2D Workspace Analysis of a Tensegrity Robotic Arm

Aarav P. Patel

Abstract

Tensegrity structures are known for their stability, which is achieved through continuous tension and unique compression elements. These features make them extremely useful in robotics as they offer benefits like lightness, adaptability, and resilience. The main goal of this study is to define a reachable workspace of a robotic arm made up of multiple 3-bar prism modules. We start by exploring the basic ideas of tensegrity and its importance in robotics. This path will provide us with both a deep understanding and advanced knowledge of the mathematical concepts that form the basis of tensegrity structures. Following this, the project will move into a detailed examination of the workspace of a single T-bar prism module. This is essential for grasping the more complex workspace of the entire multi-prism robotic arm system. The analysis phase includes identifying all the possible positions within the 2D workspace that the robotic arm can reach. This requires the use of mathematical models and simulations to visualize and measure the arm's spatial abilities.

Keywords: Tensegrity structures, Reachable points

1. Introduction

The concept of tensegrity with its diverse applications in robotics creates a web of biology, engineering, and art. The origins of tensegrity date back to the innovative contributions of artist Kenneth Snelson and architect Buckminster Fuller. Snelson's 1948 creation, "X-Piece" (Snelson and Kittel 2015), and Fuller's following advancement and naming of the concept had established the founding principles for modern tensegrity studies. ("Tensegrity – Buckminster Fuller Institute", n.d.)

Tensegrity robotics, which expresses the principles of tensile tensegrity, is composed of a network of stiff struts and flexible cables. This distinctive architecture enables them to change shape as they can balance their rigid nature for structural support and flexibility for absorbing impacts. With such versatility, tensegrity robots perform exceptionally well in dynamic settings as they are capable of various locomotion modes including rolling, hopping, and crawling. Designing and simulating these robots presents us with numerous challenges such as state sensing and kinodynamic motion planning due to the complex interactions among their components. ("Tensegrity – Buckminster Fuller Institute", n.d.)

Kinodynamic - is a class of problems for which velocity, acceleration, and force/torque bounds must be satisfied, together with kinematic constraints such as avoiding obstacles (“Kinodynamic planning”, n.d.)

In context of tensegrity robotic arms, the importance of morphing capabilities and equilibrium conditions are critical. These robots maintain structural integrity through a precise balance of tension and compression which necessitates the need for exact control over the cables’ lengths and tension. This involves form-finding problems to determine the optimal or most efficient structural shape for specific functions.

The development of these robots also entails cataloging various shapes for both open-loop and closed-loop shape control trajectories which are crucial for understanding how the robotic arm can adjust and respond to different tasks and environments. The design principles guide or create a balance between rigid and flexible elements creating continuous actions of bending and movement.

Furthermore, the biomimetic aspects of tensegrity structures, which mimic biological forms and functions, have gathered interest from biologists, engineers, and artists alike. Tensegrity principles are seen in various natural structures, from the cellular level to larger biological systems, which provides insights into efficient, durable, and resilient designs.

However, when modeling and simulating tensegrity structures there are significant challenges. The complexity of these systems can create potential inaccuracies in data collection and analysis. Recognizing the limitations is essential for further advancing the design and control strategies of tensegrity robots.

The primary goal for researching the T-bar prism tensegrity robotic arm is to examine and delineate its workspace so that we can understand the capabilities and limitations inherent within the system. This research is aimed to further enrich the broader field of robotics by offering adaptable, efficient, and biomimetic solutions. The study of tensegrity in robotics continues to be driven by the mission to completely control these structures’ unique properties flexibility, strength, and biomimetic potential - so that we can advance the field of robotics with innovative and practical systems in the application of diverse systems.

2. Mathematical Background

Vectors are critical mathematical tools in numerous scientific and engineering disciplines, as they serve as a representation of magnitude and direction. These are indispensable in fields like physics, mathematics, engineering, and computer science. In physics, vectors are crucial for modeling forces, velocities, and accelerations letting comprehensive analysis of physical phenomena such as motion, electromagnetism, and fluid dynamics take place. Mathematics uses vectors for spatial reasoning, transformations, and exploring vector spaces which are foundational to much of modern algebra and geometry. In engineering, vectors are applied in designing and analyzing structures, mechanical systems, and simulating electrical circuits which helps us understand and manipulate complex systems. In computer sciences, vectors are used in algorithms, data structures, and particularly in computer graphics, where they model shapes, paths, and motions within virtual environments. Vectors' broad utility makes them a connective element between theoretical concepts and practical applications which allow for them to provide precise description, analysis, and resolution of problems across these related fields.

