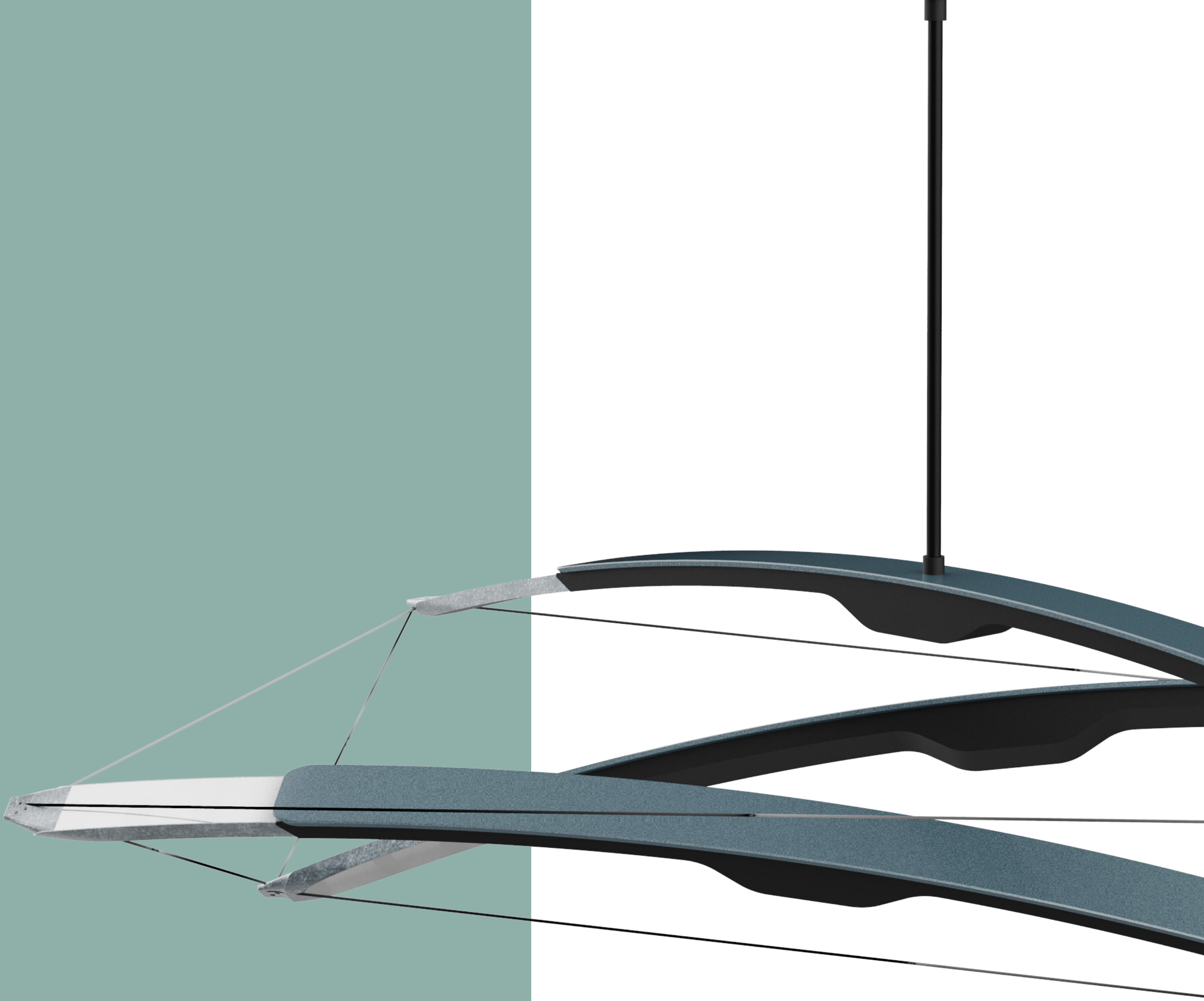

TEN-X

lighting design with dynamic tensegrity structure

Master Thesis
Design & Engineering
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The following MSc. Thesis will summarize my final project at Politecnico di Milano incorporation with Ecole Centrale Nantes. During this final step of my education I will be working on the theory and product design of dynamic tensegrity lightening unit.

Most of this thesis was written during my exchange period at the Ecole Centrale de Nantes, where I studied in the L2SN Group. For being given the opportunity to research there for 5 months, and for all the valuable help and guidance during my stay, I would like to take this opportunity to thank Director Prof. Damien Chablat and PhD. Matthieu Furet.

Abstract

This Master thesis investigates the new ways of using tensegrity structures in product design field. By consisting of struts and cables, tensegrities offer various structural advantages such as being strong, lightweight,dynamic and deployable. A detailed mathematical model of tensegrity structures developed to build up the initial concept and apply to real-product scenario. Lighting application is chosen as a product concept with dynamic tensegrity structure aiming to change the way that people interact with the lightening units and open up new possibilities for future lighting applications.

Keywords
Tensegrity, Lighting Design, Deployable Structure, Mathematical Model

Sommario

Questa tesi di laurea studia i nuovi modi di utilizzare le strutture tensegrity nel campo della progettazione di prodotto. Costituiti da montanti e cavi, i tensegrities offrono vari vantaggi strutturali come essere forti, leggeri, dinamici e schierabili. Un modello matematico dettagliato delle strutture tensegrity è stato sviluppato per costruire il concept iniziale e applicato allo scenario di prodotto reale. L'applicazione di illuminazione viene scelta come concept di prodotto con una struttura dinamica di tensegrità che mira a cambiare il modo in cui le persone interagiscono con le unità di illuminazione e ad aprire nuove possibilità per future applicazioni di illuminazione.

Parole Chiave
Tensegrity, Unità di illuminazione, Strutture Schierabili, Modello Matematico

Résumé

Cette thèse étudie les nouvelles façons d'utiliser les structures de tenségrité dans le domaine de la conception de produits. Constituées de montants et de câbles, les tenségrité offrent de nombreux avantages structurels, étant solide, légère, dynamique, deployable. Un modèle des structures de tenségrité a été développé pour construire le concept initial et appliqué au scénario de produit réel. L'application d'éclairage est choisie en tant que concept de produit qui vise à modifier la façon dont les personnes interagissent avec les unités d'éclairage et à ouvrir de nouvelles possibilités pour les applications d'éclairage futures.

Mots Clés
Tenségrité, Unité d'éclairage, Structure déployable, Modèle Mathématique

Özet

Bu yüksek lisans tezi, tensegrity(çek-ger-tümle) yapılarının endüstriyel tasarım alanında kullanımının yeni yollarını araştırmaktadır. Gergi ve kablolardan oluşan kafes şeklindeki bu yapıların, güçlü, hafif, dinamik ve yeniden şekillendirebilir olmak gibi çeşitli yapısal avantajları vardır. İlk konspeti oluşturmak ve gerçek ürün senaryosuna uygulamak için ayrıntılı bir matematik model geliştirilmiştir. Dinamik tensegrity (çek-ger-tümle) yapısına sahip aydınlatma ünitesi konsepti ile insanların aydınlatma ürünleri ile etkileşim şeklini değiştirmeyi ve gelecekteki aydınlatma uygulamaları için yeni olanaklar sunmayı amaçlamaktadır.

Anahtar kelimeler
Tensegrity, Aydınlatma Tasarımı, Dinamik Yapılar, Matematik Model

01 Introduction

This chapter will provide the aim of the research and guide for the incoming chapters. It will cover overall idea and provide meaningful picture of this thesis.

1.Introduction

With the development of new technologies in the structure field, today it is possible to design and create unique, lightweight and responsive structural elements. This thesis focuses on one of this new type of structures which is called **tensegrity**. This relatively new kind of structure is investigated in research phase with all aspects (advantages,challenges and applications and design computation) and using these knowledge gathered in the research phase, this unique structure is applied to **lightening product** which is planned to change the way that people interact with the lightening units.

The research phase creates a theoretical foundation for tensegrity mechanism where these special and unique properties investigated. For decades these properties allow this structure to be present not only in the architectural field but also for many engineering applications. Nowadays the new applications come from mostly deployable and controllable structures.

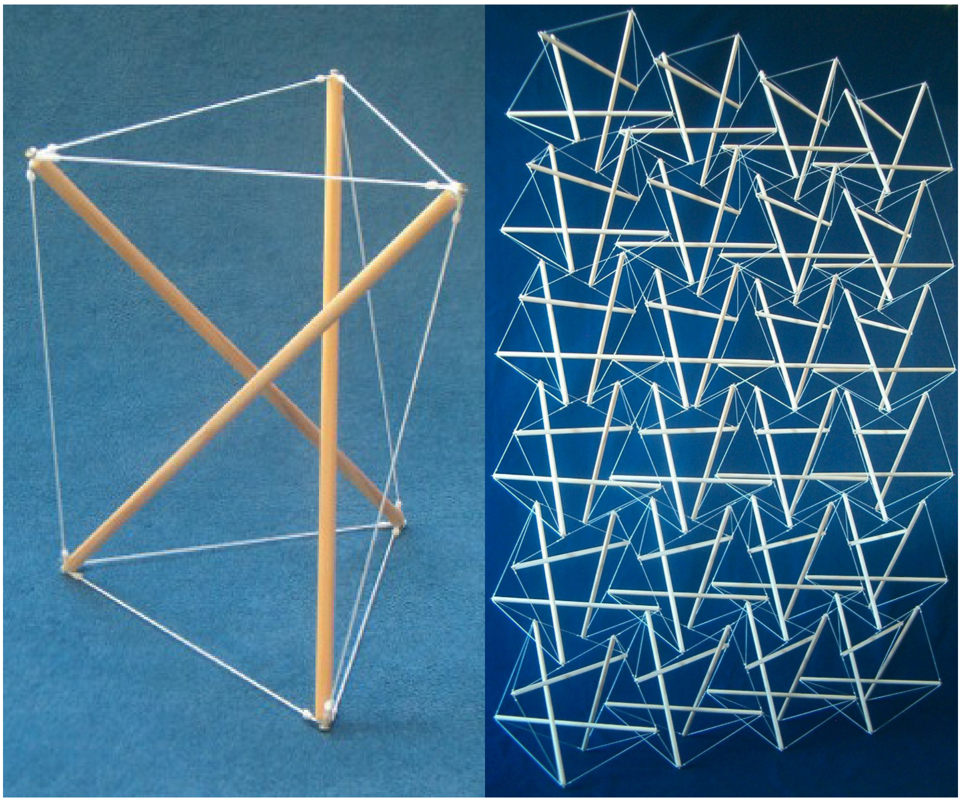


FIG1. Geometric representation of basic tensegrity structures.

1) 3-strut T-prism
2) Tensegrity wall

This thesis covers the technical basis for required technology, product itself and how to transform the concept to reality. The initial step has been determined to understand the capabilities of the tensegrity structures including the literature survey about the current state of art, investigation of the applications from different fields. The main idea here to understand the basis and the concept of tensegrities and application possibilities to a product.

With the time, this thesis has been evolved from more technical research to more artistry design project which illuminate inspiring places with its unique structure. It is really interesting to apply the tensegrity structure to artistary project with such a complex form.

The ideation of the product has been deepened on the lack of experience that we get from the conventional lightening units on the market. Current products are not enough to get attraction because of their static state. With using the advantages of the dynamic tensegrity, this new concept can be a solution for the new kind of lightening design products.

Despite the general lightening units, this new innovative design creates exceptionally powerful experiences through both emotional and physical responses using dynamic tensegrity structure. To achieve this kind of experience the product should be designed for not only aesthetic purposes but also for functionality. With the knowledge of this, the suggested design uses these unique properties as a source of creation innovative product in lightening design sector. With the combination of two fields **(lightening design & tensegrity structure)** is expected to achieve very interesting result, that could provide new ideas and inspirations for both fields.

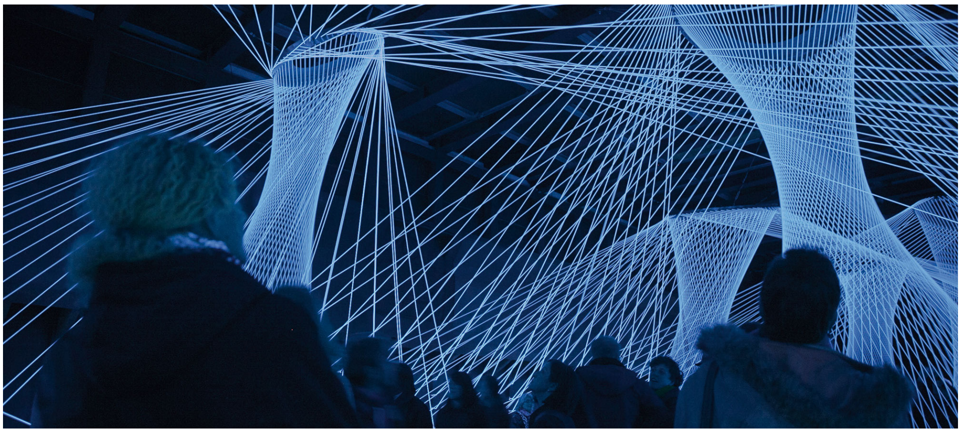


FIG 2. Representation of new era of lighting design sector and interactions.

Resonate: Installation for the light festival luminale 2012 in Frankfurt.

1.1. Scope and Aims

The first aim of this thesis is to have a meaningful understanding of the tensegrity systems and realization of the general concept and design of statically balanced tensegrity mechanism. To achieve this goal, several mathematical concepts will be introduced, analyzed with the current computation methods and validation has been done with simulations and prototype.

The second aim of the thesis is the applicate this technology to a product. The product ideation and brief definition will be introduced. Functioning features, material selection and manufacturing methods will be applied for real life product.

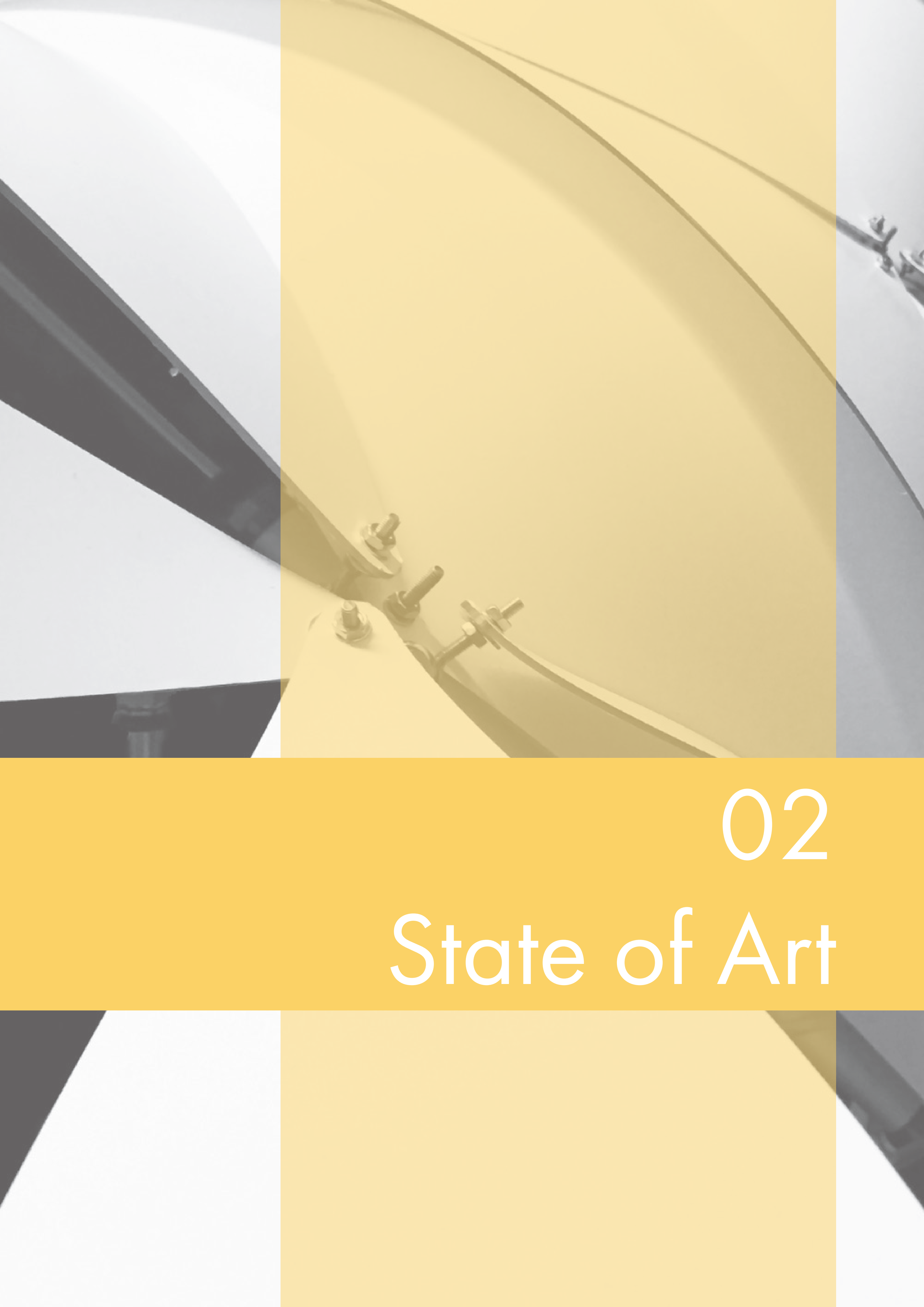
Overall, this report will outline the principles of tensegrity structures with suggested basic proof of concept design. Validation of these theoretical concepts has been made through prototyping and simulations.

