure 2.20.

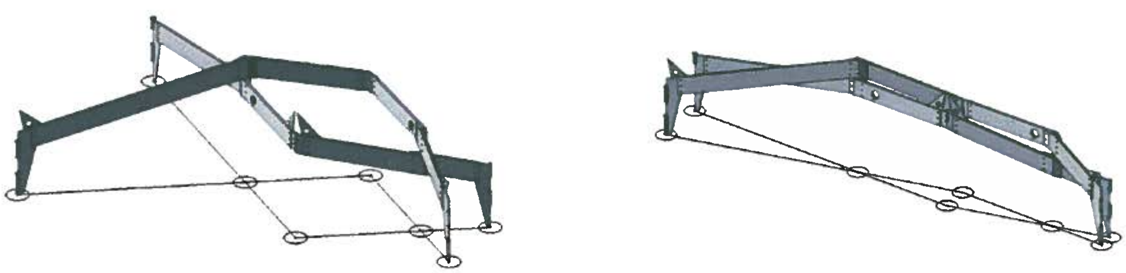

Figure 2.19. Foldable frame.

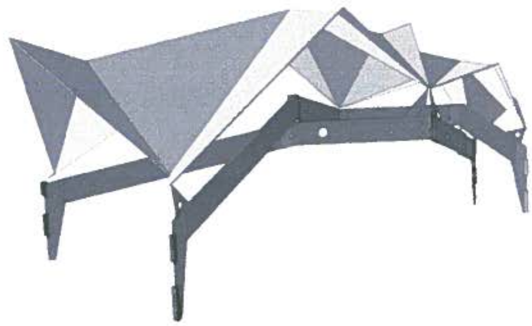

Figure 2.20. Complete modular segment.

2.4.2 Arrayed Assembly

Arrayed assemblies of typical modules (Figure 2.21) can form a variety of on-demand adjustable configurations. The next section discusses possible applications of such assemblies.

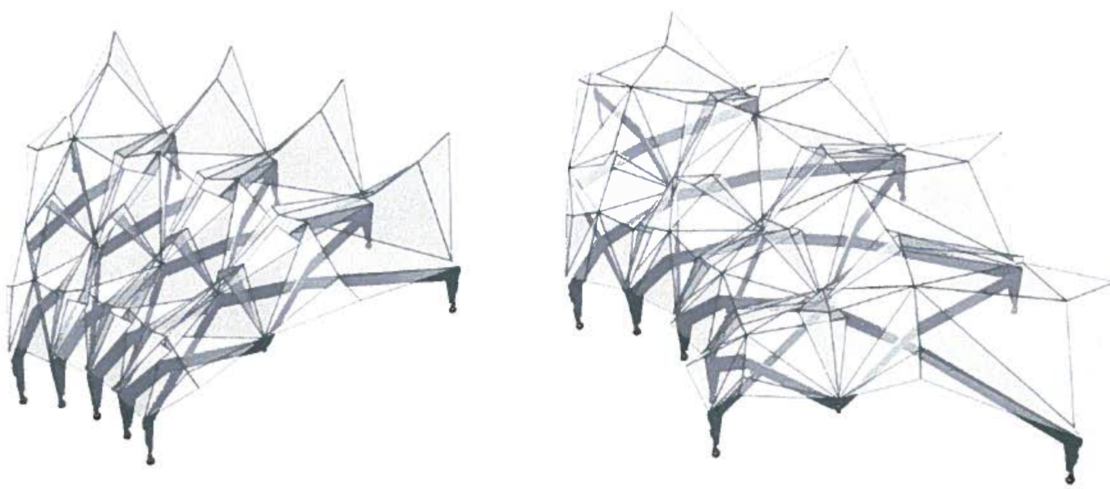

Figure 2.21. Arrayed modules.

2.5 Operation and Applications

2.5.1 Deployment

An adjustable and portable shelters, as shown in Figure 2.22, offer beneficial features for outdoor exhibitions as the space can be easily adapted to accommodate different scenarios and weather conditions. It also allows for dramatic changes in the appearance of the space.

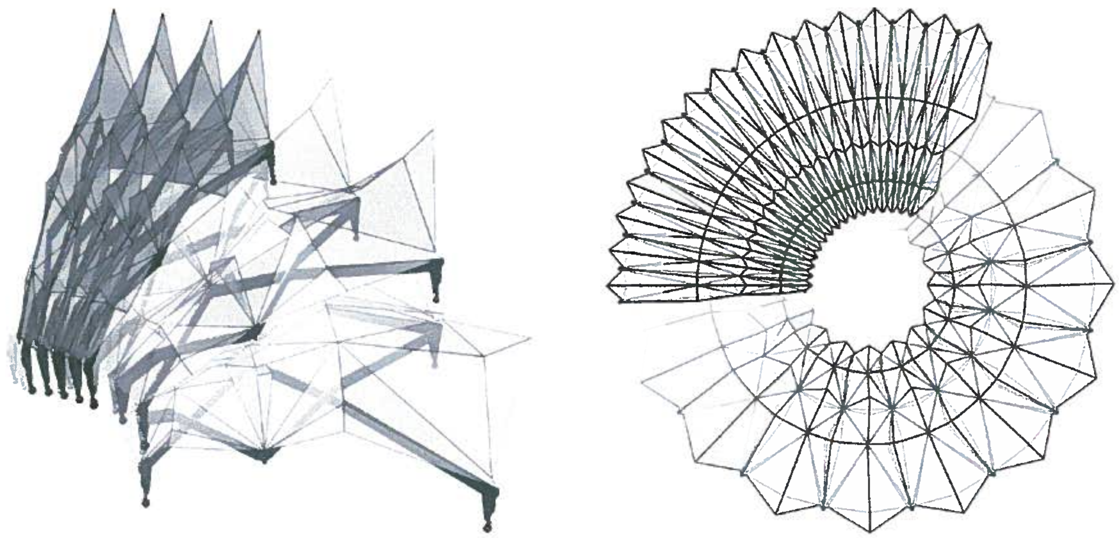

Figure 2.22. Adjustable shading system.

Figure 2.23 left, illustrates mobile shelter systems deployed in a desert This particular solution proposes integration of solar panels into the structure.

Folded shells can be used for creating adjustable and visually expressive solutions for exhibitions, as depicted on figure 2.23 right. The development of quickly deployable, mobile shelters may be useful for emergency situations and harsh climatic conditions. Figure 2.24 illustrates a foldable system that can be deployed off a dedicated, motorized platform.

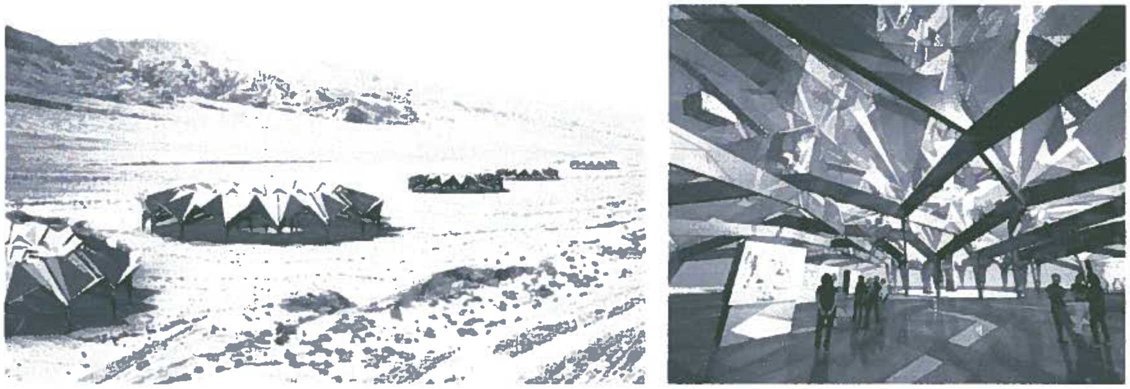

Figure 2.23. Applications: Shelters and exhibition.

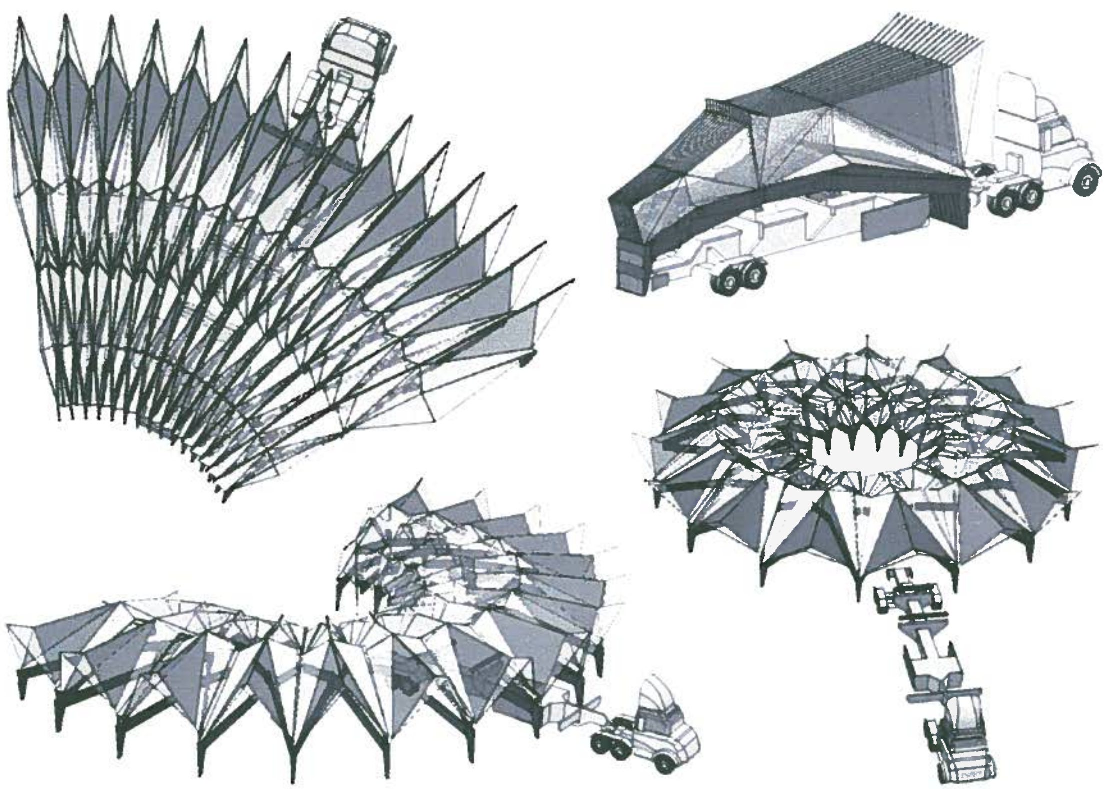

Figure 2.24. Mobile system.

Figure 2.25 shows an application of laminated wood frames for a folding structure. Figure 2.26 illustrates details of such a frame. All these are potential applications of kinetic structures.

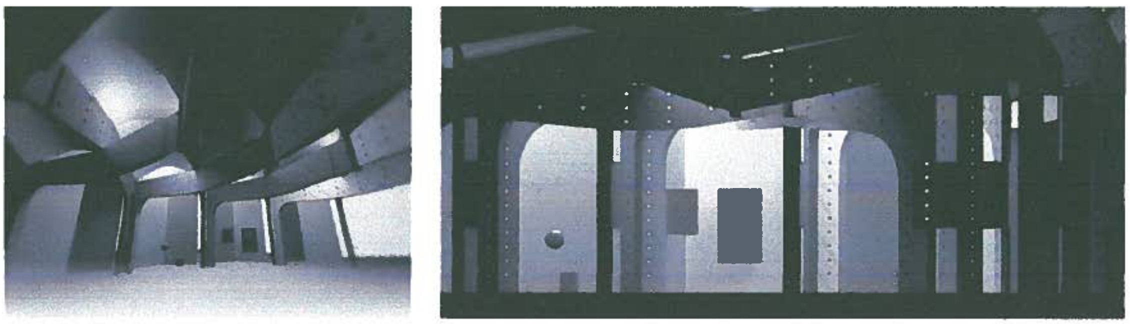

Figure 2.25. Exhibition space, glulam structure.

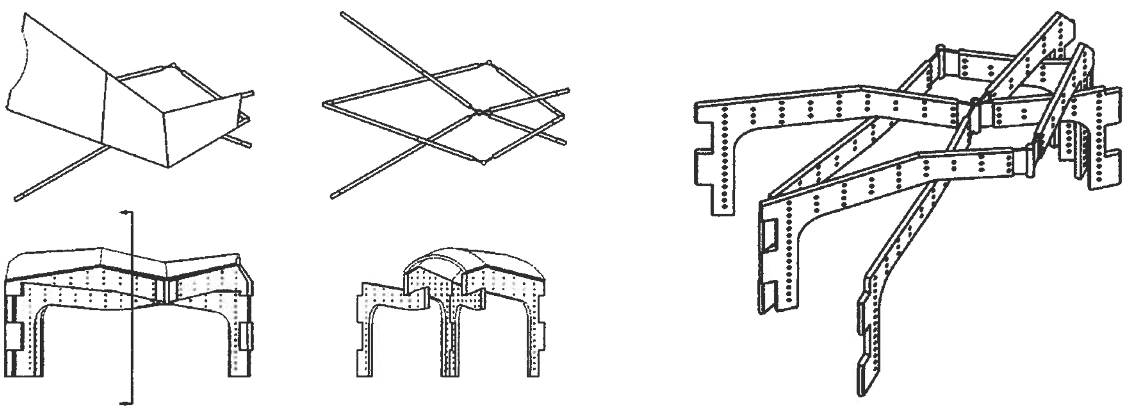

Figure 2.26. Details of glulam frame.