Mathematical vectors are essential in the simulation of tensegrity structures as they act as the central language for describing and analyzing the complex interactions of forces and displacement in these systems. In the realm of tensegrity, which features a network of elements under tension and compression, vectors are crucial for representing both the directions and magnitude of forces exerted by cables (tension elements) and struts (compression elements), as well as for determining the positions of nodes, where these elements converge. Accurately calculating vector quantities is vital for simulating the ever-changing nature of tensegrity, as they facilitated predictions of structural behavior under stress and deformations. This mathematical concept is essential to understanding how tensegrity structures manage stress distribution and adapt to change which is furthermore essential for the design and control of robotic systems based on the principles of tensegrity. Through the application of vector analysis, engineers and researchers alike can fine-tune tensegrity configurations to enhance stability, flexibility, and efficiency. Therefore, vectors play a crucial role in the development of tensegrity applications not only in robotics but also in broader fields. ("Network and vector forms of tensegrity system dynamics", n.d.) ("Equilibrium Conditions of a Tensegrity Structure", n.d.) ("Equilibrium Conditions of Class 1 Tensegrity Structures", n.d.)

$$\vec{x} = \begin{bmatrix} 5 \\ 2 \\ 9 \end{bmatrix} \qquad \vec{y} = \begin{bmatrix} 3 & 1 & 4 \end{bmatrix}$$

Figure 1: Example of Vector

Using Figure 1 as an example, imagine the construction of a robotic arm using tensegrity (for reference look at Figure 7 below). Here the nodes of the structure are represented in space by vectors. To arrive at a vector like $\vec{x} = [5 \quad 2 \quad 9]$, each entry would correspond to the position of a node along the x, y, and z axes in a three-dimensional model. The vector x could represent the position of a node from the arm's base when the arm is extended to reach an object. Similarly, vector $\vec{y} = [3 \quad 1 \quad 4]$ can describe the forces applied along the links or compression forces connecting the nodes where each number describes the magnitude of the tension in the cables or compression force in the struts. In the context of tensegrity, vectors are incredibly important for mapping out how the structure will react to different positions and forces.

Matrices are critical in linear algebra and hold significant importance both in mathematics generally and specifically in their application to tensegrity structures. In mathematics, matrices serve as a compact and powerful tool for representing and manipulating linear transformations, solving systems of linear equations, and executing operations like rotations, scaling, and translation, which are vital in various mathematical branches and applications. Their significance also extends to the study of tensegrity structures where matrices are incredibly vital for modeling the complex interactions among the components of the structure. In the context of tensegrity systems, matrices are used to depict the stiffness of the structure, the distribution of forces, and the geometry of the components which therefore gives aid in the analysis and simulation of the structure's behavior under different loads and conditions. This matrix-based method is crucial for accurately calculating deformations, vibrations, and stability criteria which provides key insights into the design, optimizations, and control over tensegrity structures. Through their capacity to represent complex relationships and further efficient computations, matrices are critical in linking abstract mathematical concepts with practical engineering applications, especially in the ever-changing area of tensegrity.

("Equilibrium Conditions of a Tensegrity Structure", n.d.) ("Equilibrium Conditions of Class 1 Tensegrity Structures", n.d.)

$$K = \begin{bmatrix} 1 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 1 \end{bmatrix}$$

Figure 2: Example of Matrix

In reference to Figure 2, Matrix K can represent the stiffness matrix of the structure which is an essential component in any tensegrity design. The matrix could hypothetically correspond to the interactions between nodes of the tensegrity module. For instance, the first row, with values 6, 3, and 1, might represent the stiffness coefficients that relate to the first node of the arm which can influence how it interacts with the other nodes. These coefficients are used to determine how much the node will respond to deflections of internal forces and external pressure. The second row, with a -2, shows a different type of variable which represents the amount of compression within the system while positive elements, such as 4, represents tension. The third row could describe the behavior of another node again with positive and negative values that indicate the different degrees of tension and compression effects from the other nodes or external interactions. In relation to tensegrity, the matrix can represent the structure's reliance on every component, where the values and arrangements within matrix K lets us understand and predict the arm’s behavior.

