Rapidly Deployed and Assembled Tensegrity System

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INTRODUCTION

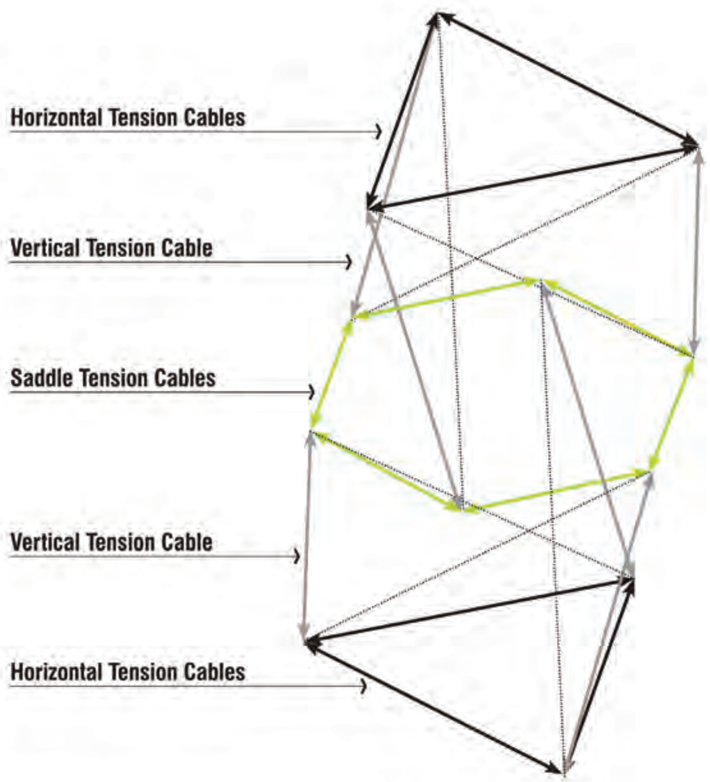
The Rapidly Deployable and Assembled Tensegrity (RDAT) system is developed based on the author) sresearch focusing on the invention of computationally produced performative full-scale building systems and how they can be utilized in an innovative manner in the building and construction industry.[1] Currently, the RDAT research is at the stage of full-scale production of tensegrity masts and plates with variable geometric configurations, including the necessary design, analysis, and production workflow. The goal of the RDAT program is to enable rapid design and deployment of a wide variety of differential-geometry tensegrity structures through computational driven design to installation workflow at the scale of architectural building systems. The project incorporates the integration of parametric and solid-modeling methods to enable computer numerically controlled (CNC) manufacturing of components and the efficient assembly of this complex system in the field through innovative design detailing and production methods.

HISTORIC TENSEGRITY SYSTEM CONSTRUCTION

The RDAT program leverages the advantages of tensegrity structures coupled with advances in science and technology produced since their inception. In 1975, Buckminster Fuller coined the term "tensegrity" as a conjunction of the two words tension and integrity.[2] The term describes a structural system of compressive and tension members that yield mechanical equilibrium. More recently, Pinaud, Masic and Skelton[3] precisely state that tensegrity structures are established when a set of discontinuous compression components interact with a set of continuous tensile components to define a stable volume in space. Recent research in tensegrity has expanded to include those biological systems such as bone and tendon configurations as the study of forces and indeterminate structures through computational analysis has allowed the science in the field to open considerably.

Although contemporary architects and designers now have access to computational tools that could potentially solve the indeterminate structural forces associated with tensegrity structures, very few tensegrity systems are developed within the architecture profession due to some of the inherent features of the structures. The systems tend to be difficult to precisely form, have flexibility under load beyond normative architectural structures, and require

Figure 1: Tensegrity prism structural topology



materials and detailing that are more advanced that is normally possible in building conditions. Renewed interest in deployable structural systems, cable facade systems, and fabric tensile structures demonstrate the need for an interface that architects can use to efficiently develop tensegrity designs prior to completing the cumbersome calculations traditionally associated with indeterminate form-finding.[4] For example, Kenneth Snelson's tensegrity sculptures are the embodiment of the Fuller and Pinaud (et al.) definitions of tensegrity. His methodology is based upon physical model building, numerous measurements, and iterative refinement of tension cable lengths on the final unique piece. Research completed at the Max Planck Institute for Intelligent Systems in Stuttgart states that one analytical form-finding method exists that requires the designer to predefine the cable length but then calculates the ratio directly without involving the iterative process.[5] Contemporary computational tools can be hardest to bring about a more efficient integration of digital and physical production in the creation of indeterminate structures.

Tensegrity structures offer numerous advantageous properties. As three-dimensional self-stressing cable systems, they have a relatively small number of disjoint compression members (fig. 1). They are self-erecting, in that tensioning the final cable transforms them from a compact group of members into a large three-dimensional volume.[6] As such, tensegrity systems are extremely lightweight and materially efficient, embody resilient properties, allow system flexibility, and are composed of primarily standardized linear elements. In addition, within the RDAT system, they are now calculable, easy to assemble, and reconfigurable, offering potential uses as structural reinforcement, infrastructural elements, reusable or left-in-place formwork, scaffolding, and other building construction elements, as well as the well understood use as flexible building components such as roofs, curtain-walls, and other similar systems.