Furthermore, the product itself will be applicable to the real life application of this unique structure. All the challenges faced during these processes has been reported for the future researches.

1.2. Document Structure

The thesis is organized as follows: Chapter 2, provides an overall idea to have a meaningful picture of tensegrity structures. History and general description show the evolution of tensegrity concept. Chapter 3 presents the related works on many fields where tensegrity applied and creates base for inspiration. Chapter 5 introduces the mechanics of tensegrity based on mathematical modeling and will cover the design process followed to prove the concept. Also with the simulations the proof of concept design will be consolidated. Chapter 6 will cover overall the new product. The brief concept,material selection and manufacturing method will be applied for real-life scenarios.

The work done in this thesis: 1) The mathematical model of a tensegrity with basic three bar tensegrity is established. 2) The initial concept of the tensegrity structure suggested and prototyped. 3) Dynamic motion simulations made by the ADAMS software. 5) Real world application for future works.



02
State of Art

This chapter will give a general introduction about tensegrity structures. It will cover overall idea and provide meaningful picture of this unique structure starting from historical point.

Quote
R. Buckminster Fuller

"Integrity is the essence of everything successful."

2.State of Art

Tensegrity is a type of structure which comprises rigid elements **(struts)** and elastic elements **(cables)** to stand alone and maintain its form.(self-balancing and self-supporting).

Even though in earlier applications of tensegrity structures mainly used for structural manner, currently this unique type of structures is developing for deployable and controllable structures. As defined by Fuller's patent application, this type structure can be explained basically as the combination of tension and integrity [1]. Tensegrity have ground on these essential terms. With these critical forces, overall structure can be constructed with basic, lightweight structural elements. Alternatively, to conventional mechanisms, tensegrity structures can be decent solution for lighter and responsive product requests.

This kind of structures had been used in several applications in architecture to art, space industry to product design which can be seen in figures. Nowadays it has been studied deeply for the future applications in robotics, space industry and deployable structures. Especially in robotics and space industry, it is feasible to use the advantage of the structural flexibility which can be the reshaping the geometry of the structure [2-4].

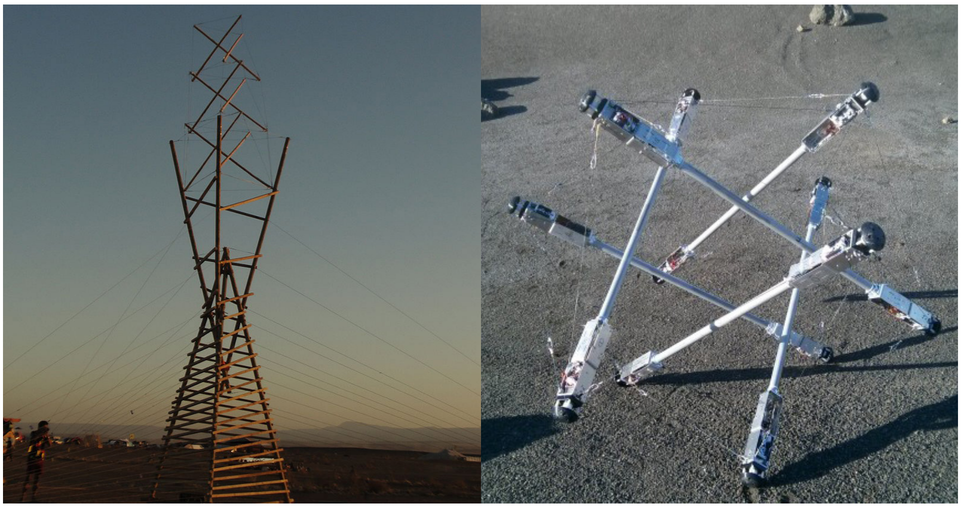


FIG 3. Tensegrity structure examples:

1) "Dissipate", an hourglass tower art sculpture including tensegrity structure, constructed at AfrikaBurn, 2015, a Burning Man regional event.

2) The NASA SUPERball Tensegrity Robot

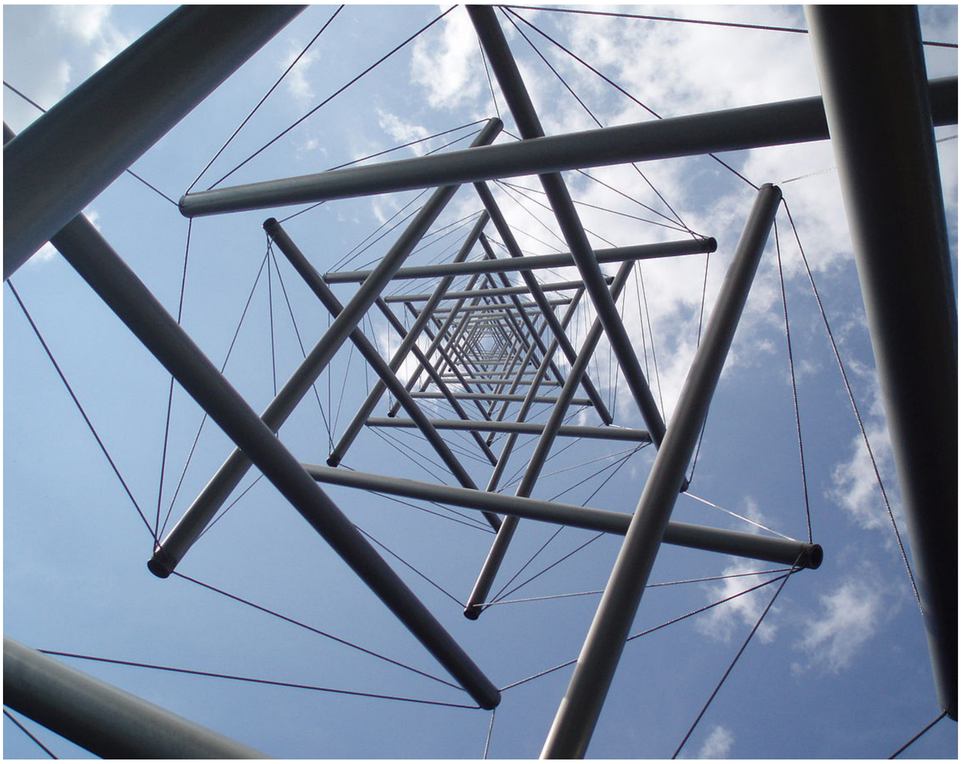


FIG 4. The "Needle Tower" Built by Kenneth Snelson in 1968.

With the development of the technology today, tensegrity is an interesting topic to study the behavior of this unique and complex structure. The use of cables in this unique structure can allow them to be deployable. This superior feature can be used in space exploration missions by folding overall structures in the world and transport to space for numerous space operations [5]. On the other hand, today most of the biologists are searching the connections tensegrity and nature. From skeletons to cells, there are evidences showing this ideas can be true. Also the complex shape itself can be source of inspiration for new artists. Moreover it is still attractive for architects for construction buildings. This unique structure can cover spaces with few elements and which can reduce the economical drain to create complex units for the building, membranes or tents.

Even though tensegrity can be too simple or too complex, tensegrity structures should be investigated for new applications due to their physical properties like flexibility, deployable, lightweight, and for numerous advantages. Upcoming sections will cover these features by starting from the historical point of view.

2.1. History

Many scientists helped the early improvement of tensegrity constructions. Although the first tensegrity structures have been started to be mentioned in mid-20th century, there are some evidences from Latvian constructionist Karl Iogasan (1920) by keeping the photographs of these products [6]. At that time, Tensegrity structures firstly initiated by art purpose and being rapidly applied to all other disciplines especially in architecture.

Latterly, the most well-known definition has been done by Buckminster Fuller (Fig. 2.1) in his patent application (1962), who explained basically with two words: Tensile Integrity. The origin of the word "tensegrity" comes from these combinations [1].

Fuller, influenced a lot of student with his lectures at Black Mountain College in North Carolina, 1948, about tensegrity structures. Kenneth Snelson (Fig. 2.1) is one of them who followed his paths afterwards. With artesian approach Snelson accomplished many concepts for the tensegrity structures. Well-known the X-shaped plywood modules can be mentioned as his first project in this field (Fig.2.1) [7].

FIG 5. Buckminster Fuller
1895-1983

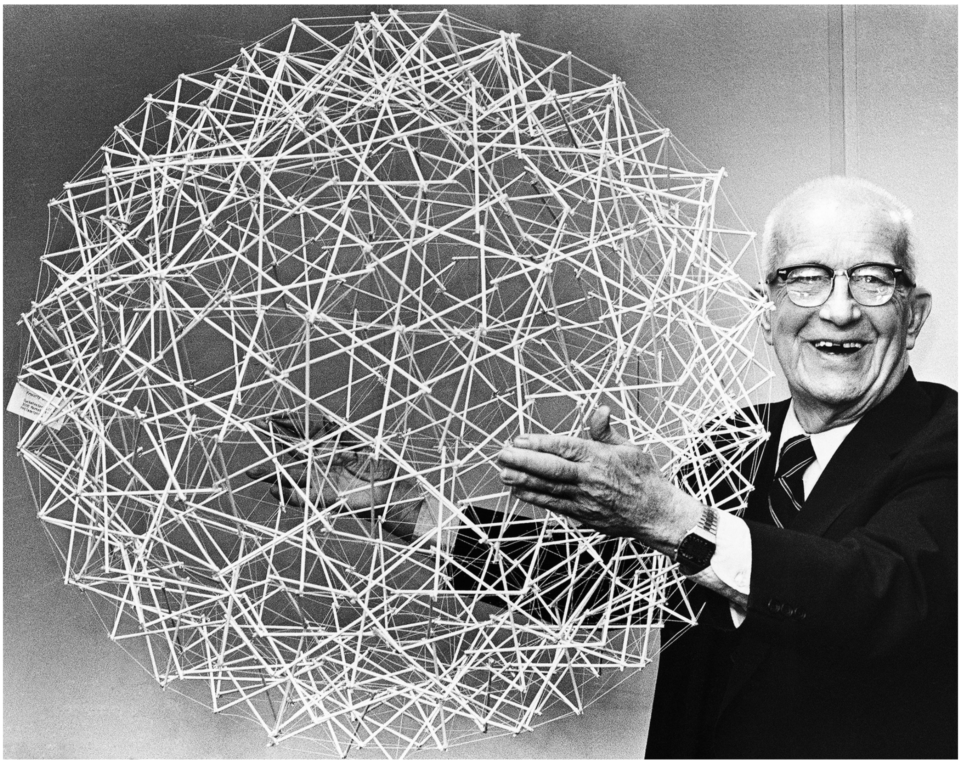


FIG 6. Kenneth Snelson
1927- 2016

Independently, in France in 1958, French architect David Georges Emmerich explored tensegrity prisms and prism combinations, his contribution to field change the way from old-fashioned structures to more complex tensegrity structures [8].

All these pioneers in this field gained reputation with demonstrating their works in the museums like Museum of Modern Art in New York and Hirschhorn Museum in Washington. The size of their work expanded and influenced many others who want to work on this field. These works remain a source of inspiration for all of the studies in this field.

From that time, many artists, engineers, mathematicians and architectures worked on tensegrities to design new forms for their applications. With the help of developments in science and technology, they achieved numerous of concepts. Nowadays, it has been seen that these specific structures can be used many other applications and products.

By using the advantages of the tensegrity structures, applications evolved from static ones to dynamic ones. Deployable structures (Fig. 2.2) are currently most interesting topic for this unique structure. Chapter 3 will mention all the new studies for this and many other applications. In addition, for the reader, a detailed review of the history of tensegrity systems can be found by Motro’s review [9].

2.2. Definition

Even though the word tensegrity itself is an unconventional term, there are many ways to explain this concept. The aim of this section is not to give exact dictionary definition, but to provide a meaningful approach to this concept by giving the essential terms. The several descriptions can be found by numerous people who has an expertise on this topic but the most common is defined by Buckminster Fuller in the 1960s.

The combination of two words: **Tension and Integrity**. Although, the system itself its more complicated, these basic and key terms are enough to build a tensegrity structure.

Tensegrity = Tensile + Integrity

From above, the definitions of these words can give an overview of the concept.

Tensile: Capable of being drawn out or stretched which refers the elastic elements in the structure

Integrity: The state of being whole and undivided which refers to overall structure that stand alone and stable.

2.3. Types of Tensional Structures

Before introducing the tensegrity concept, classifying tensional structures can help through the understanding of the concept. Classifying them as self-stressed structures and prestressed structures assists the objective of this unique structure. Briefly, the self-stressed structures are freestanding, so that they can maintain their self-equilibrium states without any support. The prestressed structures such as tensegrity domes, cable nets and membrane structures should be attached to supports to retain equilibrium [10].

2.3.1. Self-Stressed Tensional Structures

Not only to deal with standing alone in self-stress states, but also to achieve this feature in tensegrity structures is a challenging task. The nature of the complex geometry and the forces acting in these types create more uncertainty in design and building phase. The reason behind the limitations of self-stressed tensegrities comes from this drawback.

On the other hand, even the absence of the supporting elements when a cable or strut break-down, the overall structure maintains its form due to having many self-state positions. Effects occur locally and doesn't create catastrophic result [11].

2.3.2. Prestressed Tensional Structures

Prestress can be defined as the application of the stress by using elements before the structure is arranged. This will lead better mechanical properties in terms of strength. The permanent stresses have been created intentionally to achieve superior properties. In this manner, these types of structures which has stable prestressed conditions can be seen similar to working principle tensegrity systems. [12].

For example, pretension can be applied to a membrane by stretching it from its edges or by tensing the cables. The change in shape of overall structure occur due to the prestresses defined in design phase. The level of pretension applied to the system determines the shape of the structure.

With the correct prestresses a statically and kinematically balanced structures can be converted to a stable tensegrity structure. This is the main need for understanding the prestressed structures. The suggested tensions in design, will determine the desired shape and form of the structure.

FIG 7. Example of presstressed tensional structure

MOOM Tensegritic Membrane Structure (Noda) by Kazuhiro Kojima

2.4. Advantages of Tensegrity Structures

Lightweight

Nowadays weight reduction is a hot topic for many industries with the development of technologies and materials. Using less material and energy in every process of the production, also creates more sustainable world. Being light is important but also the structure should achieve the mechanical properties like being tough,strong and durable. There are many ways to create a lightweight property like using different materials and new manufacturing methods. In this case the shape plays an important role for being light.

To achieve this goal in tensegrity structures, tensile elements (cables or springs) are being used to create the overall forces that creating the structure, basically using more stiff elements in light bodies. This is the most important advantage for this unique structure. It allows architecture and engineers to create products with less weight without compromising the required properties from the structure [13].

Deployable

With the early applications in space industry, deployable structures have been used for several applications like solar panels or satellites. Deployable structures can change their shape from packed condition to extended positions in desired time. This property allows them to be used in space industry. Engineers and scientist pack the equipment in the world and then they send it for space applications [4].

For this purpose, using the advantage of flexible tensile elements tensegrity structures can be packed with/without tension and later actuating the structure to desired shape.

Energy efficient

The main energy loss in many engineering applications occurs due to the frictions in the mechanisms. On the other hand, in tensegrity structures the friction from one state to another is almost zero. This type of concept can be useful in many engineering applications in the future for energy efficient movable objects or robots.

2.5. Challenges of Tensegrity Structures

Like in our nature, there have been always drawbacks for everything as well as tensegrities. Engineers and designers have been always tackling with these problems to achieve better performance and desirable outcomes. Also, this unique structure comes with many different drawbacks. Below, summarizing most visible challenges faced during this thesis.

Design problems

Although the basic shape can be seen as effortless to build up, the problems for tensegrity occurs mostly in design phase. The correlation between the shape and the forces, creates too much uncertainty when the required task gets more complex. It is really hard to define the form with solely using geometry. Many methods like form-finding are suggested to create this unique form but still the practical approach for this structure as not easy as conventional ones.

Instabilities

One of the challenges that seen in tensegrity structure is lack of stability. If the structure is not settled well in terms of actuation this will lead vibrations. The problem here, these undesirable vibrations can create instability problems enduringly with the tensions in the structure itself [14].

Integrity

Sometimes the source of the problems can be found in the roots of the question itself. The term integrity mentioned before in the definition section is one of the other challenging issue for this type of structures. Failure in one component can be fatal for the overall structure. Also, when we consider the geometry and cables this can occur in many ways.

