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Deployable Structures: An Interdisciplinary Design Process

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Abstract
History reveals that architects and engineers have constantly sought new and creative structural systems. Many special systems have thus evolved, namely: deployable structures, tensegrity, tensioned-membrane and other unconventional systems.

Deployable structures find use in terrestrial architecture and outer-space applications. Disaster-relief and other emergency shelters need minimal storage space and rapid assembly on site. Temporary events such as market spaces and Worlds' Fairs have similar requirements. Space explorations require compact and rapidly deployable assemblies; these include solar arrays, antennas, reflectors, among others. Beyond these applications, there is also excitement and inspiration that deployable geometries offer to artists, industrial designers, mathematicians, and biologists.

This paper emphasizes the need for interdisciplinary design thinking to tap the creative and intellectual potential from various disciplines for the design of deployable structures. The paper desscribes why knowledge from biology, mathematics, material science and engineering together can inform design thinking effectively. Select assignments and projects are included as examples.

Keywords: Interdisciplinary, structures, deployable, tensegrity, disaster-relief, outer-space, project-based learning.

Introduction

Building structures are conventionally designed to have a long life-span. Structural designers are trained to think about design of stable structures. Materials and systems have been discovered to support that sentiment. There is, however, an advantage in introducing measured instability in structures. The result is a whole new world of transformable structures whose effectiveness and survival may depend on their adaptability to external conditions.

The architecture of future is one that can respond and adapt. Needless to say, a building with such attributes would serve human needs better. They also represent a dynamism and excitement that architecture constantly seeks. The field of deployable structures has been evolutionary and progress in realizing built forms has been relatively slow. Zuk [16] remarked that acceptance of kinetic architecture would force substantive changes to traditional practices of which will now need to be recognized as a continuous and evolving process that would not stop when the building is erected.

Deployment is the transformation of a structure from a compact closed configuration to a relatively large open configuration. The design of deployable structures requires solving three problems, namely: geometrical, mechanical and structural [2]. The goals are: (1) To develop maximum deployable and foldable structures; (2) To design connections that provide the required movements of members while keeping them together; and (3) To create strong and stiff structures under applied loading. This should be followed by a reliability analysis to ensure that structures would deploy and fold without collision of members.

Deployable structures are characterized by lightness, transformability, compactness, rapid assembly and disassembly, ease of transportation, and material reuse. Designers have found great potential in deployable structures for various terrestrial and outer-space applications. Disaster-relief housing, moving theatres and military installations are some of the main rapidly assembled structures. They may be controlled and made adaptable to natural events such as earthquakes, extreme winds, and thermal loads. As such, their overall performance may be greatly enhanced.

Interdisciplinary Design Thinking

Systems in nature are integrated and multifunctional**.** Vascular tissues provide structural support to organisms while also carrying out other primary functions such as transportation of fluids and enzymes. This helps a plant to maintain a small cross-section while carrying out its primary life-sustaining processes. Facades and windows with solar panels may be designed to be multipurpose − as envelopes and also as energy generators for a building [7]. Thus, if the structural system of a building is designed not just for resisting and transferring loads but also for heating, cooling, air-conditioning and water supply, we have developed a highly efficient system with optimal use of resources. This section describes how various allied fields can help in the design of deployable structures.

Nature and Biology

Humans have looked upon nature as a teacher and a valuable encyclopaedia that motivates man's aspirations to be realized with materials, forms, structure and mechanisms that enable its efficient functioning. The principles governing nature have been a source of inspiration to scientists, engineers, architects and designers. Leonardo da Vinci was inspired by the flight of birds and tried to emulate the wings and create mechanical advantage in structures, and the Roman's based one of their battle tactics on the turtle [12]. While examples found in nature cannot be directly translated to architecture, its underlying principles can be effectively used to improve the efficiency of man-made structures. Principles of particular relevance to architecture and structures are — symmetry, lightness, movement, self-healing, multi-functionality, hierarchy, and compliance, among others [1]. Lightweight structures result from optimal use of materials and deployability helps to reduce the volume of structures, thereby facilitating storage, transportation and re-use.

Deployable systems in nature are often based on flexibility, as observed in plant, insect and animal movements. The Al-Husayn Mosque canopies that were designed by Bodo Rasch [10] are deployable structures inspired by the burgeoning of buds. Thomas Heatherwick's Rolling Bridge derives its inspiration from a series of vertebrae and the operation of muscles. It contains a series of linked units that are operated by hydraulic rams. Contracting or extending these rams allows the bridge to roll up for boats or extend across the channel for pedestrians [11].