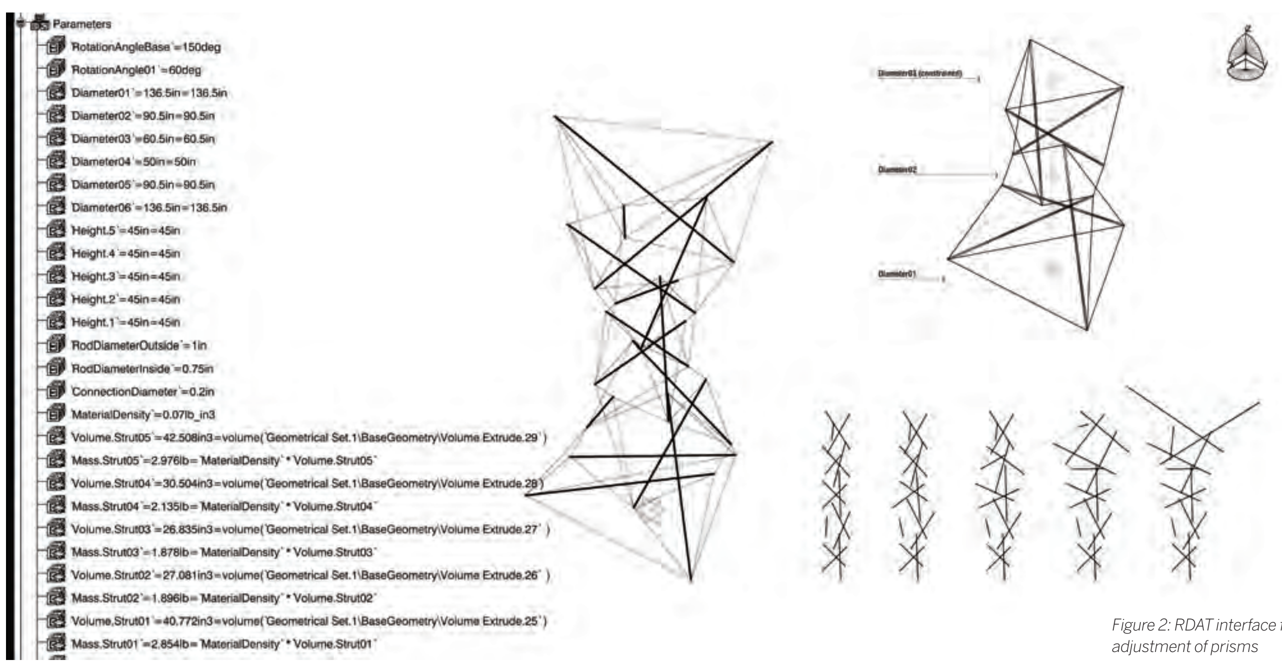


Figure 2: RDAT interface for adjustment of prisms

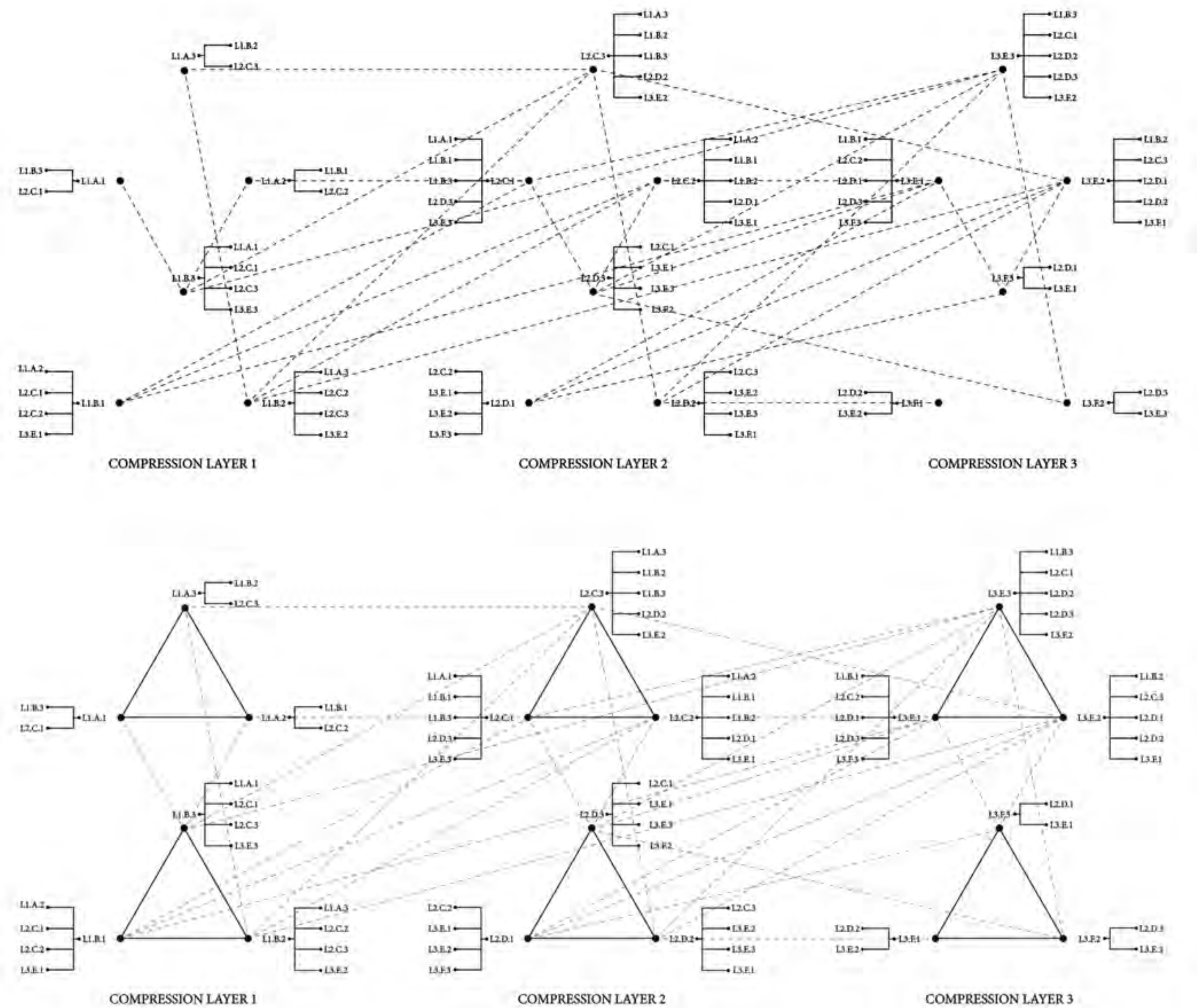


Figure 3: RDAT tools allows for free design while retaining fabrication specifications

RDAT DESIGN METHOD

As a design methodology, the RDAT system integrates these properties with digital design tools, a detailed set of components, and digital fabrication technologies into a cohesive system, mitigating the interoperability issues associated with existing cross-platform design, analysis, fabrication, and project delivery methods. The goal is to develop an optimized, project-dependent workflow to resolve interoperability conflicts by adapting existing solutions and proposing innovative alternatives.

Since the late 1980s, architects and engineers have used computer-aided design and manufacturing (CAD/CAM) tools to develop building projects while narrowing the gap between representation