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New Approaches and Recent Applications of Tensegrity Structures

Juan C. Guacheta-Alba[1,*], Angie J. Valencia-Castaneda[1], Max Suell Dutra[1], Oscar F. Aviles[2] and Mauricio Mauledoux[2]

[1]Robotics Laboratory, Mechanical Engineering Department, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-914, Brazil.
[2]Davinci Research Group, Mechatronics Engineering Department, Universidad Militar Nueva Granada, Bogotá 111071, Colombia.

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Abstract

Tensegrity is composed of structures that are characterized by compressive elements (bars) and tension elements (cables) that work together to transmit and/or withstand forces in an efficient and balanced manner. Their kinetic analysis, design, and control are study topics with various methods still being explored. Furthermore, research and development have been conducted in different areas such as architecture, engineering, biomechanics and robotics, exploring lightweight and resilient tensegrity structures for more flexible and adaptable movements. Tensegrity is a structure increasingly used and studied in different areas, thanks to its ability to transmit forces efficiently and its versatility in the application of designs and solutions in different areas. So, this review presents initial definitions of this area, as well as recent methods and applications that have been developed and are the focus of study for future advances.

Keywords: Deployable structures, Flexible mechanisms, Structural analysis, Tensegrity, Topology

1. Introduction

Tensegrity has had a significant boom in recent years, presenting new structures and design techniques for applications in engineering and architecture. The term tensegrity was first approximated in 1955 by Buckminster Fuller, representing the union of words tension and integrity [1]. Tensegrity structures (TSs) are connected arrangements of tensioned cables and compressed bars that are the main characteristic of self-supported and pre-stretched [2]. The development of these structures was introduced due to the little flexibility, inability to avoid obstacles, and restricted workspace presented by specific systems, giving field to flexible structures, which present infinite degrees of freedom, high flexibility and adaptability[3].

Given their topological composition, TSs are generally light and smooth, as most of their internal volume is empty [4]. In turn, they present properties such as high stiffness per unit of mass, adaptability, flexibility, modular construction [5], as well as collision resistance, obtaining characteristics of rigid and soft structures. The TSs have different stiffness states related to prestress states and equilibrium configurations [6]. The first approximation of these structures can be found in nature, where certain biological organisms, musculoskeletal systems, and cells can be seen as TSs [7].

The first classification performed on the TSs refers to the number of contacts between bars, where a class-1 TS has no contact between its bars, while class-k has k bars in contact [8]. Due to their composition, these structures have different equilibrium configurations, stable and unstable [9], situations that complicate their construction and control, and even simple structures with few cables and bars [10]. The stiffness and deformation of the TSs can be programmable, varying their preview state [11]. However, it is emphasized that this state cannot call a tensegrity structure [12].

Some of the main characteristics of TSs that differentiate them from other structures are their deformability, adaptability to the environment, impact resistance [13], lightness, folding, modularity, stiffness [14], high stiffness-mass ratio, dexterity, and resilience [15], controllability, reliability, flexibility [16], mobility and self-reliance [17]. They have been used to design metamaterials, reaching negative bulk modulus behaviors, negative Poisson ratio, high energy absorption, and effective negative mass [18]. However, it is to denote that a disadvantage of the TSs is their intrinsic softness, being a limitation in situations where it is necessary to exercise high forces [11][19].

Due to the characteristics mentioned above, its applications cover broad fields of action, such as rolling, vibrating, hopping, and crawling [15], among many others, which can be visualized in Figure 1 and are exposed and analyzed in the document. For these applications, some design requirements include modular assembly capability, automotive capability, structural confidence, being able to respond to changes in environment and withstand collisions, so tensegrity is a recurring option to encompass these problems [20][21]. Another skill that TSs present is their easy storage and transport [22], performing it in a simple, fast, effective, and economical way, allowing interaction with humans and delicate objects [19].

This review presents the highlights of recent years in tensegrity advances, compiling their methods and applications that have been used. Section 2 presents initial considerations that define tensegrity, its inclusion in areas of deployable structures and intelligent materials, and its classification into topics of geometry, structure, and stability, among others. Section 3 compiles the principal methodologies used for the structural, kinetic, optimization and control analysis of tensegrity structures and develops new methods. Section 4 presents recent applications of TSs in areas such as modular robotics, structural design, metamaterials, and additive manufacturing, among others.

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[*] E-mail address: juan.camilo@mecanica.coppe.ufrj.br

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Finally, in the last section are presented the final considerations of the review, as well as future works recommended to investigate in tensegrity.

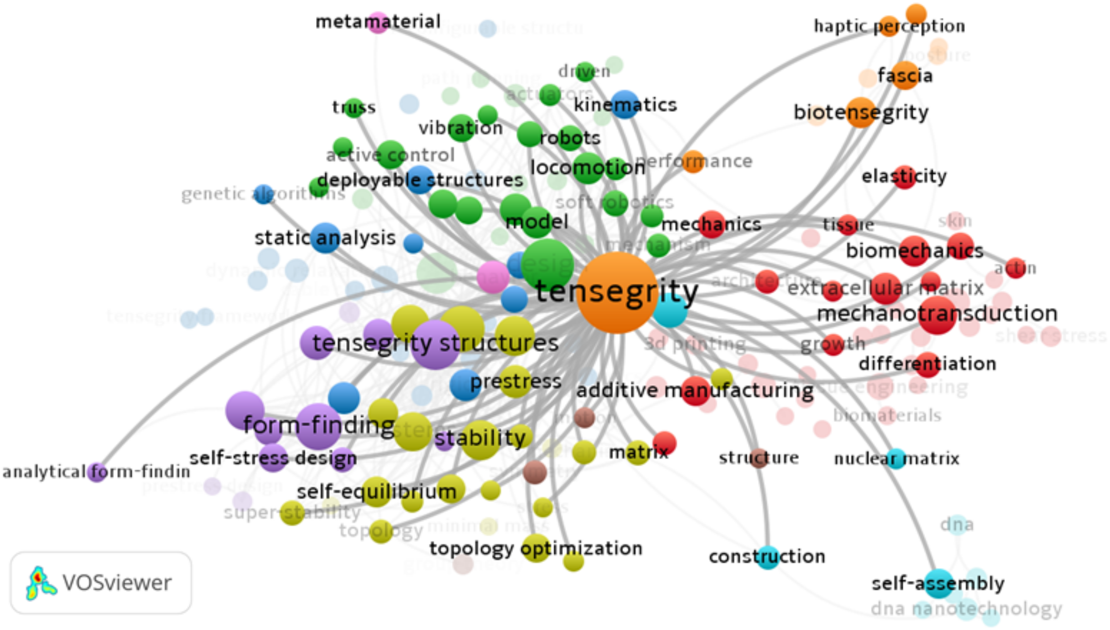
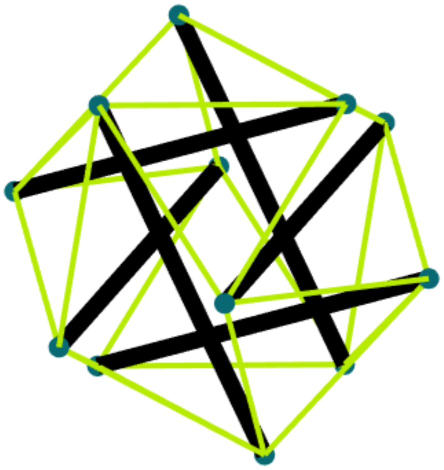


Fig. 1. Tensegrity knowledge map by VOSviewer, for the last 5 years of research using databases such as IEEE, Web of Science, Elsevier, among others.

2. Initial considerations

TSs are defined as structures with bars and cables; however, additional features must be satisfied: be a truss with a self-stress state, generating an infinitesimal mechanism stiffened; bars do not touch each other, constitute a discontinuous set, and are included inside the set of tensile components; and cables have no rigidity in compression. Various classifications of structures are presented in the literature, for example, by their characteristics of tensegrity, classifying them as structures with tensegrity features, pure tensegrities, and non-tensegrities, given by the composition of their elements and their morphology [12].

In turn, TSs can be categorized into three levels: unit, constituted by a prism, as is the triangular icosahedron presented in Figure 2; cell, constituted by two connected units; and chain, composed of a certain number of interconnected cells formed by adhesion and fusion, generating various structures defined by their self-stress forces and modifying their properties [23][24].



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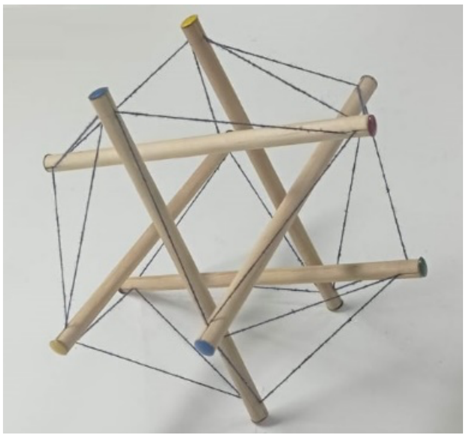
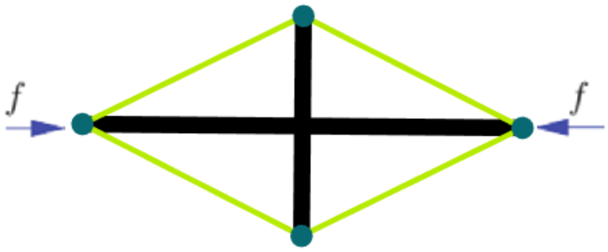


b)

Fig. 2. Triangular icosahedron tensegrity unit, a) design and b) construction.

Usually, structures and their connections are made symmetrically, although asymmetric structures can offer high deformability and low wear [25]. The design of these units is a study topic. However, two basic topologies can reduce the behavior of the units, which are the T-bar and D-bar [26], exposed in Figure 3, and which have their 2D and 3D representation. TSs can also be analyzed for stability, classified as unstable, prestress stability, and super stability [27].