Beetles demonstrate reversible folding with their wings. When they walk on the ground, they risk their wings getting caught or damaged. So, they tuck them neatly under a protective shell until they need to fly again. Armadillos armored with thin body plates when threatened can roll themselves into a tight ball leaving only its armor plates exposed. The idea of self-repair in man-made structures is also nature-inspired. Self-repairing concrete has adhesive-filled hollow tubes that rupture when a crack forms and releases the adhesive to facilitate bonding of the fragmented parts. There are many such mechanisms in nature and biologists can thus inform design decisions for deployable structures.

Mathematics and Origami

The art of origami has evolved from paper toys to resilient engineering structures. Deployable space structures use a variety of deployment techniques, such as mechanical systems deployed with motors, self-deploying structures using stored strain energy among other mechanical approaches. Mathematicians, architects and engineers have demonstrated interest in the geometrical aspects of origami forms and their potential for maximum foldability. Space explorations require compact and rapidly deployable assemblies such as solar arrays, antennas, reflectors, among others. NASA's needs include large size, lightweight, compact, reliable, simple and robust deployable structures [13].

Megahed [8] provides a good overview of the origins and development of origami, its geometrical, structural and architectural capabilities. Evans et al. [3] gives a rigorous, comprehensive and thorough mathematical analysis of folding patterns, including the well-known Miura [9] and Yoshimura fold patterns. After understanding the geometric fundamentals of these forms, students in my course are encouraged explore the architectural potential and engineering strengths and weaknesses of these patterns. In general, knowledge of plane geometry, fold-patterns, polyhedra and linkages would provide a solid foundation for students to pursue advanced origami-based projects.

Materials

Viollet-le-Duc [14] noted that proper use of materials contributes to the clarity of the structural expression while their misuse diminishes the effectiveness of the design. Inventions in materials has a direct effect on innovations in structural systems. Without fundamental innovations in material science, the development of new deployable forms and structures would be rather slow. This is especially true for connections in three-dimensional deployable structures, where compliant materials would greatly facilitate the movement of parts by providing the necessary degrees of freedom. Other new construction materials such as fiber-reinforced polymers (FRP) combine high tensile strength with low bending stiffness, allowing large deformations. The potential of auxetic polymeric materials, i.e. those that exhibit negative Poisson's ratio, should be explored. Such materials expand in the lateral direction when stretched in the longitudinal direction, and vice-versa. They are thin, lightweight and have high resistance for impact and blast loads.

Architecture and Engineering

Gantes [4] provided an elaborate list of potential terrestrial and outer-space applications. The former includes emergency shelters and bridges for use after earthquakes or other natural disasters, temporary buildings in remote construction sites, retractable roofs for sport facilities, relocatable maintenance facilities, lightweight recreational structures and exhibition structures. FEMA needs rapidly deployable mobile bridges, floating causeways, disaster-relief shelters, emergency clinics, among others. Outer-space applications include: components of space stations, platforms, solar panels, radiators, space cranes and remote manipulator arms, foldable wings and booms, impact protection systems, parabolic reflectors and antennas, and habitable units for space stations. There may be other applications that are indigenous and based on social and cultural needs.

Teaching Deployable Structures

As part of the regular course offerings, the author assigns projects on deployable structures in the required graduate-level Structures course "ARCH 536 – Planning and Design of Structural Systems (formerly ARCH 502)" at the University of Illinois' School of Architecture. The author also guides and supervises independent and group studies on this subject. The latter is for students who have focussed topics within the area of deployable structures; for example, transformable dome structures. This way, students get an opportunity to explore and learn about specialized topics not offered in the regular curricula.

A highlight of the independent studies has been the "learning by making" component. Through the construction of physical models and connection details, students understand how precision in geometry is essential for proper movement of parts and thereby foldability of a structure. Some students find the process cumbersome as they work through the models, but on completion, the joy of seeing static structures come to life and breathe makes them want to learn more.

Assignments and Projects

Students first create and examine two-dimensional forms followed by more intricate three-dimensional structures. The goals are the same, i.e., design of a structure for maximum deployability and foldability. These may be deployable rings, grids, polyhedra, hypar and saddle shapes.

In general, projects start with a group discussion about what makes deployment of a structure possible. We recognize the types of scissors-like units and their merits and demerits in terms of the mobility they offer. Depending on the type of scissors-like unit, a deployable structure may either translate only, both translate and rotate, and radially deploy [15]. The next step is to examine the geometric relationship between the parts of a deployable structure. These are called deployability and foldability constraints. If violated, the scissors-like units may only partially deploy and fold.