03
Applications

3.Applications of Tensegrity

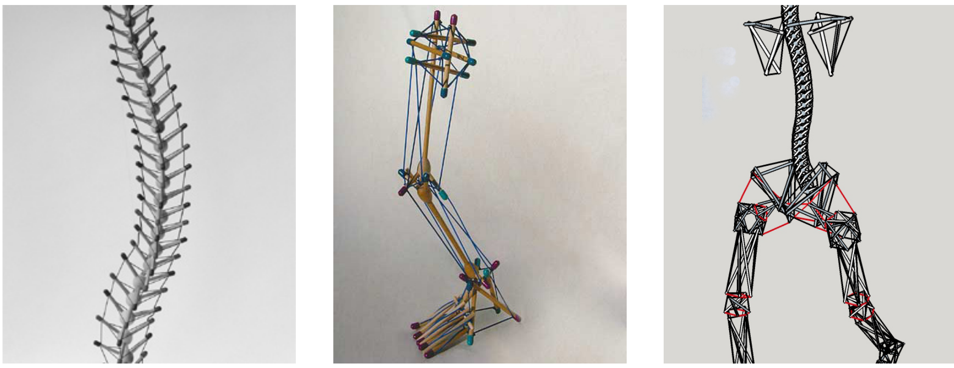
3.1. Tensegrity in Nature

To understand deeply the concept of tensegrity, the nature itself can be good starting point. The beauty of the universe and excellence of the math in nature has given inspiration to many people especially artists, designers and engineers. To simplify and realize the math behind this concept we should look to our world for the functional applications of this sophisticated structure. Before starting to observe our environment, it is better to enter our own body to understand how tensegrity structures are well functioning in our body also.

As well as most of the animals are using their limbs to perform their movement also as a human being, we should consider our body has the similar bones and muscle groups to move our bodies. Bones and muscles are structural elements of whole body to stay in form and perform actions. When we look to the tensegrity structure, we can see the same thing in similar way. Bones are the elements which carry the compressive loads and the muscles preserve the tensional forces. In the following figures it can be seen how tendons are connected to bones and how it can be similar to tensegrity structures.

Nowadays these representations of human body with tensegrity help doctors, biologists and even robotics to understand this working principle of human body. With the development in the biomechanics, all kind of living structures can be implemented to the tensegrity and can be scaled up for new approach in the robotics. This new paradigm for understanding the movement of living structures like cells, tissues, organs and structural bones with tensegrity can open up doors for biomechanics for the future. This approach can make it possible for inspirations for complex systems in for any future applications in our life.

FIG 8. Tensegrity in human body



Cellular Tensegrity

The concept of tensegrity in cells was proposed by Donald E. Ingber in Harvard University. He describes the cellular phenomena with the universal set of building rules. He explained this concept with numerous examples in his work 'Architecture of Life'. The idea in molecular level that the forces between the cell elements create a balance which can be explained by tensegrity structures [15].

He stated the tensegrity cell model with the possible forces acting on elements of the cell. The tensional forces can be caused by actin-myosin network, focal adhesion cell-cell adhesion or polymerization of cytoskeletal elements. And compressive forces can be caused by the microtubes or adhesion. The balance of these forces shapes the cell and moreover the genetic programs. From the micro level to macro level understanding the behavior of nature in our body (movement off cells, migrations, skeletons), tensegrity will be always exciting and interesting topic for bio-mechanical field.

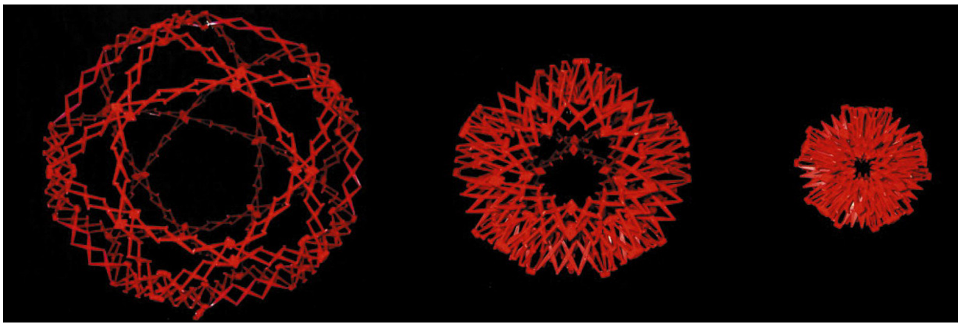


FIG 9. In geodesic molecular networks, molecular shape changes.

Spider Silk/Fiber tensegrity

In nature, spider fiber is one of the best examples of tensegrity structure with a continuous network of tension members and a discontinuous network of compression members. The overall continuous network shape contains circular segments which forms a silk fibril. By arranging many of these segments it forms silk thread. This architecture of the structure resembles the tensegrity structure. The figure shows resemblances of the tensegrity structure in the spider web architecture.

Another approach for the spider tensegrity relation can be as seen in the figure. The spider itself can be assumed as the rigid body of the tensegrity structure where the nets are tensional elements. Still today, the tensegrity systems that we made do not match with natural excellence in terms of size and functionality. The engineered products in this field are still far away from the efficiency of our biological structures. The beauty in this world still gives inspiration to understand the functional capabilities of this sophisticated structure.

To conclude this section, we can say that our body and our nature itself gives us really great examples how tensegrity structures can be functional and real even this topic seems as complex and complicated system.

FIG 10. Spider fiber, tensegrity structure with a continuous network of tension members and a discontinuous network of compression members.

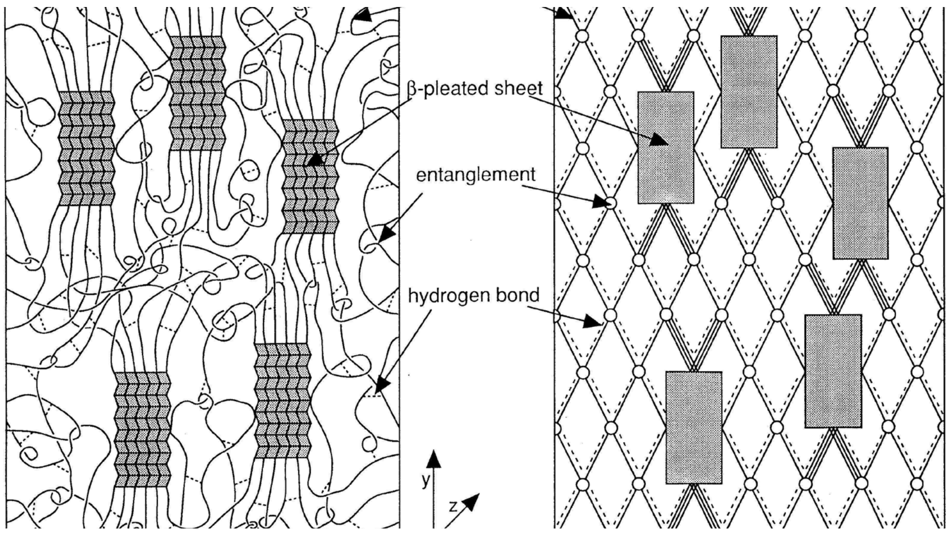


FIG 11. Spider and the nets creating,tensegrity structure.

3.2. Tensegrity in Art

As an artform tensegrity structures have been appearing in our world from mid-21st century, but this structure is more powerful than what we thought in the past. With the development of the analytic and numerical tools in the field, now we can achieve deployable, smart structures. Which leads engineers to involve in this process. In spite the field of engineering is lack of aesthetic beauty, art have been always there to help individuals to give a form using the materials, shapes and geometry. Especially geometrical beauty plays big role with art to create fabulous artworks, inventions and life-changing products since the beginning of the humanity. This reality should not be underestimated by engineers, who especially working something like tensegrity structures. Even tensegrity has ambiguous shape itself, people with aesthetic point of view always seen this unique geometry as a challenge: beauty from complexity. With help of this mindset, the first practical applications of tensegrity structures initiated by artists [16].

The well-known artist in this field, Kenneth Snelson create countless tensegrity artworks all over the world. These figures selected to give an inspiration to reader for inspiration. From the beginning of this thesis he is the reason who creates the base for the ideation part.

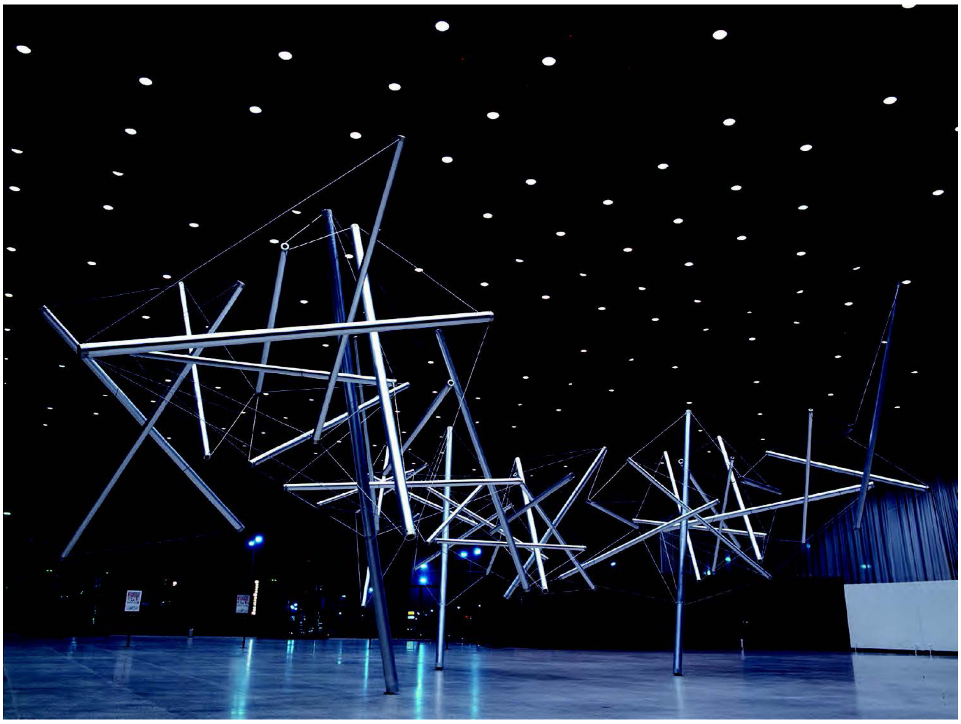


FIG 12. New Dimension, 1977
Aluminum and stainless steel

17 x 63 x 45 ft
5.2 x 19.2 x 13.7 m

Kenneth Snelson Exhibition, Nationalgalerie, Berlin, Germany

FIG 13. Vortex III, 2002
Stainless steel
23.5 x 13 x 13 in
59.6 x 33 x 33 cm

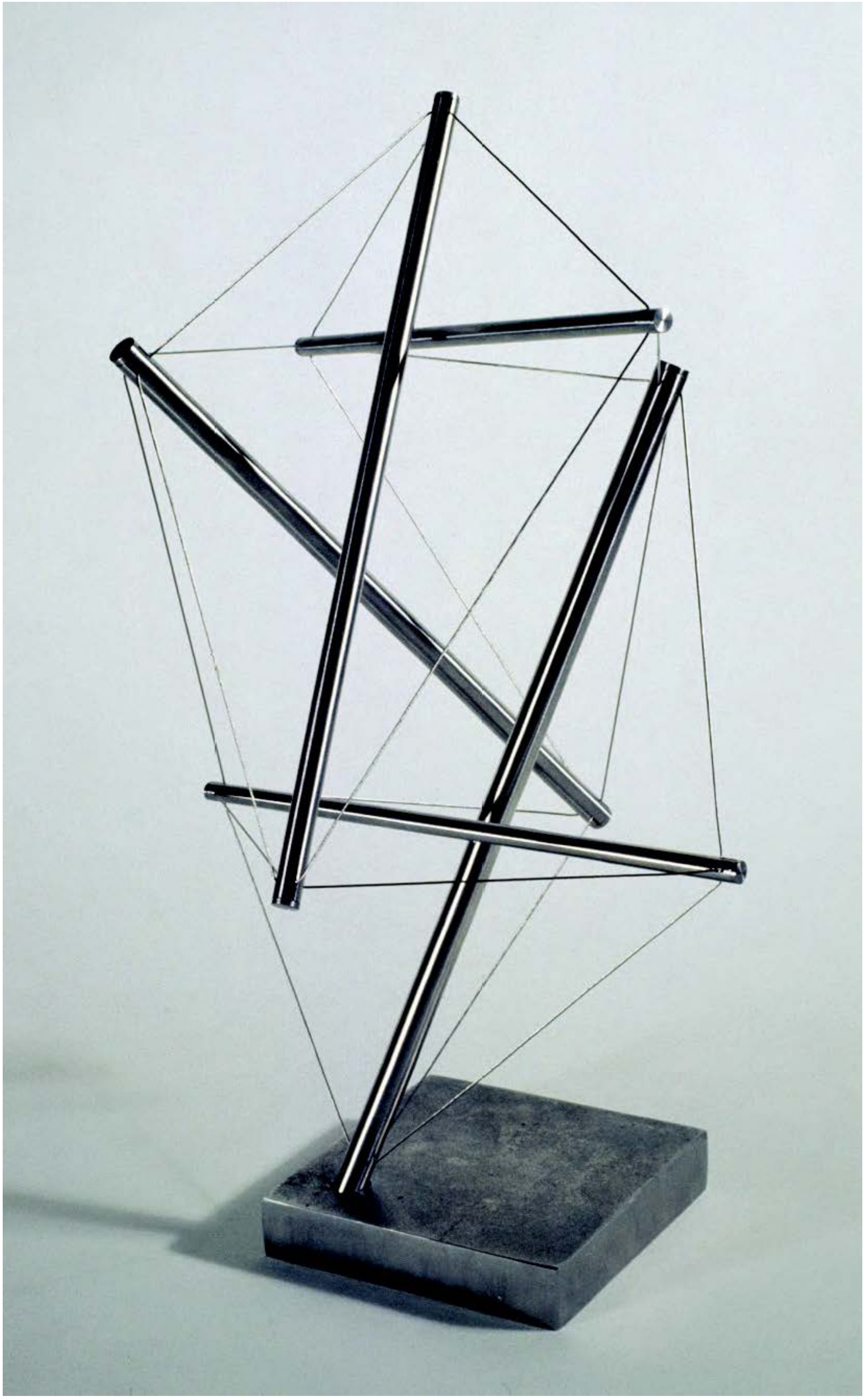


FIG 14. Sag Harbor II, 1965
Stainless steel
17 x 9 x 9 in
43 x 23 x 23 cm

3.3. Tensegrity in Architecture

One of the most important applications of the tensegrity structure can be seen in architectural field and it looks like the trend will increase in this field more in the future. With the development of the technology and the developing requirements of the world, lightweight and new structures will be actively used in this sector. The advantages mentioned before; this unique structure go beyond the limits with new architectural applications. Due to their super lightweight structures, achievable spaces with minimum elements are now possible with tensegrity structures. Especially in efficient buildings, this unique structure can be sustainable solution in terms of energy and using spaces. Using controllable structures in buildings will allow architectures to involve the environment in the process by making the building sensible to external circumstances [17]. In addition, with the controlling the motion of the structure, new approaches developed in construction methods. To achieve this new goal, all the structure and design should be developed together.

One of the first pioneer for applications in architectural field Buckminster Fuller designed the geodesic dome was latterly come to life as The Biosphere which is a museum dedicated to the environment.

FIG 15. La Biosphère de Montréal
Montreal, Quebec, Canada.

Tensegrity Domes

In 1992, further improved done to the cable dome and Georgia Dome was built in form of quasi-elliptical for Atlanta Olympic Games, which is considered to be the first tensegrity dome built in the world.

FIG 16. Georgia Stadium in Atlanta

Reconfigurable Systems of Tensegrity

One of the exciting new application in the architectural field is come from Reconfigurable Systems of Tensegrity by Kuan-Ting Lai at the University of Stuttgart. This structure is transforming its shape to required configuration using tensegrity principals. By using pneumatic cylinders and polycarbonate panels to adjust the illumination of places or the ventilations conditions.

This project is showing the possibilities of tensegrity structure by showing the capabilities of being deployable. With the same layout but with using another anchoring points this project can be applied to current and scaled construction systems.

FIG 17. Reconfigurable Systems of Tensegrity Kuan-Ting Lai University of Stuttgart.

3.4. Tensegrity in Engineering

Despite the art and design, in engineering field the functionally plays more important role than beauty. Realization of the tensegrity concept is fundamental for engineering applications. To achieve stable and well performing tensegrity structure, it should be analyzed precisely in terms of equilibrium equations. The acting forces, loads and torsions effect the stability of the structure and the geometrical arrangement of the whole system.

When we consider the efficiency of structures the first subject come up with mass efficiency. Nowadays, conventional structure elements like beams, columns and even truss elements are not sufficient enough for the future applications in terms of weight to performance ratio. With the need in the market and new engineering applications led to achieve more efficient but at the same time complex structures. This complexity can be reduced with several methods suggested in the upcoming chapters.

Although this unique structure looks like a static application at first glance, with including interdisciplinary fields this can be the future of structural elements. Design and engineering play important role for this purpose. The art of the state applications in engineering field listed below to give more practical examples to tensegrity concepts.

Tensegrity Robots

This new kind of structures (tensegrities) can retain their shape without touching each other in space and this feature lead them to be present in the robotic filed. Currently, the applications mostly come from the locomotion of the structures, with their ability of strength to weight ratio can be applied to robotics.

With new algorithms developed in this field successful shape-changing amorphous robot can be driven with principles of tensegrity. Compromising rods, string and actuators, this new robot can change their shape to roll, collapse or crouch. They can tolerate the harmful effects. These properties of tensegrity robots can serve efficient and sustainable space exploration. Moreover, they can open the door to other applications.