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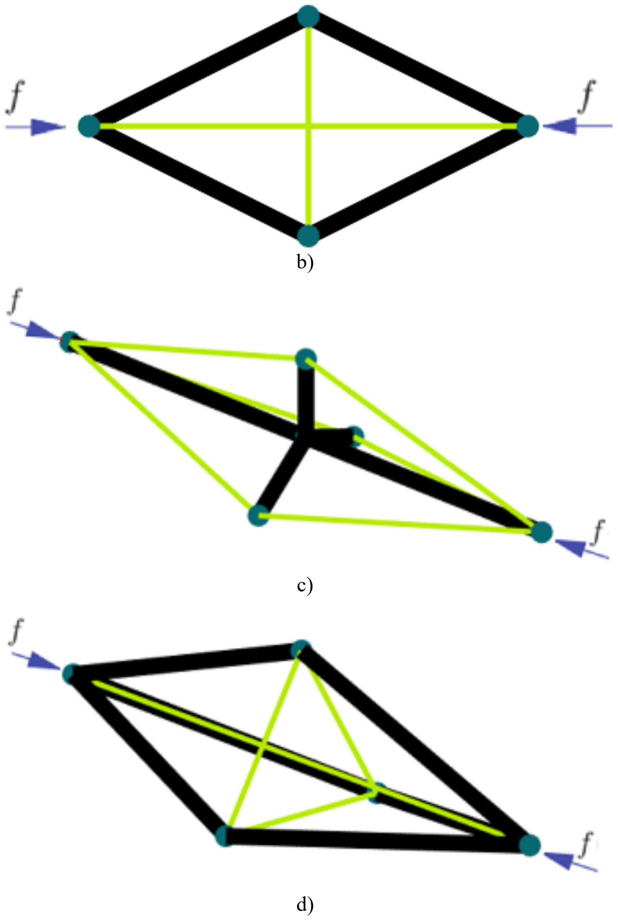


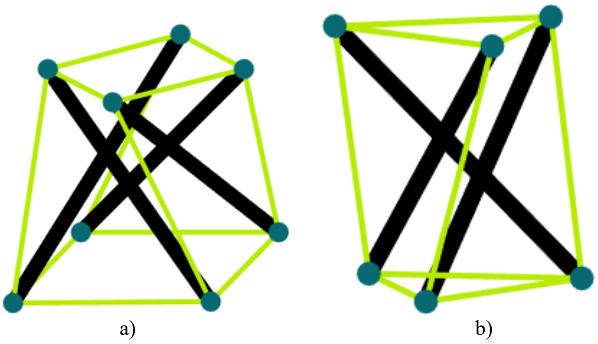
b)

c)

d)

Fig. 3. Configurations of tensegrity units under compression load a) Two-dimensional T-Bar, b) Two-dimensional D-Bar, c) Three-dimensional T-Bar with 3 sides, and d) Three-dimensional D-Bar with 3 sides.

TSs can be combined and classified by the type of element they use for their construction, such as bar, plate, spatial, and combined [28]. The plate element increases flexibility between the connected modules [25]. Another element used in engineering and architecture is membranes, which are also subjected to stress and must ensure that no wrinkles are generated on the surface [29][30]. These new elements and unit types fit into the design of infinite TSs and their structural analysis [31][32], so it is also necessary to define dual units, where cables replace the bar elements and vice versa, as an example, the D-bar is dual unit T-bar [33]. These units have infinite configurations and may vary depending on the number of bars and cables defined. Some of the most used and analyzed units are presented in Figure 4, such as 3-strut and 4-strut, commonly used to generate tensegrity chains.



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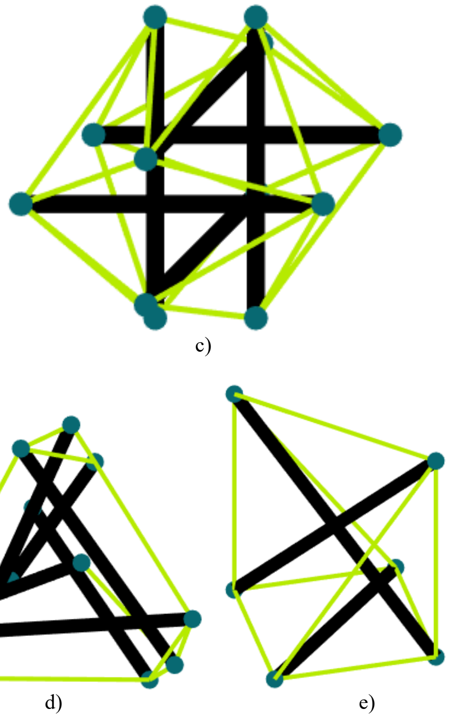


c)

d) e)

Fig. 4. Tensegrity units by Sabouni-Zawadzka [34], a) 4-strut simplex, b) 3-strut simplex, c) expanded octahedron, d) truncated tetrahedron, and e) X-Module.

Within the TSs, there is a subclass called tensegrity cluster, characterized by continuously grouping cables [35], decreasing the number of cables in the construction stage and bringing advantages in their performance [36]. Also, their natural frequency is lower compared to traditional structures, giving them greater flexibility, but as a consequence, them are weaker [37][38]. A feature of the TSs is the decrease of stiffness when the external load increases, presenting the phenomenon of buckling [9], in addition, when units in a chain increase considerably, the difference in mass of the structure is no longer noticeable [39]. The equipment of sensors and actuators is beneficial for the control of deflections and for avoiding the phenomenon of buckling [40].

TSs have a significant advantage in their adaptability since they are light, robust, favorable for different environments and offer physical interaction [17][41][42]. However, they can become slow and complicated in their assembly and control [43], being essential to analyze the requirements of the problem. Another item that complicates its analysis is the high nonlinearity. It is a system with multiple solutions and equilibria states [5][44], conditions by which it is necessary to consider the structure's overlap, buckling, displacement limits and multiple load cases [45]. Its construction also has design criteria, such as cable selection. It is recommended to use cables of variable stiffness to apply higher forces and soft cables to absorb energy and allow flexibility [11].

3. Methods applied

This section will present a compilation of the leading and newest methods used for the analysis, design and control of TSs, covering the levels to which the design is linked: mechanical design, control design and global layout design [46]. For a correct design of structures, an initial structural analysis must be performed, then static, then dynamic, and finally is made a feedback, using the methods developed below [47].

3.1. Structural analysis

Given the topology of TSs, the initial analysis to be performed is on their stability and equilibrium, which can be represented mathematically by the standard forms of the structure: nodal coordinates, force density and force vector [37]. Since the connection between elements gives the structure, the connectivity matrix is initially defined. Then, the connectivity between the nodes is described by matrix C with dimension of m members by n nodes, and its structure is expressed in equation (1).

$$C_{(r,p)} = \begin{cases} 1 & p = i \\ -1 & p = j \\ 0 & other\ nodes \end{cases} = [C_B \quad C_S]^T \tag{1}$$

The force densities of each element are written in a single vector q, which is formed by the ratio between the internal forces (f) and the length of the element (l), as described in equation (2).

$$q_r = \frac{f_r}{l_r} \tag{2}$$

Assuming that there are no external forces applied to the structure, the equilibrium condition of the TS is represented in equation (3), where it relates to the equilibrium matrix A defined in equation (4), and the force density vector q, matching the three coordinate axes of the system. Nonlinear equilibrium equations can be solved by the Newton-Raphson method with an appropriate estimation of the initial solution [36][38].

$$A \cdot q = 0 \tag{3}$$

$$A = \begin{pmatrix} C^T diag(C_x) \\ C^T diag(C_y) \\ C^T diag(C_z) \end{pmatrix} \tag{4}$$

The classical Newton-Raphson method solves a continuous, smooth and differentiable problem, so strategies such as parametric variables introduced in the model are used to eliminate the model's soft nature [48], presented by cable status changes between taut and loose [49]. An energy-based method is also used to estimate the equilibrium state, where the bars and cables are assumed to be rigid [50]. Finally, strategies such as multibody simulation are used to analyze TSs [36].

3.2. Static analysis

Continuing with the analysis of structures, is crucial to analyze the kinematics and static behavior of the system, which relates the kinematic components using equations where the movements are compatible and accessible. The kinematics of TSs is defined by the relationship between the displacement of the nodes d and the deflection δ resulting from elements e. Since the coordinates of the free nodes can vary over time, it is convenient to express them temporarily, so by deriving the kinematic relationship, we get equation (5).

$$A^T\, d = e; A^T\, \dot{d} = \delta \tag{5}$$

Kinematic analysis for TS assumes zero-free length springs that facilitate the simplification of motion equations [51]. This premise is used by the main kinematic analysis methods: approach energy, virtual working principle, screw method and force density method [50]. The last method uses the force density matrix D defined in equation (6) and considers the flexibility of the bars and cables.

$$D = C^T diag(q) C \tag{6}$$

Based on equation (7), the force density method defines a kinematic expression by differential equations, to obtain a set of positions varying in time, that describes the trajectory of the TS [52]. Another widely used method is the virtual working principle, which analyzes the infinitesimal deformation of the TS [18]. Furthermore, the virtual joint method is also used to allow the analysis of rigidity and stability states, described by linear relations between deflection and external forces [5]. Finally, new techniques that replace the force density method have been developed with deep learning techniques, which perform training based on information of the force density of the elements [53].

$$D_x = 0;\ D_y = 0;\ D_z = 0 \tag{7}$$

3.3. Dynamic analysis

Once a static analysis has been carried out, the dynamics of the TSs must be analyzed. The dynamic modeling of the TSs is nonlinear and is derived from the Lagrange equation, generating a system of ordinary differential equations described in equation (8), where M is the mass matrix; λ are the Lagrange multipliers, γ denotes the generalized coordinates, f_i and f_e denotes the generalized internal and external forces, respectively, $\Phi(\gamma, t)$ are the kinematic constraints and Φ_γ is the Jacobian matrix [54]. In this formulation, to ensure dynamic stability, the effects of inertia and damping, as well as some assumptions, must be considered [8]. Some of these are that pin joints connect cables and struts, cable members only carry axial tensile forces, strut members carry axial tensile or compressive forces, the external loads only act on the nodes, and the local and global bucking of struts are neglected [2].

$$\begin{aligned} &M\ddot{\gamma} + f_i(\gamma, \dot{\gamma}) + \Phi_\gamma^T \lambda - f_e = 0 \\ &\Phi(\gamma, t) = 0 \end{aligned} \tag{8}$$

TSs are characterized by presenting dynamic behaviors with stable-periodicity, multi-periodicity, quasi-periodicity or chaos, under different frequencies [55]. Therefore, in the dynamic analysis, the change in their equilibrium configurations is analyzed and allows the development of action strategies [6]. However, traditional modeling methods are inaccurate for predicting the dynamic response of TSs, since they do not consider internal displacements, so new methodologies have been proposed [54]. Some of them are the cartesian spatial discretization method, which does not simplify the structure and includes the internal displacements of the elements in their longitudinal and transverse directions. Other methods have been used, like the corotational formulation [56], where is performed a displacement decomposition in the global frame and deformation in the local frame; and Bloch's theorem [24][57], which verifies dynamic behaviors such as default states and bandwidth of the TS.