and fabrication. Researchers have argued that advances in digital design and fabrication have led to a triumph of appearance over substance and that few truly new materials, features, and processes have resulted from the proliferation of digital design techniques. Furthermore, the reliance of architects on craftsmen and fabricators to carry out their designs suggests that architects are disconnected from the skill of making. Research on the use of digital design tools (CAD/CAM, BIM, scripting and computational analysis), project delivery methods, and fabrication technologies, in order to synthesize full-scale case study projects led to new proposals to develop the use of

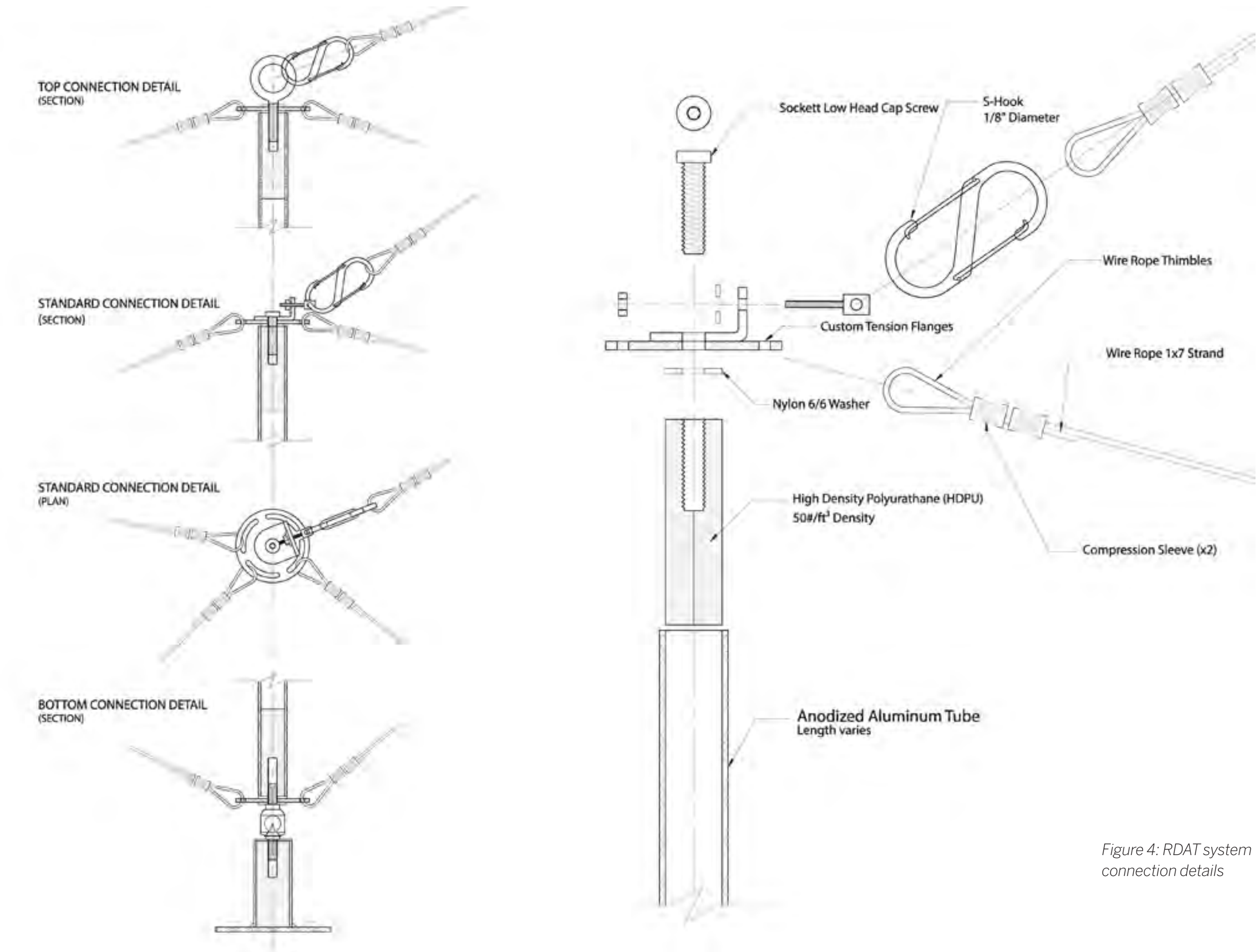


Figure 4: RDAT system connection details

innovative materials and novel processes, and ultimately, to reintroduce making to architects as an integral component of digital design and fabrication.[7]