In the study and construction of tensegrity structures, node matrices, and connectivity matrices are crucial for understanding the interactions within tensegrity systems. A node matrix records the positions of the nodes (or junctions) where the structural elements of a tensegrity system - tension cables and compressed struts - meet. This matrix is incredibly important for outlining the spatial configuration of tensegrity structures as it allows us to visualize and analyze their geometric properties. Conversely, the connectivity matrix, also known as the incidence matrix, outlines the connections between nodes and structural elements. It details which elements are connected to which nodes which allows it to represent the network of forces and dependencies that define the tensegrity’s structural integrity and behavior. These matrices are dynamic tools and are utilized in simulations to predict how tensegrity structures react to external forces, deformations, or changes in configurations. They aid in the calculation of structural parameters or limits with factors such as stiffness, stability, and potential configurations of failure. Ultimately, node and connectivity matrices are key when translating the conceptual design of tensegrity systems into practical tangible applications. They allow precise design, analysis, and optimization of these structures in various fields, from robotics to architecture, where tensegrity laws are used to create systems that are both lightweight and structurally sound. (“Analytical definitions of connectivity, incidence and node matrices for t-struts tensegrity prisms”, n.d.)

$$N = \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}$$

Figure 3: Node matrix for D-Bar Simulation

Figure 3 represents a node matrix for the D-Bar simulation found in Figure 6. As stated previously a node matrix records the position of the node so when considering node matrix N, the assumption is made that these values represent the node placements in a 2D plane. In this matrix, each column corresponds to a node in the structure while each row represents the x and y coordinates. The 1s in the first and second row columns describe the end of a structural element while the -1s represent the start of a bar or string. For a tensegrity structure, this matrix is vital in tracking which nodes affect one another and in which direction forces need to be calculated during the simulation. When programming the robotic arm’s response to external stimuli or movements, engineers would use matrix N to calculate the changes in node positions that allow the structure to flex and move while maintaining structure. (“Analytical definitions of connectivity, incidence and node matrices for t-struts tensegrity prisms”, n.d.)

$$C_b = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 1 & 0 & 0 & -1 \end{bmatrix}$$

Figure 4: Bar Connectivity matrix for D-Bar Simulation

In tensegrity robotics, a connectivity matrix like $C_{b,}$ is used to map out the relationships between nodes and components - cables and struts. Each row in C_b represents a bar and each column is a component with the -1s and 1s, the number of columns representing the number of nodes. This matrix is essential for simulations that reveal how a robotic arm maintains stability and reacts to external forces which is crucial for creating robots that can navigate and manipulate themselves with the adaptability that is inherent in tensegrity laws.

Forward kinematics plays a crucial role in the simulation and operation of tensegrity structures while also playing a particular role in robotic applications where we need to understand the position of each given segment. In the context of tensegrity robotics forward kinematics involves calculating the positions of the end-effector ~~or nodes~~ of the structure based on the given joint parameters and link geometries without considering the forces involved. This approach is essential for tensegrity simulations because it allows engineers and researchers to predict the movement and behavior of the end effector all based on the input commands to the joints. By applying forward kinematics, the simulation can efficiently demonstrate how a tensegrity structure will shape itself in its given area which furthermore helps us create the most optimal design and control strategies.

3. Tensegrity Simulation

When simulating a tensegrity T-bar structure (Figure 5) using Python the first step involves coding the geometric details of the structure, pinpointing node locations, and delineating the interactions between the tension cables and the compressed struts. Python scripts are used to create a node matrix that captures the spatial coordinates of each node which then creates the foundation of the simulation's basis or framework. Next, a connectivity matrix is constructed to define the connections between nodes and structural components. This is essential for modeling the structure's equilibrium and the distribution of the forces acting on the system.