Computationally, these techniques have a high cost, so linear models must be implemented to describe an approximation of the system's dynamics [58]. Methods such as periodic boundary conditions are also used to analyze a single unit of tensegrity for structures with many units, considering symmetries and boundary conditions [59]. For cluster TSs, the system dynamics are obtained using the finite element method of positional formulation [60]. Also, the critical dynamics have to be evaluated if the load duration is long enough on the TSs [8].

3.4. Form-finding techniques

Another fundamental field of study in the analysis of TSs is shape searching, a problem in which the position of the nodes is initially given, and the topology is the principal design variable [61]. A design condition that must be considering is its stability, since the element combinations obtained can be unstable, stable and super stable, as well as possible restrictions in the volume or area of the structure [62][63]. It is worth mentioning that finding multiple solutions for the same topology is possible [64]. In Figure 5, updated TS configurations are presented iteratively, improving the final structure. The principal methodologies used to find the shape of TSs are the stiffness matrix method, natural shape finding, force density method, geometric stiffness method, updated reference strategy, multistep FDM, natural DM, dynamic relaxation, and particle spring system [47].

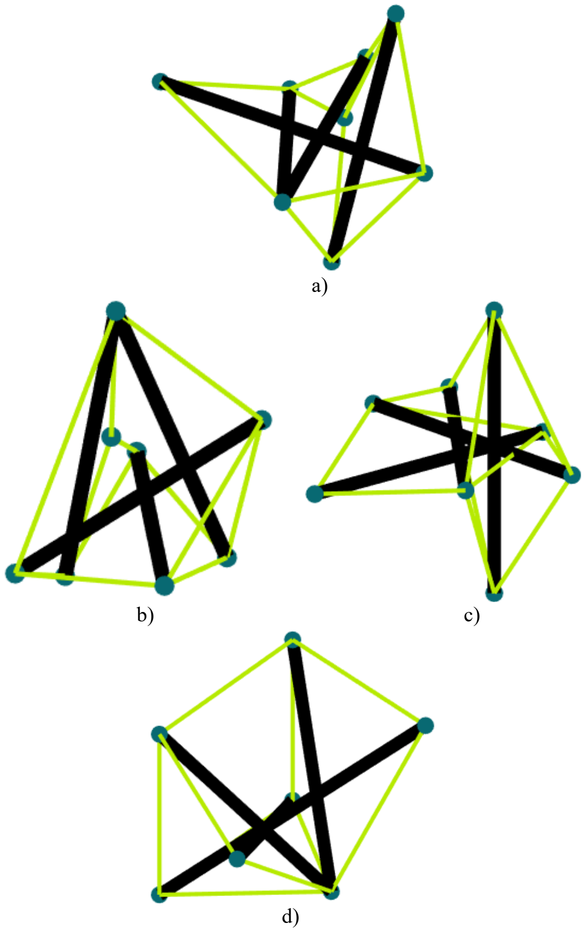


Fig. 5. Form-finding process for 4 bar tensegrity unit a) First generation, b) generation 100, c) generation 200 and, d) generation 500.

The dynamic relaxation method has been lately employed in the form search. This method updates the coordinates by viscous and/or elastic damping on the equilibrium equations, using the kinetic energy K_E described on equation (9), for each element of the TS [65].

$$K_E(t) = \sum_{i=1}^{N_n} \frac{1}{2} m_i v_i(t) \cdot v_i(t) \qquad (9)$$

Where N_n is the number of elements in TS, m_i is the mass of the element, and v_i is the element velocity vector. Modifications of this technique have been proposed, implementing greedy search and multigeneration Monte Carlo methods to find suboptimal solutions [4]. In addition, a new method based on non-rigid-body motion analysis, which use virtual rigidity to obtain balanced shapes, has been unwrapped [66].

3.5. Control techniques

Due to their topology, TSs are deployable and lightweight, with the possibility of being controlled by modifying the stresses and adjusting the level of equilibrium forces [67][68]. These modifications will change the structure's mechanical characteristics, such as its elastic modulus, Poisson relationship and phononic band gap, providing advantages to tensegrity metamaterials by adjusting the geometry [69][70]. With this, TSs can be controlled to achieve certain design parameters, and as a result, are capable to offer actuation, reconfiguration and attenuation of disturbances [2]. In these control strategies, it is suggested to explore the natural modes of vibration ω through the tangent stiffness matrix K_0, represented in equation (10), to propose attenuation strategies based on vibration modes, like a robust active control technique [58] or simplified control laws [71].

$$(M\omega^2 - K_0)\Phi_\Upsilon = 0 \qquad (10)$$

Multiple control techniques are applicable in TSs, presenting some advantages and disadvantages on the behavior of the structure, and must be selected predefining the desired application. For example, Lyapunov stability control derives the laws of nonlinear control, guaranteeing the system's stability [26]. The linear quadratic regulator (LQR) active control maintains integrity on dynamic loads and is applied for vibration mitigation [2]. Other methods also are used, such as the integrated force method and singular value decomposition approach, offering efficiency in estimating external loads, TS performance and reducing the computational cost involved in control. Finally, new techniques as decoupled data-driven control (D2C) optimizes a trajectory using black box simulation with LQR, with penalty constraints offering sophisticated control results [72][73].

3.6. Optimization techniques

TSs can be optimized from various approaches, and recent research has focused on the topological optimization of the structure, kinodynamic planning, and mass minimization. The main objective in topology is to find the connectivity between elements and/or node positions [74][75]. This purpose can be analyzed as a mixed-integer linear problem, where the minimization of a specific function is sought, varying input parameters [76][77]. The use of techniques such as the ground structure method and graph theory, are recently used to obtain the required topology, considering, for optimization that the problem's constraints must be defined. Some constraints are self-equilibrium, unilateral internal forces, and the class-k condition, represented by Lagrange multipliers [27][77]. The self-equilibrium in TSs is only achieved when the accuracy in the stress states is guaranteed. This can be expressed as an optimization problem, by defining the inverse static [78].

Methods based on the discrete variational and the Lagrange-d'Alembert principles have been programmed to find transformations on the TS from one possible configuration to another. This problem can be defined by kinodynamic planning, performing iterations, and penalizing configurations [60]. In addition, in the design of structures, topologies with minimum volume and/or mass with applied external loads are desired. This minimization problem can be considered as a nonlinear programming problem [79]. Goyal et al. [80] developed the MOTES software, which reduce the TS mass by minimizing internal forces, using linear programming (LP). Also, maximization problems are proposed, such as those ones that increase the deficiency range of the force density matrix, to enhance the chance of finding stable and superstable TSs [81].

4. Applications

The tensegrity field has had a great boom in recent decades, being useful in many applications at different scales. On large scales, TSs are developed for scaffolding, antennas, and buildings; on medium scales, they are used as modular and biomechatronic robots. On small scales, they can be implemented for medicine and material design [21][25]. Applications become infinite, so in this section will be presented the newest applications of the latest research and their potential in various areas such as structure design, control, manufacturing, vibration, among others [46][82].

Tensegrity is a design technique that can be applied to larger-scale structures, such as transmission towers and antennas. In the case of the transmission tower, the tensegrity reduces the area of the base of the tower, making it more compact and easier to deploy [83]. In space exploration, tensegrity has also been proposed as a solution for lunar structures and for designing lightweight, high-capacity antennas [79][84]. With cable length control, tensegrity can effectively deploy antennas and ensure their stability.

The introduction of TS in quadruped robots has significantly improved their flexibility, adaptability, and safety. A recent study by Gao et al. [85] explored 3D printing and metamaterials to create flexible TSs that allow robots to complete more complex movements. Also, challenges such as implementing simple design and control solutions or creating suitable locomotion strategies for exploring and avoiding obstacles, have been studied [86]. The connection of modular robots through electromagnets, as proposed by Meng et al. [87], has also been explored as a way to assemble large, solid, and light structures. As a requirement, modular robots must be lightweight and robust, with the capability to vary their rigidity [11]. TSs are a promising tool in robot design and can significantly improve their performance in various applications.

The integration of tensegrity technology into robotics has led to create more flexible and adaptable robots, employed in various fields, from urban search to planetary exploration [88]. Therefore, the use of pre-stretched SMAs has improved their autonomous jumping capability and enabled the design of customizable locomotion algorithms [89][90]. The application of machine learning in robots has made it possible, discovering the most effective gears for locomotion, and multistable structures, used to overcome obstacles and make shape changes for predefined trajectories [91][92]. Tensegrity is a promising technology for robotics, offering an innovative solution to robotic locomotion and structural flexibility challenges [4].

In addition, the tensegrity units are highly made of lightweight materials, allowing the transport of fragile objects and attach themselves to the environment and people [93], developing soft tensegrity cages to protect the robot during landing and allow it to roll on the floor [86]. This type of cage offers soft and controlled cushioning, reducing the impact energy and protecting the internal components of the robot.