Prototyping done within the framework of existing software is a critical method of rapidly developing a set of processes for testing, while simultaneously developing the criteria for the eventual programming of the custom design and analysis tools that the author is currently engaged in. Using CATIA Generative Shape Design and CATIA Knowledge Patterns combined with Rhino and Grasshopper studies, the RDAT system concludes with the fabrication of a tensegrity tower derived from designs parameterized in the computational system through a customized program interface (fig. 2). The digital and associated physical fabricated components address pre-stressing or post-stretching of the tension elements during the assembly process, as well as assembly tolerances, while being able to track each category of element for optimizing strength, assembly sequence, and inventory (fig. 3).

The RDAT detailing was developed to allow for variable parametric assembly processing with the ability to be quickly deployed, demounted, and reassembled for numerous tension line configurations. Additionally, the node is simple to construct, as strong as traditional tensegrity connection methods, efficient, and elegant (fig. 4). The fundamental process relies on the inherent compressive forces on the strut at the node detail by the combination of three acute angle tension wires and one obtuse angle wire. At each node, the three-dimensional vectors combine to a resultant vector that is always directed into the node, thus preventing the separation of node and strut (fig. 5). This allows for rotation to relieve internal stresses from system flexing, and the struts easily engage and disengage during assembly and demounting of the structure.

The RDAT node, currently under patent application, is fundamentally composed of a cylinder of material that is machined to fit within the strut. In the case study, fabricated high-density polyurethane foam was used to

Figure 5: RDAT node in Urban Forest case study

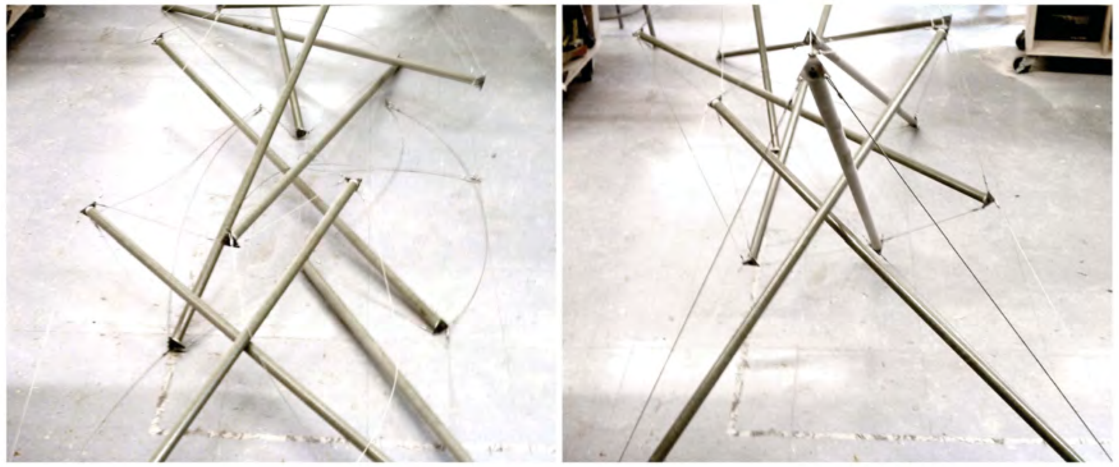


Figure 6: Final assembly step in RDAT tower

Figure 7: RDAT six-meter tower is light enough to be erected by only one or two people

prototype the cylinders to fit snugly within the anodized aluminum tubes. The CNC equipment was used to tap a thread into the center of the cylinder for the attachment of the connection disk. The connection disk is a disk of plasma-cut steel that can be bolted to the cylinder as well as connected to the four tension lines at the node. The cutting of the disk is detailed to allow for tolerance at the tension connections; the load is transferred to the disk and strut simultaneously for seamless force-flow through the system.

Once all elements are produced using extracted computer model data, the process for assembling a completed tensegrity prism is 1) construction of nodes, 2) assembly of an end-prism, and 3) attachment of the remaining prism elements linearly to the end-prism (fig. 6). Once constructed on a horizontal surface, the structure is lightweight enough to be positioned vertically by one or two people, depending on the height of the complete structure (fig. 7). If the structure is to be demounted and transported, the procedure is reversed: place the assembly in a horizontal position and 1) remove the primary tensioning cable at one end-prism, 2) collapse the end-prism, 3) remove one cable from the adjacent prism, collapsing the prism, repeating step three until all prisms are collapsed, and then bind and fold each set of rods on the others until a single package of rods and cables is collected and bound together (fig. 8). While assembly is longer in duration than disassembly, a five-prism structure such as the case study has been assembled in as little as one hour.