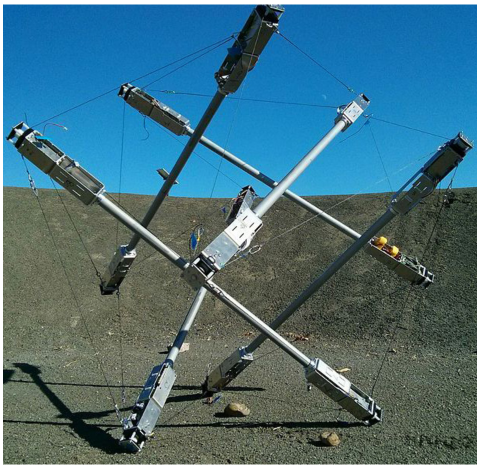


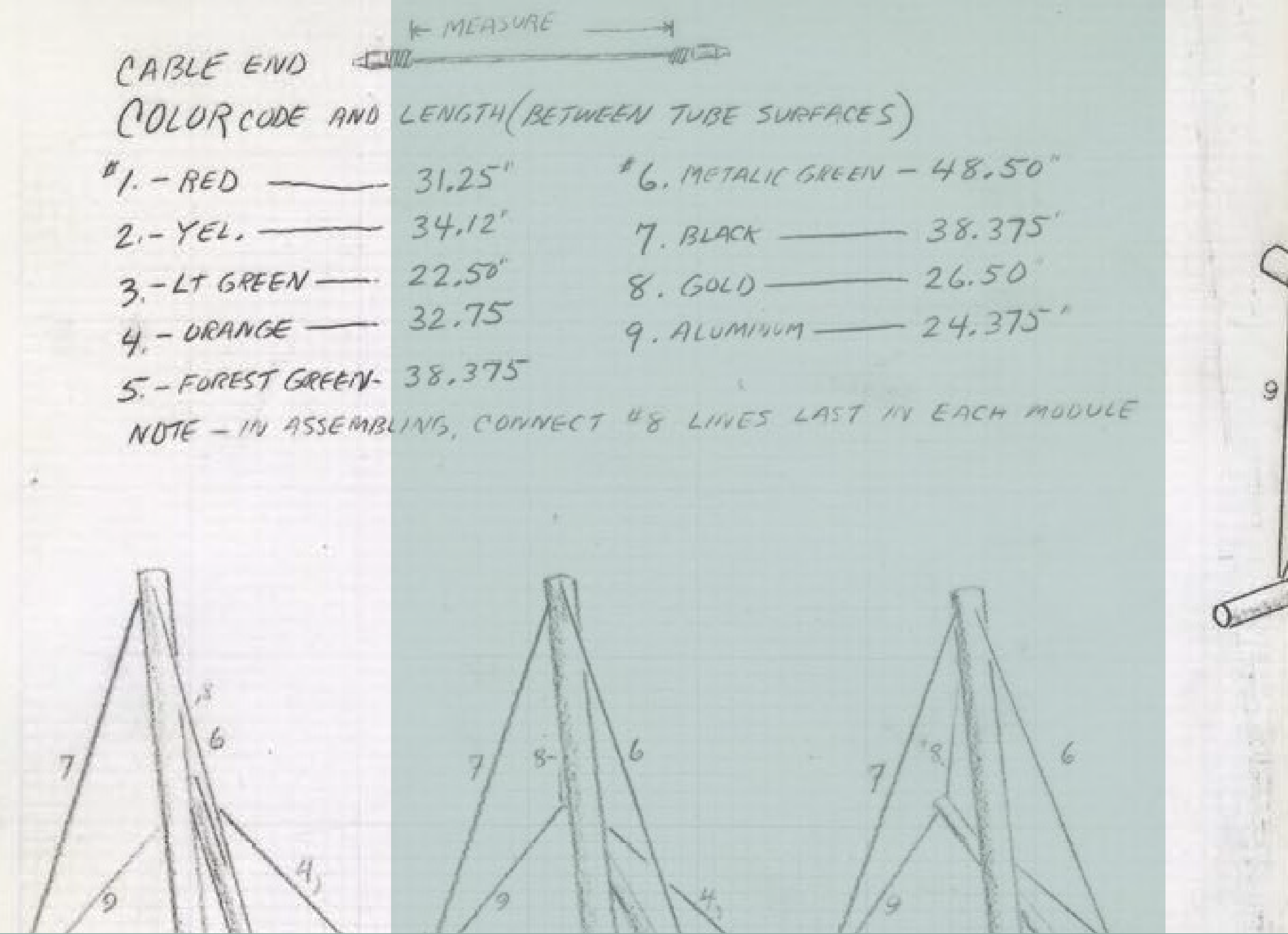
FIG 18. Tensegrity Robots
1) IcoTens
2) NASA Superball

Deployable Space Antennas

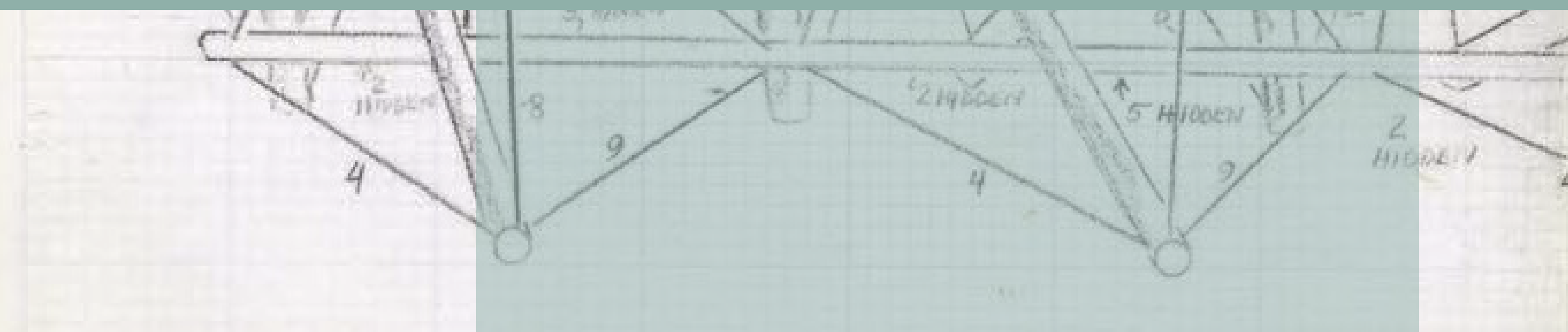
Deployable space structures are mission-critical technologies for space exploration. And one of the critical parts of these operations are antennas. These structures are large and hard to squeeze in minimal places. The idea of tensegrity plays important role in this manner. Several applications have been made for deployable antennas in the past and different concepts suggested but only few of them actually present themselves in the space. Packaging efficiency, mass, surface accuracy is determining their workability.

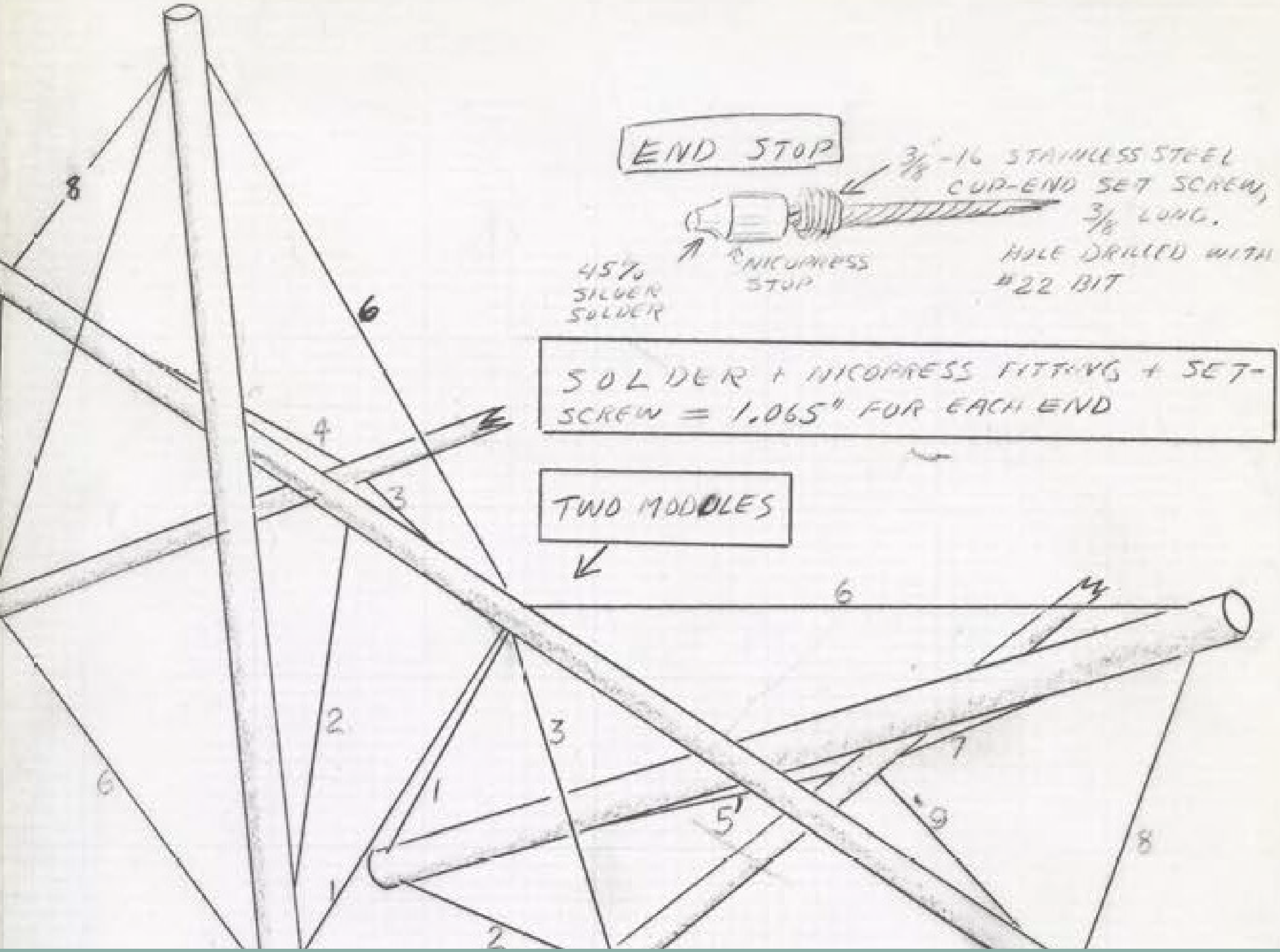
The main function is that keeping the ties elastic and at the same time to extend the struts. This allows the change shape for the surface antenna. With the reduction of the numbers of joints used in conventional methods, tensegrity is becoming more popular for deployable structures in space operations. The overall structures off-loaded by gravity in space. Current studies include stiffness, deployment repeatability, and geometric precisions for fully deployed configuration and full-scale products.

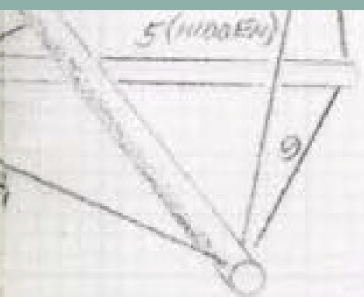
FIG 19. Deployable Space Antennas for HALCA (Courtesy of ISAS)



04 Computation







CABLE SYSTEM FOR VINE STREET

CABLE 1/8" - 1X19 CONSTRUCTION

1966-1972

KENNETH SNELSON 6-11-72

4.Computation Methodology

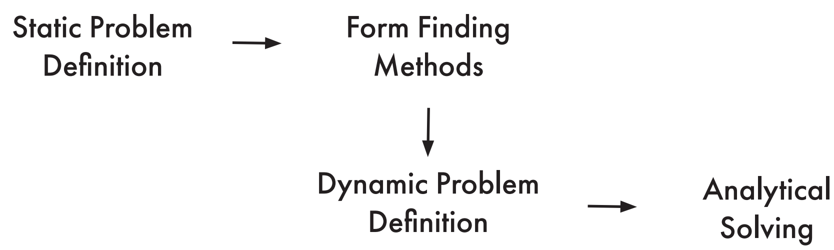
To understand deeply the tensegrity structure computations, it is required to cover the theory behind. For this purpose, this chapter will establish the basics for tensegrity structures. The main aim here is not to give complex theory but meaningful approach in the available literature starting from static analysis to dynamic modeling. The literature today about the computation of the tensegrity structure has been expressed in considerable amount of different methods and by many authors. The object of this section suggesting basics while not creating more complexity for the readers who wants to understand the mechanics behind this structure. Also, more detailed reviews for computation of the tensegrity models listed in the references.

In this thesis, the following methodology taken from Arsenault [21] which is determined as understandable and practical approach for both designers and engineers. The following method will provide a methodology from the static problems to dynamic problems.

The static problem will be solved by common form finding methods for tensegrity structures which computes of the equilibrium position of unactuated system with a given set of physical properties. A detailed review about form finding can be found in Tiberg and Pellegrino's study [4]

On the other hand, the static application is not enough to cover fully the behavior of this structure. Dynamic analysis should be done due to deformation of the external loads. These deformations can be studied both numerical and analytical way. In this work the analytic approach has been gathered from Oppenheim and Williams using energy formulations. With deriving the equations linked to loads and deformation the stiffness of the mechanism can be evaluated.

FIG 20. Computation method for solving general tensegrity design problems.



Before entering the theory, some definitions will be provided to demonstrate this tensegrity concept.

4.1. Static Balancing

To understand the computation methods better, the static balancing condition can be good starting point. The definition can be done as it follows: In static balance condition, static equilibrium position (generally center of gravity) should be in the line in the range motion (axis of rotation), without any external force. In this balance situation the system itself should remain stable and stationary. Neutral equilibrium or neutral stability [22].

Generally, the balancing can be done in many ways like using external masses or springs. In this case tensegrity structure uses the forces between the elastic elements (spring force) for balancing.

4.2. Spring Characteristics

To simplify the conceptual design phase of tensegrity structures, the elastic elements in the system, ideal spring approach should have been done. To understand these phenomena general spring characteristics explanied below.

Despite the normal springs, **ideal springs** has considered as **zero free length**, constant spring stiffness, limitless strain, zero mass and forces acting along their centerline. This approach will allow computational advantages for every step of the conceptual design.

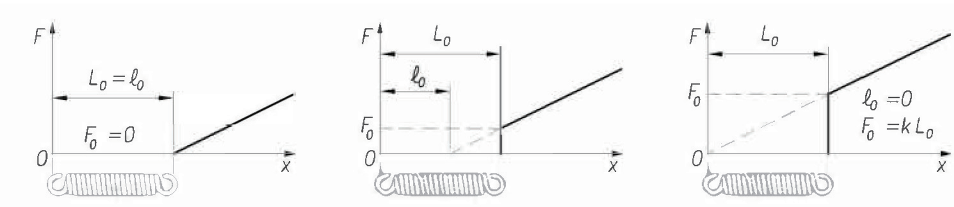


FIG 21. Spring characteristics:

1) normal spring,
2) a normal spring with
3) pretension and a zero-free-length spring.

4.3. Form finding methods

Actual first step for conceptual design is form finding. It can be defined as finding a self-stressed configuration. Basically, the equilibrium configuration of the system. In this phase the tensegrity structures modeled with no external forces and no constraints. For tensegrity structures there are several form-finding methods. These different methods (static and kinematic) can be found in Tibert and Pellegrino's reviews [4]. In this work, the suggested methods for form-finding will be explained briefly.

4.3.1. Kinematic form-finding methods

As the nature of the kinematic methods, the elements included in the system should change their positions or geometries. This can happen by changing the lengths of the elastic elements or the rigid elements while keeping one constant. This change should be done until the maximum or minimum position is reached. The desired method is chosen by the practical application of the concept.

4.3.1.1. Analytical solutions

This method is more convenient for simple structure types where the definition of the geometry can be done with the angles between upper and lower nodes of the connected struts. Using the advantage of the symmetry, the geometry can be defined directly. The method here comes from the static approach and adding the symmetric polygon definition. Without symmetry this method cannot respond for more complex systems [23].

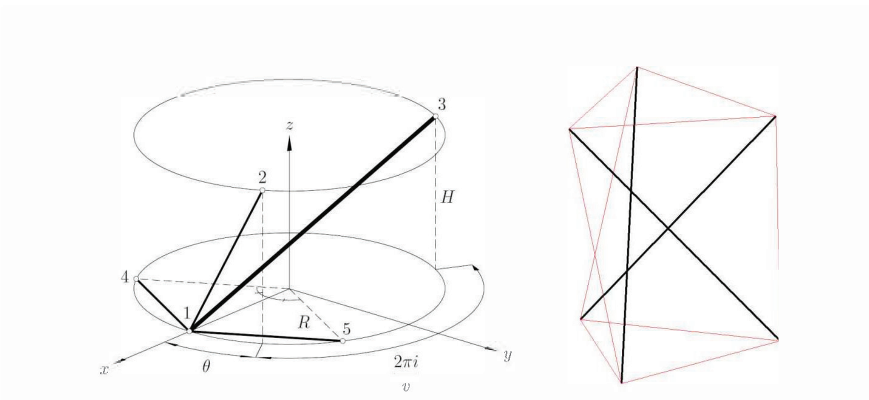


FIG 22. Geometric description for analytic computation methods

4.3.1.2. Non-linear programming

The method here suggested with non-linear programing is approaching the system with constrained minimization problem. This method initially starts with the known elements and nodes coordinates. Elongation applied one or more struts while keeping some parameters fixed. This continues until the configuration reached the maximum lengths [24]

Generally, this method can be expressed as it follows:;

Defining objective function $f(x,y,z)$ as minimization with the constraint function as $g_i(x,y,z)$

Advantage of this method is achieving general solvation with the standard programs in the market. Using MATLAB fmincon function constrained optimization can be achieved easily. On the other hand, the capabilities of this method are limited with the number of constraint equations. These constrained equations increase with the number of the elements. So, this method is not suitable for larger and complex structures. Also, this method doesn't respond the need for analyzing the pre-stress configurations.