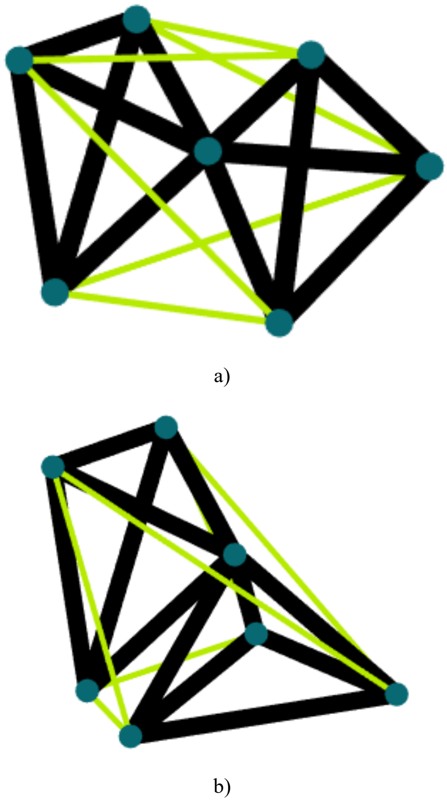
Also, robots with tensegrity have features of flexible and adaptable structures and are particularly suitable for uneven and unpredictable environments and can operate in extreme environments such as space [43][94]. Despite this, increasing structural rigidity can decrease packaging efficiency, limiting its application in certain situations [95]. However, most of the behaviors of these robots are discovered through empirical trial and error and manual adjustment, which limits their effectiveness and efficiency.

As mentioned in the previous section, the control of TSs allows building systems with high reliability and mobility. The control is carried out using actuators located in the system to change the kinetic and kinematic behavior of the TS elements. The actuators are used not only to counteract load but also to ensure prestressing. These can be located on cables, offering flexibility and expandability, or on bars, with better performance over displacements and internal forces [2]. Traditionally, elastic actuators with impact and mechanical energy storage advantages are used, but active and/or passive tendons can also be implemented [19][96]. These antagonistic actuators are inspired by biology, allowing the control of mechanism's rigidity and position [40].

Significant advances in actuator design have been far-reaching lately, and their application in tensegrity has also been developed. For example, Zhou et al. [93] designed and constructed a TS acted by twisted artificial muscles responsive to electrical, thermal, or chemical stimuli. At the same time, Li et al. [97] used artificial McKibben muscles to actuate a TS. In various applications, the equipment with actuators of the TSs is fundamental, using piezoelectric ceramic actuators [98], twisted and coiled [99], dielectric elastomer in the form of tape [100], among others, offering deformations in the structure, that can be controlled electrically, thermally, or magnetically. Hybrid techniques have also been developed, using 3D printing combined with magnetoactive materials to generate shape-changing structures [101].

Beside of actuators, TSs are recently equipped with sensors that allow measuring physical variables on the structure. In turn, highly elastic and reliable sensors are required to detect the structure's tension and shape in real-time accurately. A recent option to measure TSs is to use capacitive sensors with metallic liquid that withstand high voltages [96]. However, the stiffness of these sensors decreases critically, which means they must be replaced after a few days of use if they are not rigidly designed. Nevertheless, these sensors, combined with soft tensegrity and recurrent neural networks, can estimate the robot's shape in real-time [96][102]. In addition, a structure with force-sensing capabilities, such as the Interlink FSR-404 resistor sensor implemented by Barkan et al. [41], can create physical interaction in human environments, enabling robot-human collaboration. To measure the structure's natural frequency, a two-axis accelerometer subjected to free vibrations can be used [103].

The use of rotational, universal, and ball joints are fundamental in the design of structures, and sometimes they can also be designed inspired by tensegrity. These joints are not fully flexible and are prescribed for a specific range, with behaviors equivalents to a rigid joint [104]. However, previous studies have shown that pin and ball joints can be selected to produce tensegrity-inspired structures with dominant stretching or bending [105]. The design of tightness joints is ideal for light manipulators and for operate in environments close to humans, such as the joint designed by Friesen et al. [106] presented in Figure 6, since they allow more excellent, safety and structural adaptability [42][107]. Therefore, it is crucial to consider in the analysis the actuation forces, stiffness, geometry, and mass of these joints; to achieve efficient transmission of forces and guarantee the system's stability [71][106].


a)

b)

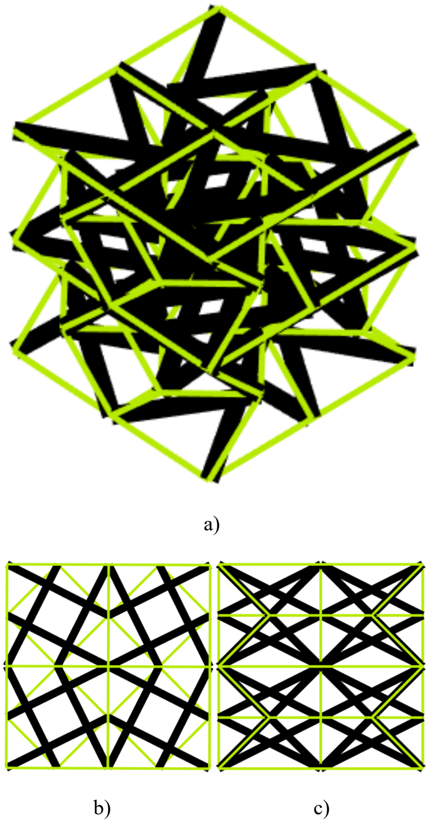
Fig. 6. Concept design for a tensegrity joint by Friesen et al. [106], a) initial position, and b) rotated position.

The technology of cables with variable rigidity has allowed the creation of adaptable and tunable TSs. Among the most outstanding applications is creating a beam with tunable load capacity. This structure can self-deploy and lock its shape or a joint with underacted deformation. In addition, the tensegrity hand is another example of the versatility of this technology since, after resisting the force of compression and tension, the hand usually returns to its original shape and functions [97].

The functionalities of the reconfiguration are multiple, including the ability to evolve, multifunctionality, and survivability. Nested configuration is a technique that transforms the morphology of TSs by modifying the internal tension of the cables [108]. The process of reconfiguring structures is analyzed in four stages: initial, deformed, shape change, and objective [76]. TSs allow modifying their shape by adjusting their internal tension, distributing impacts, and preventing damage [15]. Tendon control technique or SMA shape memory alloys, can achieve shape changes in the membrane [29]. In lightweight robotics and artificial muscle applications, large but reversible deformations with stable and unstable equilibrium positions are crucial. Variable stiffness cable technology is emerging as an ideal solution for these applications [82].

3D printing has proven to be a helpful tool in developing TSs. In particular, the possibility of printing metamaterials and titanium alloys has allowed the creation of lighter structures with non-linear behavior [67][109]. In addition, 4D printing techniques have been explored to create structures that can change their configuration or function over time in response to external stimuli [110][111]. These techniques also allow the fabrication of liquid crystal elastomers "on the fly", providing greater control over the structure’s deformation [112]. Another advantage of 3D printing is the ability to create molds to generate tensile structures, eliminating the need of post-assembly [16]. 3D and 4D printing are promising tools for creating more efficient and adaptable TSs.

Cellular metamaterials based on tensegrity patterns are an exciting new area of research in the field of engineering. Tensegrity lattices are recognized as a metamaterial due to their ability to absorb energy and have tuneable dynamic properties [113][114]. An example of a tensegrity lattice is presented in Figure 7, using the 4-strut unit in Figure 4a, to obtain orthogonal properties given the arrangement of the units. Butler & Peraza [115] have proposed the use of active materials, such as SMAs, to achieve memory form performance.


a)

b) c)

Fig. 7. 3D tensegrity lattice formed by sixteen 4-strut units by Sabouni-Zawadzka & Gilewski [34], a) isometric, b) top, and c) front views.

Tensegrity metamaterials have high mobility and scalability, making them ideal for building intelligent robots. In addition, their ability to have a zero Poisson coefficient and compression-torsion or stress-torsion coupling makes them a unique material [27]. Yin et al. [18] have used supercells and patterns such as the regular octahedron, to program their Poisson coefficient in designing cellular metamaterials.

Tensegrity composite metamaterials are being extensively investigated for their potential in wave control and vibration mitigation. It can control its kinetic properties by tuning its rigidity using internal prestressing and loads. Spectral analyses of elasticity matrices have been conducted to compare different metamaterials and define their extreme properties [57]. These materials have applications in mechanical wave control, mechanical cloaking technology, and vibration attenuation [116]. In addition, these devices are expected to generate compact, tunable compression waves in an adjacent host medium, which will improve structural resilience against possible damage [117]. Finally, machine learning can minimize the physical tests necessary to design and optimize these metamaterials [118].

In the study of the actuation of movement and the response to vibrations caused by wind forces, it has been observed that modal dynamic ranges increase with pretension [119]. This means that modifying the prestress level, is possible to change a material's natural frequencies [58]. As pretensions increase, resonant frequencies are pushed to a higher frequency region where modal damping increases [98]. For example, Figure 8 shows the behavior of a tensegrity cell in a deformation mode, modifying its shape and supporting high loads.