Figure 8: RDAT six-meter tower packed for shipping

RDAT COMPUTATIONAL/ PRODUCTION HYBRID METHOD

Production of a tensegrity structure—fabrication, assembly, and installation—has historically been the site of trial-and-error methods as described above. The RDAT system integrates the design, analysis, fabrication, and assembly of the system through developments based on the authorssepprevious work in advanced networked structural systems. A critical aspect of the development of a seamless workflow is the step between the computational form-finding and analysis and the manufacturing of the components for physical construction. The creation of a detail that is designed from its inception to conform to the algorithms and parameters that are incorporated into the software, including geometry, material properties, degrees of freedom, and other aspects of the system, is essential to assure that the produced components have the capacity to perform as designed. Simultaneously, a feedback loop is put in place to allow developments during prototyping, case studies, and physical testing to integrate results into the programming of the CAD/CAE system to ensure that the computational component conforms to the production component. Through a series of case studies where building scale production is realized, the system can be tested against performative and production criteria.

CASE STUDY 1: URBAN FOREST, MONTPELLIER, FRANCE, 2010

The *Urban Forest* installation was assembled at the Seventh Annual Festival des Architectures Vives exhibition in Montpellier France in June, 2012, and served as a test for rapid deployment of a full scale system due to the requirements of erection within one night. The structures are composed of three six-meter tall conical tensegrity towers of anodized aluminum compression members and stainless steel tension members (fig. 9). Installed in the Hotel de Griffy courtyard in Montpellier, the towers suspend a network of metallic mylar "leaf" elements that reflect and colorize sunlight through dichroic action as it streams down the courtyard to the inhabited space below (fig. 10). The modified five-prism tower structure incorporates an innovative nodal design allowing for rapid deployment with a minimal amount of time and labor, and folds to fit a shipping container measuring two meters long and 50 centimeters in diameter.

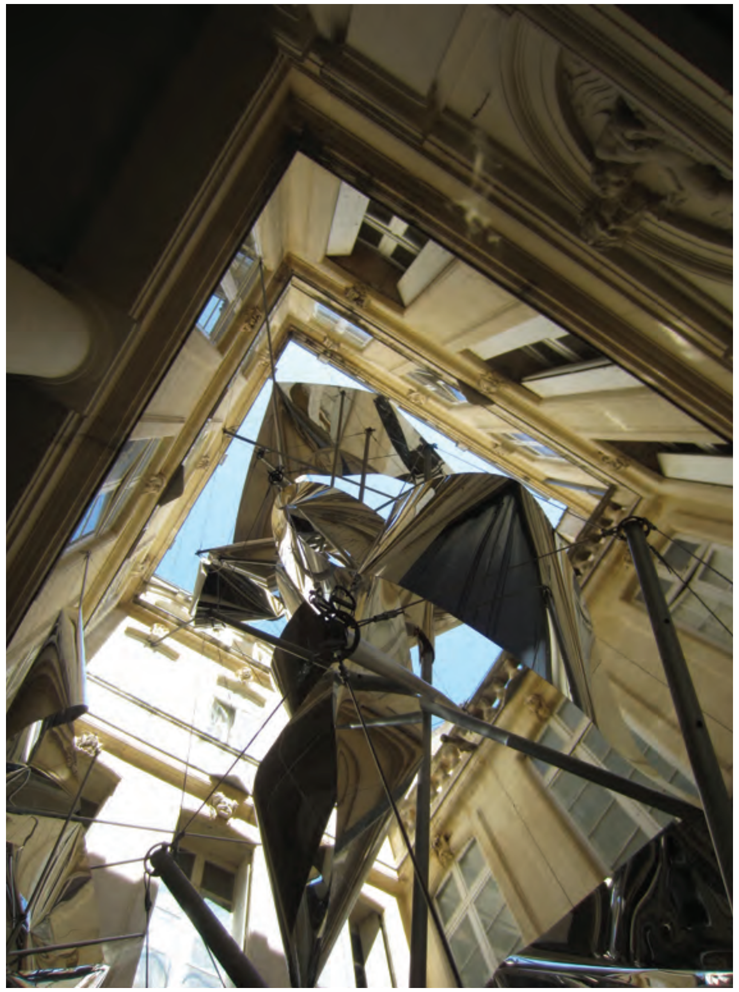


Figure 9: Urban Forest installation in Montpellier, France

Urban Forest is a prototype for digitally fabricated tensegrity structures in the form of self-supporting towers, and a means to demonstrate and test the structural strength as well as its formal capacities. *Urban Forest* is an initial prototype driven by ideas in the greater context of potential architectural applications, such as efficiency in materials, structural strength, and other technical