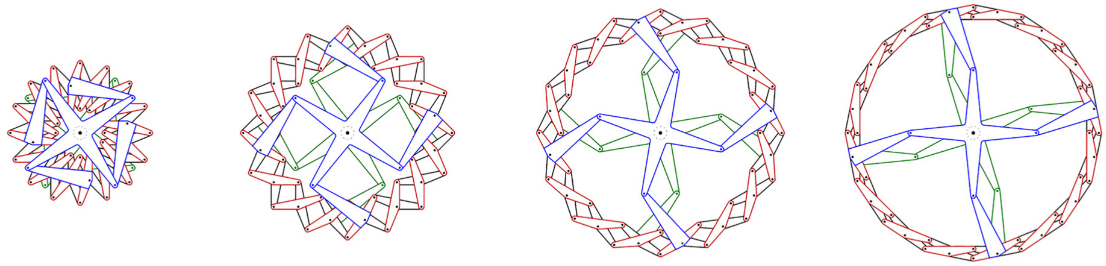

Fig. 1 Deployment sequence of an expandable ring made using angulated scissors members

Once the basic units are understood, students work on two-dimensional (or planar) forms such as single and multi-layer rings (Fig. 1), plane grid and grids of single and double curvature. The mathematical theory for geometric design is derived ensuring that all deployability and foldability constraints are satisfied. Physical models (Fig. 2) are constructed using appropriate connection details to ensure reliable deployment. Students are also encouraged to use the commercial program *Grasshopper* which facilitates parametric studies with relative ease. Knowledge of computer programming helps with developing codes to allow better control of design variables. Some students also pursue advanced topics such as kinematic analysis where they do a position, velocity and acceleration (PVA) analysis to study the motion of deployable structures.

Fig. 2 Folding sequence of Hoberman arch [5]

The goal of the projects was to create smoothly working deployable structures based on accurate geometric formulation. A physical model along with AutoCAD drawings and photos showing the deployment sequence were the deliverables for each assignment. The projects are assessed based on the design complexity, derivation of correct geometry, quality and completeness of models and connections. Students are provided feedback and errors are pointed out for them to resubmit their work. This arrangement works well as students also like to preserve complete and working projects as a keep-sake. Usually, six to eight assignments ranging from low to high complexity are completed in a semester.

The size of the projects range from a foot to four feet. Of the available model-making materials, aluminium, high density fiberboard (HDF) and acrylic of appropriate thickness have worked well depending on the geometry of the form. HDF lends itself well to laser-cutting and members made of HDF are connected using styrene rods. For more robust models, aluminum tubes secured with screws and nuts are recommended. The cutting of tubes may be accomplished with tools from a hardware store. Flattening the ends of tubes and drilling holes may require tools usually found in a machine shop. After the kit-of-parts is ready, securing the members is far easier with screws and nuts as compared with using HDF and styrene rods.

After working through the project assignments, a general sentiment has been that what seemed to be very attractive but intimidating to design and construct was not as difficult. The familiarity and knowledge gained has alleviated unfounded fears and students are more confident about designing deployable structures. It was just that they had no academic setting to learn about such structures.

Implementation in Design Studio and Research Projects

Students have been successful in implementing deployability concepts to their architectural design studio projects. Students in a design studio participated in the LAKA competition 'Architecture that Reacts' [17] during Fall 2016. As part of the competition, students explored the idea of architecture that reacts and responds to social needs, particularly to unforeseen and unpredictable conditions. Students found direct relevance and complementarity between the deployable structures course and their design studio.

In another design studio titled "Japanese Cultural Center in University of Illinois Arboretum" in Spring 2016, graduate student Nahid Akram designed of an origami-based deployable structure. One of the program requirements was to provide either a Noh Theater or a Kabuki Theater. Traditional Noh theaters were outdoor structures and as Japanese Architecture has a strong relationship with nature, an outdoor theater was a reasonable choice. To protect it from elements when necessary, a deployable shading structure was desired. The Japanese art of origami provided a strikingly appealing solution.