2.5.2 Typical Scenarios

Free standing kinetic structures can fulfill a variety of functions ranging from emergency shelters and remote exploration stations to temporary exhibitions, seasonal installations and adjustable protection systems. If integrated with existing buildings, they can increase the flexibility of space sharing between different programs, for example between commercial and residential. Kinetic structures are well suited to create adjustable and reconfigurable buffer zones to shield against elements and extreme weather conditions.

2.5.3 Typical Lifecycle and Sustainability

Foldable structures can be temporary or permanently installed according to the intended use and function. Unlike traditional buildings that are static and lasting, they are portable, adaptable and evolving. They are sustainable, and typical construction, renovation and demolition work can be complemented with assembly, adjustment, reassembly, relocation and reuse. This inherent versatility facilitates reduced ecological footprint and economic burden.

2.5.4 Overview of Advantages

This thesis postulates that further research of kinetic structures can benefit social functioning within a confined urban space. For example, connecting spaces of an atrium can be time shared between commercial and residential functions to provide a convenient way of managing complex and dynamic access patterns. Close integration of commercial and residential spaces in urban centers facilitates revival of street based retail and reduction of commute. Adjustable structures protect, on demand, street sectors to provide a regulated, comfortable climate for the inhabitants. Kinetic structures can be used in an urban context during sunny and hot weather conditions to shield people from excessive solar radiation while allowing for air circulation. Most importantly, such structures can offer better protection during emergencies. They facilitate faster evacuation and can provide on demand protection from hazards and controlled fire containment.

The many unique features of foldable structures will change the traditional building maintenance and lifecycle models and offer reconfiguration and portability as options to demolition. In general, configurable structures will provide less environmental impact than traditional technologies as they are better suited for re-using, modifications and re-location. Being inherently modular, they facilitate assembling of infinite variations from a limited set of prefabricated components.

Chapter 3 – The Design Process

This chapter discusses the overall design methodology for kinetic structures with special attention paid to efficient and productive workflows. The interdisciplinary context is detailed, which is the key element in kinetic structure projects that pursue novel solutions. The available design tools, their suitability for integrated design workflows and the areas requiring new design algorithms are reviewed. The kinematics of the developed folding structure are explained and the performance validation process is outlined.

3.1 Design Objectives

Design inputs for traditional building structures outline an initial set of functional requirements projected onto a conceptual, sketchy spatial layout. Subsequent detailed design develops construction specifications for the building to be erected. Kinetic structures add the need to consider temporal functional variations as well as resolve the kinematics of the moving elements. In particular, resolving of the motion for more complex, architecturally expressive shapes introduces considerable challenges to the design process.

Design objectives for any building encompass the development of detailed specifications for its structure. In addition, kinetic elements require specifications for a viable foldable geometry. These new design objectives focusing on the foldable geometry and how to address them are an important consideration of this thesis and will be discussed in detail.

3.2 Design Workflow

3.2.1 Available Design Tools

Mainstream CAD tools are, by now, mature and feature rich 3d design environments. Most of the packages targeted for mechanical design offer parametric control of the geometry, assembly modeling and motion analysis. Typically, a 2d sketch is the starting point for modeling a 3d geometry. Individual facets of the foldable shell are initially outlined as 2d sketches, for example as shown in Figure 3.1.

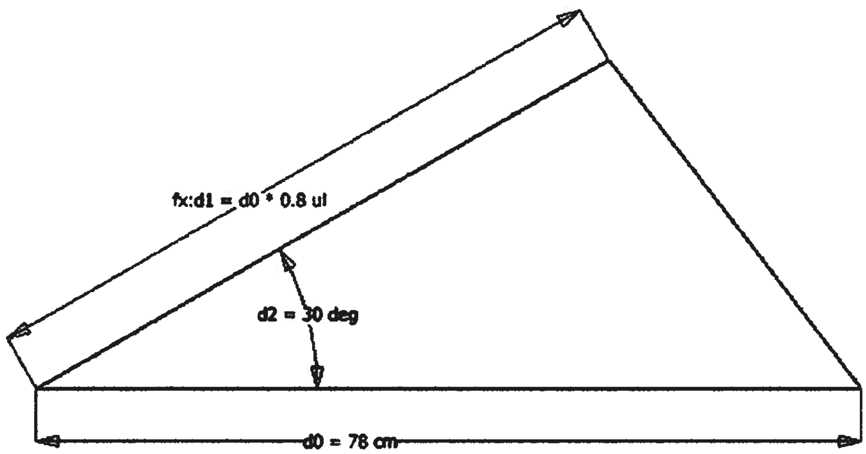

Figure 3.1. Sketch of a facet.

If needed, the parametrically driven dimensions can be used to embed formulas that express desired dimensional dependencies. In-progress adjustments can be easily applied as all dimensions remain editable. For further assembly into a foldable shell, the individual facets can be extruded or lofted into 3d shapes or retained as 2d outlines.

An initial geometrical concept for the folding geometry can be, with reasonable ease, modeled as an articulated assembly of facets and subjected to simulated motion. Starting with the controlling grid layout, individual facets of the shell are added to the assembly and bonded together using typical assembly constraining tools that allow the modeling of desired joint behaviors. This is achieved by locking together the edges of neighboring facets while retaining the rotational, hinge like degrees of freedom, as shown in Figure 3.2.

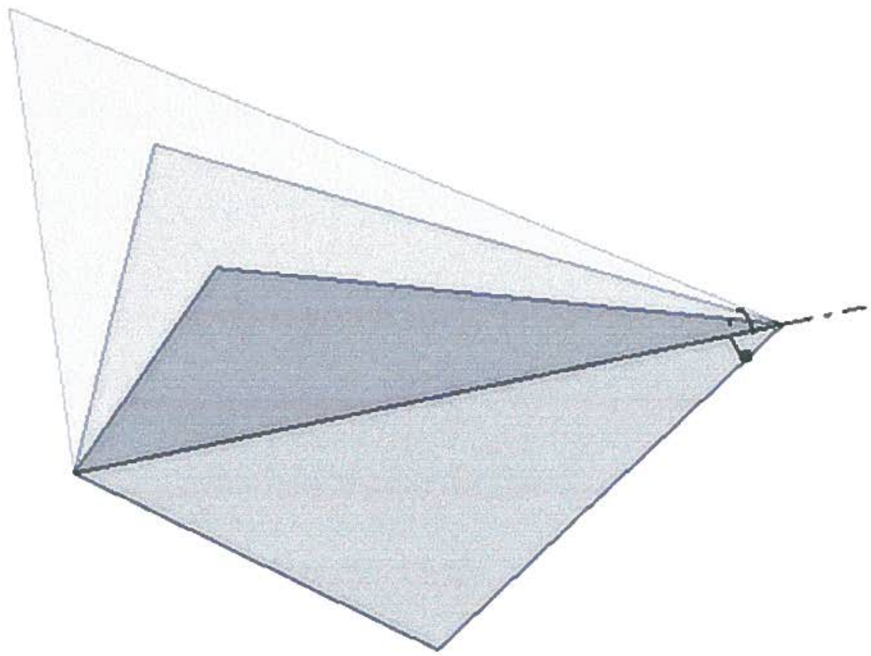

Figure 3.2. Assembly constraining.

Common within engineering CAD packages, motion analysis tools allow the animation of selected driving parameters as well as collision detection thus allowing a detailed inspection of the kinematic performance of the constructed shell. However, achieving an error free, adequate range of folding becomes challenging as the complexity of the model increases. As explained in detail later, the mostly parallel character of folding shell topologies is difficult to express algebraically. Therefore, the parametric capabilities of CAD cannot be readily utilized for the development of algorithmic tools that facilitate performance-targeted, intentional shell adjustments.

3.2.2 Interdisciplinary Approach

Various specialized disciplines of science, engineering, architecture and manufacturing, though they often share common roots in the underlying theoretical formalism, have developed their own methodologies, problem solving methods and software tools that are tailored to their specific needs. Such specialized, disciplinary methodologies are efficient and reliable when applied to problems that are defined within the boundaries of a given discipline or domain. For example, architectural CAD tools emulate the operations of conventional design and construction documentation development. They efficiently handle designing and detailing of static structures in compliance with the applicable drafting and building standards.

Introduction of new technologies and solutions, however, may often exceed the capabilities of the established workflows and tools that are available within them. In case of folding (kinetic) structures, though the final design deliverables are to be co-developed and integrated with conventional building structures, the kinematic requirements cannot be readily resolved with traditional building design tools. Interdisciplinary exchange is instrumental for developing novel concepts that exceed the boundaries of traditional disciplines. The incorporation of kinetic structures in buildings introduces into the architectural domain expertise from mechanics and mechanical engineering, thereby significantly expanding the traditional involvement of science and engineering in architectural projects, as expressed in Figure 3.3.

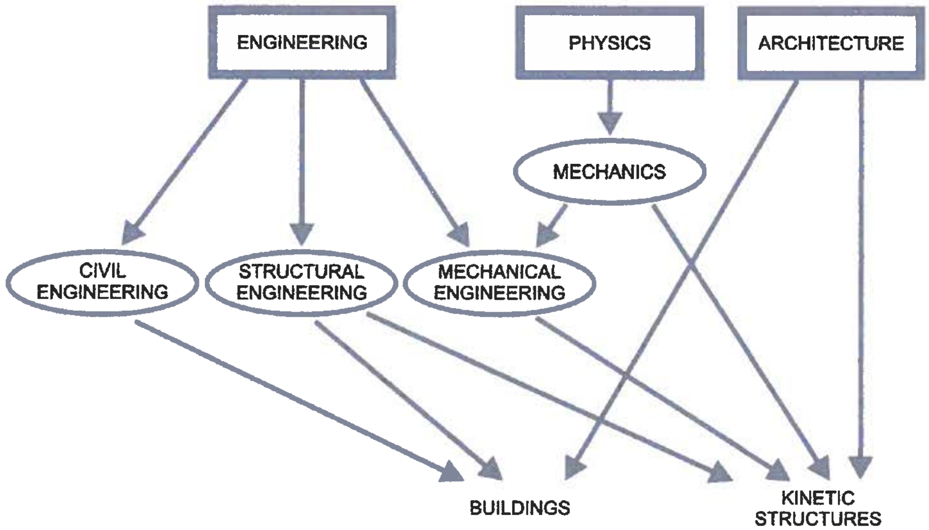

Figure 3.3. Interdisciplinary requirements for kinetic structures.

Technological advances in the area of information exchange, processing and management afford faster research and development cycles through efficient access to vast knowledge resources and ease of global communication. However, the very same technological tools do not necessarily assure simultaneous effective interdisciplinary exchange because of the particular focusing and at the same time often isolating the characters that the well-established disciplinary processes tend to exhibit. Therefore it is prudent to augment novel and exploratory research scopes with a clear matrix of anticipated interdisciplinary dependencies. Such a matrix will evolve together with the knowledge gained through the project development process as necessities emerge in regards to new design tools, computational methods and standards.

Initial design development of a foldable shell has highlighted the quite apparent applicability of mechanics and especially kinematics in the mechanical engineering domain for providing geometrical concepts and modeling methods. Detailed motion simulations that followed have revealed a necessity for a tedious geometry adjustment process to achieve a desired, error free degree of motion. The search for an effective adjustment method has proven to be a challenging one as the topology of folding shells could not be easily expressed in terms of forward kinematics equations as explained in Section 4.1. Involving yet another expertise, the methodology of fuzzy logic has allowed to build an algorithm based on intuitive, manually performed adjustments as described in Section 4.3. Interestingly, fuzzy logic as well as many other domains of science and engineering have started out as interdisciplinary initiatives, as indicated in Figure 3.4.

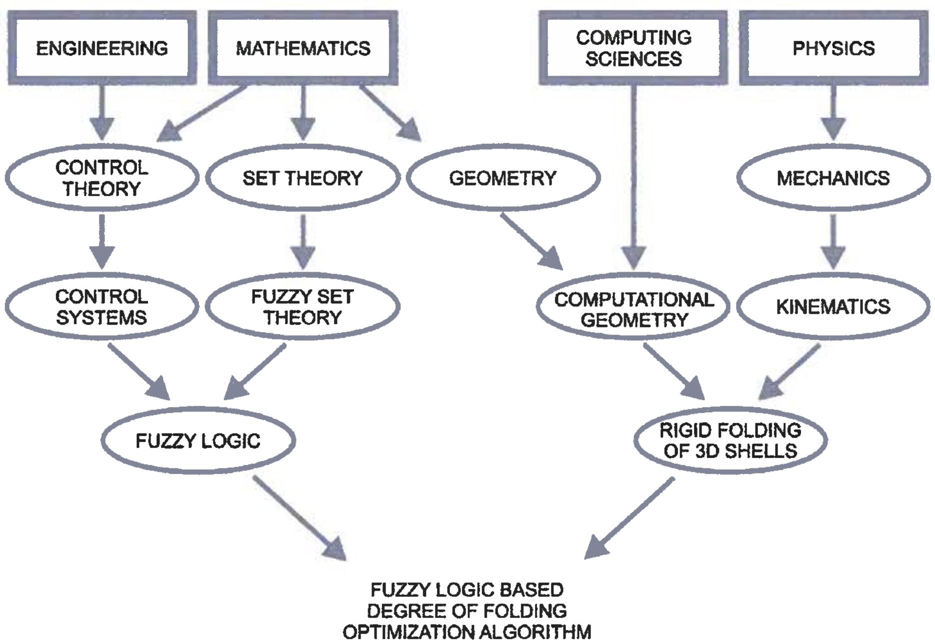

Figure 3.4. Fuzzy logic and the interdisciplinary context.