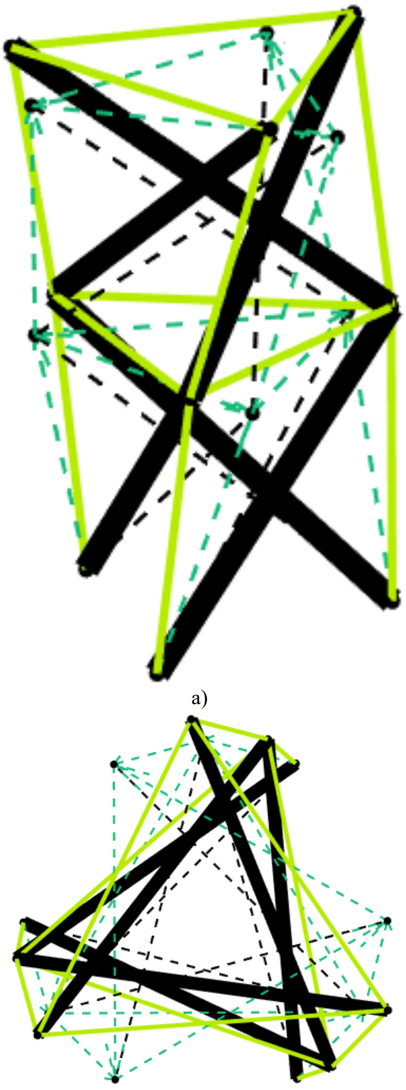

a)
b)

Fig. 8. Deformation response of a tensegrity cell to a vibration mode of 10.9mHz, a) isometric and b) top views.

In addition, smooth and rigid strain modes corresponding to eigenvectors can be calculated using the elasticity tensor, allowing create extreme materials with maximum mechanical properties [34]. To ensure robustness, linear elastic designs are adopted to withstand loads in nonlinear scenarios. These designs are characterized by six deformation modes: rigid extensional, soft extensional, medium extensional, high-cut and low-cut mode [67]. The system's resonance frequencies are related to the pretension levels of the active cables, and nonlinear resonance phenomena appear if the actuator harmonically varies the tensile force and stiffness of the beam [2][120].

TSs are widely used in nature, from the cytoskeleton to flexible muscles, providing mobility and robustness to animals [27]. In the human body, bones, muscles, tendons, and connective tissues form a network of continuous tension, provides structural integrity, stability, and flexibility. This idea has been applied by Liu et al. [121] to design of bioinspired soft robotic grippers, introducing the concept of tensegrity into robotics. In addition, Stephen M. Levin proposed the term "biotensegrity" to apply this idea to the biomechanics of the shoulder, elbow and spine. Other examples of biomimetic robotics include the design of a robotic fish, developed by Li et al. [97], capable of swimming and maneuvering like a real fish, and continuous robots based on elephants, earthworms, snakes and octopuses, capable of traversing confined spaces and manipulating objects [3]. In this context, Brandão & Savi [122], and Sun et al. [13][123] have investigated the design of a foot structure with flexibility, self-stability and self-adaptability inspired by the biomechanics of the human body.

5. Conclusions and future work

Tensegrity structures (TSs) are presented as a solution to reduce the risk of failure and facilitate transport, although, it is crucial to ensure fixation, repeatability, and reversibility during deployment [124]. Features such as stiffness-to-weight ratio, frequency bands, negative elastic modulum, negative mass density, auxeticity, optimized piezoelectric properties, and solitary wave propagation are sought [109]. However, there are drawbacks, such as motor weight, prestressing adjustment, and heat dissipation. Implementing smart materials with adaptive rigidity would enable the realization of highly conformable systems with adaptable mechanical properties. In the future, a better comparison between the theoretical and the experimental is sought, as well as deepening the controlled active deployment of the cables [22]. One of the current challenges is measuring a tensile structure's shape without using external hardware.

Designing a locking structure that does not allow high deformations is crucial to ensure the safety and stability of any construction. In addition, switching the structure when it is subjected to a certain level of load can further improve its resistance capacity [123]. Analyzing and integrating tensegrity and other technologies, such as topological optimization, intelligent structures, renewable energies, additive manufacturing, and origami, can offer innovative and efficient solutions. Future applications of these technologies are promising, including impact protection equipment and vibration isolation devices. To further improve these structures, active or passive control with shock absorbers and actuators can be considered [120]. Future work could also focus on machine learning to improve the movement of these structures. However, one of the biggest challenges in this field remains the implementation of micro-deployable structures [47]. Finally, future experiments studying robotic manipulators with tensile joints are needed to improve their functionality and applications [107].

The development of TSs has presented significant challenges in the rapid manufacture and equipment of sensors and actuators. However, it is expected to develop rapid parametric modeling of these structures soon [27][125]. To this end, they have proposed the development of analytical designs and custom algorithms that allow faster and more efficient manufacturing. In addition, it seeks to propose algorithms for the automatic design of tensegrity structures that simplify the design process [43]. Also, tensegrity joints can be created as breaks in triangulation, allowing greater flexibility in design. However, lightweight robots present difficulties with accurate models, scalable designs, and robust controls. Developing tensegrity structures is expected to create lighter and more efficient robots.

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References

[1] S. Ma, M. Chen, and R. E. Skelton, “Tensegrity system dynamics based on finite element method,” *Compos. Struct.*, vol. 280, p. 114838, Jan. 2022, doi: 10.1016/j.compstruct.2021.114838.

[2] X. Feng, M. S. Miah, and Y. Ou, “Dynamic behavior and vibration mitigation of a spatial tensegrity beam,” *Eng. Struct.*, vol. 171, pp. 1007–1016, Sep. 2018, doi: 10.1016/j.engstruct.2018.01.045.

[3] D. Wei, T. Gao, X. Mo, R. Xi, and C. Zhou, “Flexible Bio-tensegrity Manipulator with Multi-degree of Freedom and Variable Structure,” *Chin. J. Mechan. Eng.*, vol. 33, Feb. 2020, doi: 10.1186/s10033-019-0426-7.

[4] K. Kim, A. K. Agogino, and A. M. Agogino, “Rolling Locomotion of Cable-Driven Soft Spherical Tensegrity Robots,” *Soft Robot*, vol. 7, pp. 346–361, Jun. 2020, doi: 10.1089/soro.2019.0056.

[5] W. Zhao, A. Pashkevich, A. Klimchik, and D. Chablat, “Elastostatic Modeling of Multi-Link Flexible Manipulator Based on Two-Dimensional Dual-Triangle Tensegrity Mechanism,” *J. Mech. Robot*, vol. 14, Sep. 2021, doi: 10.1115/1.4051789.

[6] V. Böhm *et al.*, *An Approach to Robotic End Effectors Based on Multistable Tensegrity Structures*. Springer International Publishing, 2020. doi: 10.1007/978-3-030-55061-5_53.

[7] A. Mitchell, U. Lafont, M. Hołyńska, and C. Semprimoschnig, “Additive manufacturing — A review of 4D printing and future applications,” *Addit. Manuf.*, vol. 24, pp. 606–626, Dec. 2018, doi: 10.1016/j.addma.2018.10.038.

[8] B. Shekastehband and M. Ayoubi, “Nonlinear dynamic instability behavior of tensegrity grids subjected to impulsive loads,” *Thin-Wall. Struct.*, vol. 136, pp. 1–15, Mar. 2019, doi: 10.1016/j.tws.2018.11.031.

[9] W. Zhao, A. Pashkevich, A. Klimchik, and D. Chablat, “Stiffness Analysis of a New Tensegrity Mechanism based on Planar Dual-triangles,” in *Proceedings of the 17th Int. Conf. Inform. Contr., Autom. Rob.*, SCITEPRESS - Science and Technology Publications, 2020. doi: 10.5220/0009803104020411.

[10] A. Zawadzki and A. Al Sabouni-Zawadzka, “In Search of Lightweight Deployable Tensegrity Columns,” *Appl. Sci.*, vol. 10, p. 8676, Dec. 2020, doi: 10.3390/app10238676.

[11] D. Zappetti, “Variable-Stiffness Tensegrity Modular Robots,” 2021. doi: 10.5075/EPFL-THESIS-8083.

[12] P. Obara, J. Kłosowska, and W. Gilewski, “Truth and Myths about 2D Tensegrity Trusses,” *Appl. Sci.*, vol. 9, p. 179, Jan. 2019, doi: 10.3390/app9010179.

[13] J. Sun, G. Song, J. Chu, and L. Ren, “An Adaptive Bioinspired Foot Mechanism Based on Tensegrity Structures,” *Soft Robot*, vol. 6, pp. 778–789, Dec. 2019, doi: 10.1089/soro.2018.0168.

[14] I. Hrazmi, J. Averseng, J. Quirant, and F. Jamin, “Deployable double layer tensegrity grid platforms for sea accessibility,” *Eng. Struc.t*, vol. 231, p. 111706, Mar. 2021, doi: 10.1016/j.engstruct.2020.111706.

[15] D. S. Shah *et al.*, “Tensegrity Robotics,” *Soft Robot*, vol. 9, pp. 639–656, Aug. 2022, doi: 10.1089/soro.2020.0170.

[16] H. Lee *et al.*, “3D-printed programmable tensegrity for soft robotics,” *Sci. Robot*, vol. 5, Aug. 2020, doi: 10.1126/scirobotics.aay9024.

[17] T. Wang, M. A. Post, and A. M. Tyrrell, “Articulating Resilience: Adaptive Locomotion of Wheeled Tensegrity Robot,” *Electronics (Basel)*, vol. 11, p. 666, Feb. 2022, doi: 10.3390/electronics11040666.

[18] X. Yin, Z.-Y. Gao, S. Zhang, L.-Y. Zhang, and G.-K. Xu, “Truncated regular octahedral tensegrity-based mechanical metamaterial with tunable and programmable Poisson ratio,” *Int. J. Mech. Sci.*, vol. 167, p. 105285, Feb. 2020, doi: 10.1016/j.ijmecsci.2019.105285.

[19] E. A. Allen, “Variable stiffness structures via mechanics modification and antagonistic actuation in soft robotic materials,” Washington State University, 2020. doi: 10.7273/000004097.

[20] M. C. Phocas, E. G. Christoforou, and P. Dimitriou, “Kinematics and control approach for deployable and reconfigurable rigid bar linkage structures,” *Eng. Struct.*, vol. 208, p. 110310, Apr. 2020, doi: 10.1016/j.engstruct.2020.110310.

[21] D. Zappetti, Y. Sun, M. Gevers, S. Mintchev, and D. Floreano, “Dual Stiffness Tensegrity Platform for Resilient Robotics,” *Adv. Intell. Sys.*, vol. 4, p. 2200025, May 2022, doi: 10.1002/aisy.202200025.