4.3.1.3. Dynamic relaxation

This method has been using for many static applications like membrane and cable nets. For tensegrity structures Motro and Belkacem started using this method for form-finding method for the tensegrity structures [29]. By given initial configuration and the external forces the new state can be computed by applying the virtual dynamic equations.

$$M\ddot{e} + D\dot{e} + Ke = f$$

Where;

K is stiffness matrix
M is mass matrix
f is vector of external forces
$\ddot{e}$, $\dot{e}$, and e are acceleration velocity and displacement vectors.

For a given initial configuration and forces, the equilibrium configuration can be computed by integrating the following previous dynamic equations. The system introduced by Motro [25] includes the elongation of the bars while calculating the resulting forces and accelerations. To satisfy the convergence of the equation, selection of damping coefficients and a technique called kinetic damping is suggested. Undamped motion of structure is traced and when local peak reached in kinetic energy. This progression followed until the peak becomes low enough. This method is good solutions for structures has less nodes. With the increase of the complexity (number of nodes, non-symmetry) in the system, this method becomes not effective anymore.

4.3.2. Static form-finding methods

The static form-finding methods include the calculation of equilibrium configurations of a structure with a given geometry and forces acting to its elements.

4.3.2.1. Analytical solutions

A general solution of the relative rotation between the upper and lower polygon of tensegrity prisms was derived by Connelly and Terrell [23]

4.3.2.2 Reduced coordinates

This method includes finding the position and orientation of the bars, by using a set of well-chosen generalized coordinates and the principle of virtual work. This method initially starts with defining the generalized coordinates with set of constraints. With set of equilibrium equations relating the forces in the elastic elements, the calculation can be done by using virtual displacements given to the system [26].

4.3.2.3. Force density method

The force density method (FDM) is a classical and popular method for tensegrity structures. It can be quick tool for finding the new forms by solving a set of linear equilibrium equations by considering the topology, boundary conditions and cable force density. Addition to this, the nonlinear method can find the new shapes under defined constraints like specific distances, force limiting or virtual actuations. Nonlinearity occurs any type of constrained added to system [27].

4.4. Discussion

This section concludes the main terms and methods for calculation of tensegrity structures, the most challenging thing for all the methods is the calculation parameters increase with the complexity. The static methods have more advantage over kinematic ones [4]. The force density model can be used for searching new configurations. Form-finding methods can be improved with reducing complexity by adding constraints or symmetry to the system.

In this research, reduced coordinate method will be used to explore the capabilities of the tensegrity structure. The static approach will be used to analyze the structure. From all the literature survey done in this section, it has been recognized that the complexity is a key factor for the calculations. The reason behind the decision made for the first model as simple and with constraints tensegrity structure is because of reducing the complexity. The future applications can be adapting the other methods suggested in this section for more complex structures.

4.5. Computation

4.5.1. Geometric Description of General Case

To make the computation of the basic three-dimensional tensegrity structure, the geometry should be defined properly. To give a better understanding, the architecture established as basic as possible which is known as Triplex, Simplex or Tensegrity Prism [28]. This defined structure consists of 3 struts and 9 elastic elements. The nodes for every strut named as A_i,B_j where **(i =1,2,3 and j=1,2,3)** and attached with universal joints. The representing vectors $\mathbf{a}_i$ and $\mathbf{b}_i$ defines the struts.

To establish the concept clearly, basically from each strut, 3 connecting elastic elements elongated to create tensional forces in the structure which is seen in figure 4.2.

To achieve more manageable solution for mechanism, reduced coordinate method will be used to define the geometry, the reason behind this decision is to achieve less complexity. The application of this method starts with the fixation of the reference frame. The nodes A_1,A_2,A_3 are positioned on this XYZ frame. The reference origin is located at A_1 and the X axis elongated to A_2 node. The Z axis is perpendicular to this reference plane defined. All the A_1,A_2,A_3 of the nodes are on this reference plane. The figure 4.2 shows this geometric definition.

In addition, to define the orientations of the struts, the struts will be represented by angles (α_i,β_i) in new reference frame.

The reason here is to represent the struts more visibly in vectorial format and relative to their nodes. The length of the elements defined as

$$L = \sqrt{(b_i - a_i)^T (b_i - a_i)}$$

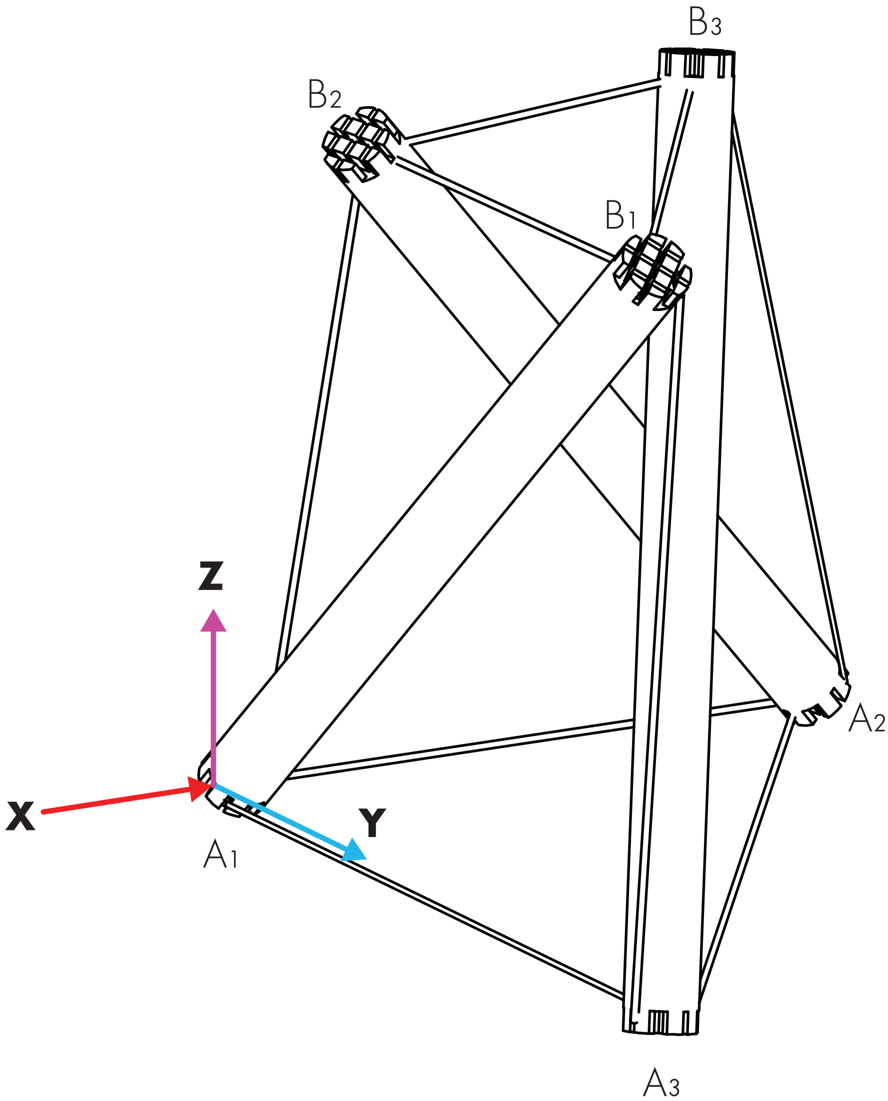
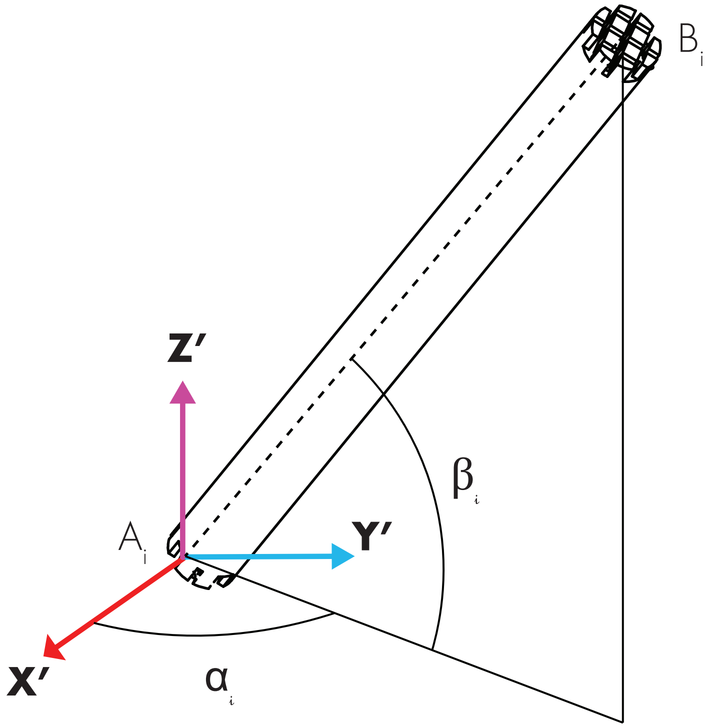


FIG 23. Geometric Description of the basic three-dimensional tensegrity structure.

With this definition, the strut vectors can be assigned relatively to nodes as it follows;

$$b_i = a_i + L\begin{bmatrix} cos\alpha_i cos\beta_i \\ sin\alpha_i cos\beta_i \\ sin\beta_i \end{bmatrix}$$

FIG 24. Geometric Description for relative single strut.



In addition, actuation mechanism defined to understand the behavior of the structure in motion. Three prismatic actuators created virtually. These actuation vectors defined in equations below;

$\mathbf{a}_1 = [0,0,0]^T$ which means the actuation vector is fixed,
$\mathbf{a}_2 = [\sigma_1,0,0]^T$ can only move in X direction,
$\mathbf{a}_3 = [\sigma_2,\sigma_3,0]^T$ can only move in XY plane.

The need for the actuation vectors is to demonstrate the effect of the motion for the system. The input vector for the system will be given by the actuators with $\varphi = [\sigma_1,\sigma_2,\sigma_3]^T$

As a result of actuation, the output should be also defined. The end effector defined at the node $B_3[x,y,z]^T$

From the description mentioned before in form-finding methods, potential energy in the springs must be minimized. Once the actuators fixed the systems in a configuration where the potential energy is minimum. In this case the nine springs create nine degrees of freedom with the advantage of using the constrained coordinate method, three actuators reduce these degrees of freedom to six.

From all the definition made above, the system has six degree of freedom, when the actuators are not in action(fixed) and can be defined with the rotation of the struts. Which can be expressed in generalized coordinates below;

$$q=[\alpha_1\beta_1\alpha_2\beta_2\alpha_3\beta_3]^T$$

To achieve a solution in the described geometry some assumption needs to be done.

These assumptions listed below;

Struts: Struts are homogeneous with a mass of m ,relative to springs their stiffnesses are infinite and with length of L defined above. The struts attached with a universal joint in lower nodes.

Springs: The springs are modeled as ideal springs. Which is massless and linear, constant stiffness with K, and lengths l_k (k=1, 2...9) with zero free lengths.

Actuators: Actuators are prismatic and only sliding with no revolution. Also, the stiffness is assumed infinite relatively to springs.

End Effector: The $B_3[x,y,z]^T$ is defined to be the end effector of the system.

In this case no singularity position analyzed.

4.5.2. Static and Kinematic Analysis

To start analyzing the behavior of the structure under the load initial assumption has been made. With the suggested method, the tensegrity structure assumed always in equilibrium condition. Unlike the conventional systems the input and output of the system are related to the forces acting in the system (integrity). This led to considering the static and kinematic analysis together with the overall system. The analysis will only include the general cases without considering the singularities.

The external force acts in the B_3 $[x,y,z]^T$ node with the force $F = [F_x F_y F_z]^T$. In addition to the external force, the gravitational force (*g*) considered in negative direction of z. To neglect the effect of the torsion in the struts the center of the mass has been assumed to be in the centerline of the struts. The resultant force of the weight will be resisted by the universal joint.

4.5.2. Solution

After defining the geometry, the process continues with the solution of the static problem. The aim here to find the end effector position $B_3[x,y,z]^T$ with knowing the actuation $\varphi = [\sigma_1,\sigma_2,\sigma_3]^T$ and the applied external forces
$F = [F_x F_y F_z]^T$.

The method here suggested to minimize the potential energy contained in the springs and adding in to account the external loads. In this case the, the potential energy contains in the springs are derived from the generalized coordinates $q = [\alpha_1 \beta_1 \alpha_2 \beta_2 \alpha_3 \beta_3]^T$ mentioned before.

The potential energy coming from the mass of the struts assigned as external force. The mass of the struts creates a torque in respect to *q*. The potential energy *U* derived from the energy stored in the spring and expressed below.

$$U = \frac{1}{2} K \sum_{k=1}^{9} l_k^2$$

$$l_k^2 = (b_i - a_j)^T (b_i - a_j), \ k = 1, 2 \ldots 6$$

$$l_k^2 = (b_i - b_j)^T (b_i - b_j), \ k = 7,8.9$$

To minimize the potential energy, the following relation should be satisfied,

$$\frac{\partial U}{\partial q} - \tau_q = 0$$

Where **0** is a 6 x 1 zero vector and Torque vector T_q is expressed below.

$$\tau_q = [\tau_{q_1}, \tau_{q_2}, \tau_{q_3}, \tau_{q_4}, \tau_{q_5}, \tau_{q_6}]$$

To expand the torque vectors in terms of gravitational and external forces geometry defined before and shown in Figure 4.2,

$$\tau_{q_1} = \tau_{q_3} = 0$$

$$\tau_{q_2} = -\frac{1}{2} mgL \cos\beta_1$$

$$\tau_{q_4} = -\frac{1}{2} mgL \cos\beta_2$$

Torques derived from gravity; T_{q1}, T_{q2}, T_{q3}

$$\tau_{q_5} = L\cos\beta_3 (F_y \cos\alpha_3 - F_x sin\alpha_3)$$

$$\tau_{q_6} = -\frac{1}{2} L[mg\cos\beta_3 + 2\sin\beta_3 (F_x cos\,\alpha_3 + F_y sin\alpha_3) - 2F_z\cos\beta_3]$$

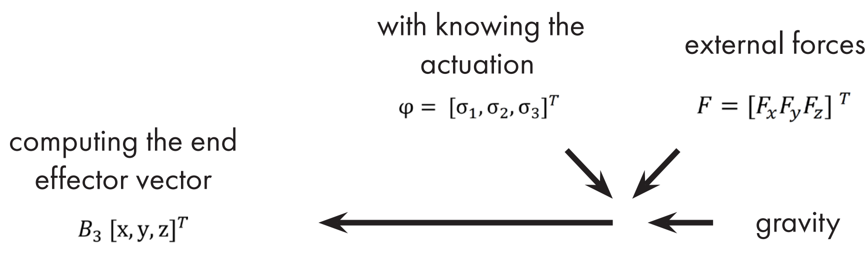
Torques derived from external forces; T_{q5}, T_{q6}

To solve this highly non-linear equation, it is solved with the Newton-Raphson algorithm to find the *q*. The output vector at node b_3 $[x,y,z]^T$ can be find at i=3 in equation defined for the b_i.

4.6 Conclusion

In this section the static and kinematic analysis of basic triangular tensegrity have been done using the methodology suggested in Arsenault and Gosselin paper [21]. The method studied here is enough for calculating the coordinates of the end effector by changing the lengths of the actuators. With using the constrained minimization approach the initial nine degrees of freedom, reduced to six with the three constrained actuators.

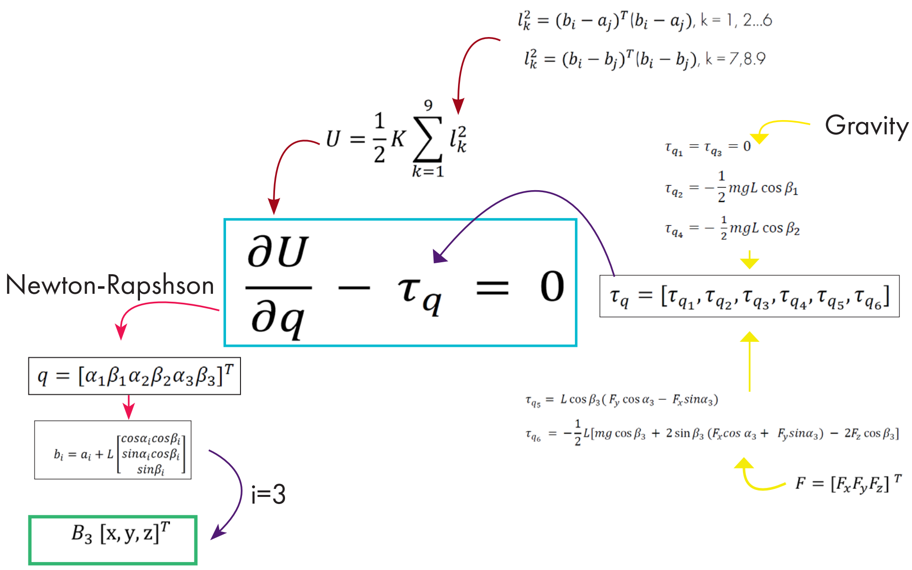
When the system is not actuated the static problem can be solved to find the geometry with the input and output variables by considering the internal and external forces. The solutions have been done by numerically minimization of the potential energy of the system. This work is done to understand the mechanism behind this type of structures. Practically this type of approach has been suggested for the tensegrity structures which are subjecting to only traction. In this thesis, this work will be applied to ADAMS simulation to understand the behavior visually better.