Overall, the present study illustrates a number of benefits of interdisciplinary expertise sharing. Methods and concepts from mechanical engineering including mechanics have been introduced into an architectural project for the purpose of developing novel structures. Furthermore, fuzzy logic has been incorporated to develop effective design utilities for such structures, through the use of human-originated knowledge and knowledge-based decision making.

3.2.3 Integrated Design Environment

The scope of the traditional architectural workflow is already undergoing expansion as motion and actuation elements migrate gradually into the building structure designs. The design of kinetic architectural structures will expose architects to the unique demands of modeling of the translation geometry and simulation of the motion range. The design tools that perform similar tasks are widely available in mechanical engineering. In particular, parametric assembly environments offer the ease and flexibility of both forward and inverse kinematics to build initial models of complex kinetic designs. The increasing importance of the detailing of material efficient assemblies that can reliably handle the structural and usage/operational loads will benefit from stress analysis tools that are often integrated with CAD packages. Furthermore, specific design challenges like kinematic performance can be addressed with engineering computing tools. Figure 3.5 illustrates a matrix of disciplines that have been involved in the process of development of the concept of the kinetic structure presented in this thesis and typical software tools available within these disciplines.

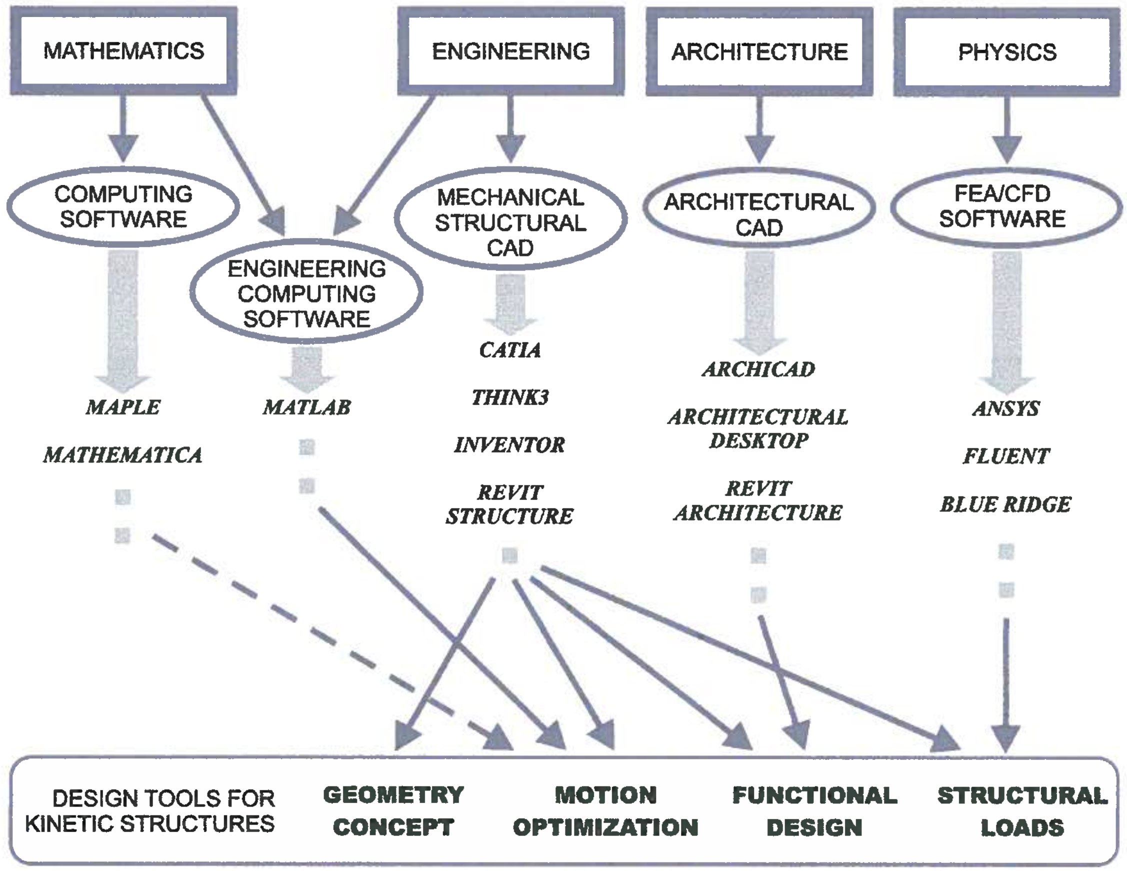

Figure 3.5. Matrix of disciplines and tools.

Figure 3.6 illustrates the logical phases of the kinetic structure design development and the benefits of the integrated parametric CAD environments that are readily available today. The key CAD feature that helps with handling the complexities of foldable structures is the flexibility of switching between bottom-up and top-down methods while developing the design. The assumed initial concept of the controlling grid and the folding frame can easily be put together while starting with components, progressing to the assembly level and employing then algorithmic capacity of forward kinematics modeling. This is a straightforward bottom-up design strategy. The development of a foldable mesh requires a different approach. The kinetic complexity of three-dimensional meshes makes algorithmic descriptions tedious to define. However, a loosely improvised set of facets that follows locally applicable geometric restrictions can be easily appended into an already defined controlling grid and quickly verified by means of inverse kinematics.

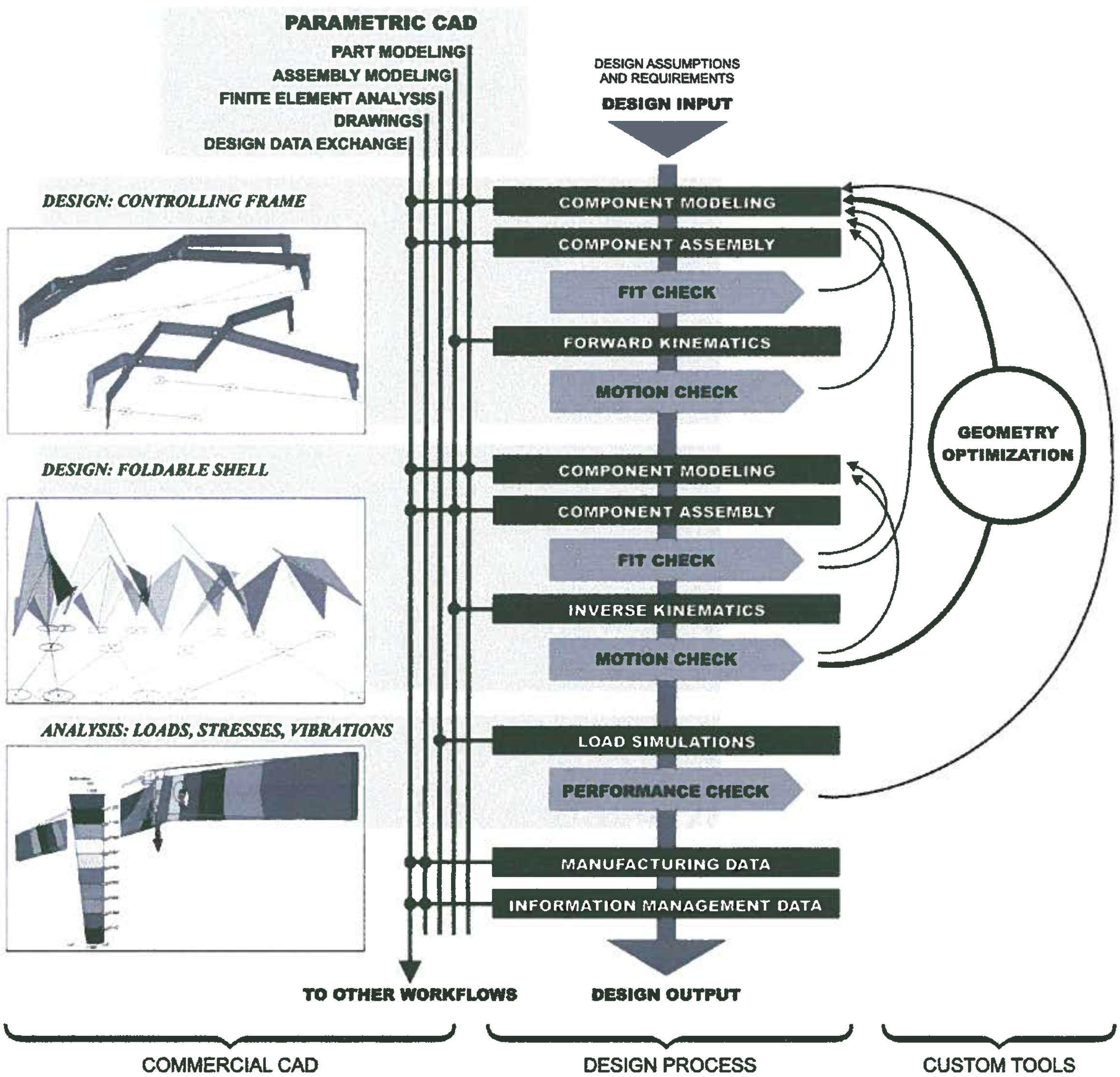

Figure 3.6. Design workflow.

The initial draft can be further refined through a sequence of design iterations. The efficiency of this process relies on the seamless integration of a solid parametric modeler with a parametric assembly modeler. Once the components can be modified directly within the environment of kinematic simulation, the development process focuses on optimization of the form without the overhead of switching between different design environments. Overall, the concept undergoes a series of design iterations as it progresses through development stages. An effectively integrated design environment streamlines the process of adjustments by retaining the overall initial geometry and providing the means to modify it as needed.

As most of parametric modelers have the finite element analysis capacity fully integrated with them, the verification of the tweaked in configuration in terms of safety and load performance can be performed within the same design environment. The design data can be shared with various development workflows, architectural development for instance, in a variety of commonly supported 2-d and 3-d formats.

3.3 Management of Kinematic and Functional Dependencies

3.3.1 Operational Parameters

The most obvious characteristics of a folding structure are the difference between the fully unfolded and fully collapsed states. The range of folding as an operational parameter reflects important functional requirements as it determines how much the structure can be compacted for transportation or storage, how much it can be adjusted in response to ambient weather conditions and the level of usage or what maximum coverage it can provide. In the next section, kinematic aspects which affect the folding range are discussed. Challenges related to achieving the sufficient folding range as well as proposed automated tools to automate this important design step are addressed in Chapter 4.

3.4 Conceptualization of Shells

3.4.1 Kinematics of Rigid Folding

In a foldable shell, the topology of an isolated node and the surrounding facets is that of an array of closed spherical kinematic chains. At the same time, any node is simultaneously supported by three or more parent nodes acting through the connecting ridges. This results in complex, compound kinematics that merges characteristics of a closed spherical linkage chain with characteristics of an actuated parallel geometry which is explained in more detail in the next section.

If the parent nodes become the driving, controlling points of the shell, then the motion of the driven node is a complex output that represents the intersection of all partial input geometries. The motion of the end node is the result of simultaneous actuation by multiple connecting ridges.

3.4.2 Foldable Shells

Computational challenges encountered in designing industrial robots provide good context for understanding the folding of shells. Two basic geometrical topologies of robots, serial and parallel, are illustrated in Figure 3.7. In the serial configuration, linkages form an open chain where only a single linkage attaches to the end node (N). In the parallel configuration, multiple linkages attach simultaneously to the end node (N).

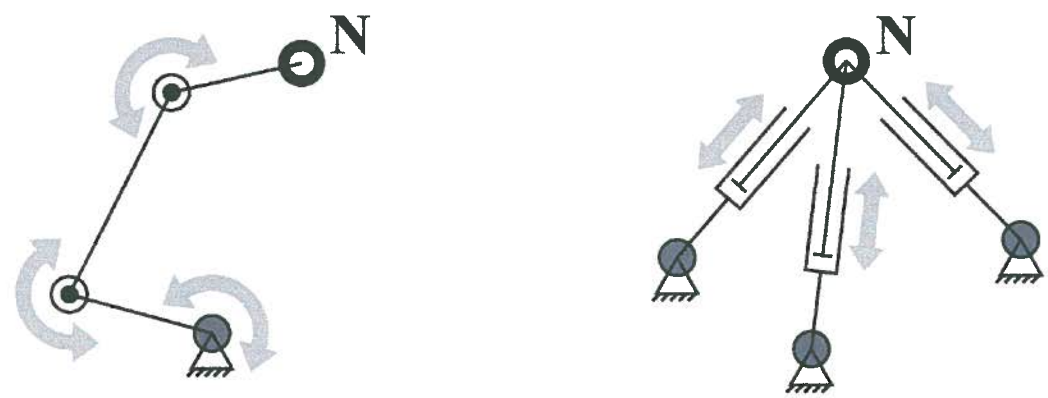

Figure 3.7. Kinematic representation of a serial robot (left) and a parallel robot (right).