Figure 10: Urban Forest installation in Montpellier, France

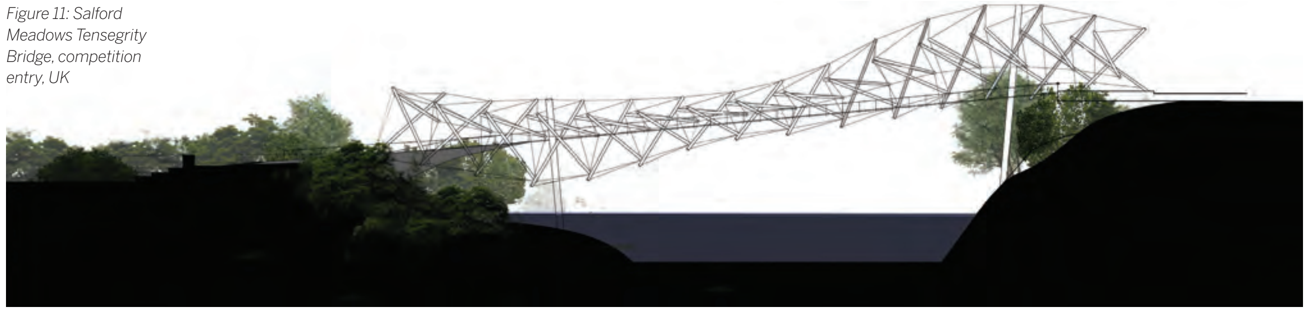


Figure 11: Salford Meadows Tensegrity Bridge, competition entry, UK

Figure 12: Salford Meadows Tensegrity Bridge, competition entry, UK

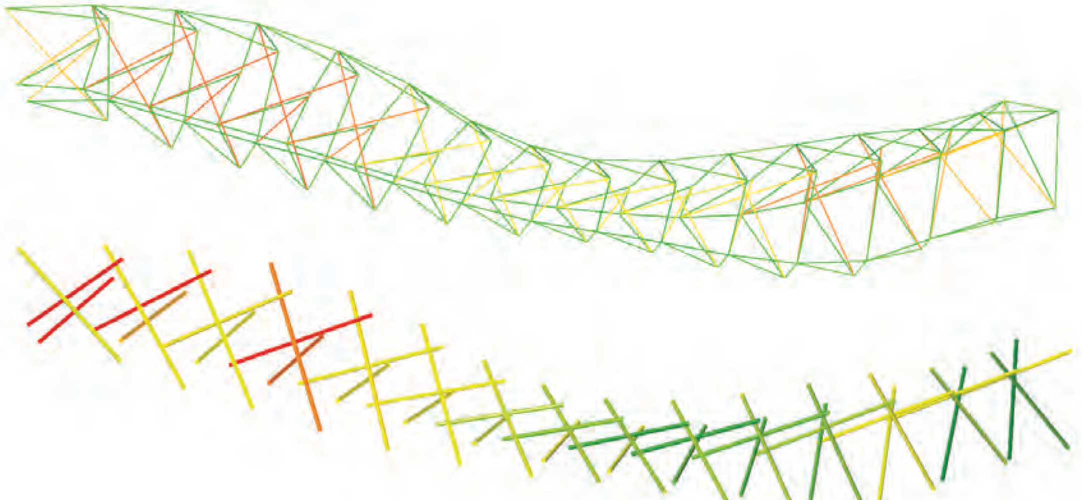


Figure 13: Tensegrity tensions and compression structural analysis

Figure 14: Form-finding algorithm iterations

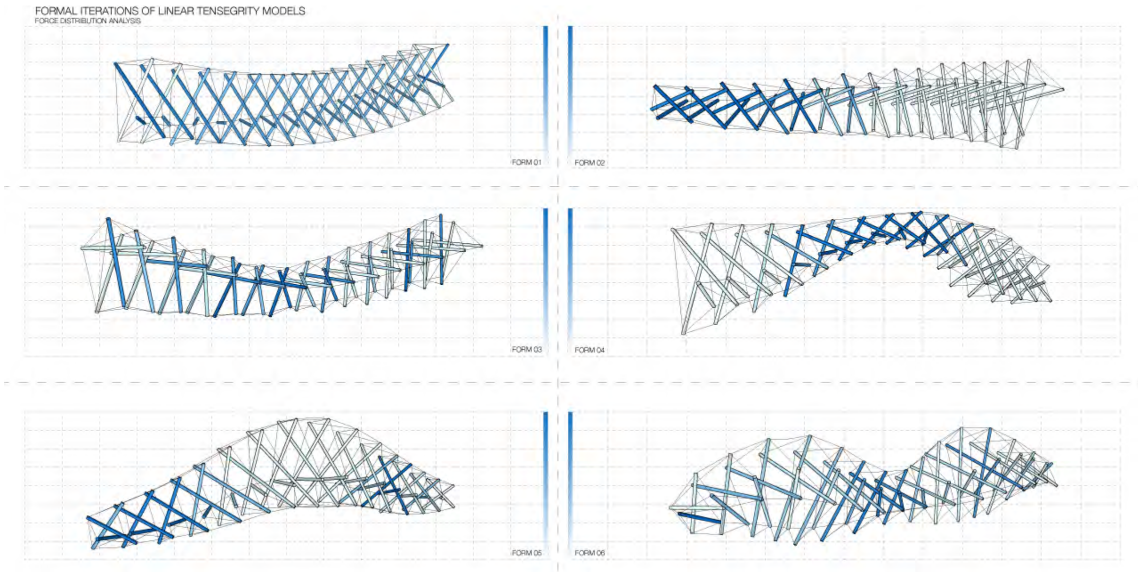


Figure 15: Rendering, Toward a New Industry installation, AIA Center for Architecture, NY

benefits. Tensegrity presents a system that is easily transportable, collapsible, and has the potential to create large walls, enclosures, and structures with a minimal amount of materials.

The *Urban Forest* case study was used to test the ability to prefabricate the components in place within the structural configuration, collapse the structure for shipping, and redeploy with a minimal of time and labor required. This project was erected in France by one person over the course of an evening, proving that the design concept was sound while revealing potentials for improvement in the design and detailing that were added to later iterations.