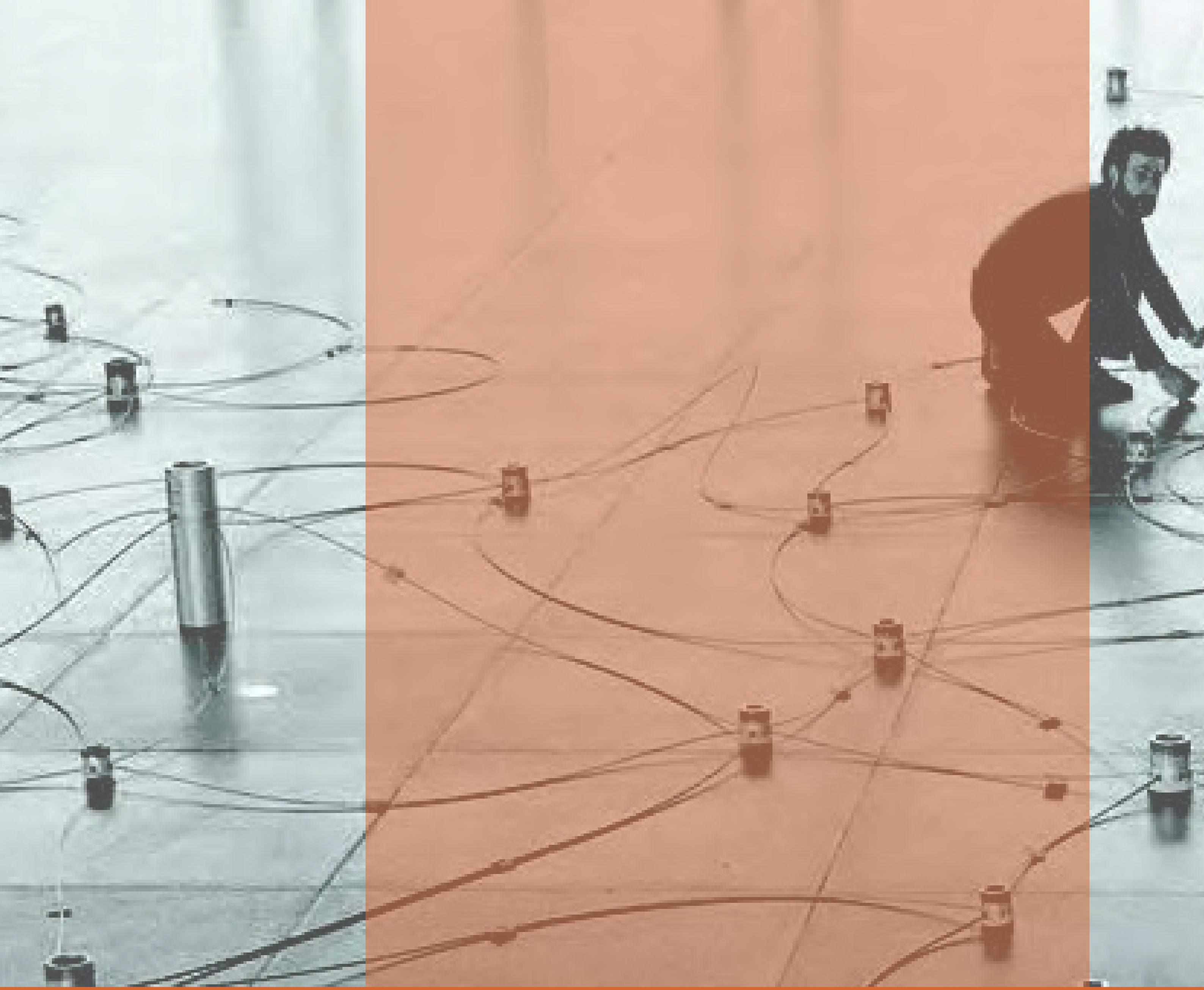
Suggested calculation methodology

In order for U (potential energy) to be at extremum the following equation need to be satisfied.

$$\frac{\partial U}{\partial q} - \tau_q = 0$$



The schematic representation of the calculation procedure applied for with all the variables.



05 Concept

This chapter will provide a validation for the mathematical theory explained before and basic concept of proof. Prototype and simulations will be done for the future applications.

5.Proof of Concept

One of the most challenging topics for tensegrity structure appears as design. The context here for design is the geometrical conditions which is applied to physical representation. From connection of the cables to the elements properties for cables and struts determined in this section by hands-on experience. Additionally, this design has been considered for future applications with shape changes and new configurations. From the previous sections, suggested mathematical model used to define structure's geometry. To visualize the concept, prototyping has been done and simulated by ADAMs software.

5.1. Ideation

When we consider design, the initial step is to create ideas that fit the project requirements. The initial sketches in Figure 5.1 show the ideation of the first concepts. Both mathematically and conceptually, the ideas have been represented. From the mathematical result, the first step determined as to create a basic 3-Prism tensegrity structure for understanding the capabilities in practical way. Considerations include the connection of the struts and the elastic elements to each other. Even some of the ideas far away from the simplicity they can introduce inspiration for future applications.

5.2. Prototype Design

In initial design concept of a project, there are significant advantages of visualizing of the concept especially for tensegrity structures. To holding the model in your hand, to feel the tensions in the cables, building up the model gives another point of view for this concept. The main aim of prototyping is to understand the movement capabilities of the structure and create a basis for the future works. The prototyping phase should achieve the results that gained in the mathematical model suggested before.

After the work done for geometrical concept of the elements, the next step is to create a basic tensegrity structure. For creating the prototype, design requirements explained.

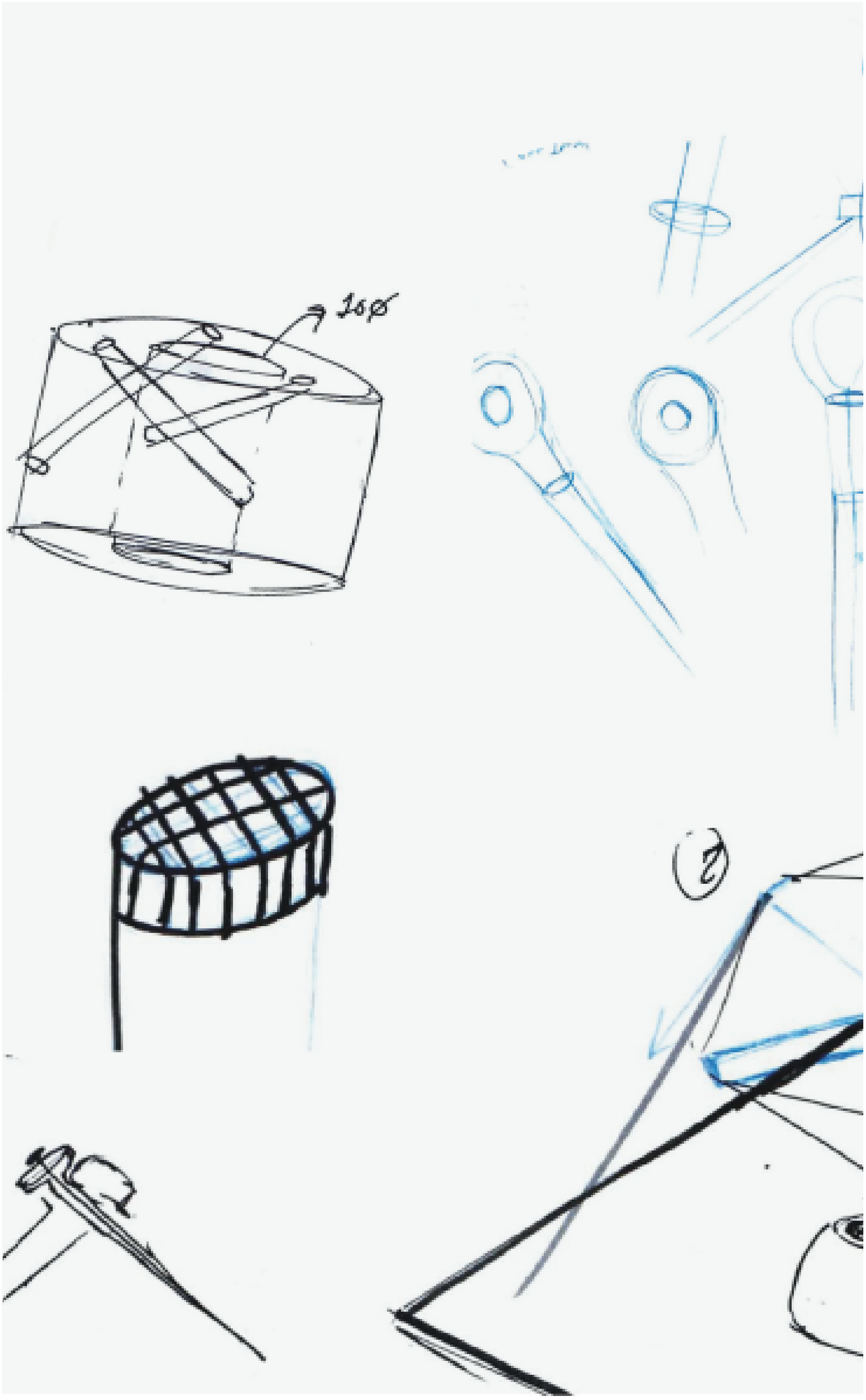


FIG 25. Ideation Sketches

5.2.1. Design Requirements for Initial Prototype

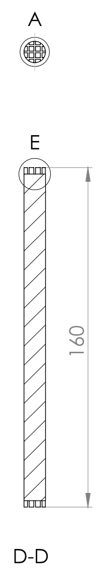
At first glance, tensegrity system can be seen as really simple and basic design (due to number of parts used) but design decisions should be made carefully for building up the structure correctly. Key design properties for this initial concept, explained below.

Stiff enough struts (rigid elements)

Struts are the essential key design parameter for the tensegrity structures, they must resist the tensions of the elastic elements (cables). Basically, they shouldn't buckle under the force applied by cables. For lightweight structure material also play important role for the struts. As a result, the struts should have enough stiffness.

Despite the general shape of the strut is basic cylinder, the top connection part has some design details. This leads to produce this part with additive manufacturing methods. This method is relatively not expensive and easy to modify for scaling the parts. In our case the main limitations of the geometry are the limited with the 3D printer settings. The detailed geometry and design showed in the Figure.

FIG 26. Initial concept design for the prototype.



Elastic enough cables (elastic elements)

One of the most challenging topics for practical application of the tensegrity structures is to find an efficient elastic element which creates the tensional forces for the structure. Springs can be a good solution, but they have standard properties that cannot be modified easily (stiffness, length, size). Also, the building up process of the structure, the flexibility of the cables can be really advantage when the tensions start to corrupt the overall shape.

For this purposes market research done and the best option find from the flexible fishing lines/jewelry lines showed in the Figure 5.2 below. Easy for adjusting the lengths and the stiffness with notches that can adjusted easily with hand.

FIG 27. Fishing lines/Jewelry lines, elastic elements

Easy assembly

The other challenging point is the assembly process. To attach the cables to the struts, design decision is made for quick and variety options. The top part of the struts shaped as a grid to have several catching points of the cables. This allows relaxed assembly process for the user. With help of this grid there are many possibilities to arrange the cables during the building up process. This grid details showed in the Figure 5.3 below.

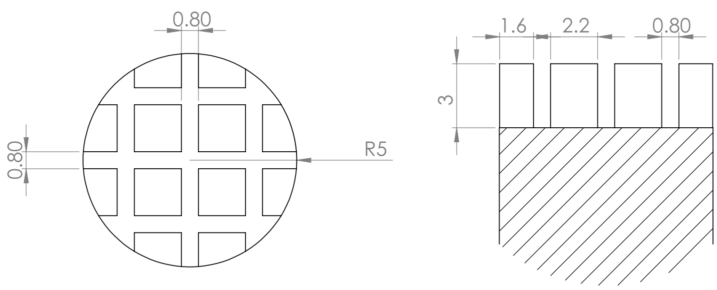


FIG 28. Designed details for easy assembly.

FIG 29. Top view with general dimensions.

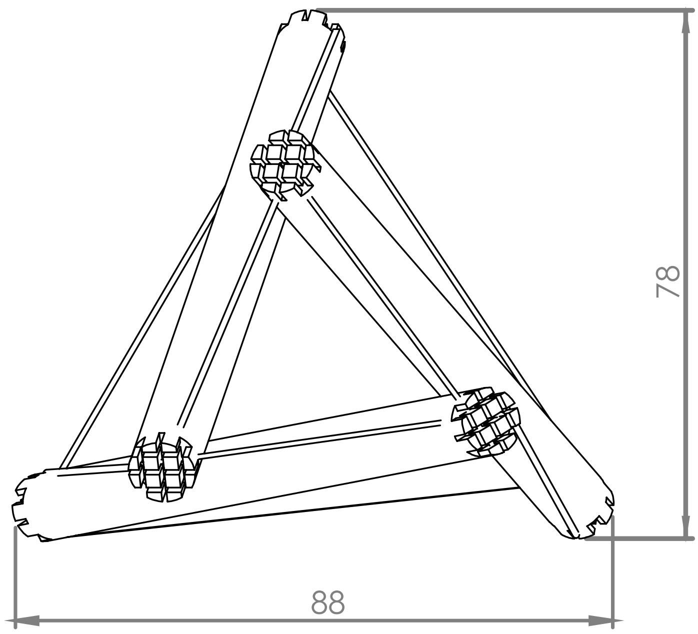
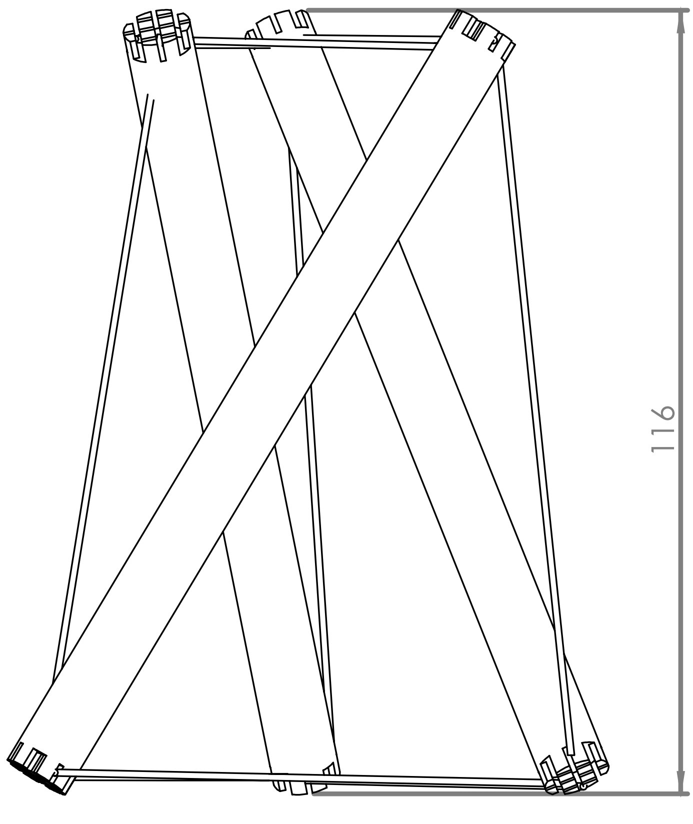


FIG 30. Side view with general dimensions.