The topology of a foldable shell is analogous to that of a parallel robot, as shown in Figure 3.8, since multiple supporting ridges attach simultaneously to the supported vertex (N). Such parallel geometries are difficult to calculate in terms of forward kinematics. If all the positions of the controlled ends of the ridges are given, expressing the position of the supported vertex (N) as a set of formulas can be challenging even for relatively simple geometries.

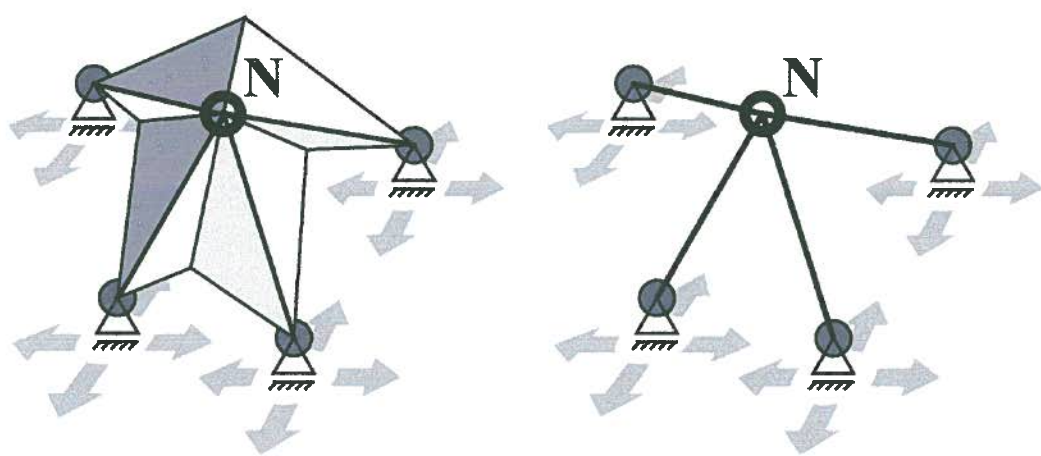

Figure 3.8. Kinematic representation of a foldable shell (left). Parallel topology of the ridges (right).

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. When compared to serial linkage arrangements, parallel topologies exhibit much greater inherent rigidity. Also, motion accuracy is better since joint errors are shared rather than accumulated.

3.5 Simulation and Testing of Shell Folding

What separates folding structures from traditional building elements is an added element of motion. The conceived geometry of the folding frame and linked folding shell needs to be verified in terms of kinematic performance. The goal is to achieve a range of folding that is free of interference and singularities and satisfies assumed functional requirements like, for instance, the maximum size after folding. Since the folding frame is a straightforward pivoting mechanism, the importance of simulations relates to the kinematics of the foldable shell.

Kinematics of the concept can be fairly easily simulated in any 3d modeling environment that provides tools of assembly constraining and motion parameterization. By using a collision detection function, an error free range of available motion can be tested. Usually, the initially conceived geometry will have a rather limited range of error free folding. In order to increase the range of motion, adjustments to the facets of the shell are needed. The next chapter focuses on encountered challenges and the methods conceived in this thesis for performing such adjustments.

Chapter 4 – Knowledge-Based Design Optimization

This chapter investigates the design challenges stemming from the topological and kinematic characteristics of foldable shells. The history and the current status of algorithmic and computational methods developed for analogous geometries in robotics are presented. The limitations of these methods for designing folding kinetic shells and achieving the desired kinematic performance are discussed, particularly in relation to error-free folding. A novel approach toward optimizing the geometry in order to achieve the desired folding range is introduced. The optimization technique proposed here utilizes the knowledge-based methods originating from human designers. Fuzzy logic is used to develop algorithms that are capable of implementing a knowledge-based approach to decision making associated with design, deployment, and operation of a kinetic structure. The structure of the developed fuzzy logic system together with its knowledge base and the decision making module (fuzzy inference system or FIS) are detailed, as well as the programmatic structure of the developed algorithm.

4.1 Optimization Challenges

The initial step of developing a folding shell is to outline the intended form with mesh facets constrained to the controlling frame. Typically, the intended form defines the unfolded state of the structure which represents the target functional, layout and aesthetic requirements to be fulfilled.

The next step determines the adjustability range of the folding shell. Adjustability is one of the defining design criteria that set it apart from traditional building structures. It is also a parameter that needs to be validated early in the development stages as it drives a number of design detailing dependencies such as element sizing, folded state envelope, actuation and articulation. This validation focuses exclusively on the kinematic characteristics of the initial construct.

The topology of shell ridges is analogous to that of parallel robots. 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, algorithmic difficulties related to calculating forward kinematics solutions pose a considerable challenge. For example, an industrially successful implementation of a parallel robot known as Gough platform, as shown in Figure 4.1, was first documented by V. E. Gough in 1956 (Gough, 1956). However, the research on forward kinematics of this six strut parallel device has progressed only recently. The number of possible theoretical forward kinematics solutions was first identified in 1991 (Raghavan, 1991) while only in 1998 that all possible poses were determined (Dietmaier, 1998). Regardless of this progress, an algorithmic model has not been developed yet.

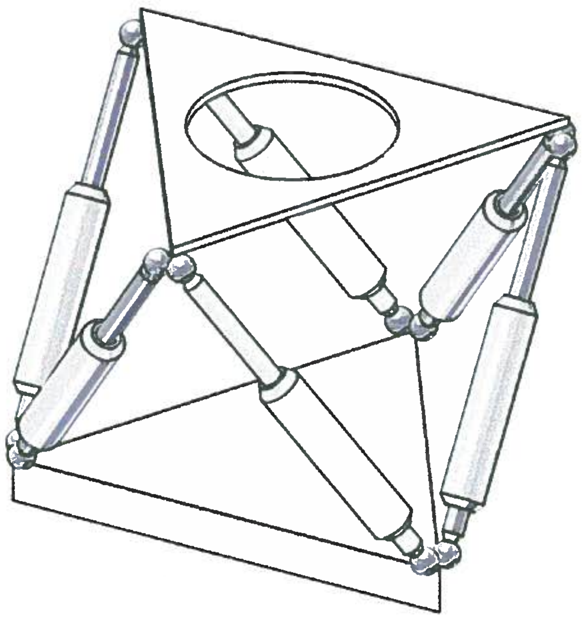

Figure 4.1. Gough platform topology.

In contrast, the inverse kinematics is straightforward for parallel geometries since the end node positions explicitly define the sizing and position of the linking ridges. As a result, 3d meshes are easy to use for approximating a desired spatial form by outlining its shape with the end node points. 3d meshes, even in simple arrangements, tend to be much more complex from a kinematics point of view, than a six linkage topology of Gough platform. Motion simulation is a practical and reasonably readily available method of evaluating their kinematic performance in terms of the range of motion and the final degree of folding. In most cases, the initial shell will fall short of the desired motion performance requirements due to interferences between facets or singularities while folding. Next two chapters will focus on the design process of folding shells.

The initial shell needs to be adjusted in terms of physical dimensions of its elements to improve the folding range. This task can be expressed as an optimization problem (Siddall, 1982) where design variables are the ridge lengths of the shell mesh expressed as vector $\mathbf{x}$. The upper and lower bounds ($\mathbf{x}_{lb}$, $\mathbf{x}_{ub}$) of ridge lengths are dictated by the overall geometry size and shape, equality constraints are the nodes of the controlling frame expressed as vector $\mathbf{h}$, inequality constraints are the limits of the desired geometry envelope expressed as vector $\mathbf{g}$, objective (J) is the desired degree of folding, and the model is a kinematic geometrical construct. The underlying optimization problem is expressed by

$$\text{find } \mathbf{x} \text{ that minimizes } J(\mathbf{x})$$
$$\text{subject to } \mathbf{g}(\mathbf{x}) \leq 0,\ \mathbf{h}(\mathbf{x}) = 0 \text{ and } \mathbf{x}_{lb} \leq \mathbf{x} \leq \mathbf{x}_{ub} \tag{4.1}$$

In a general case, the objective would be formulated as the target of a Multidisciplinary Design Optimization (MDO) problem (Eschenauer, 1990) and expressed as a weighted result of optimum folding, optimum structural strength and optimum actuation. In such case, the goal of the optimization would be finding the best feasible solution within the collection of available feasible solutions. Optimum folding which calls for a perfect flat fold conflicts with both optimum structural strength which calls for material thicknesses and the resulting assembly offsets as well as with optimum actuation which calls for a zone separating from singularities and the resulting indeterminate directions and infinite forces. However, for the purpose of clarity and focusing on the issues pertinent to the kinematics within the working range of a parallel geometry, the objective is expressed only as the degree of folding while the structural strength and actuation requirements are culled into a reasonable, discrete and non null value that becomes the target for the degree of folding. Once the best feasible kinematic solution is determined, this target forms the limits for the development of the dynamic and structural aspects of the design. At that stage, components would be sized to withstand static and dynamic loading and actuation elements would be added and calculated. Another phase of the design would need to deal with safety. This would encompass operational safety parameters like motion envelope that interferes with occupants, potential pinch points and maximum velocities within occupied zone. Most importantly, failure modes like failure of actuation and collapse under excessive loads would need to be investigated. Such investigation would, for instance, define the desired weakest structural points to control the mode of potential collapse. Again, the focus of this thesis is the development of the initial kinematic model which, as explained earlier in this chapter, poses considerable challenges because of lack of formulaic methodology.

Though the desired degree of folding can be expressed as an optimization target, practical impossibility of conceiving an applicable algorithmic model for the parallel geometry prevents from utilizing conventional optimization tools. The only immediately available recourse is the manual approach based on trial and error. Iterations of adjustments to the lengths of ridges and folding simulations can be performed to seek an improvement of the degree of folding. This manual process is tedious and time consuming even for relatively simple geometries.

The issue of developing manageable tools for optimization of the kinematic performance may be the deciding factor in successful commercialization of kinetic structures based on rigidly foldable shells. Mainstream design workflows traditionally depend on methods that can assure a certain degree of predictability, productivity, and ease of application. For solving rigidly foldable shells and, for that matter, any complex parallel geometry, the forward kinematics formalism does not offer, at present, any usable methods.

4.2 Decision Making Using Fuzzy Logic

Manual adjustment of shell elements is based on readily observable local dependencies between ridge length adjustment and their kinematic behavior changes. In general terms, the manual methods rely on accumulated experience and learned knowledge about relationships between element sizing, proportions and exception occurrences.

Intuitive and experience-based adjustments are applied in gradual steps to the initial geometry until the desired degree of folding is achieved. Obvious disadvantage of this method is unpredictability which is the result of underlying trial and error approach, in addition to the design duration which can be prohibitively long and tedious. Also apparent is the difficulty to automate this process since missing is a clearly defined algorithm that links the performance (the degree of folding) with the sizing of the shell geometry.

This scenario is well suited for implementing Fuzzy Logic as an automation and process efficiency tool.

> *Fuzzy Logic is useful in representing human knowledge in a specific domain of application and in reasoning with that knowledge to make useful inferences or actions.* (Karray and de Silva, 2004)

Fuzzy Logic offers the possibility of using intuitive, often imprecise and conflicting instructions based on human knowledge and reasoning to build robust and reliable algorithms. As explained in chapter 4.1, traditional optimization approaches can not be applied because of impossibility of parametrizing of complex parallel geometries.

In the present thesis a set of typical steps one would perform while adjusting a real life prototype of a folding structure is examined as a prelude to the use of fuzzy logic. Such an exercise yields numerous clues and hints about the kinematic behavior of the geometry and possible ways of improving the degree of folding. Based on readily observable parameters like collisions or slopes and intuitive remedial actions like shortening or lengthening of linkages, they capture 'cause and effect' dependencies in the shell geometry and can be further formulated as 'If-Then' statements or "rules." Such a compilation of statements readily interfaces with Fuzzy Logic and forms the Knowledge Base of the Fuzzy Inference System (FIS). The Knowledge Base is then used to identify problem conditions and infer appropriate corrective actions, through a suitable method of decision making; particularly the compositional rule of inference (Karray and de Silva, 2004).

The advantage of the Fuzzy Logic formalism lies in its effectiveness when dealing with human-originated approach which, while intuitive and easy to understand, usually brings along ambiguities, contradictions, uncertainties, redundancies, qualitative attributes, and in essence a degree of "fuzziness." Experiential clues are local in nature as they relate to the immediate circumstances of an observed singularity or interference. Fuzzy Logic allows the inference of geometry adjustments based on these local and loosely defined indications. More importantly, it allows forming algorithms that attempt to reconcile iterations of such adjustments within the context of performance of the complete shell thus negotiating contradictions and overlaps between locally made decisions.

4.3 Optimization through Fuzzy Logic

4.3.1 Fuzzy Logic-based Process Overview

Design process delivers a solution to a set of initial requirements or performance specifications. The solution, typically, is a result of numerous iterations through stages of design modification and testing (Cross, 1994), as indicated in Figure 4.2. The Fuzzy Inference System is intended to govern the modification loop in the design workflow that is aimed at foldable shells.