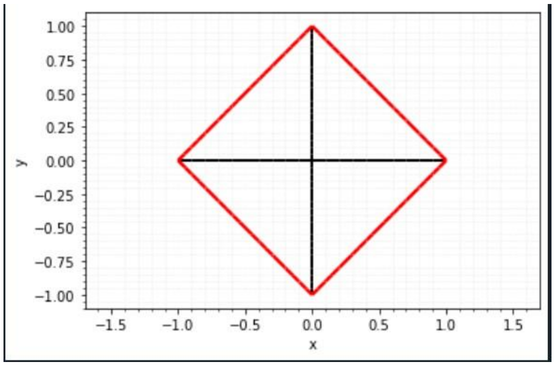

Figure 5: T-bar Simulation

In the Python simulation of the D-bar tensegrity (Figure 6), the first step is developing a node matrix to chart out the node positions of the D-bar configuration. This is crucial for accurately depicting the geometric foundation of the structure. A connectivity matrix is also programmed to define the structural connections to ensure that the simulations mirror the interdependencies of the D-bar's components.

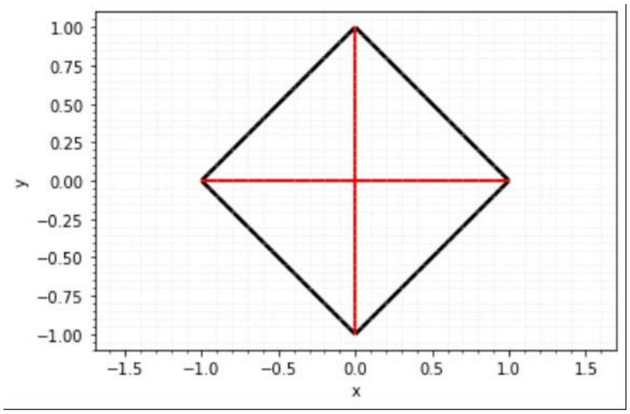

Figure 6: D-bar Simulation

The current project on hand focuses on the complex construction of a robotic arm (Figure 7) that is designed using two to three modules of tensegrity structures. Each module features T-bar elements that can be articulated in both vertical and horizontal orientations, which demonstrates the integration of precision when applying the laws and principles of tensegrity structures. Tensegrity is a principle where structural integrity is maintained through an equilibrium of tension and compression forces, forming the foundation of the robotic arm design. This approach ensures that the arm is not only a rigid assembly but also a dynamic system that is capable of performing subtle movements and adjustments. The design specifies the range of motion for each joint within set limits which simulate a spectrum of movements. This simulation allowed us to explore the potential motion and reach of the system and just how much of said system can effectively navigate or manipulate its environment.

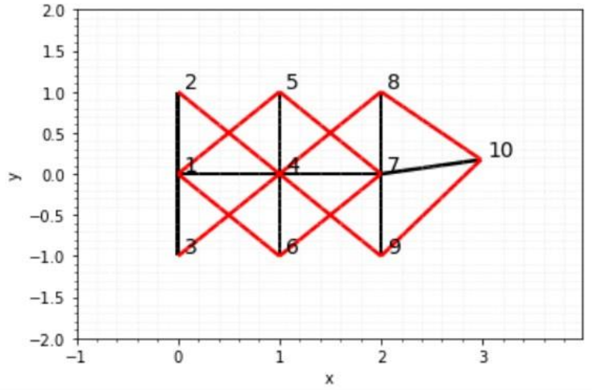

Figure 7: Robotic Arm Simulation

The creation of this project is not just a robotic arm but also a visualization that serves multiple purposes. Firstly, it outlines the arm’s tensegrity structure as it showcases the precision and functionality of design and shows how each bar and string contributes to the overall stability and flexibility. More importantly, it maps out the workspace of the end-effector , which can be thought of as the hand of the robotics arm. This mapping provides us an insight into the arm’s operational capabilities and is able to detail all the points within a two-dimensional space that the end-effector can potentially reach. This feature is paramount for applications that demand precision and adaptability as it gives us a foundation for understanding the limits and potential of the arm’s reach. Additionally, this visual representation also creates a link between theoretical concepts and their practical applications, as they demonstrate how a tensegrity robotic system can be altered to meet diverse operational needs. It simulates the integrations of form and function as it shows the practical applications of tensegrity laws in creating robotic systems that are not only efficient and flexible but also capable of navigating the intricacies of movement and the execution of tasks in varied environments.