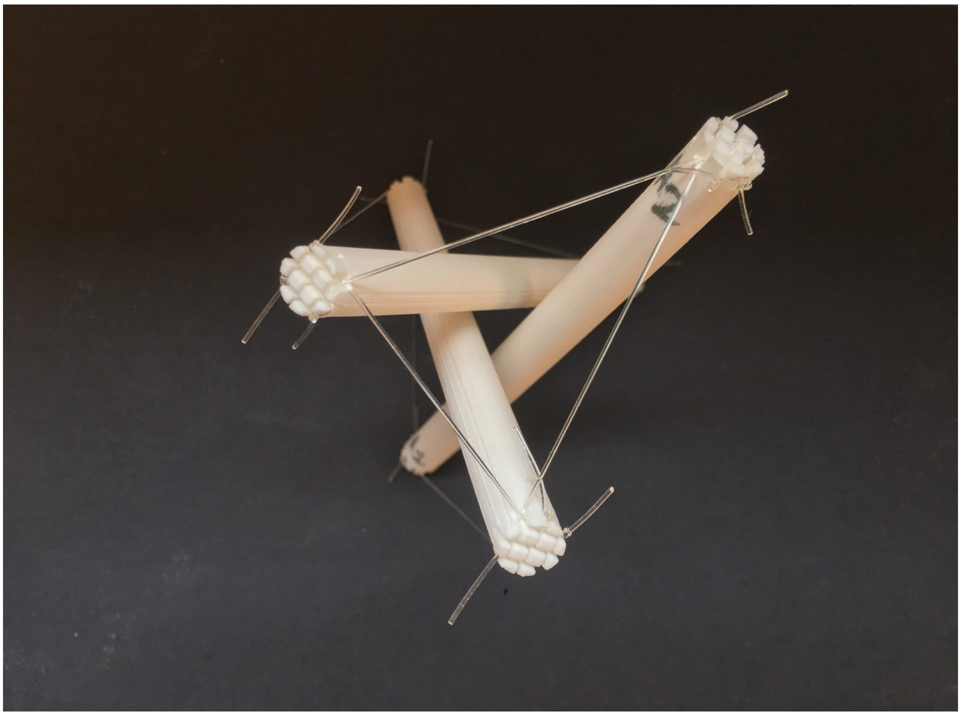


FIG 31. Top view 3D printed prototype

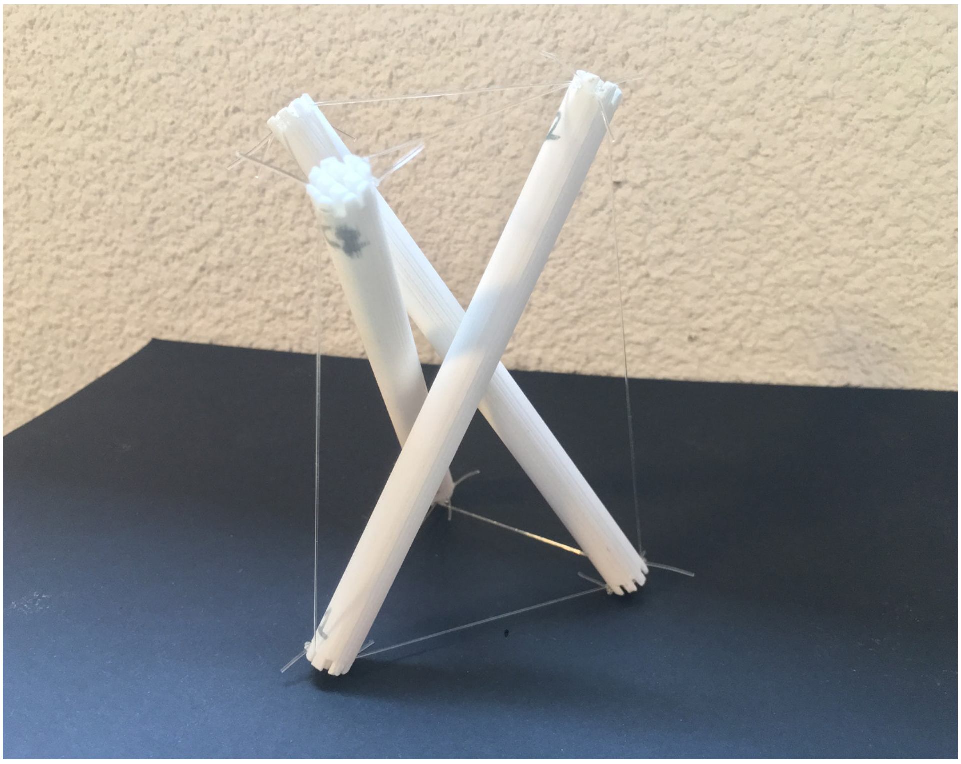


FIG 32. Side view 3D printed prototype.

5.3. Motion Simulation with ADAMS Software

The purpose of this section is to validate the feasibility and applicability of the tensegrity structures while they are in motion using computer software MsC ADAMS [30]. This will build up the concept suggested before on this thesis and create a physical representation with the concept of basic triangular tensegrity structure. Simulation results will be provided at the end of this section to give a meaningful understanding of the overall structure.

5.3.1. Simulation Description

The geometry of the model described in the previous section and the same model will be used to confirm the applicability of the mathematical model. The geometric description includes three main constraints for the system. These constraints implement to the system with defined joints. The movement of the system is controlled by the lower nodes (A_1,A_2,A_3).

To use the advantage of the software, 3D model imported to the ADAMS software without the springs. The springs will be added to system as feature of the software. The imported position will be the initial starting point for the system. Also, to achieve a realistic solution, the gravity has been added to system in negative Y direction.

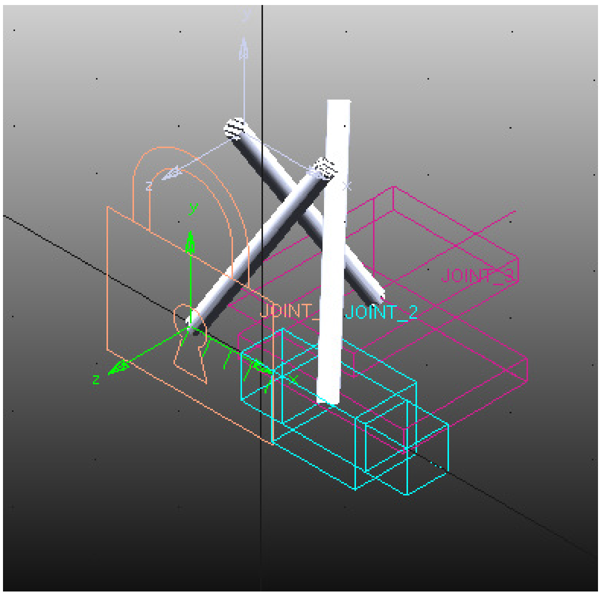
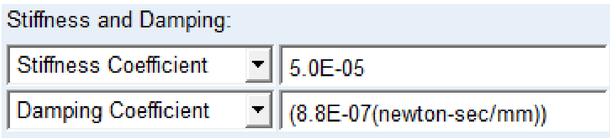


FIG 33. ADAMS Software definition of constraints.

To create a meaningful simulation, some procedure applied, and necessary assumptions have been made for the defined system and listed below;

- Springs are considered to be massless and linear with elastic module $k=5x10^{-5}$ N/mm and damping with 8.8 $5x10^{-5}$ Ns.
- The damping ratio for the springs neglected.
- The length of the spring defined by the software(geometry).



The struts are modeled in SolidWorks software and the materials defined in ADAMS.

The constraints have been defined with ADAMS connectors feature and showed in the Figure 6.1.

After building up the model and constraints the next step is to apply the actuation. In this manner, the forces applied in the given directions and shown in Figure 6.2. below.

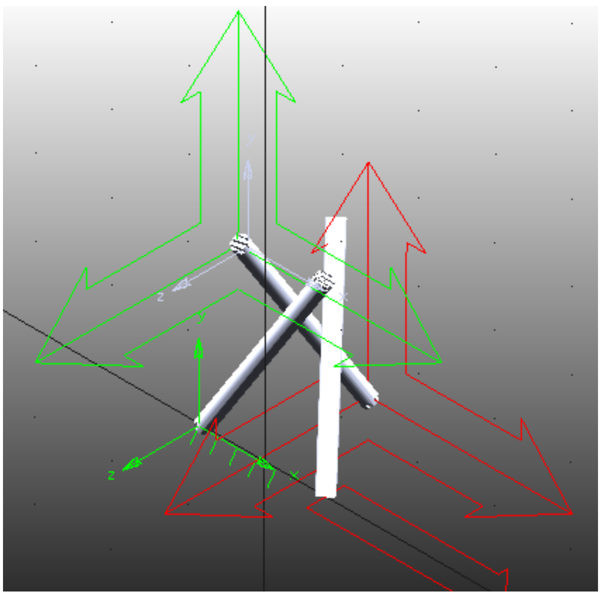


FIG 34. ADAMS Software definition of actuations.

To simulate the actuation, 0.002 Newton is applied to A_2 node in X direction. At A_3 0.002 Newton applied to X and 0.002 Newton to Z direction.

In addition, to simulate the external forces, force vector applied in the end effector point B_3. All the external forces acting in the simulation shown below in Table 2.

Table 2. Force vectors defined in ADAMS software

Position	Force Vector (Newton) [XYZ]
A_2	$[2x10^{-4}, 0,0]$
A_3	$[2x10^{-4}, 2x10^{-4},0]$
B_3	$[-8x10^{-4},4x10^{-4},8x10^{-4}]$

The simulation of the structure controlled as follows. Motion is divided into step size 0.01 and applied 6.5 seconds.

5.3.2 Simulation Results

For better understanding simulation results, the end effector point B_3 selected to be analyzed deeply. Firstly, results will be showed and then commented in the discussion section. To understand the motion of the B_3, displacements, velocity and the acceleration plots have been plotted for each direction Figures

Moreover, to understand the relation between the input and output results, displacements of upper nodes (B_1,B_2,B_3) investigated relatively to A_2 in X direction which shown in Figure 6.6.

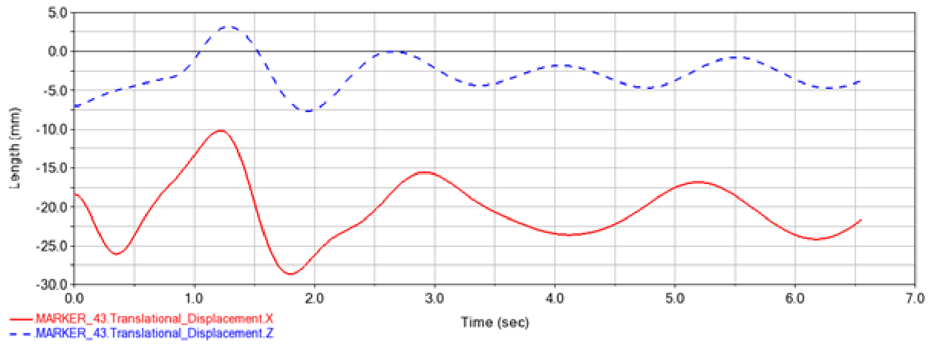


FIG 35. ADAMS Software Results

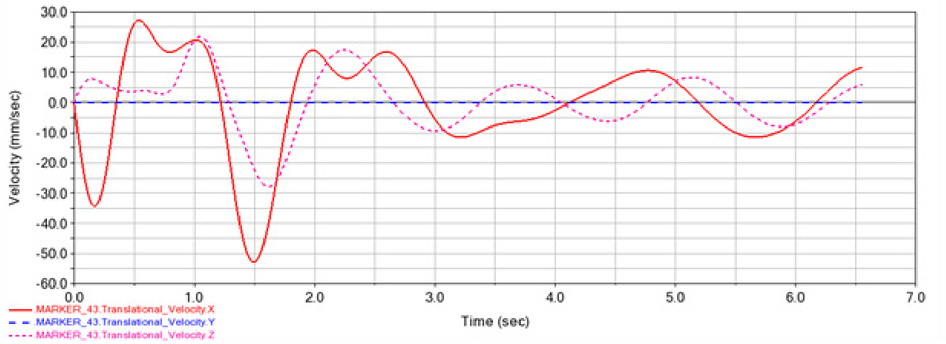


FIG 36.ADAMS Software Results

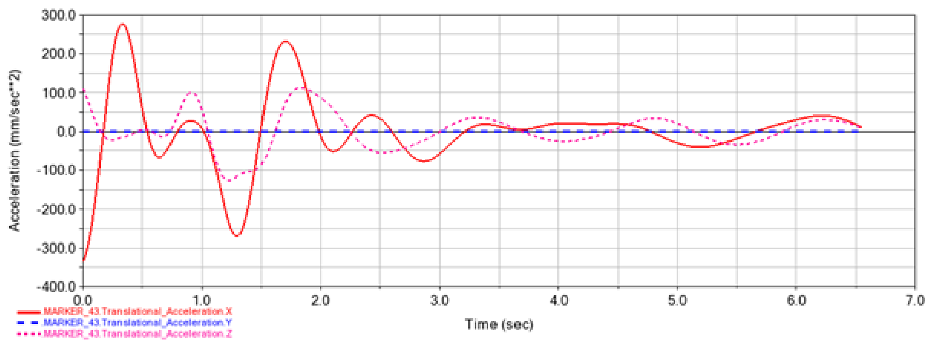


FIG 37. ADAMS Software Results

5.3.3. Simulation Discussion

When investigated the motion of the node B_3, the first remarkable result is can be seen as the constant values in Y direction. When it is investigated more detailed, it can be seen that there are similar oscillations like other two (X, Z) directions. But relatively to the X and Z direction this movement is not effective to the general structure. The reason here due to the constrained defined in initial setup. The general structure has oscillations in X and Z direction. This is expected results from the way of actuations acting in the system. The oscillations reduced with time as effect of damping defined. These values for damping are estimated through trial and error method. Lots of things still remain in this manner, the future work can be done by implementing control tools for the prototype and testing the actual prototype modeled. This can be useful for checking the simulation results also.

To understand the overall structure behavior, input and output values compared in the same plot. The Figure 6.6 shows the displacement of all the upper nodes respect to actuated node in the A_2 X direction. The constant line shows the actuation effect. The other oscillated curves show the upper nodes. The comment for the resultant graphic can be done as follows:

Curves for the upper nodes have the similar peak points on the movement. This can be used as advantage for translation mechanisms in the future. This can be mentioned the term integrity from the introduction part. This proves the method used in this work can be useful for the robotic applications in reduced movements (only translation on plane). The resultant oscillations can be reduced with using the correct damping ratio.

Of course, it would be interesting to build up the simulation settings as a prototype for this project. This research can be starting point for the future works for suggested method here including three main issues: Computation, Design and Simulation. Tensegrity is an exciting topic for robotics applications where new kind of deployable structures are needed. On the other hand, in this work the concept purposely tried to be kept simple with only including comprehensive overview, application possibilities and better understanding for others who will include in the future of this unique topic. The future works should be covering the real-world applications.

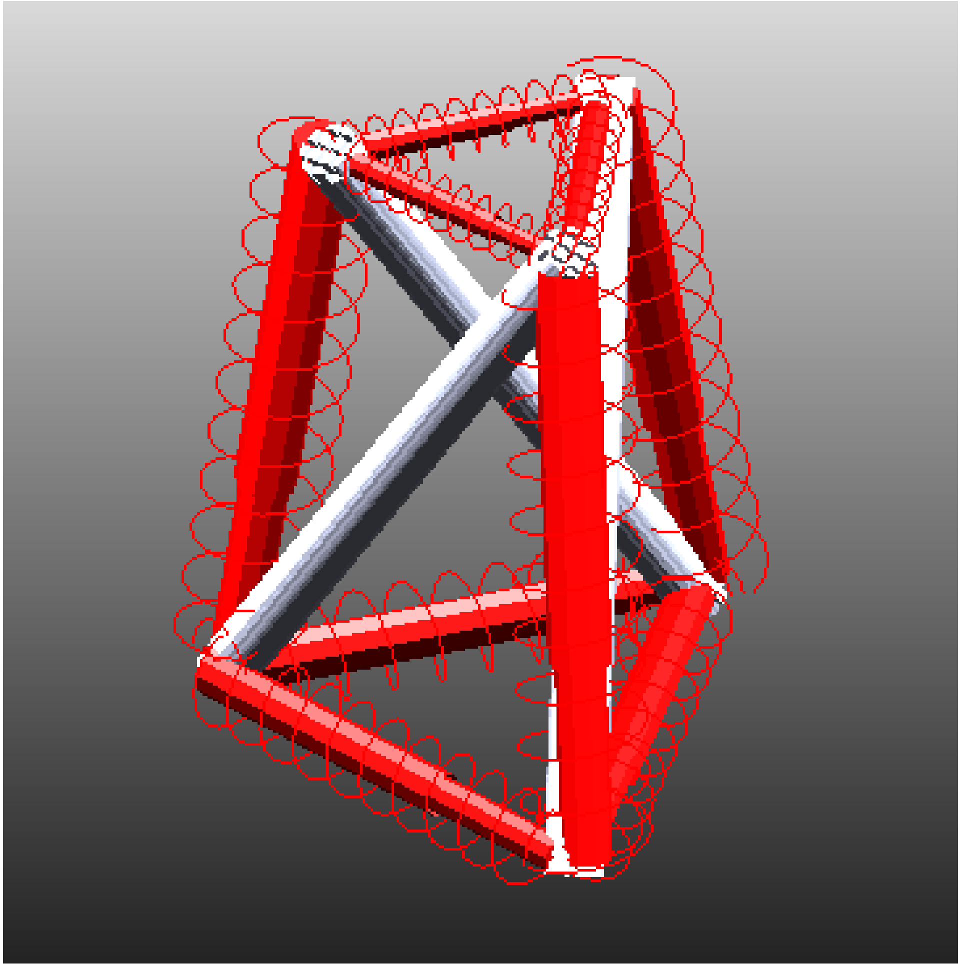
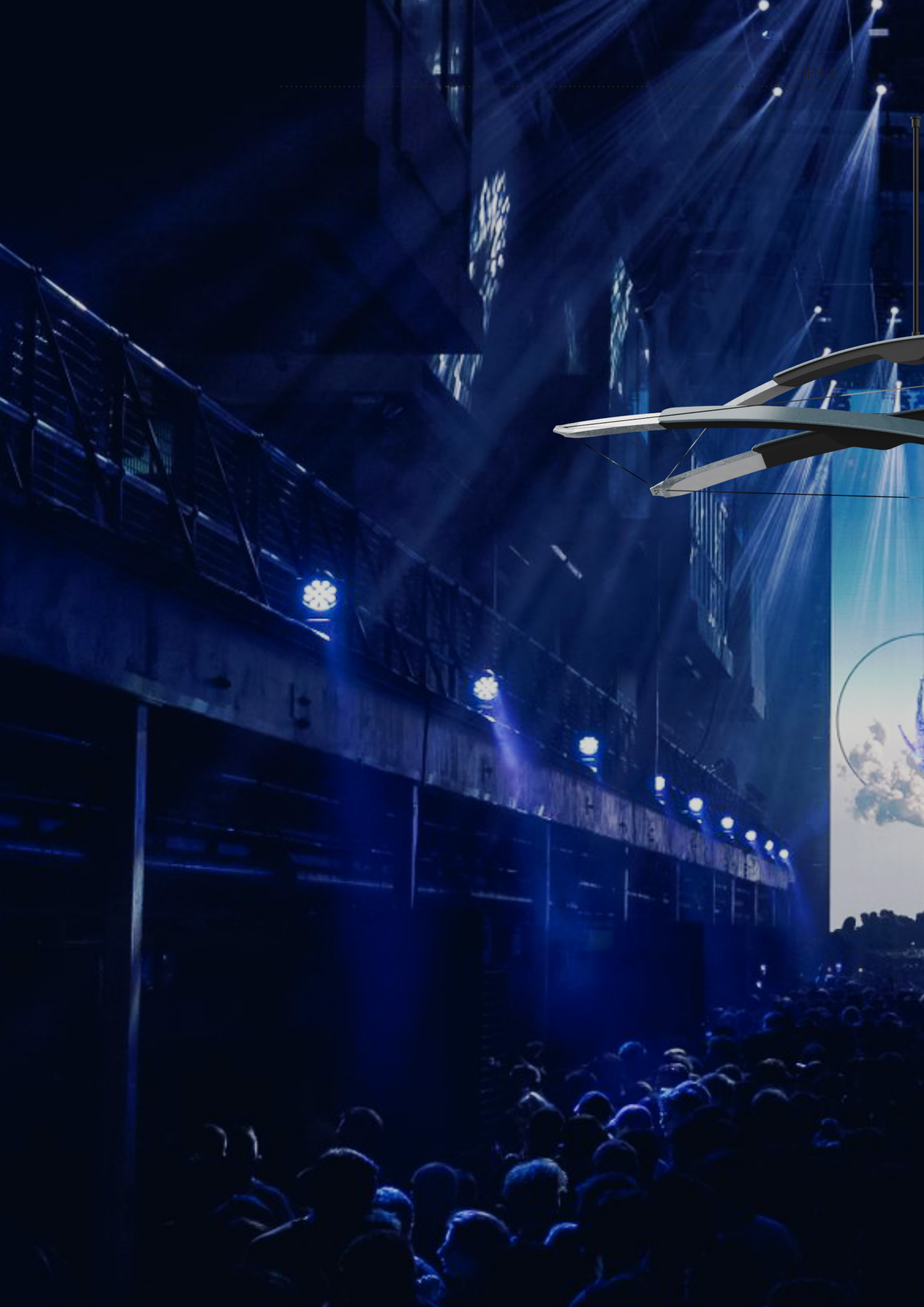