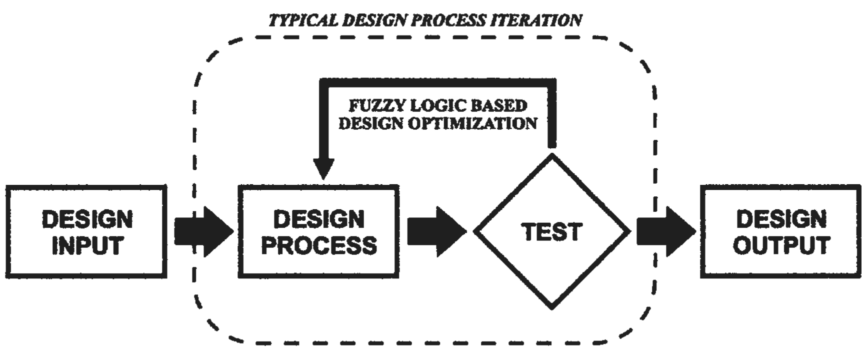

Figure 4.2. Block diagram of the design process.

The purpose of implementing Fuzzy Logic for the design of a kinetic structure is to avoid the prohibitively difficult forward kinematics modeling of complex parallel assemblies. Instead, the designer would devise a sketchy geometrical topology and rely on the optimization process which implements a FIS to fine-tune the linkage sizing. The cornerstone of such FIS is a set of simple, intuitive, empirically-derived adjustment dependencies compiled into the Knowledge Base, as indicated in Figure 4.3.

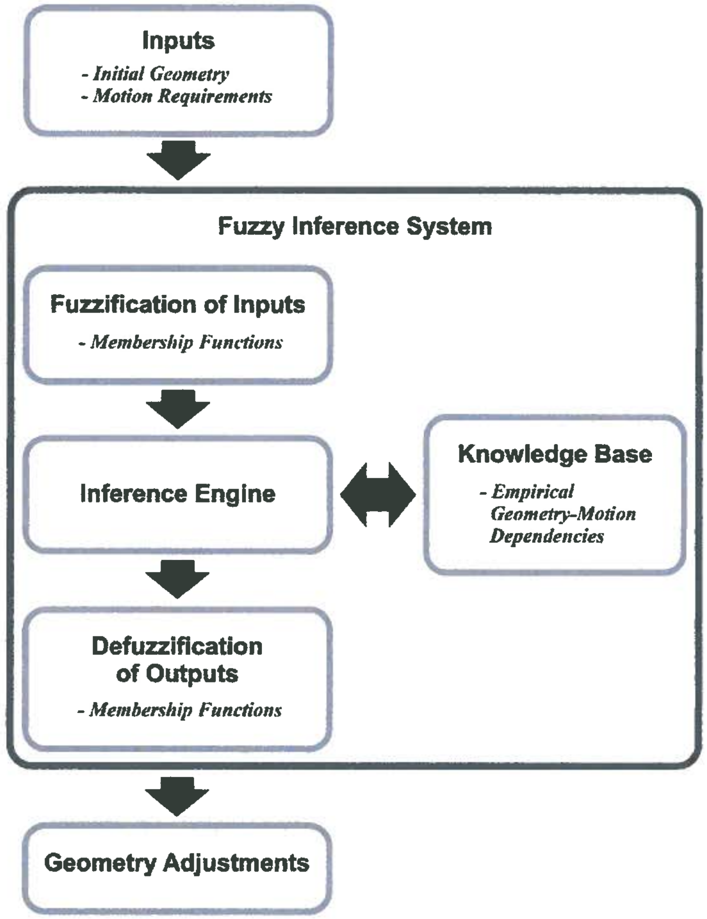

Figure 4.3. Block diagram of the FIS.

FIS block interfaces with the crisp domain of a geometrical model through the steps of fuzzification (of crisp inputs) and defuzzification (of fuzzy outputs). The Inference Engine interprets the fuzzified input data and infers appropriate adjustments based on the Knowledge Base. A detailed flow of the optimization algorithm is illustrated in Figure 4.4.

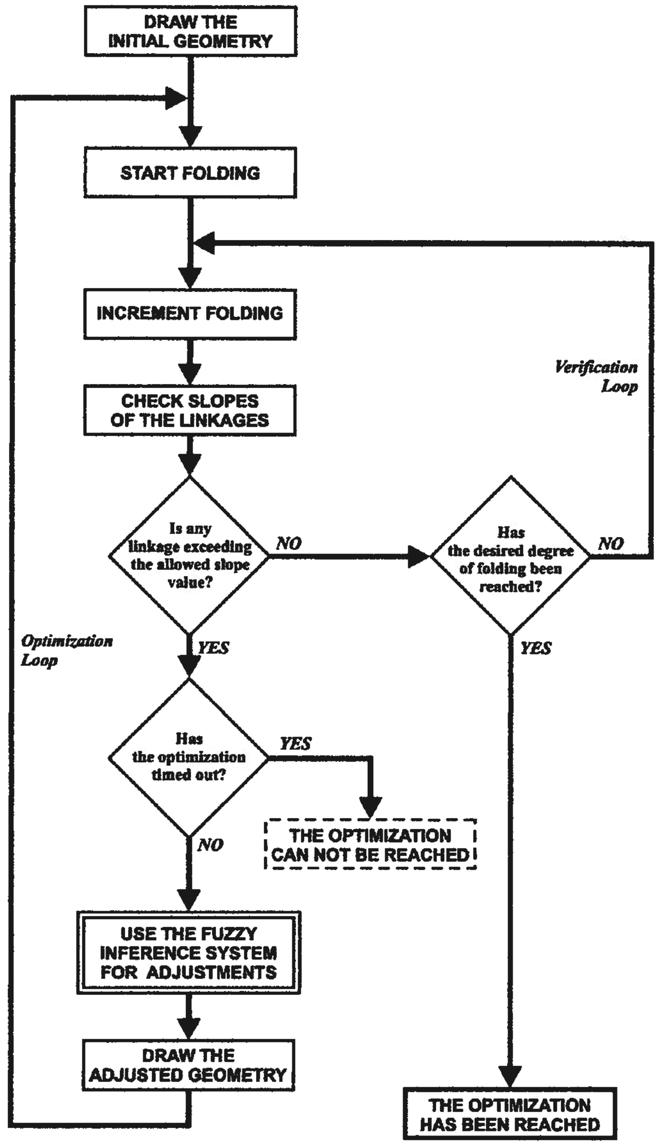

Figure 4.4. Flow diagram of the optimization algorithm.

The algorithm is inserted into a typical design iteration loop where an action of design change is performed and then followed by a qualifying test step. Depending upon the results of the test, two possible outcomes are available. Either further modification steps are continued or the loop terminates with an optimized solution. Hence, clearly defined are two distinct process flow loops: verification (on the right side) and optimization (on the left side). Fuzzy Inference System plays a key role in the optimization loop where it generates the necessary adjustment data. For practical programmatic reasons, a timeout test is inserted. It prevents run-away code execution if the optimization cannot be reached in a specified number of design iterations.

The algorithm allows, through its FIS module, the utilization of the empirically observed, knowledge-based dependencies to infer appropriate geometry adjustments. It performs all the necessary steps automatically in a progressive succession where the worst, from the folding viewpoint, areas of the shell are adjusted first. The strategy is to be able to achieve the optimization of relatively large geometries by iterating through localized corrective actions on geometry fragments. The scalable nature of this approach facilitates application for optimization of very complex geometries.

4.3.2 Test Conditions and Membership Functions

Observed simulated folding of articulated shells provides designers with apparent information about typical behaviors and error conditions. One of geometrical attributes of facets in a 3d mesh-like shell is the angle between each facet and the reference horizontal plane or, in other words, the slope. In an unfolded state, this angle assumes values that are fairly far from the vertical condition of 90 degrees. As the shell is being folded and its shape becomes more compact, and the slope becomes steeper. In a perfectly folded shell, most of the facets have a slope that is close to vertical. If the slope happens to exceed 90 degrees, it means that the particular facet has flipped over and, together with its companion facet, is nearing a singular state where both facets coincide. Therefore, slopes of facets have been observed as an effective source of information about the kinematic behavior of the shell and utilized, in the algorithm, as the primary test condition. During folding, if any slope becomes too steep, further folding is aborted and corrections to the geometry are initiated. Effectively, the slope condition is used to intercept pre-singular stages. The algorithm detects conditions that precede a singular event rather than detect the singular event itself. The corrective action involves adjusting the lengths of linkages that formed the undesirable angle. The values of the adjustments are determined based on the following contextual conditions: the degree of folding and the relative node height.

The degree of folding expresses quantitatively the actual kinematic state of the shell as a complete system. In absolute terms, any of the angular geometrical dependencies in the underlying controlling grid can be used to express the degree of folding. In relative terms, it is the ratio between the actual, folded angle and the angle in the fully unfolded state. The larger the degree of folding, the smaller should be the adjustments, as minimal linkage tweaks cause large slope changes for steep conditions.

The relative height of the subject node in relation to neighboring nodes affects the ratio of shortening and lengthening of sibling linkages. The reason is to avoid a systematic, excessive vertical drift of the subject node while performing multiple adjustments.

In the developed algorithm, angles of slopes have been utilized as test conditions to detect folding errors. The degree of folding and the relative height of the subject node are the inputs of the algorithm while the adjustment values are the outputs.

The fuzzy logic formalism is used to infer design decisions from pre-compiled, knowledge-based data. However, the model of the geometry, the driving parameters, the test conditions as well as adjustments to the geometry are discrete numerical sets. Interfacing between the fuzzy logic system and the discrete inputs and outputs is accomplished by means of fuzzification and defuzzification where fuzzy parameters are assigned to numerical variables, as indicated in Table 4.1.

Table 4.1. Input/output parameters and their fuzzy representations.

<table>
<tr><th></th><th>variables</th><th>fuzzy values</th></tr>
<tr><td rowspan="6">INPUTS</td><td rowspan="3">Degree-of-Folding</td><td>Unfolded</td></tr>
<tr><td>Half-Folded</td></tr>
<tr><td>Fully-Folded</td></tr>
<tr><td rowspan="3">Relative-Crown-Node-Height</td><td>Lower</td></tr>
<tr><td>Equal</td></tr>
<tr><td>Higher</td></tr>
<tr><td rowspan="6">OUTPUTS</td><td rowspan="3">Lengthen-Subject-Linkage</td><td>Minimally</td></tr>
<tr><td>Moderately</td></tr>
<tr><td>Significantly</td></tr>
<tr><td rowspan="3">Shorten-Sibling-Linkage</td><td>Minimally</td></tr>
<tr><td>Moderately</td></tr>
<tr><td>Significantly</td></tr>
</table>

Membership functions are used to correlate the numerical input (Figure 4.5) and output (Figure 4.6) subsets with fuzzy parameters (fuzzy states).

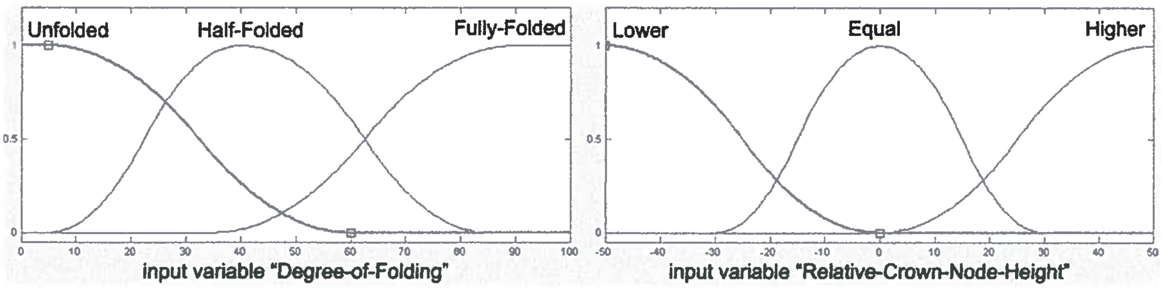

Figure 4.5. Input membership functions.

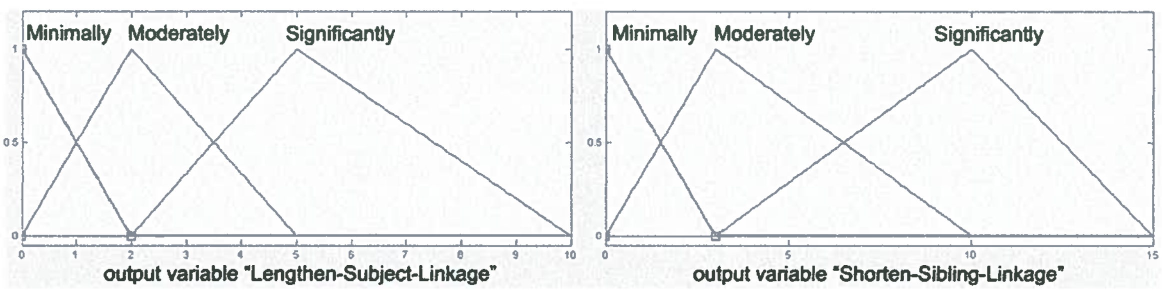

Figure 4.6. Output membership functions.

For the outputs, the relationship between the actual degree of folding ***F*** and the magnitude of necessary length adjustments ***dA*** is nonlinear if the resultant relative movement ***dN*** of the node being adjusted is to be maintained within a consistent range, as shown in Figure 4.7.