4. Workspace Analysis

The exploration of the workspace of the tensegrity robotic arm is a crucial section in this research as it shows the practical application or implementations of tensegrity robotics through the use of theoretical concepts. This analysis is paramount to this study and it guides our efforts to map out the limits and capabilities of the robotic arm within a specified two-dimensional (2D) operational space. Through a detailed process that incorporates forward kinematics~~,~~ we are trying to identify the reachable points that this arm can achieve, thus revealing the spatial dimension within which the arm can effectively operate. While this section does showcase the technical expertise and innovative use of tensegrity principles in robotics it also sets the stage for the future phases of trajectory and control strategy refinement. The approach to the workspace analysis represents an examination of how the arm’s unique structure - inherent within tensegrity structures - can be used to navigate and manipulate its environments with precision and adaptability. In this context, the workspace analysis serves not only as an analytical task but as a testament to its potential by exploring the extent to which tensegrity principles can be pushed.

Following the roadmap established by our workspace analysis, we are able to advance to the simulation phase of the robotic arm as we use the capabilities of Python and its scientific libraries to bring our theoretical models to life. This simulation process is able to breathe life into a blueprint as it This simulation process allows us to see the transition from a blueprint to static designs into dynamic movements that are able to mirror real-life operations. We precisely define the spatial configurations of our tensegrity structure through our node matrices and define their interconnections with connectivity matrices which are used to construct a digital twin of our robotic arm within a digital environment. This process not only visualizes this tensegrity model but also demonstrates the use of advanced mathematical tools to adjust joint angles and simulate the arm’s motion across its entire reachable workspace. This allows us to monitor, in real-time, how the arm navigates through its operational environments while adapting its posture and reach so that there is optimal performance. Through the simulations, we further refine the arm’s movements to ensure each action is both feasible and efficient within the physical constraints of the system. The stage of simulation is instrumental as it serves not only to validate the initial workspace but also to serve as a foundational step towards the subsequent phase of trajectory planning and control mechanism design. Through this process, theoretical concepts are integrated with practical application which transforms the aforementioned mathematical models into actionable insights that make way for the robotic arm's real-world implementation and use.

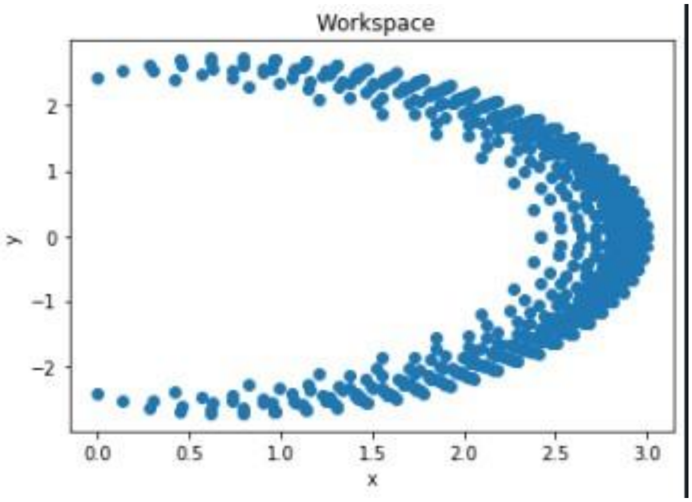

Figure 8: Reachable Points from Figure 7 System

Building on the foundational concepts discussed, the inclusion of Figure 8 visually represents the outcomes of the robotic arm's operation capabilities or in more simple terms the reachable points of the system's end-effector. The dense accumulations of points around the point x=2.8 and y=0 show a high level of flexibility and accessibility within that area. In contrast, as reach the outskirts of the reachable points we are able to see the distribution of the points progressively become fewer in numbers which lets us visually quantify the reachability limit inherent within the system due to the structure's geometry. (“Whole Body Connecting Force: Biotensegrity Model for Movement — Madeline Black” 2023) (“An Introduction to the Mechanics of Tensegrity Structures”, n.d.)