CASE STUDY 2: SALFORD MEADOWS TENSEGRITY BRIDGE COMPETITION, 2013

The Tensegrity Bridge entry for the Salford Meadows Bridge Competition seeks to provide a needed link between Salford Meadows and the surrounding community, while simultaneously promoting an efficient and functional structure and celebrating the future potentials of Manchester (fig. 11). With a nod to the rich industrial past of the local community, the innovative tensegrity structure proposed reinforces the dynamic nature of the nearby Engineering Faculty of the University of Salford and develops a catalyst for encouraging future growth (fig. 12). The importance of the local community demands a world-class structure as a response to the development of the city.

Tensegrity Bridge was developed through an in-house computational program to streamline the design, analysis, and production of a tensegrity system through parametric solid-modeling and computational physics simulations, allowing for the formulation of a sinuous shape that weaves the cable supports around a linear direct pathway (fig. 13). The design strategy develops the potential of Salford Meadows by creating a link and attracting new visitors, while expressing the bridge as a landmark through the highly visible configurations at the landings of the bridge. The system is engineered to take advantage of the forces developed in a pedestrian bridge of this scale through computational sizing and configuration of the elements and the tensegrity form. The structure is naturally resilient and self-tunes to develop counter-vibration, dampening movement due to passage of pedestrians. Suspension supports for the footbridge, connected with an isolating detail, reduce vibrations through dispersing the forces in the naturally resilient tensegrity system. The lightness of the structure reduces the need for extensive foundations at the embankment so that support can be focused primarily on two point loads above the river, providing a less invasive grounding condition and simultaneously expressing the gracefulness of the proposal.

This competing entry allowed for the study of a full-scale application with the collaboration of Dr. Will Laufs, an engineer with extensive specialty structures expertise, including tensegrity structures. The author was able to test the form-finding and analysis of his computational format in response to the program and the engineerlysadvice (fig. 14). Further refinements in the algorithms used resulted from the application of the system at bridge scale.

CASE STUDY 3: AIA CENTER FOR ARCHITECTURE INSTALLATION, NEW YORK, NEW YORK, 2014

The *Towards a New Industry* installation quietly explores the ambient possibilities of new industry, tensegrity systems, and new media with an exhibition of projects and content related to AECOM's 2014 student competition Urban SOS: Towards a New Industry. Featuring video integrated in three tensegrity sculptures, the exhibition curates the four finalist projects as well as schemes from other program participants. The system is a triad of self-supporting tensegrity towers where the placement of the structures allow individuals to freely circulate around each respective tower, experiencing the layering of materials and video projection from different vantage points (fig. 15). The self-supporting nature of the tenseg-

Figure 16: Toward a New Industry installation, AIA Center for Architecture, NY

rity towers introduced a unique design and fabrication challenge. The formal quality of the sculptures along with an intelligent use of materials required the collaboration and expertise of various designers (rounding condition and simultaneouone which defines the success and spirit of the Urban SOS program.

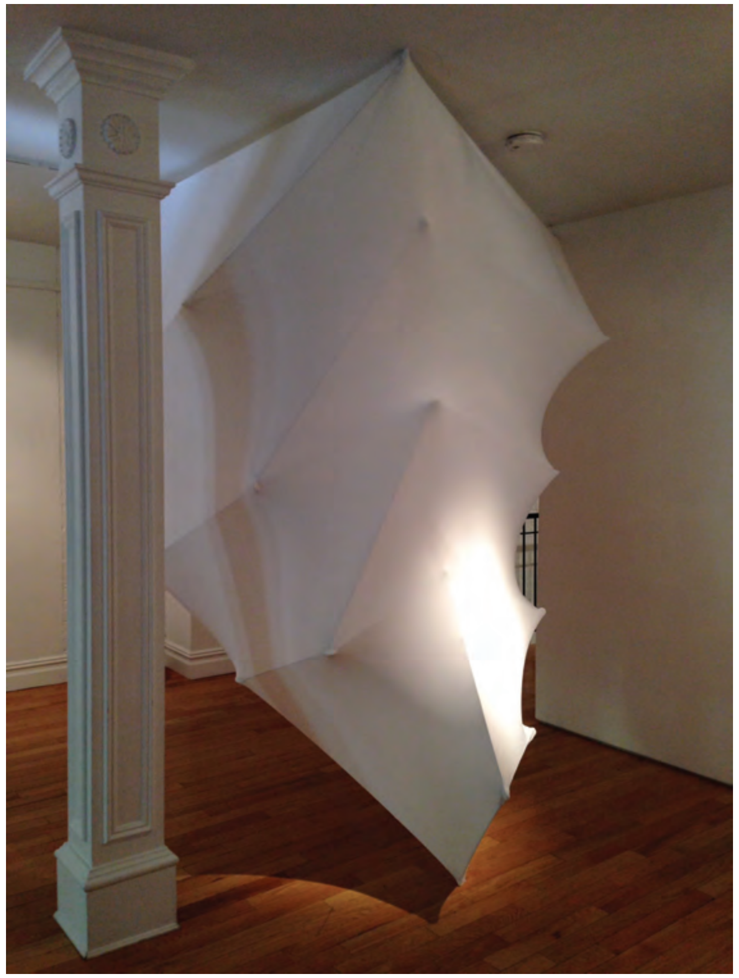
The *Towards a New Industry* installation allowed the author to further refine the system to include adjustable detailing for field modifications (fig. 16). The addition of relatively high weight projectors to the system on-site posed a challenge to the form-finding algorithms that needed to have adjustment capabilities once installed (fig. 17). A novel adjustable node and strut system was added that accommodated changes on-site to the system and loading conditions, bringing the RDAT system closer to the goal of an automatically actuated system.