[22] V. Gomez-Jauregui, M. Quilligan, C. Manchado, and C. Otero, “Design, Fabrication and Construction of a Deployable Double-Layer Tensegrity Grid,” *Struct. Eng. Int.*, vol. 28, pp. 13–20, Jan. 2018, doi: 10.1080/10168664.2018.1431379.

[23] O. Aloui, J. Flores, D. Orden, and L. Rhode-Barbarigos, “Cellular morphogenesis of three-dimensional tensegrity structures,” *Comput. Methods Appl. Mech. Eng.*, vol. 346, pp. 85–108, Apr. 2019, doi: 10.1016/j.cma.2018.10.048.

[24] L.-Y. Zhang, X. Yin, J. Yang, A. Li, and G.-K. Xu, “Multilevel structural defects-induced elastic wave tunability and localization of a tensegrity metamaterial,” *Compos. Sci. Technol.*, vol. 207, p. 108740, May 2021, doi: 10.1016/j.compscitech.2021.108740.

[25] L.-Y. Zhang, Y. Zheng, X. Yin, S. Zhang, H.-Q. Li, and G.-K. Xu, “A tensegrity-based morphing module for assembling various deployable structures,” *Mech. Mach. Theory*, vol. 173, p. 104870, Jul. 2022, doi: 10.1016/j.mechmachtheory.2022.104870.

[26] A. M. Popescu, R. Goyal, and M. Majji, “Design and Control of a Tensegrity Torus Spacecraft Composed of Reconfigurable Units,” in *AIAA Scitech 2021 Forum*, American Institute of Aeronautics and Astronautics, Jan. 2021. doi: 10.2514/6.2021-1387.

[27] P. Zhang, J. Zhou, and J. Chen, “Form-finding of complex tensegrity structures using constrained optimization method,” *Compos. Struct.*, vol. 268, p. 113971, Jul. 2021, doi: 10.1016/j.compstruct.2021.113971.

[28] A. Šljivić, S. Miljanović, and M. Zlatar, “A new classification of deployable structures,” *E3S Web of Conf.*, vol. 244, p. 5016, 2021, doi: 10.1051/e3sconf/202124405016.

[29] S. Yang and C. Sultan, “Deployment of foldable tensegrity-membrane systems via transition between tensegrity configurations and tensegrity-membrane configurations,” *Int. J. Solids Struct.*, vol. 160, pp. 103–119, Mar. 2019, doi: 10.1016/j.ijsolstr.2018.10.017.

[30] M. Palmieri, I. Giannetti, and A. Micheletti, “Floating-bending tensile-integrity structures,” *Curv. Layer. Struct.*, vol. 8, pp. 89–95, Jan. 2021, doi: 10.1515/cls-2021-0008.

[31] J.-H. Jiang, X. Yin, G.-K. Xu, Z.-Y. Wang, and L.-Y. Zhang, “A unified analytical form-finding of truncated regular octahedral tensegrities,” *Int. J. Mech. Sci.*, vol. 239, p. 107857, Feb. 2023, doi: 10.1016/j.ijmecsci.2022.107857.

[32] X. Xu, S. Huang, T. Shu, Y. Wang, and Y. Luo, “A Novel Two-Step Tensegrity Topology-Finding Method Based on Mixed Integer

Programming and Nonlinear Programming," *Int. J. Steel Struct.*, vol. 22, pp. 1266–1282, Jul. 2022, doi: 10.1007/s13296-022-00634-x.

[33] K. Song, F. Scarpa, and M. Schenk, "Form-finding of tessellated tensegrity structures," *Eng. Struct.*, vol. 252, p. 113627, Feb. 2022, doi: 10.1016/j.engstruct.2021.113627.

[34] A. Al Sabouni-Zawadzka, "Extreme Mechanical Properties of Regular Tensegrity Unit Cells in 3D Lattice Metamaterials," *Materials*, vol. 13, p. 4845, Oct. 2020, doi: 10.3390/ma13214845.

[35] M. C. Phocas, M. Matheou, A. Müller, and E. G. Christoforou, "Reconfigurable Modular Bar Structure," *J. Int. Assoc. Shell Spat. Struct.*, vol. 60, pp. 78–89, Mar. 2019, doi: 10.20898/j.iass.2019.199.028.

[36] Z. Kan, H. Peng, B. Chen, and W. Zhong, "A sliding cable element of multibody dynamics with application to nonlinear dynamic deployment analysis of clustered tensegrity," *Int. J. Solids Struct.*, vol. 130–131, pp. 61–79, Jan. 2018, doi: 10.1016/j.ijsolstr.2017.10.012.

[37] S. Ma, M. Chen, and R. E. Skelton, "Dynamics and control of clustered tensegrity systems," *Eng. Struct.*, vol. 264, p. 114391, Aug. 2022, doi: 10.1016/j.engstruct.2022.114391.

[38] Z. Kan, H. Peng, B. Chen, and W. Zhong, "Nonlinear dynamic and deployment analysis of clustered tensegrity structures using a positional formulation FEM," *Compos. Struct.*, vol. 187, pp. 241–258, Mar. 2018, doi: 10.1016/j.compstruct.2017.12.050.

[39] A. Vumiliya, A. Luo, H. Liu, and A. González, "Fundamental parameters for a minimal mass design of prismatic tensegrity cylinder subjected to a compressive force," *Eng. Comput. (Swansea)*, vol. 38, pp. 1368–1384, Jan. 2021, doi: 10.1108/ec-05-2020-0284.

[40] Y. Wang and G. Senatore, "Design of adaptive structures through energy minimization: extension to tensegrity," *Struct. Multidiscip. Optim.*, vol. 64, pp. 1079–1110, Jul. 2021, doi: 10.1007/s00158-021-02899-y.

[41] A. R. Barkan *et al.*, "Force-Sensing Tensegrity for Investigating Physical Human-Robot Interaction in Compliant Robotic Systems," in *2021 IEEE Int. Conf. Robot. Autom. (ICRA)*, IEEE, May 2021. doi: 10.1109/icra48506.2021.9561816.

[42] V. Ramadoss, K. Sagar, M. S. Ikbal, J. H. L. Calles, R. Siddaraboina, and M. Zoppi, "HEDRA: A Bio-Inspired Modular Tensegrity Robot With Polyhedral Parallel Modules," in *2022 IEEE 5th Int. Conf. Soft Robot. (RoboSoft)*, IEEE, Apr. 2022. doi: 10.1109/robosoft54090.2022.9762130.

[43] T. E. Flemons and D. Blostein, "New Approaches to Mechanizing Tensegrity Structures," in *Earth and Space 2018*, American Society of Civil Engineers, Nov. 2018. doi: 10.1061/9780784481899.086.

[44] A. Al Sabouni-Zawadzka and W. Gilewski, "Inherent Properties of Smart Tensegrity Structures," *Appl. Sci.*, vol. 8, p. 787, May 2018, doi: 10.3390/app8050787.

[45] X. Xu, Y. Wang, Y. Luo, and D. Hu, "Topology Optimization of Tensegrity Structures Considering Buckling Constraints," *J. Struct. Eng.*, vol. 144, Oct. 2018, doi: 10.1061/(asce)st.1943-541x.0002156.

[46] A. Zawadzki and A. Al Sabouni-Zawadzka, *Critical Issues in Designing Controllable Deployable Tensegrity Structures*. Springer International Publishing, 2021. doi: 10.1007/978-3-030-86001-1_38.

[47] X. Zhang, R. Nie, Y. Chen, and B. He, "Deployable Structures: Structural Design and Static/Dynamic Analysis," *J. Elast.*, vol. 146, pp. 199–235, Oct. 2021, doi: 10.1007/s10659-021-09860-6.

[48] Z. Kan, F. Li, N. Song, and H. Peng, "Novel Nonlinear Complementarity Function Approach for Mechanical Analysis of Tensegrity Structures," *AIAA J.*, vol. 59, pp. 1483–1495, Apr. 2021, doi: 10.2514/1.j059828.

[49] Z. Kan, H. Peng, and B. Chen, "Complementarity Framework for Nonlinear Analysis of Tensegrity Structures with Slack Cables," *AIAA J.*, vol. 56, pp. 5013–5027, Dec. 2018, doi: 10.2514/1.j057149.

[50] Y. Dong, J. Ding, C. Wang, and X. Liu, "Kinematics Analysis and Optimization of a 3-DOF Planar Tensegrity Manipulator under Workspace Constraint," *Machines*, vol. 9, p. 256, Oct. 2021, doi: 10.3390/machines9110256.

[51] M. M. Tanouye and V. Vikas, "Static and Stability Analysis of a Planar Compliant Tensegrity Mechanism," in *Volume 5A: 42nd Mechan. Robot, Conf.*, American Society of Mechanical Engineers, Aug. 2018. doi: 10.1115/detc2018-85998.

[52] A. González, A. Luo, and D. Shi, "Reconfiguration of multi-stage tensegrity structures using infinitesimal mechanisms," *Latin Amer. J. Sol. Structur.*, vol. 16, 2019, doi: 10.1590/1679-78255331.

[53] S. Lee, Q. X. Lieu, T. P. Vo, and J. Lee, "Deep Neural Networks for Form-Finding of Tensegrity Structures," *Mathematics*, vol. 10, p. 1822, May 2022, doi: 10.3390/math10111822.

[54] S. Yuan and W. Zhu, "A New Approach to Nonlinear Dynamic Modeling and Vibration Analysis of Tensegrity Structures," in *Volume 5: Dyn., Vibrat., Contr.*, American Society of Mechanical Engineers, Oct. 2022. doi: 10.1115/imece2022-94746.

[55] D. He, Q. Gao, and W. Zhong, "An accurate method for the dynamic behavior of tensegrity structures," *Eng. Comput. (Swansea)*, vol. 35, pp. 1250–1278, May 2018, doi: 10.1108/ec-08-2016-0298.