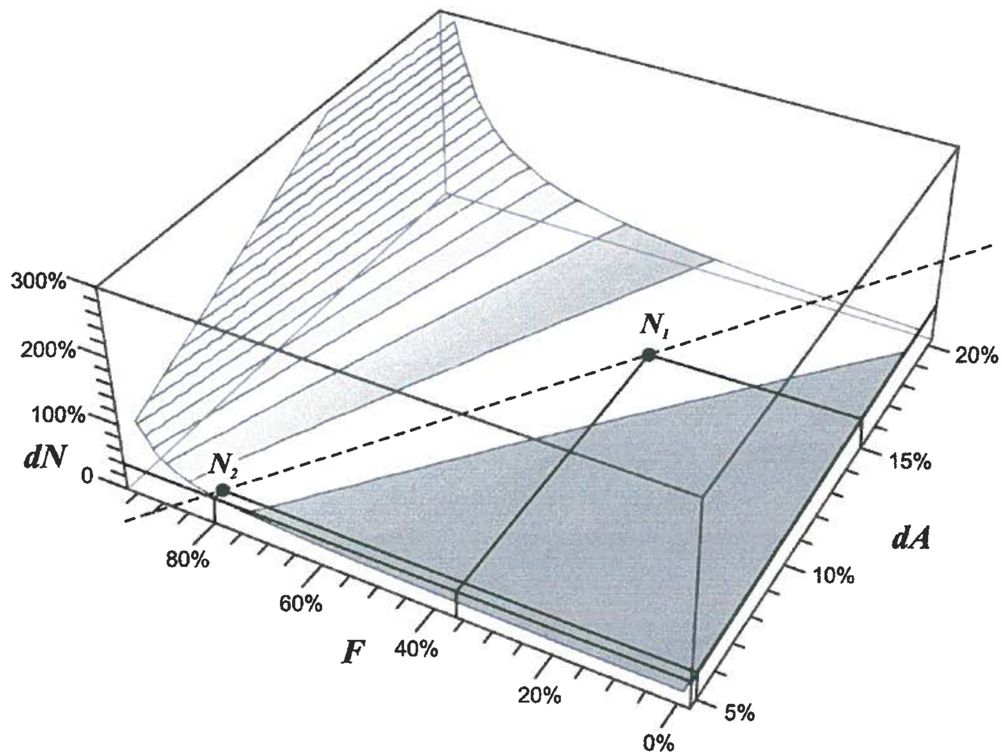

Figure 4.7. Node movement versus the degree of folding and magnitude of adjustments.

For example, at a folding rate of 80%, a 5% relative adjustment to the linkage length results in similar lateral adjustment of the subject node (N_2) as a 15% adjustment at a folding rate of 40% (N_1).

4.3.3 Inference Clauses

To develop the algorithm, a set of typical steps one would perform while adjusting a real life prototype of a folding (kinetic) structure has been considered. Based on readily observable effects like collisions or slopes and intuitive remedial actions like shortening or lengthening of linkages, the knowledge acquisition process can capture 'cause and effect' dependencies in the shell geometry which can be formulated as 'If-Then' statements. For example, a rule may take the form: if a set of neighboring facets would fold onto each other while the shell folded very little then increase significantly the appropriate dimensions of the bottom facet and reduce significantly the appropriate dimensions of the top facet. The 'if' part expresses a set of input conditions (*antecedent*) while the 'then' part describes the desired actions (*consequent*). Though simple and localized in their scope, such statements are sufficient to build the so-called Knowledge Base which can interface with fuzzy decision making (or, the inference engine) to identify problem conditions and infer appropriate corrective actions.

4.3.4 Knowledge Base

The knowledge base comprises a compilation of if-then statements or rules which express the expert knowledge of human designers. The scope of these statements needs to be correlated with the spectrum of possible scenarios as coded through input membership functions. Otherwise, an incomplete knowledge base would not be able to identify some of the scenarios or infer solutions for some of the problems. Figure 4.8 presents the set of if-then statements as compiled for the knowledge base in the present thesis. The utilization of such a knowledge base in the present problem is illustrated in the next chapter.

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 4.8. The knowledge base of statements.

Chapter 5 – Design Study and Results

This chapter details a case study to illustrate the implementation, testing and evaluation process of the developed optimization algorithm. The strategies involved in modeling the behavior of a foldable shell and in developing the testing simulation environment are explained. The structure and the interface of the testing program are described. Test results are presented and discussed and the behavior and performance of the algorithm are evaluated.

5.1 Design Case Study

The subject of the experimental phase of the thesis is the elementary module of the circular, arrayed folding structure as introduced earlier in the thesis. In order to achieve the desired folding range, manual adjustments were applied to the initial geometry within the parametric modeling CAD environment. The process was tedious, unpredictable and time consuming. The proposition of the thesis is that an effective optimization algorithm that implements a Fuzzy Inference System and an experiential knowledge base can be used for adjusting such parallel geometries instead of using prohibitively complex forward kinematic computations.

5.2 Testing of the Optimization Algorithm

The important part of the present thesis is the evaluation of the effectiveness of a Fuzzy Logic based optimization algorithm. If proven to be feasible, efficient and effective, such optimization tools hold a significant potential for the development of design workflows aimed at foldable structures. Consequently, they can greatly contribute toward the integration of kinetic structures with mainstream design.

The purpose of the optimization algorithm is to use a sketchy, initial geometry, simulate its kinematic behavior and, if necessary, apply adjustments to achieve the desired kinematic performance. For most practical applications, the kinematic performance reflects the desired, error free degree of folding.

5.2.1 Modeling of 3d Mesh Behavior

It is important for the test simulation to be able to accurately model the key kinematic effects that occur in a 3d shell that is being folded. On the other hand, it is also beneficial for the efficiency of the simulation to avoid modeling of features and phenomena that are not relevant for the kinematic aspects of folding. Kinematics deals with non-real-time aspects of the subject geometry. In this case, the focus is achieving the desired motion range by adjusting the sizing of the geometry while retaining its original topology. Issues of load bearing, vibration and actuation are dynamic issues that do not affect the degree of the folding; therefore, they are not considered during this stage of the design process, and in the present thesis. Also, the general shape of the envelope as set by the initial topology is not the subject of this optimization.

While developing the simulation model, an advantage has been taken of the fact that a 2d projection of a 3d mesh is, topologically, a continuous function (Artin, 1991). This represents the morphism between 3d and 2d topological spaces, as indicated in Figure 5.1. As such, it maps the parallel character of the geometry, the motion range as well as all the kinematic exceptions like interferences and singularities from one space into the other. For instance, if the distance between $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ diminishes in the 3d space, it will also diminish in its 2d projection. The detection of interferences and singularities (fully stretched or flat folded states) and performing adjustments that eliminate them is the objective of the optimization algorithm. Therefore, a simulation model that employs a 2d lattice instead of a 3d mesh is equally effective in validating the performance of such an algorithm. Figure 5.2 illustrates a singularity instance Q occurring in a 2d lattice.

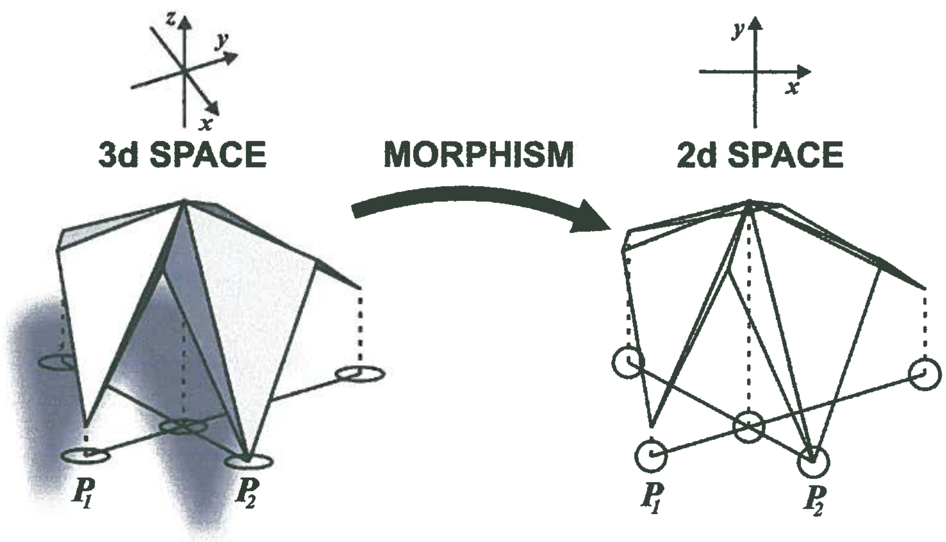

Figure 5.1. Mapping of the geometry between topological spaces.

The main advantages of using a 2d construct for simulation are simpler programming, effective use of computer resources and fast execution of simulation code. Such streamlined approach facilitates thorough testing of the algorithm and implementation of the necessary parameter adjustments in a resource efficient manner.

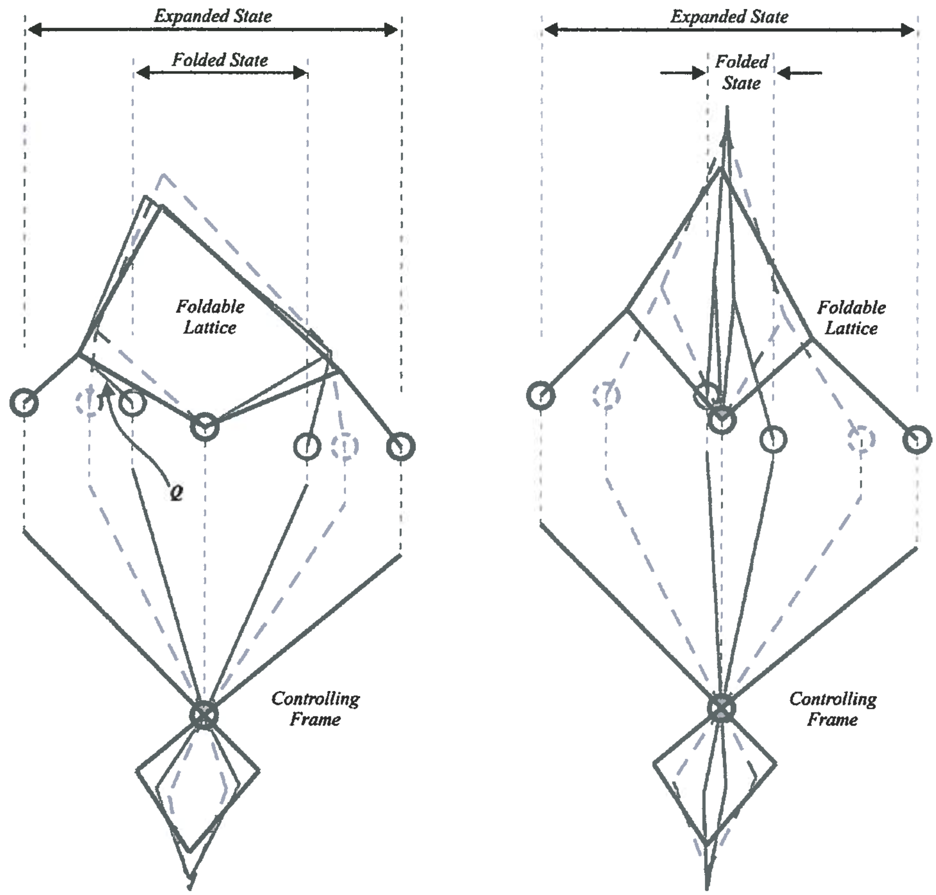

Figure 5.2. Folding of a 2d lattice: initial (left), optimized (right).

5.2.2 Development of the Test Set-up

A virtual testing experiment has been developed entirely using MATLAB while utilizing its Fuzzy Logic Toolbox for programming the Fuzzy Inference System. The program is divided into logical modules that are easy to modify or replace (see Figure 5.3). Each module is accessible as an individual MATLAB script file.

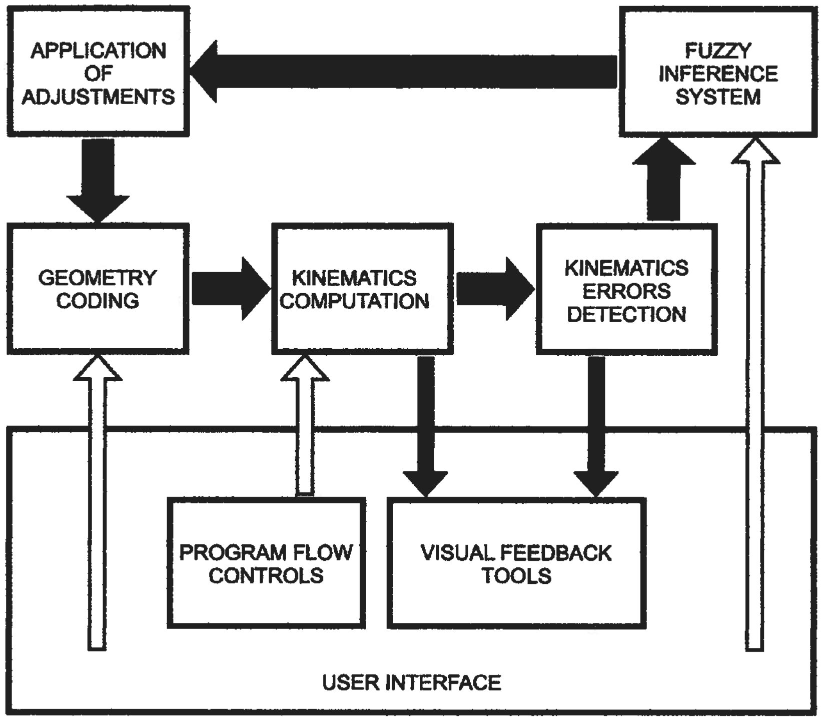

Figure 5.3. Modules of the optimization program.