CURRENT RESEARCH AND FUTURE DIRECTIONS

Initial research partially addresses digital design and fabrication issues with tensegrity systems, but more importantly, it exposes the disconnect between ease of digital design and the realities of constructing complex geometric systems. In particular, the tensegrity tool provides the designer with a CATIA dependent workflow that adjusts the tensegrity structural system based upon user inputs while also generating the necessary fabrication specifications. However, successful deployment of a tensegrity structure remains in the execution of the assembly methods used outside of the digital design and digital fabrication toolbox. Furthermore, synthetic biology research affirms the need for physical testing of prototype composite materials in order to validate the computational analysis. With the existence of an optimized digital workflow, efforts should be focused on developing an interface for transitioning digital design content into manufacturable objects by adapting existing fabrication technologies or designing new fabrication solutions.

The goal of future work will be to contribute to the design, production, and realization of innovative projects through continued research in digital design and fabrication technologies (fig. 18). Current developments include generalizing the prism geometry beyond three struts, expanding the mast structure into a planar surface, and incorporating actuated sensing and programmed systems into the structure. Currently, work is being initiated by the author at the CUNY College of Technology in collaboration with interdisciplinary teams to innovate in the computational algorithms and interface (with the Computer Engineering Technology Department), and to develop a reconfigurable MEMS joint and strut system that will allow tuning and topology adaption (with the Mechanical Engineering & Industrial Design Department) and a system to research modes of automated assembly in on-site constructor conditions (with the Civil Engineering & Construction Management Department). Future interdisciplinary research trajectories include the incorporation of energy generating and storage strategies with a robotics industry partner as part of a building integrated system.

Figure 17: Toward a New Industry installation, AIA Center for Architecture, NY



ENDNOTES

1. For instance, see the author's "Systems and Methods for Construction of Space-truss Structures," USPTO# US20060254200.

2. R. B. Fuller, *Synergetics: Explorations in the Geometry of Thinking* (London: Collier-Macmillan,1975).

3. J.P. Pinaud, M. Masic, and R. E. Skelton, "Path planning for the deployment of tensegrity structures," *Smart Structures and Materials*. Vol. 5049 (2003): 436-47.

4. J. Y. Zhang, M.Oshaki, Y. Kanno, "A direct approach to design of geometry and forces of tensegrity systems," *International Journal of Solids and Structures*, vol. 43 (2006): 2260-278.

5. H. J. Bugartz, "Analytic and numeric investigations of form-finding methods for tensegrity structures," Stuttgart: Max Planck Institute for Metals Research, 2007.

6. I. J. Oppenheim and W. O. Williams, "Mechanics of Tensegrity Prisms" (Pittsburgh: Carnegie-Mellon University, 1997).

7. http://www.arch.columbia.edu/labs/laboratory-applied-building-science/projects/fabrication-workshops

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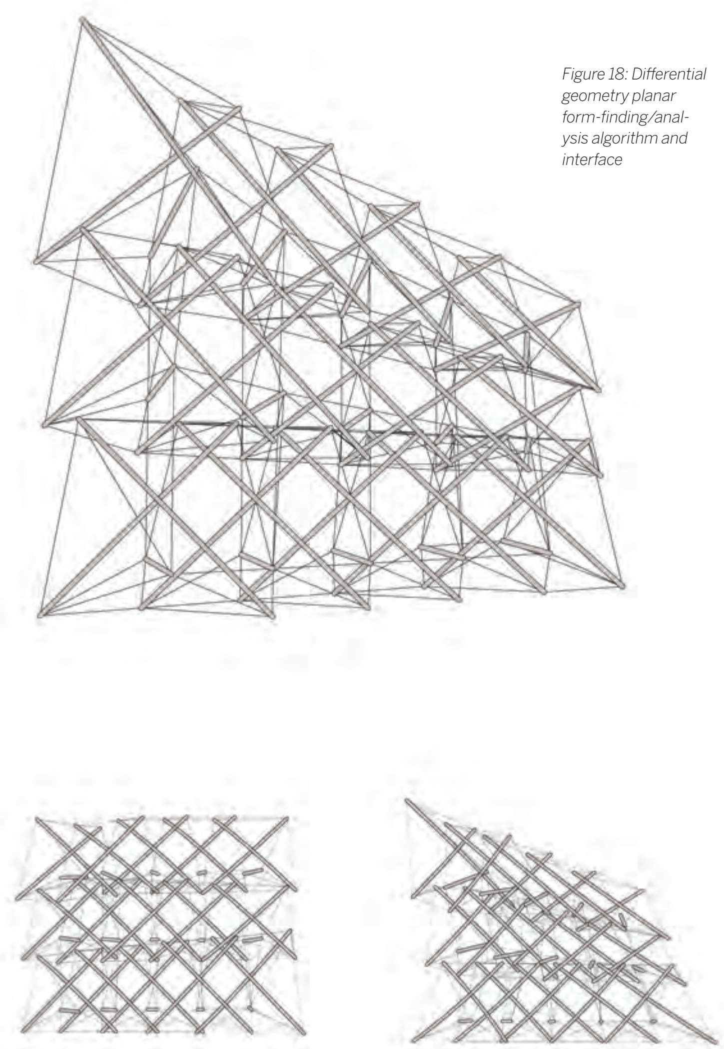

Figure 18: Differential geometry planar form-finding/analysis algorithm and interface