[56] X. Feng, "Geometrical nonlinear dynamic analysis of tensegrity systems via the corotational formulation," *J. Mech. Mater. Struct.*, vol. 13, pp. 263–281, Aug. 2018, doi: 10.2140/jomms.2018.13.263.

[57] X. Yin, S. Zhang, G.-K. Xu, L.-Y. Zhang, and Z.-Y. Gao, "Bandgap characteristics of a tensegrity metamaterial chain with defects," *Extreme Mech. Lett.*, vol. 36, p. 100668, Apr. 2020, doi: 10.1016/j.eml.2020.100668.

[58] D. Martins and P. J. P. Gonçalves, "On the dynamics of a smart tensegrity structure using shape memory alloy," *J. Phys. Conf. Ser.*, vol. 1264, p. 12001, Jul. 2019, doi: 10.1088/1742-6596/1264/1/012001.

[59] H. Salahshoor, R. K. Pal, and J. J. Rimoli, "Material symmetry phase transitions in three-dimensional tensegrity metamaterials," *J. Mech. Phys. Solids*, vol. 119, pp. 382–399, Oct. 2018, doi: 10.1016/j.jmps.2018.07.011.

[60] F. Li, H. Peng, H. Yang, and Z. Kan, "A symplectic kinodynamic planning method for cable-driven tensegrity manipulators in a dynamic environment," *Nonlinear Dyn.*, vol. 106, pp. 2919–2941, Oct. 2021, doi: 10.1007/s11071-021-06927-w.

[61] Y. Wang, X. Xu, and Y. Luo, "Topology-Finding of Tensegrity Structures Considering Global Stability Condition," *J. Struct. Eng.*, vol. 146, Dec. 2020, doi: 10.1061/(asce)st.1943-541x.0002843.

[62] O. C. Lian, C. K. Keong, T. Nishimura, and K. Jae-Yeol, "Form-Finding of Spine Inspired Biotensegrity Model," *Appl. Sci.*, vol. 10, p. 6344, Sep. 2020, doi: 10.3390/app10186344.

[63] W. Dong, P. J. Stafford, and A. M. Ruiz-Teran, "Inverse form-finding for tensegrity structures," *Computers &amp Structures*, vol. 215, pp. 27–42, Apr. 2019, doi: 10.1016/j.compstruc.2019.01.009.

[64] J. Cai, X. Wang, X. Deng, and J. Feng, "Form-finding method for multi-mode tensegrity structures using extended force density method by grouping elements," *Compos. Struct.*, vol. 187, pp. 1–9, Mar. 2018, doi: 10.1016/j.compstruct.2017.12.010.

[65] H. Q. Bui, M. Kawabata, and C. Van Nguyen, "A combination of genetic algorithm and dynamic relaxation method for practical form-finding of tensegrity structures," *Adv. Struct. Eng.*, vol. 25, pp. 2237–2254, May 2022, doi: 10.1177/13694332221092675.

[66] Y. Su, J. Zhang, M. Ohsaki, and Y. Wu, "Topology optimization and shape design method for large-span tensegrity structures with reciprocal struts," *Int. J. Solids Struct.*, vol. 206, pp. 9–22, Dec. 2020, doi: 10.1016/j.ijsolstr.2020.09.002.

[67] A. Al Sabouni-Zawadzka and W. Gilewski, "Soft and Stiff Simplex Tensegrity Lattices as Extreme Smart Metamaterials," *Materials*, vol. 12, p. 187, Jan. 2019, doi: 10.3390/ma12010187.

[68] J. V Henrickson, R. E. Skelton, and J. Valasek, "Shape Control of Tensegrity Structures," in *AIAA SPACE 2015 Conf. Expos.*, American Institute of Aeronautics and Astronautics, Aug. 2015. doi: 10.2514/6.2015-4502.

[69] A. Al Sabouni-Zawadzka and W. Gilewski, "Smart Metamaterial Based on the Simplex Tensegrity Pattern," *Materials*, vol. 11, p. 673, Apr. 2018, doi: 10.3390/ma11050673.

[70] F. Fraternali and F. Santos, "Mechanical modeling of superelastic tensegrity braces for earthquake-proof structures," *Extreme Mech. Lett.* vol. 33, p. 100578, Nov. 2019, doi: 10.1016/j.eml.2019.100578.

[71] B. Chen and H. Jiang, "Swimming Performance of a Tensegrity Robotic Fish," *Soft Robot*, vol. 6, pp. 520–531, Aug. 2019, doi: 10.1089/soro.2018.0079.

[72] R. Wang, R. Goyal, S. Chakravorty, and R. E. Skelton, "Model and Data Based Approaches to the Control of Tensegrity Robots," *IEEE Robot Autom. Lett..*, vol. 5, pp. 3846–3853, Jul. 2020, doi: 10.1109/lra.2020.2979891.

[73] A. C. Sychterz, "Biomimetic adaptive control of a deployable tensegrity structure," 2018. doi: 10.5075/EPFL-THESIS-8778.

[74] X. Xu, Y. Wang, and Y. Luo, "An improved multi-objective topology optimization approach for tensegrity structures," *Adv. Struct. Eng.*, vol. 21, pp. 59–70, Jul. 2017, doi: 10.1177/1369433217706780.

[75] X. Xu, S. Huang, Y. Wang, and Y. Luo, "A generalized objective function based on weight coefficient for topology-finding of

tensegrity structures," *Appl Math Model*, vol. 115, pp. 541–567, Mar. 2023, doi: 10.1016/j.apm.2022.10.038.

[76] C. L. Oh, K. K. Choong, T. Nishimura, J.-Y. Kim, and O. Hassanshahi, "Shape change analysis of tensegrity models," *Latin Amer. J. Sol. Struct.,* vol. 16, 2019, doi: 10.1590/1679-78255407.

[77] Y. Wang, X. Xu, and Y. Luo, "Topology design of general tensegrity with rigid bodies," *Int. J. Solids Struct.*, vol. 202, pp. 278–298, Oct. 2020, doi: 10.1016/j.ijsolstr.2020.05.030.

[78] A. P. Sabelhaus *et al.*, "Inverse Statics Optimization for Compound Tensegrity Robots," *IEEE Robot Autom. Lett.*, vol. 5, pp. 3982–3989, Jul. 2020, doi: 10.1109/lra.2020.2983699.

[79] M. Chen, R. Goyal, M. Majji, and R. E. Skelton, "Deployable Tensegrity Lunar Tower," in *Ear. Sp. 2021*, American Society of Civil Engineers, Apr. 2021. doi: 10.1061/9780784483374.100.

[80] R. Goyal, M. Chen, M. Majji, and R. Skelton, "MOTES: Modeling of Tensegrity Structures," *J. Open Source Softw.*, vol. 4, p. 1613, Oct. 2019, doi: 10.21105/joss.01613.

[81] Y. Wang, X. Xu, and Y. Luo, "Form-finding of tensegrity structures via rank minimization of force density matrix," *Eng. Struct.*, vol. 227, p. 111419, Jan. 2021, doi: 10.1016/j.engstruct.2020.111419.

[82] C. Wang, Z. Vangelatos, C. P. Grigoropoulos, and Z. Ma, "Micro-engineered architected metamaterials for cell and tissue engineering," *Mater. Today Adv.*, vol. 13, p. 100206, Mar. 2022, doi: 10.1016/j.mtadv.2022.100206.

[83] A. Sonawane, C. Hawaldar, P. Ankad, and A. Joshi, "Non-linear geometric analysis of multilayer tensegrity tower," *Mater. Today Proc.*, vol. 77, pp. 788–793, 2023, doi: 10.1016/j.matpr.2022.11.448.

[84] S. Krishnan and B. Li, "Design of Lightweight Deployable Antennas Using the Tensegrity Principle," in *Ear. Sp. 2018*, American Society of Civil Engineers, Nov. 2018. doi: 10.1061/9780784481899.084.

[85] R. Gao, Y. Liu, Q. Bi, B. Yang, and Y. Li, "Design of a Novel Quadruped Robot Based on Tensegrity Structures," in *2021 IEEE Int. Conf. Mechatr. Automat. (ICMA)*, IEEE, Aug. 2021. doi: 10.1109/icma52036.2021.9512612.

[86] S. Mintchev, D. Zappetti, J. Willemin, and D. Floreano, "A Soft Robot for Random Exploration of Terrestrial Environments," in *2018 IEEE Int. Conf. Robot. Autom. (ICRA)*, IEEE, May 2018. doi: 10.1109/icra.2018.8460667.

[87] P. Meng, W. Wang, D. Balkcom, and K. E. Bekris, "Proof-of-Concept Designs for the Assembly of Modular Dynamic Tensegrities into Easily Deployable Structures," in *Ear. Sp. 2021*, American Society of Civil Engineers, Apr. 2021. doi: 10.1061/9780784483374.103.

[88] K. Doney, A. Petridou, J. Karaul, A. Khan, G. Liu, and J. Rieffel, "Behavioral Repertoires for Soft Tensegrity Robots," in *2020 IEEE Sympos. Seri. Comput Intellig. (SSCI)*, IEEE, Dec. 2020. doi: 10.1109/ssci47803.2020.9308218.

[89] Y. S. Chung, J.-H. Lee, J. H. Jang, H. R. Choi, and H. Rodrigue, "Jumping Tensegrity Robot Based on Torsionally Prestrained SMA Springs," *ACS Appl. Mater. Interf.*, vol. 11, pp. 40793–40799, Sep. 2019, doi: 10.1021/acsami.9b13062.

[90] L. Wen, F. Pan, and X. Ding, "Tensegrity metamaterials for soft robotics," *Sci. Robot*, vol. 5, Aug. 2020, doi: 10.1126/scirobotics.abd9158.

[91] D. H. Myszka, J. J. Joo, D. C. Woods, and A. P. Murray, "Topology Optimization of Cable-Actuated, Shape-Changing, Tensegrity Sys. Path Gener.," in *Volume 5B: 43rd Mechan. Robotics Conference*, American Society of Mechanical Engineers, Aug. 2019. doi: 10.1115/detc2019-97367.