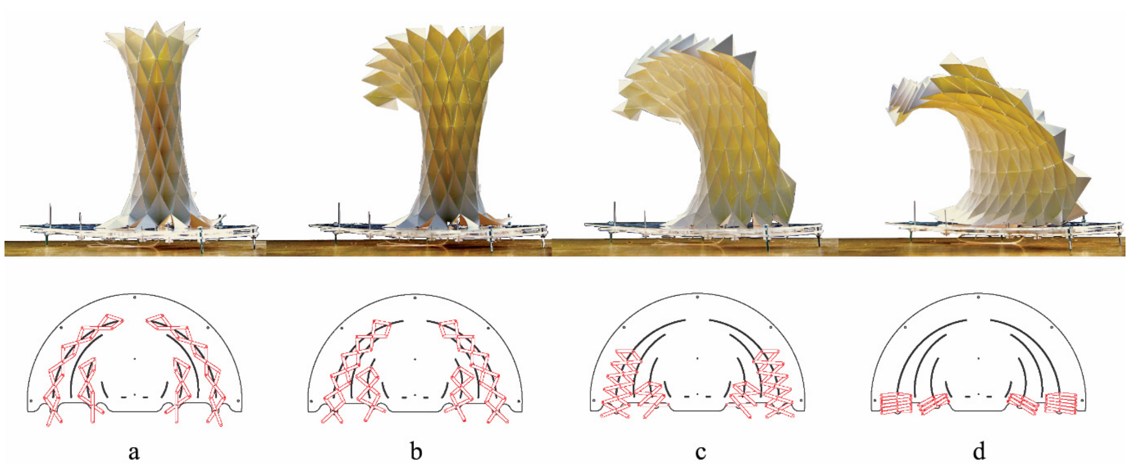

Fig. 3 Deployment sequence of origami-based pavilion facilitated by a base mechanism using polar scissors linkages (in red)

The student wanted the form to be a symbolic element in the closed state (Fig. 3a) and to serve as a canopy in the deployed state (Fig. 3d). The change from initial to final form required precision of movement while ensuring stability at each step of the deployment. To achieve this, the origami form was connected to deployable rings made of scissors-like units at the base. A mechanism was used to trigger the motion such that the form would deploy in a polar trajectory resembling the burgeoning of a bud.

Beyond these semester long pursuits, there are students who also work on the author's research projects. One of the ongoing projects is to develop deployable dome geometries for Indian temple-cars (Fig. 4). These special cars have existed for over a thousand years, first in stone and later in movable form. There were secular cars and temple cars [6]. The former were used for military, conveyance, wedding and funeral purposes, while the latter were used for taking the deities from temples for a public procession. Some temples have austere scriptural prescriptions for the design and construction of temple-cars. The type of wood used (available only in select locations) and traditional carpentry methods (passed down through the generations only through experience and without written procedures) are two of them. Usually the dome portion is dismantled and reassembled every year. However, such rules may be relaxed for many temples. Befitting the changing times and to overcome obstacles (such as electrical power cables that crisscross roads) presented by modern cities, deployable domes have been proposed by the author. The challenge is to design dome forms that are innovative yet traditional in spirit. The intent is not to break away from traditional ways but to revive and maintain the eroding tradition in temples. The new deployable domes would allow for their re-use in subsequent festivals.

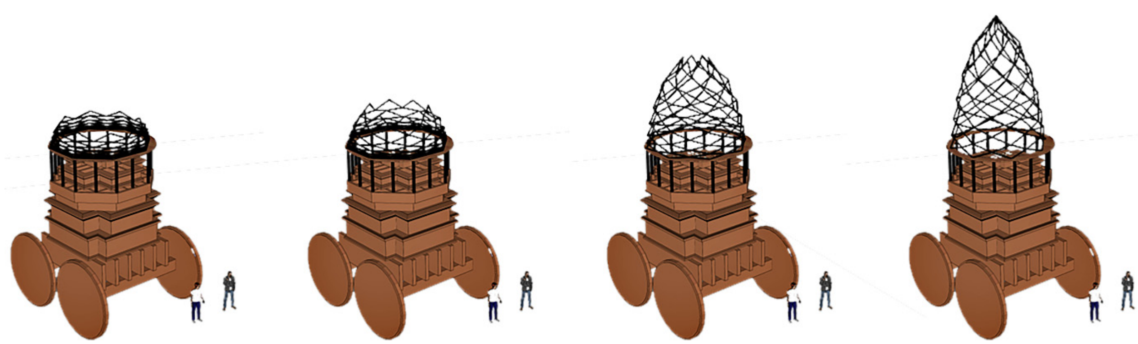

Fig. 4 Deployment sequence of a temple-car dome.

An Interdisciplinary Course Proposal

Deployable structures has become a subject of growing relevance and students recognize the importance and need for architecture that responds to external conditions and stimuli. Seeing the enthusiasm in students, the author has proposed a campus-level interdisciplinary course on *Deployable Geometries and Adaptive Structures* as part of the new Illinois Design Center curricula.