The application models a pre-defined 2d lattice, subjects it to a simulated folding operation, and performs adjustments to linkage lengths in order to meet the target degree of folding.

The main components of the interface (see Figure 5.4) are:

- The lattice plot window where the progress of folding as well as all consecutive adjustments are shown in real time (1).
- Trigger condition plot window which displays, in real time, all linkage slope values imposed over the slope membership function (2).
- FIS edit and review pane (3).
- Optimization progress plot (4).
- Optimization progress statistics (5).

- Program flow parameters and controls (6).

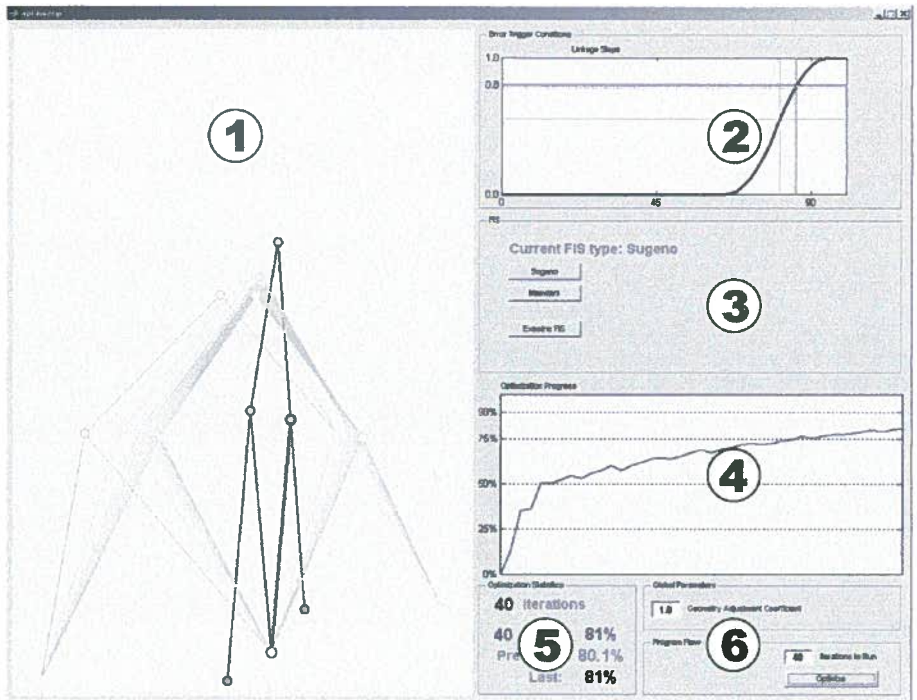

Figure 5.4. The interface of the testing application.

5.3 Test Results and Evaluation

Various linkage arrays extrapolated from the geometry of the folding module have been coded into the optimization program. Initially, a basic construct has been tested to analyze the behavior of the algorithm. Figure 5.5 presents a set of sample optimization results, using Mamdani inference an Sugeno inference (Karray and de Silva, 2004). Both these optimizations iterated 40 times and reached a folding rate in excess of 80%, which is a notable improvement when compared with the initial folding rate of 12%. Figure 5.6 gives the surface plots for the input/output correlation for these two optimizations.

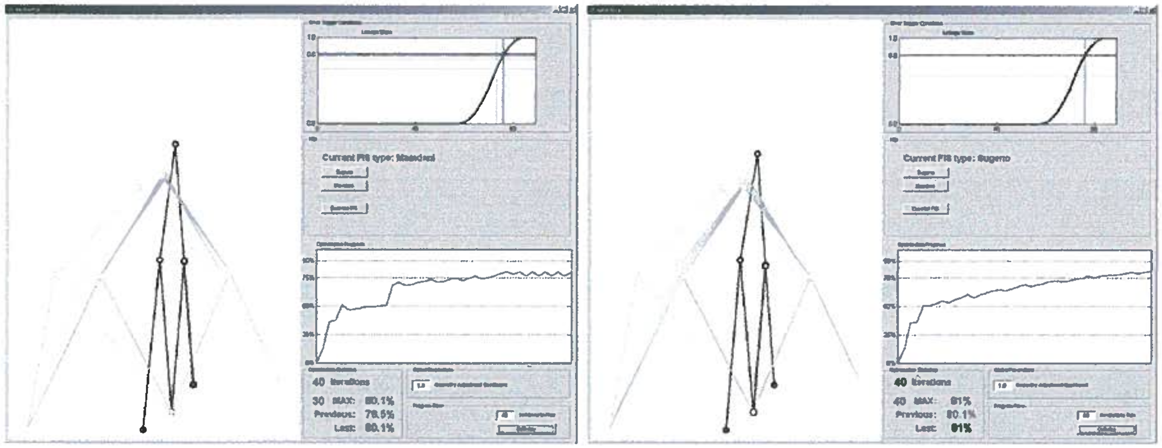

Figure 5.5. Sample optimizations using: Mamdani method (left); Sugeno method (right).

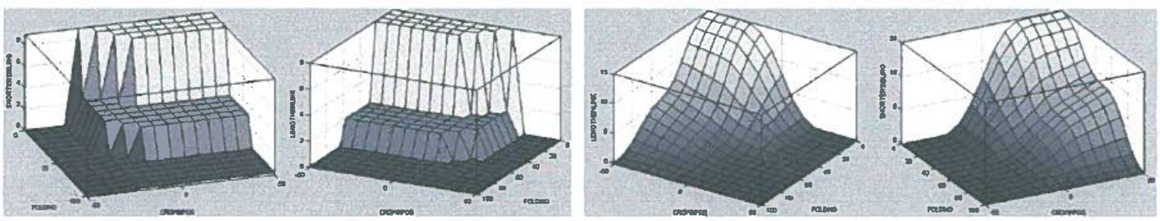

Figure 5.6. Input/output surface plots for: Mamdani method (left); Sugeno method (right).

These results provide resources to discuss practical aspects of the programmatic implementation of various FIS options. The Knowledge Base reflects empirical observations and contains directives based on partial statements--statements that ignore some of the input/output parameters. In this case, the knowledge base contains a few statements that ignore one of the outputs. The implementation of Mamdani's method expects all of inputs and outputs to be in the fuzzy domain. An ignored I/O becomes a discrete assignment, a singleton which causes problems with most defuzzification methods as they interpret such null assignment as a constant value. One possible workaround uses SOM (Smallest Of Maximum) as the defuzzification method. It

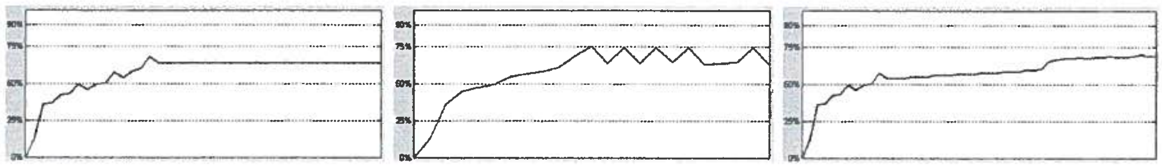

Figure 5.7. Typical behaviors: ceiling (left), oscillating (center), diminishing progression (right).

The observations gathered during the testing of simple 2d lattices help with characterizing the dynamic behavior of the algorithm, sensitivity to parameters and membership functions adjustments as well as the overall effectiveness of increasing the degree of folding. This analysis is helpful in applying optimization to more complex geometries (see Figure 5.8).

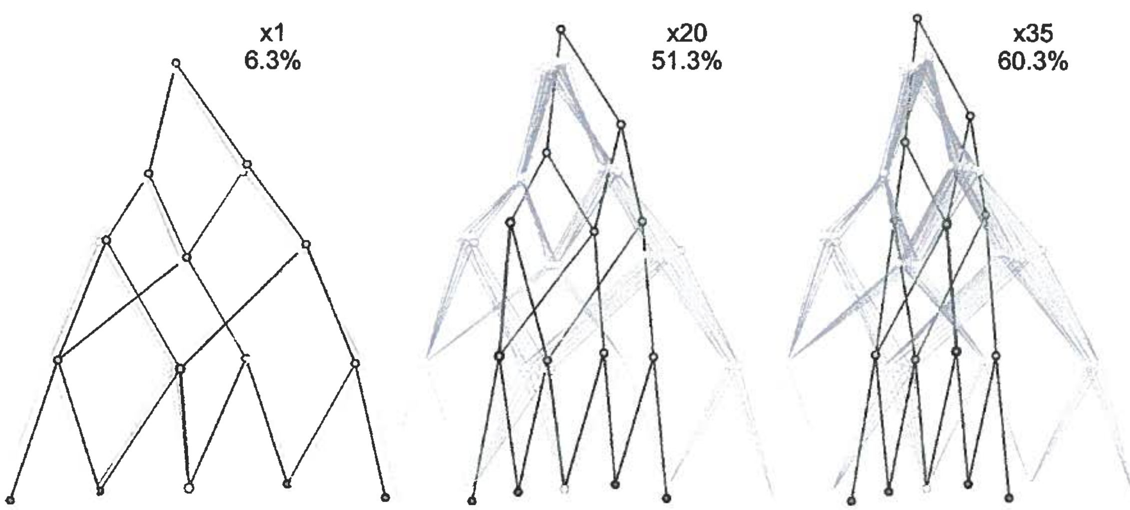

Figure 5.8. Progress of optimization of a complex 2d lattice.

interprets a zero assignment as a zero value thus preserving the programmatic intent. The drawback of this approach is a significantly stepped, non-smooth surface of input/output function.

The Sugeno implementation is well suited for managing a mix of fuzzy domains and discrete singletons. More importantly, it is designed to assure smooth input/output functions under these conditions. The difference is noticeable in Figure 5.5 where the optimization progression plot for the Sugeno method is smoother and exhibits less ripple than the corresponding plot for the Mamdani method. Interestingly though, despite obvious differences in the I/O surface plots, both methods have been capable of achieving a similar degree of optimization.

Figure 5.7 illustrates typical behaviors of the algorithm when reaching optimization limits that are attainable within the preset programmatic constraints. These can be described as: ceiling, where the degree of folding fixates at a certain value; oscillating, where the degree of folding toggles within a certain reasonably broad range of values; and diminishing progression where the degree of folding consistently improves as the optimization continues. Diminishing progression is the desirable behavior as it assures that the last performed iteration results in achieving the highest degree of folding thus simplifying the programmatic automation. Also, it delivers improved folding with prolonged optimization. The behavior of the algorithm is influenced by many factors. In general, the Sugeno method helps reduce the tendency toward excessive output oscillations. However, tweaks to mapping of input functions also play a significant role as all plots shown in Figure 5.7 are outputs of the Mamdani method.

As the kinematic behavior of a lattice is highly susceptible even to minor adjustments to linkage lengths, careful management of magnitudes of these adjustments is important for achieving a feasible and efficient optimization. The adjustments are governed through three components of the algorithm. Two of them are part of the core FIS: Membership Functions provide precise means of coding and decoding of physical adjustment ranges as fuzzy logic values like 'Significant' or 'Moderate' while If-Then statements contained within the Knowledge Base determine which of the fuzzy values will be used within a given set of circumstances. The computational outcome of Fuzzy Inference as governed by the Membership Functions and the Knowledge Base, may be expressed as Input/Output plots, as depicted in Figure 5.6.

The third method applies, if desired, uniform scaling to the Input/Output plots. It provides additional control of the magnitude of the adjustments depending upon the dynamics of the optimization. If frequent over-adjustments of geometry affect the progress of optimization (see Figure 5.9), flattening of the Input/Output function by applying a reducing coefficient will bring the adjustment values down and out of the erratic range.

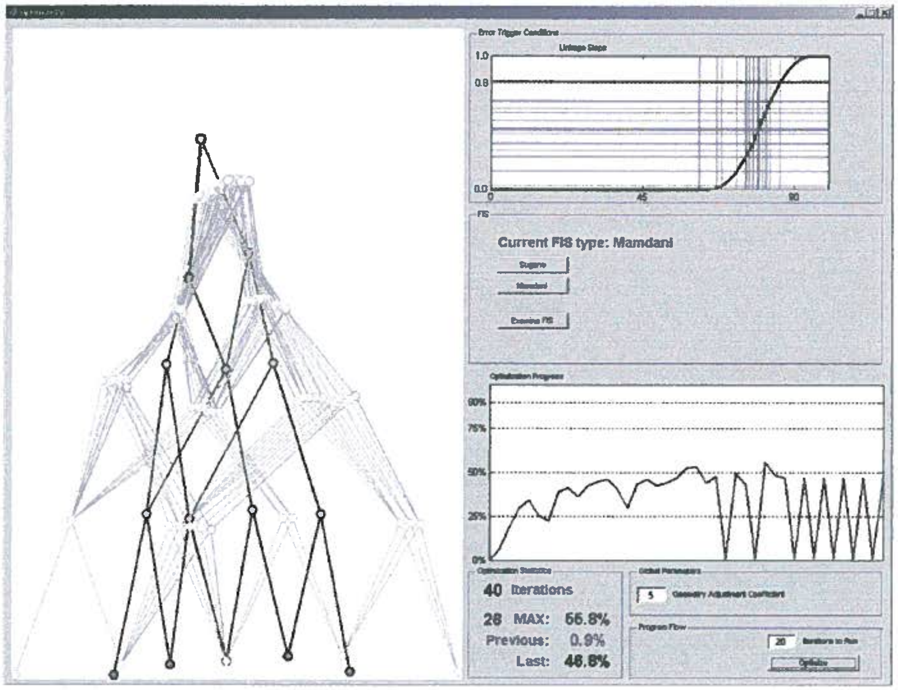

Figure 5.9. A case of over-adjustment of geometry.