The pattern of reachability of the tensegrity arm offers an assessment of its potential to perform complex tasks. Where the densely populated area of the graph is, the arm is shown to have a wider range of motion with agility decreasing as we approach the outer edges of the workspace. This characteristic curve informs us that when designing there is a need for considering task-specific applications, suggesting that activities should be prioritized within the densely populated region to maximize the arm's performance. This analysis aids in optimizing the efficiency of the robotic arm for specific operational needs so that we can ensure efficient utilization of its range and flexibility. (“An Introduction to the Mechanics of Tensegrity Structures”, n.d.)

The theoretical introduction of a new node to the structure is projected to impact the workspace significantly. Based on current findings, this addition could potentially expand the denser region of the workspace which would consequently grant the arm increased maneuverability and precision at extended reaches. This expansion would also signify a shift in the tension-compression dynamics which would require a recalibration of the entire system to take advantage of the enhanced capabilities while preserving the integrity of the tensegrity framework. Due to this, the simulation and workspace analysis further provides another perspective ensuring that any changes improve functionality without compromising the system’s overarching tensegrity principles.

5. Conclusion

The investigation into the reachability and operational dynamics of tensegrity arms, supported by the detailed simulations, has brought forward the significant real-world implications and practical applications of these structures. By mapping out the workspace of these robotic arms this study advances both the theoretical understanding of tensegrity principles and demonstrates their practical applicability across a variety of challenging environments. This research not only deepens our understanding of tensegrity-based systems but also brings forth their versatility and effectiveness.

A key finding from this research is the impressive adaptability and precision of tensegrity robotic arms. These characteristics that are driven by the unique combination of tension and compression within their structure are what make tensegrity arms especially well-suited for tasks that require a balance between strength and flexibility. For instance, in space exploration, the light yet strong nature of these structures could greatly improve the functionality and survival of robotic systems which allows them to perform complex tasks more efficiently and with less risk. Being able to determine the arm’s reachability zones also helps in designing systems that can function effectively in the unpredictable and restrictive environment of space. (“Tensegrity Approaches to In-Space Construction of a 1g Growable Habitat” 2016)

Similarly, in medical applications, the precise readability and maneuverability of tensegrity arms open up new avenues for surgical robotics. Tensegrity robotic arms, with their ability to navigate tight spaces and perform accurate movements, could revolutionize minimally invasive surgery which offers patients quicker recovery times and reduces the risk of complications. The data gathered from the simulations provide a solid foundation for developing robotic systems that can adapt to the complicated and complex landscapes of the human body. (“Tensegrity - what holds us together?” 2019) (“Stacked Tensegrity Mechanism for Medical Application”, n.d.)

In scenarios of disaster recovery and emergency response, the tensegrity robotic arm’s ability to stretch and pull back from cluttered environments due to its highly precise nature could transform search and rescue operations. The versatility and resilience of tensegrity structures may allow robotic arms to travel over debris-filled areas or collapsed structures while also being able to access inaccessible regions that are too dangerous for human responders. The workspace analysis conducted through the simulation presents a blueprint for designing robots capable of navigating the unpredictable and often hazardous terrains encountered in disaster zones which could potentially save lives and speed up recovery efforts.

Furthermore, the data we have gathered from our simulations of the arm’s operational space emphasizes the importance of potential real-world deployment. These insights that were gained are crucial in transitioning tensegrity robots from the lab into everyday, practical applications. They demonstrate the practicality of using such systems in environments that require exceptional resilience and precision.

As we conclude this study, it is evident that through the progression from theoretical models to practical simulations, and the detailed examination of the robotic arm’s reachability and capabilities there is a mark of significant advancement within the field of tensegrity robotics. However, the journey ahead is still filled with opportunities for further discovery. Future efforts will aim to refine and further design and control strategies, experiment with new materials and configurations and broaden the application areas of tensegrity robotic arms. The goal in to continue pushing the limits and using the unique qualities found in tensegrity to develop robotic systems that can have a deeper influence in fields like space exploration, health, and disaster response. The intersection between art, science, and engineering in tensegrity principles holds a promising future for creating solutions that are not only effective but also aesthetically pleasing, hoping to usher in a new era in the evolution of robotics.

References

“Analytical definitions of connectivity, incidence and node matrices for t-struts tensegrity prisms.” n.d. Wikipedia. Accessed April 28, 2024. https://www.sciencedirect.com/science/article/abs/pii/S0093641324000314.