Deployable structures intrinsically have an integrative capacity and the possibilities of creating new and efficient deployable systems are endless when concepts natural to certain disciplines but alien to others are considered in the context of disciplinary diversity. The course would demonstrate how knowledge from biology, architecture, mathematics, computer science, materials science and engineering (Fig. 5) when combined can systematically inform design thinking and the making of deployable and adaptive structures. Explicitly understanding the relations between the various disciplines and integrating their potential during the conceptual phase enhances design quality and lead to a coherent design. There is also an intellectual onus in such an endeavour as experts from several disciplines are part of the design process right from the onset of a project. Consequently, the motivation would enhance the possibility for highly successful collaborative designs.

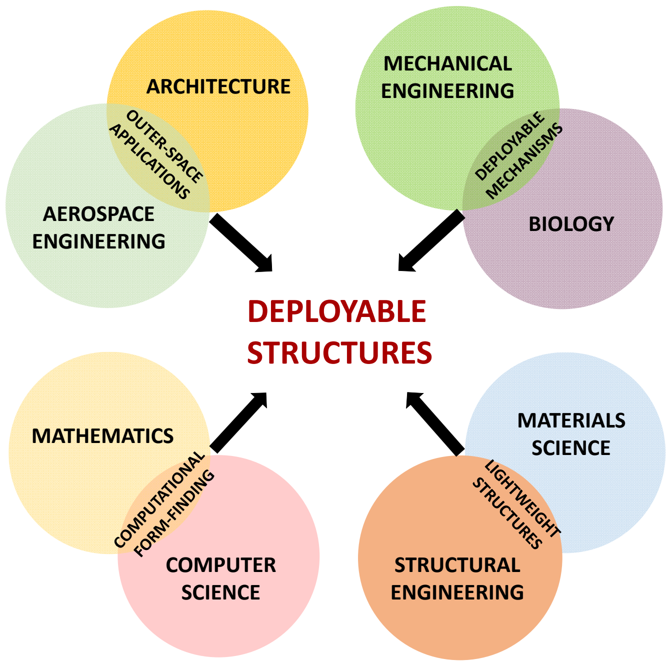

Fig. 5 Interdisciplinarity in the Design of Deployable Structures

The course would include:
1. Weekly discussions and presentations
2. Project-based assignments
3. Lectures and workshops by specialists from allied disciplines

As part of design projects, teams would develop new geometries, mechanisms, algorithms, details and fabrication methods and eventually construct their project for a particular use. Computer models and physical models will be required to demonstrate the deployment process and trajectory. Depending on the nature of the project, teams may comprise of students from biology, architecture, industrial design, mathematics, computer science, aerospace, mechanical and structural engineering. A partial list of potential topics include: (1) Designs of deployable roofs for stadia; (2) Design of a kinetic façade system and its actuation mechanism; (3) Design of foldable furniture for efficiency or studio-type apartments; (4) New mechanical linkages using mechanisms from nature; (5) Actuation methods through external mechanisms, thermal variation, and/or self-folding processes; (6) Applications of origami-based deployable systems in architectural structures; (7) Mathematical algorithms for foldable geometrical forms; among others. Topics shall be updated to reflect new advances in materials, analyses and design methods.

The course is expected to strengthen project-based instruction, optimize student learning experiences and help them achieve their potential by fully employing the intellectual resources available in the Urbana-Champaign campus. The aim is to tap the creative and intellectual potential across the campus where allied disciplines could bring the much-needed difference to the design of deployable structures. The course may be offered as undergraduate capstone design course or graduate-level seminar.

Conclusions

1. Design of deployable structures falls in the interface between biology, mathematics, art, architecture and engineering. Such structures may be the main structural system of a building or may be employed selectively in kinetic facades, enclosures, roofs and other parts of a building.
2. Structural engineering and architecture curricula do not typically include courses on special structures such as tensegrity, tensioned-membrane and deployable structures. As such, students graduate with a glaring omission in their body of knowledge unless they take up independent study courses under the supervision of specialized faculty doing research on the said structures.
3. Courses on special structural systems should be considered in the core body of knowledge in architectural and architectural engineering curricula with the aim to strengthen project-based instruction, optimize student learning experiences while fully engaging the intellectual resources available on university campuses.
4. A course on deployable structures would be best realized when taught as a design studio or as a complementary course parallel to a studio. The possibilities of creating new and efficient deployable systems are endless when taught in the context of disciplinary diversity.

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