Adjustments that are consistently too small will significantly prolong the optimization duration, as indicated in Figure 5.10. In such cases, increasing the dynamics of the Input/Output function will improve the efficiency of the algorithm.

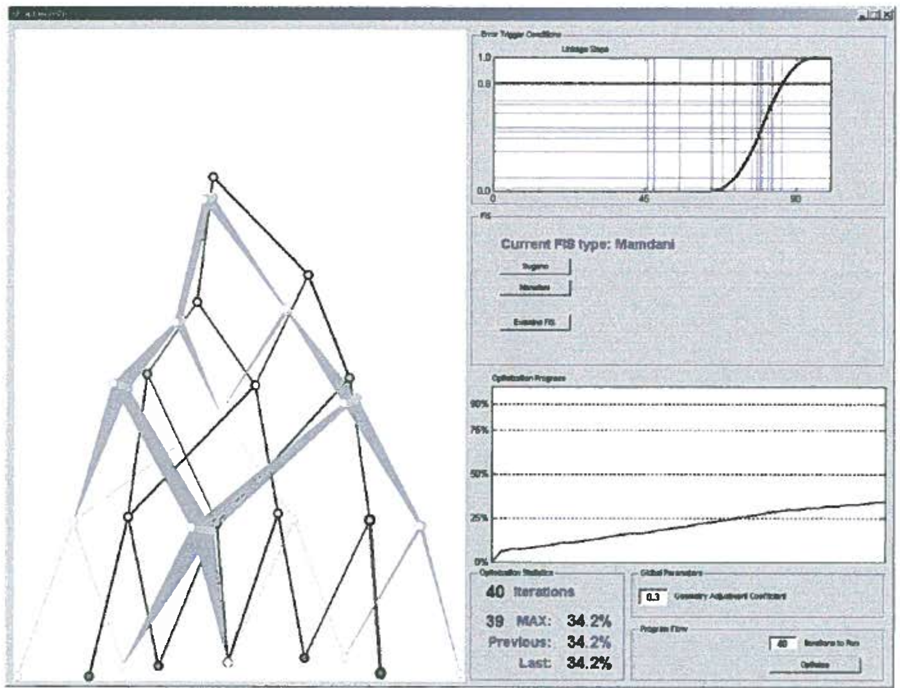

Figure 5.10. A case of under-adjustment of geometry.

The scaling coefficient can be governed by an additional 'supervisory' Fuzzy Logic thread that is dedicated to monitoring of the optimization outcome. Such a supervisory function would be able to detect erratic output due to over-adjustments of geometry or consistently low rate of optimization progress and, consequently, would apply appropriate adjustments to the global magnitude of the geometry corrections. Such an approach provides programmatic means of performing optimizations that are efficient and can reach the feasible degree of folding within a reasonably short timeframe while avoiding over-adjustments. Figure 5.11 presents an example of desired dynamics of the algorithm.

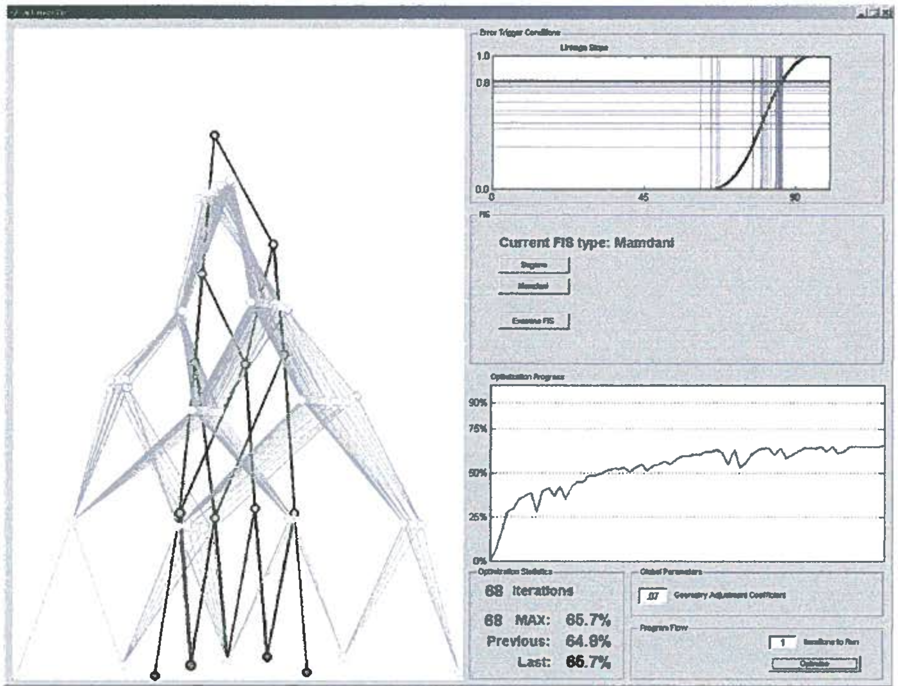

Figure 5.11. Sample optimization of a complex 2d lattice.

Chapter 6 – Conclusions

This concluding chapter summarizes the main contributions and significance of the work presented in the thesis. Also it provides some possible directions for further work in the area.

6.1 Conclusions

The complexities of the forward kinematics parameterization of parallel geometries pose significant challenges when fine-tuning their motion range. The only recourse available within mainstream parametric CAD packages is a manual process based on trial and error. Such an approach, although occasionally successful, has proven to be tedious, time-consuming and unpredictable, as discussed in the thesis.

This thesis has outlined the potential benefits of folding or "kinetic" architectural structures based on parallel geometries. It proposed novel topologies for such structures and detailed their structural and functional integration. The thesis identified the difficulties of the forward kinematic modeling of parallel constructs as a serious obstacle that needs to be addressed before broader commercialization of the various free-form folding structures can take place.

A significant contribution of the thesis is the development and testing of an applied Fuzzy Logic Inference System for motion range optimization of parallel geometries. The optimization algorithm implementing fuzzy logic offers the possibility of using a human-oriented knowledge-based approach to build on easily observable dependencies, as well as intuitive inferences to reliably and predictably emulate the kinematic effects of adjustments to parallel geometry elements. Subsequently, an alternative to formulaic forward kinematics algorithms was provided.

The algorithm developed as part of this thesis has been tested on structural geometries of various complexity. Despite its conceptual simplicity, based solely on localized adjustments, it performed reliably and always improved the folding range by a substantial margin within a practical number of iterations. These promising results encourage continuing the work on this type of algorithm, with significant practical advantages in the domain of kinetic structures.

6.2 Future Research Directions

The overall goal of the work presented in the thesis is to develop a foundation for reliable design tools that can be utilized within existing workflows. The areas that need further research fall into three categories: performance improvement of the Fuzzy Logic Inference System, and systematic design of program flow control and programmatic interface shell. It is important to gage the theoretical limits of optimization based exclusively on localized adjustments when applied to very complex geometries. Potential improvements may involve expanding the Knowledge Base with statements reflecting a broader awareness of the geometrical context.

As mentioned in Chapter 5, an additional, program flow supervisory function of the Fuzzy Inference System may significantly improve the performance of the algorithm. Further improvements may include the training and learning capabilities of the algorithm. For example, an approach based on neural networks (Karray and de Silva, 2004) may be used to progressively improve an initial, human-oriented knowledge base while it is applied to various problems of kinetic structure design. Furthermore, genetic algorithms (Karray and de Silva, 2004) may be incorporated to optimize the overall fuzzy inference system. Production tools based on this algorithm will need to interface directly with CAD models and their 3d geometry, which will require research and development of toolkits for various CAD environments.

Further development of folding structures needs to include real-time motion and dynamics issues such as dynamic loading, actuation, sensors, and automatic control, prior to product commercialization. This enhancement may be pursued as an integration of Fuzzy Logic based motion optimization with the FEA and dynamic-system capabilities of a selected (or developed) CAD package.

Bibliography

1. Arkin, E., Fekete, S., and Mitchell, J., "An algorithmic study of manufacturing paperclips and other folded structures," *Computational Geometry*, Vol. 25(1-2), pp. 117-138, 2003.

2. Artin, M., *Algebra*, Prentice Hall, Englewood Cliffs, NJ, 1991.

3. Ataman, O., *Proceedings of Association for Computer-Aided Design in Architecture Conference, ACADIA 2005 Smart Architecture*, Savannah, Georgia, pp. 4, October, 2005

4. Craig, J.J., *Introduction to Robotics*, Addison-Wesley, Reading, MA, 1989.

5. Chen, Y., *Design of Structural Mechanisms*, PhD Thesis, Department of Engineering Science, University of Oxford, England, pp. 58-59, 2003.

6. Cross, N., "Forty years of design research," *Design Studies*, Vol 28, pp. 1-4, 2007.

7. Cross, N., *Developments in Design Methodology*, John Wiley & Sons, New York, NY, 1984.

8. Cross, N., *Engineering Design Methods: Strategies for Product Design*, John Wiley & Sons, New York, NY, 1994.

9. Dietmaier, P., "The Stewart–Gough platform of general geometry can have 40 real postures," *Advances in Robot Kinematics: Analysis and Control*, J. Lenarcic and M. L. Hust, eds., Kluwer, Norwell, MA, pp. 7–16, 1998.

10. Eschenauer, H., Koski, J., and Osyczka, A. ed, *Multicriteria Design Optimization*, Springer Verlag, New York, NY, 1990.

11. Escrig F, Arquitectura Transformable, Escuela Técnica Superior de Arquitectura de Sevilla, 1993

12. Escrig F and Valcarcel J P, Geometry of Expandable Space Structures, International Journal of Space Structures, Vol. 8, No. 1 & 2, pp 71-84, 1993.

13. Gough, V. E., *Automobile stability, control, and tyre performance*, Automobile Div., Inst. Mech. Eng., UK, 1956.

14. Hoberman C, Reversibly expandable doubly-curved truss structure, USA Patent no.4,942,700, 1990.

15. 8. Hoberman C, Radial expansion/retraction truss structures, USA Patent no. 5,024,031,1991.

16. Karray, O. F. and de Silva, C. W., *Soft Computing and Intelligent System Design*, Addison Wesley, New York, NY, 2004.

17. Kassabian P, You Z, and Pellegrino S, "Retractable roof structures," *Proceedings Institution of Civil Engineers Structures and Buildings*, Vol. 134, Feb 1999, pp. 45-56.

18. Medina, J., Ojeda-Aciego, M., and Ruiz-Calvini, J. "Multi-lattices as Basis for Generalized Fuzzy Logic Programming," *Proceedings of the 6th International Workshop, Fuzzy Logic and Applications*, Crema, Italy, pp. 61-70, September 2005.

19. Pellegrino S. and You Z, "Foldable ring structures," *Space Structures*, Vol. 4 (edited by G A R Parke and C M Howard), Thomas Telford Publishing, London, England, pp. 783–792, 1993.

20. Raghavan, M., "The Stewart platform of general geometry has 40 configurations," *ASME Design and Automation Conf.*, Miami, FL, Vol. 32(2), pp. 397-402, 1991.

21. Rittel, H. and Webber, M., "Dilemmas in a General TMerlet, J.," *Parallel Robots*, Kluwer, Norwell, MA, 2000.

22. Siddal, J. N., *Optimal Engineering Design*, CRC Press, Boca Raton, FL, 1982.

23. Rittel, H. and Webber, M., "Dilemmas in a General Theory of Planning," *Policy Sciences*, Vol. 4, pp. 155-169, 1973.

24. Wohlhart K, "Double-Chain Mechanisms," *Proceedings of IUTAM-IASS Symposium on Deployable Structures: Theory and Applications,* (edited by S Pellegrino and S D Guest), Kluwer Academic Publishers, The Netherlands, pp. 457-466, 2000.

25. You Z, "A new approach to design of retractable roofs," *Proceedings of IUTAM-IASS Symposium on Deployable Structures: Theory and Applications* (edited by S

Pellegrino and S D Guest), Kluwer Academic Publishers, The Netherlands, pp. 477-483, 2000.

26. You Z and Pellegrino S, "Foldable bar structures," *International Journal of Solids and Structures*, Vol. 34, No. 15, pp. 1825–1847, 1997.

27. Zeigler T R, Collapsible self-supporting structures and panels and hub therefore, USA, Patent no. 4,290,244, 1981.