“Equilibrium Conditions of a Tensegrity Structure.” n.d. UC San Diego. Accessed April 28, 2024. http://maeresearch.ucsd.edu/groups/skelton/publications/han_equil_class1_como_conf.pd f.

“Equilibrium Conditions of Class 1 Tensegrity Structures.” n.d. MAE Class Websites. Accessed April 28, 2024. http://maecourses.ucsd.edu/groups/skelton/publications/han_RFGC_mod.pdf.

“An Introduction to the Mechanics of Tensegrity Structures.” n.d. UC San Diego. Accessed April 28, 2024. http://maeresearch.ucsd.edu/skelton/publications/pinaud_mechanics_CRC.pdf.

“Kinodynamic planning.” n.d. Wikipedia. Accessed April 28, 2024. https://en.wikipedia.org/wiki/Kinodynamic_planning?scrlybrkr=5b08bb23.

“Network and vector forms of tensegrity system dynamics.” n.d. Wikipedia. Accessed April 28, 2024. https://www.sciencedirect.com/science/article/abs/pii/S0093641314000329.

Snelson, Kenneth, and Verena Kittel. 2015. “Making the invisible visible: Kenneth Snelson's

“Early X Piece.”” black mountain research.

https://black-mountain-research.com/2015/02/19/making-the-invisible-visible-kenneth-sn elsons-early-x-piece/.

“Stacked Tensegrity Mechanism for Medical Application.” n.d. Wikipedia. Accessed April 28,

2024. https://arxiv.org/abs/2204.01312.

“Tensegrity Approaches to In-Space Construction of a 1g Growable Habitat.” 2016. NASA.

https://www.nasa.gov/general/tensegrity-approaches-to-in-space-construction-of-a-1g-gro wable-habitat/.

“Tensegrity – Buckminster Fuller Institute.” n.d. Buckminster Fuller Institute. Accessed April

28, 2024. https://www.bfi.org/about-fuller/big-ideas/tensegrity/.

“Tensegrity - what holds us together?” 2019. FitPro. https://www.fitpro.com/blog/tensegrity/.

“Whole Body Connecting Force: Biotensegrity Model for Movement — Madeline Black.”

2023. Madeline Black. https://www.madelineblack.com/movement-science/whole-body-connecting-force-bioten segrity-model-for-movement.

"BEST (BERKELEY EMERGENT SPACE TENSEGRITIES) ROBOTICS." best.berkeley.edu.

Accessed April 24, 2024.

https://best.berkeley.edu/best-research/best-berkeley-emergent-space-tensegrities-robotics

/.

"Design and Control of Compliant Tensegrity Robots through Simulation and Hardware

Validation." royalsocietypublishing.org. Accessed April 24, 2024.

https://royalsocietypublishing.org/doi/10.1098/rsif.2014.0520. "Development of a

Modular Tensegrity Robot Arm Capable of Continuous Bending." frontiersin.org.

Accessed April 24, 2024.

https://www.frontiersin.org/articles/10.3389/frobt.2021.

"NASA Tensegrity Robotics Toolkit (NTRT) V1." software.nasa.gov. Accessed April 24, 2024.

https://software.nasa.gov/software/ARC-17093-1.

"A Review on Tensegrity Structures-based Robots." sciencedirect.com.

https://www.sciencedirect.com/science/article/abs/pii/S0094114X21003153.

"Tensegrity Robotics." eng.yale.edu. Accessed April 24, 2024.

https://www.eng.yale.edu/faboratory/publications/journal/2021/Shah%20et%20al.%20-%

202021%20-%20Tensegrity%20Robotics.pdf.

"Tensegrity Robotics." pubmed.ncbi.nlm.nih.gov. Accessed April 24, 2024.

https://pubmed.ncbi.nlm.nih.gov/34705572/.

"TENSEGRITY ROBOTS." creativemachineslab.com. Accessed April 24, 2024.

https://www.creativemachineslab.com/tensegrity.html.

"Tensegrity Robots to the Rescue." techbriefs.com. Accessed April 24, 2024.

https://www.techbriefs.com/component/content/article/48556-tensegrity-robots-to-the-res cue.

"Truth and Myths about 2D Tensegrity Trusses." mdpi.com. Accessed April 24, 2024. https://www.mdpi.com/2076-3417/9/1/179.