[92] J. Kimber *et al.*, "Low-Cost Wireless Modular Soft Tensegrity Robots," in *2019 2nd IEEE Int. Conf. Soft Robot. (RoboSoft)*, IEEE, Apr. 2019. doi: 10.1109/robosoft.2019.8722723.

[93] D. Zhou, Y. Liu, X. Tang, J. Sun, and J. Deng, "A Lightweight and Multimotion Crawling Tensegrity Robot Driven by Twisted Artificial Muscles," *IEEE Trans. Industr.Electr.s*, vol. 69, pp. 11447–11457, Nov. 2022, doi: 10.1109/tie.2021.3125646.

[94] J. W. Booth, O. Cyr-Choinière, J. C. Case, D. Shah, M. C. Yuen, and R. Kramer-Bottiglio, "Surface Actuation and Sensing of a Tensegrity Structure Using Robotic Skins," *Soft Robot*, vol. 8, pp. 531–541, Oct. 2021, doi: 10.1089/soro.2019.0142.

[95] K. Yildiz and G. A. Lesieutre, "A Novel Deployment Strategy for Tensegrity Towers," in *2018 AIAA Spacecr. Struct. Conf.*, American Institute of Aeronautics and Astronautics, Jan. 2018. doi: 10.2514/6.2018-0693.

[96] W. R. Johnson, A. Agrawala, X. Huang, J. Booth, and R. Kramer-Bottiglio, "Sensor Tendons for Soft Robot Shape Estimation," in *2022 IEEE Sens.*, IEEE, Oct. 2022. doi: 10.1109/sensors52175.2022.9967136.

[97] W.-Y. Li, H. Nabae, G. Endo, and K. Suzumori, "New Soft Robot Hand Configuration With Combined Biotensegrity and Thin Artificial Muscle," *IEEE Robot Autom. Lett.*, vol. 5, pp. 4345–4351, Jul. 2020, doi: 10.1109/lra.2020.2983668.

[98] Y. Tang, T. Li, Q. Lv, and X. Wang, "A self-vibration-control tensegrity structure for space large-scale construction," *Mech. Syst. Signal Proc.*, vol. 177, p. 109241, Sep. 2022, doi: 10.1016/j.ymssp.2022.109241.

[99] D. Zhou, Y. Liu, J. Deng, J. Sun, and Y. Fu, "Force Enhanced Multi-Twisted and Coiled Actuator and Its Application in Temperature Self-Adaptive Tensegrity Mechanisms," *IEEE/ASME Transact. Mechatr.*, vol. 27, pp. 3964–3976, Oct. 2022, doi: 10.1109/tmech.2022.3150761.

[100] S. Watanabe, Y. Ikemoto, and J. Shintake, "Tensegrity structures using dielectric elastomer cables," in *Electroac. Polym.Actuat. Dev. (EAPAD) XXIV*, J. D. Madden, I. A. Anderson, and H. R. Shea, Eds., SPIE, Apr. 2022. doi: 10.1117/12.2614653.

[101] A. K. Bastola and M. Hossain, "The shape – morphing performance of magnetoactive soft materials," *Mater. Des.*, vol. 211, p. 110172, Dec. 2021, doi: 10.1016/j.matdes.2021.110172.

[102] R. Kobayashi, H. Nabae, G. Endo, and K. Suzumori, "Soft Tensegrity Robot Driven by Thin Artificial Muscles for the Exploration of Unknown Spatial Configurations," *IEEE Robot Autom. Lett.*, vol. 7, pp. 5349–5356, Apr. 2022, doi: 10.1109/lra.2022.3153700.

[103] S. Lee, J. Jeong, S. Ahn, Q. X. Lieu, and J. Lee, "Performance of quadruplex module tensegrities using new pin-jointed connections," *J. Constr. Steel Res.*, vol. 172, p. 105763, Sep. 2020, doi: 10.1016/j.jcsr.2019.105763.

[104] W. Zhu, J. Liu, H. Li, and K. Gu, "Design and analysis of a compliant polishing manipulator with tensegrity-based parallel mechanism," *Australian J. Mech. Eng.*, vol. 19, pp. 414–422, Jun. 2019, doi: 10.1080/14484846.2019.1629678.

[105] B. Lu *et al.*, "3D Hexagonal Arrangement of DNA Tensegrity Triangles," *ACS Nano*, vol. 15, pp. 16788–16793, Oct. 2021, doi: 10.1021/acsnano.1c06963.

[106] J. M. Friesen, J. L. Dean, T. Bewley, and V. Sunspiral, "A Tensegrity-Inspired Compliant 3-DOF Compliant Joint," in *2018 IEEE Int. Conf. Robot. Autom. (ICRA)*, IEEE, May 2018. doi: 10.1109/icra.2018.8460593.

[107] V. Muralidharan and P. Wenger, "Optimal design and comparative study of two antagonistically actuated tensegrity joints," *Mech. Mach. Theory*, vol. 159, p. 104249, May 2021, doi: 10.1016/j.mechmachtheory.2021.104249.

[108] N. Tan, A. A. Hayat, M. R. Elara, and K. L. Wood, "A Framework for Taxonomy and Evaluation of Self-Reconfigurable Robotic Systems," *IEEE Access*, vol. 8, pp. 13969–13986, 2020, doi: 10.1109/access.2020.2965327.

[109] C. Intrigila, A. Micheletti, N. A. Nodargi, E. Artioli, and P. Bisegna, "Fabrication and experimental characterisation of a bistable tensegrity-like unit for lattice metamaterials," *Addit. Manuf*, vol. 57, p. 102946, Sep. 2022, doi: 10.1016/j.addma.2022.102946.

[110] X. Kuang *et al.*, "Advances in 4D Printing: Materials and Applications," *Adv. Funct. Mater.*, vol. 29, p. 1805290, Nov. 2018, doi: 10.1002/adfm.201805290.

[111] D. Niazy, A. Elsabbagh, and M. R. Ismail, "Mono–Material 4D Printing of Digital Shape–Memory Components," *Polymers (Basel)*, vol. 13, p. 3767, Oct. 2021, doi: 10.3390/polym13213767.

[112] X. Peng *et al.*, "4D Printing of Freestanding Liquid Crystal Elastomers via Hybrid Additive Manufacturing (Adv. Mater. 39/2022)," *Adv. Mater.*, vol. 34, p. 2270272, Sep. 2022, doi: 10.1002/adma.202270272.

[113] A. Al Sabouni-Zawadzka and W. Gilewski, "Towards unusual mechanical properties of tensegrity lattice metamaterial," *MATEC Web of Conf.*, vol. 196, p. 4093, 2018, doi: 10.1051/matecconf/201819604093.

[114] Y. Ma *et al.*, "Meta-tensegrity: Design of a tensegrity prism with metal rubber," *Compos. Struct.*, vol. 206, pp. 644–657, Dec. 2018, doi: 10.1016/j.compstruct.2018.08.067.

[115] G. M. Butler and E. A. P. Hernandez, "Tensegrity Structures Incorporating Actuator and Pseudoelastic Shape Memory Alloys," in *Volume 4: Adv. Aeros. Techn.*, American Society of Mechanical Engineers, Nov. 2020. doi: 10.1115/imece2020-24645.

[116] X. Yuan *et al.*, "Recent progress in the design and fabrication of multifunctional structures based on metamaterials," *Curr. Opin. Solid State Mater. Sci.*, vol. 25, p. 100883, Feb. 2021, doi: 10.1016/j.cossms.2020.100883.

[117] A. Micheletti, G. Ruscica, and F. Fraternali, “On the compact wave dynamics of tensegrity beams in multiple dimensions,” *Nonlinear Dyn.*, vol. 98, pp. 2737–2753, May 2019, doi: 10.1007/s11071-019-04986-8.

[118] J. Rieffel and J.-B. Mouret, “Adaptive and Resilient Soft Tensegrity Robots,” *Soft Robot*, vol. 5, pp. 318–329, Jun. 2018, doi: 10.1089/soro.2017.0066.

[119] R. Miranda, E. Babilio, N. Singh, F. Santos, and F. Fraternali, “Mechanics of smart origami sunscreens with energy harvesting ability,” *Mech. Res. Commun.*, vol. 105, p. 103503, Apr. 2020, doi: 10.1016/j.mechrescom.2020.103503.

[120] C. Boni and G. Royer-Carfagni, “Nonlinear effects in the vibrations of flexural tensegrity beams,” *Int. J. Non Linear Mech.*, vol. 128, p. 103616, Jan. 2021, doi: 10.1016/j.ijnonlinmec.2020.103616.

[121] Y. Liu, Q. Bi, and Y. Li, “Development of a Bio-inspired Soft Robotic Gripper based on Tensegrity Structures,” in *2021 IEEE/RSJ Int. Conf. Intellig. Rob. Sys. (IROS)*, IEEE, Sep. 2021. doi: 10.1109/iros51168.2021.9635929.

[122] A. Brandão and M. A. Savi, “Nonlinear Mechanics of a Smart Biotensegrity Human Foot Prosthesis,” *Int. J. Appl. Mech.*, vol. 14, Jan. 2022, doi: 10.1142/s1758825121501246.

[123] J. Sun, S. Zhang, Z. Wang, G. Song, M. Zhang, and J. Chu, “Design of a new foot structure based on the mast-type octahedral tensegrity structure,” *Mech. Mach. Theory*, vol. 177, p. 105016, Nov. 2022, doi: 10.1016/j.mechmachtheory.2022.105016.

[124] M. Aberoumand, D. Rahmatabadi, A. Aminzadeh, and M. Moradi, *4D Printing by Fused Deposition Modeling (FDM)*. Springer International Publishing, 2021. doi: 10.1007/978-3-030-68024-4_20.

[125] Y. Liu, Q. Bi, X. Yue, J. Wu, B. Yang, and Y. Li, “A review on tensegrity structures-based robots,” *Mech. Mach. Theory*, vol. 168, p. 104571, Feb. 2022, doi: 10.1016/j.mechmachtheory.2021.104571.