FIG 38. ADAMS Software modeling.

06
Product



TEN-X lightening unit beyond the expectations...

6.Product Definition

TEN-X will be developed for exclusive places such as elegant hotels, inspiring museums, unique events. These exclusive areas generally restricted to the person or a group of people who wants to achieve extra-ordinary interactions with the interiors and places around them. These areas give people the feeling of being high-end, elite, and stylish.

This definition set a goal for the TEN-X working environment to be in a specific context. The experience should be optimized to the place surrounding the product. It should be designed not for everywhere but for specific to places.

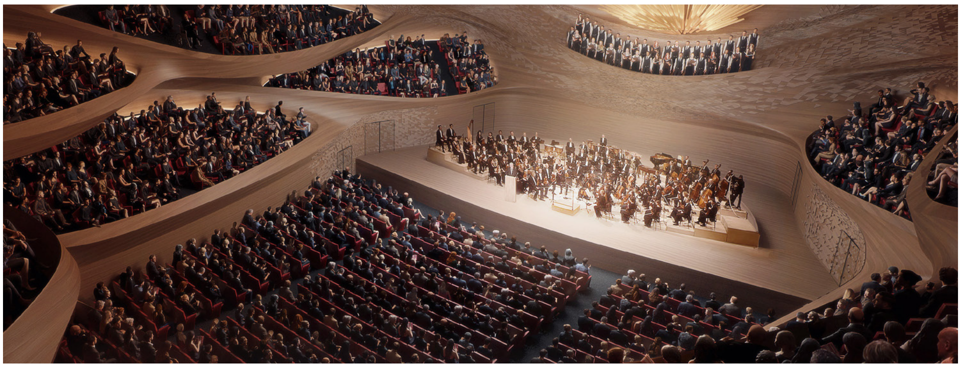
The innovative technology that have been used for the structure allows this exclusive feeling to the user. The complex shape of the TEN-X gives a unique attraction at first sight. The second main key feature of the TEN-X to achieve a feeling of interaction with lightening.

The idea is to create a connection with the people beneath of TEN-X. This powerful experience and emotional responses can be achieved by changing the way we are currently using the light systems.

The problem of the current lightening products can be defined to be static and stable products. Although the light source should be constant when its rest, the lighting unit can perform shape/form change during the switch from on to off. This can be achieved by tensegrity unique properties. The elastic elements in tensegrity structure help to the structure to be dynamic. This is the reason behind the selection of this unique structure and connection with lighting unit in this manner.

This product can be implemented in different environments in order to enhance user interaction with the lighting unit which represents visual translation movement. This interactions can be given by dynamic visual results both emotional and physically Thorough new technologies this product can connected to smart systems and information networks.

In this project, it is aimed to create a one integral prototype to prove its workability. The future works will include scalable products for different sizes and shapes. Because of tensegrity capabilities, scalability will be the most needed key factor. After the prototype, project planned for standardization to apply any place on demand.



ENVIRONMENT

ILLUMINATION

TENSEGRITY

ARTISTRY

6.1. Product Design Specification

As in definition of lighting, which can be defined as arrangement or effect of lights, current applications of lighting design are generally static ones. Using the tensegrity technology discussed in previous parts on this paper can be innovative solution to achieve dynamic, responsive lighting units. It is considered that this project will be applicable in most unique and memorable places such as inspiring halls, elegant lobbies, breathtaking museums and more where transforms the places to mesmerizing attractive centers.

There are a lot of ways to illuminate places with the artificial light sources, such as using LEDs, classic light bulbs or more. Motivation of this project is to create an exceptionally powerful experiences through both emotional and physical responses using dynamic tensegrity structure. Achieving reconfigurable and responsive product that gets the attentions can be new solution to current lighting design applications (generally static and monotonous). As an elegant and luxury product, this project has wide marketing potential in all over the world.

The project aims that designing an efficient deployable structure for illuminating the spaces with tensegrity structures and rearranging its form by changing the illumination level while in motion. Product is iteratively designed for specific places like airports, malls, museums and stations. Projects target unique and complex movement on lighting unit for achieving deployable units that can be preserved by the people who are beneath this product. This project is a new design approach to current conventional lighting unit problems which is less attractive, static and stable products. Later in this report, design requirements listed below.

This project has important customer requirements, first key function is to achieve durable and stiff enough lighting units which are working in under tensions and with harmonies integrity. This function is designed in the previous part of this paper. All the calculations mentioned in the research phase to create a realistic base to this concept. To achieve a deployable structure in this product the struts should increase their longitudinal lengths. This can be achieved with a telescopic mechanism. This function will create a motion in overall structure due to integrity of the cables.

Other design parameter is an input source of the telescopic mechanism. The product itself is designed relatively flat to achieve a uniform wide range of illumination, and thinness for the aesthetic purposes. That is the reason the moving mechanism should be hidden in the center with covered body. In this manner the efficient method is determined as rack and pinion mechanism which is translating the rotational movement to translational movement. The source is given by stepper motor and the movement is translated with gear system.

More detailed project requirements explained below in product design specification.

PRODUCT DESIGN SPECIFICATION	
Product Identification	Dynamic tensegrity lightning unit
Function	Moving overall lightning structure with using the tensegrity technology while changing the illumination during the motion.
Special Features	Usable in specific places Efficient Dynamic, Attractive Durable
Key Performance	Standard 220volt. Public current Quiet Movement,
Physical Descriptions	Expanded Size 300x300mm Closed Size
Life Cycle Parameters	LED ,gear, friction life

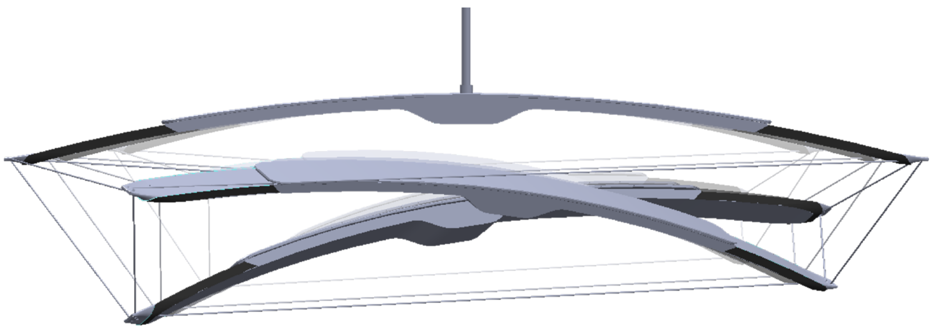
What makes
TEN-X different...

6.2. Product Features

Unexpected Experience

At first glance, the artistic look of TEN-X is stable under the ceiling, but with the hidden functional elements inside the product create unexpected results from the lightening unit. TEN-X will exceed all the expectations with unique working movement. The main feature of the product is to achieve an amazing emotional response with the movement of this artistry piece.

FIG 39. *Representation of movement*



Unique shape and form

The tensegrity structure is already unique and different than current structure types used for the lightening units. To push the limits, it is designed to achieve thin and elegant look for not taking too much space. With the general curve shape the idea of the lightening directions defined.

FIG 40. *Top & Side view of the product.*

Tensegrity Technology

The tensegrity itself it's an already attractive structure by itself. The combination of elastic elements and the rigid elements create the feeling of balance and wholeness. This technology is the source behind this unique project.

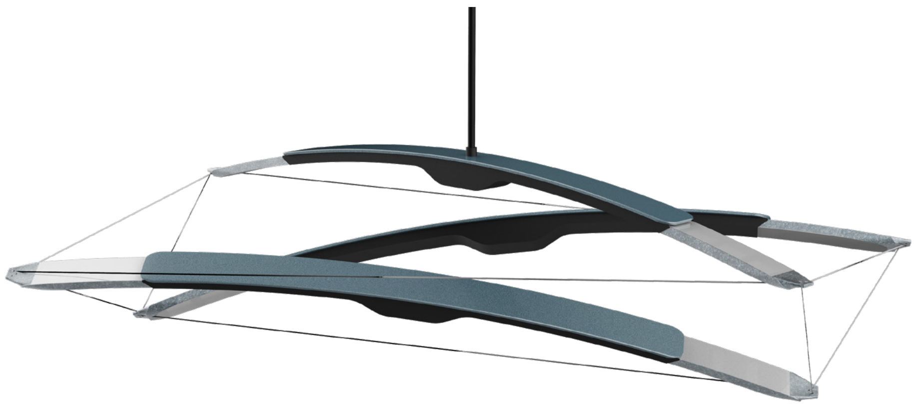


FIG 41. *Overall Structure*

Customizable to the place

Interior spaces vary widely in shape, details, and interiors. That's why some parts of the TEN-X is customizable to the places. Includes material, texture and color choice for different conditions, and scenarios, enabling to choose the experience that's best for the place.

FIG 42. *Customization*

6.3. Product Architecture

Product is designed for at least the spaces bigger than 50m^2 free space to illumination. The general maximum dimension without intersecting each other assigned as 2x2x2 meters. Figure shows the size compared to human size. Major differences from other products in the field is that tensegrity mechanism used for achieving kinetic interactive lighting unit.

For proper arrangement of physical elements and assembly purposes, the main element of the product divided in to 3 subassembly. Figure shown below gives basic representation of these three subsystems. For each three subsystems, detailed working principle and material selection procedure explained later in this report.

FIG 43. *From up to bottom,*
Mechanical Input Subsystem
Telescopic Arm Subystem
Main Shell Subsytem.

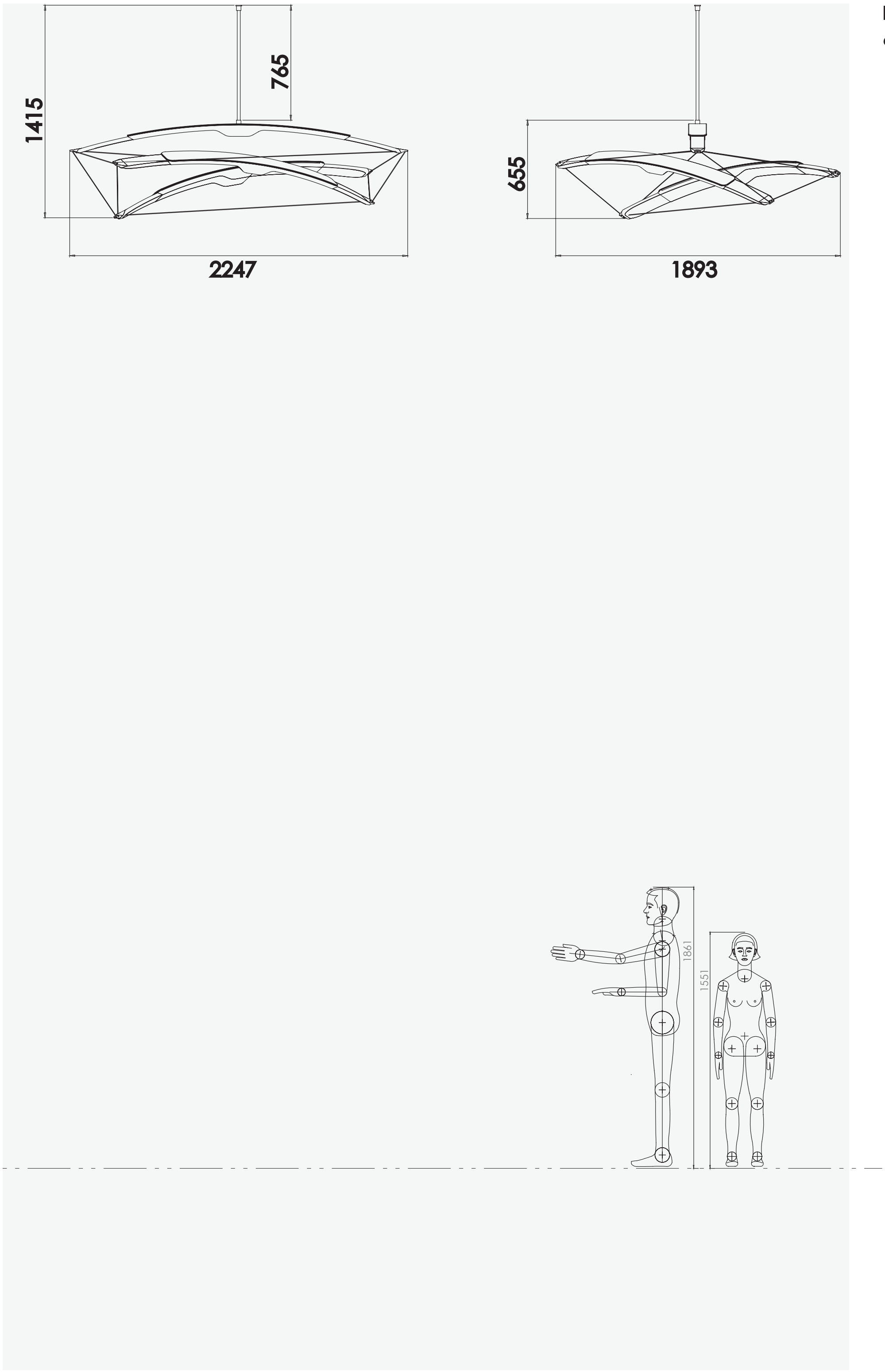


FIG 44. *General dimension compared to human size.*

How TEN-X Works ?

6.4. Technical Relation

In design phase it is essential to show functional diagram, working principle, material and manufacturing selection methods. This part is going to cover all these in this section.

The lightening design business is highly popular and elegant sector and it is not structured around one industry or one product. Nowadays there are a lot of way to illuminate places with different methods in the world. With the new requirements of the changing world, the new lightning units should be dynamic, and more technology included. The lights should be integrated with new smart systems and should be controllable.

To achieve these requirements controllable dynamic system is really important to achieve perfect effect of the unique experience. This is the main reason behind this proposal. In this report, all the technical relations of this system explained detailed.

The technical base for the tensegrity system is explained previously before in this report. This following part will include the parts that have been used in this concept to achieve a dynamic lightening unit with clear and unexpected experience.

6.4.1 Working Principle

When we analyze the working principle of the product, the idea that suggested previously is defined as ‘dimming during the movement of dynamic tensegrity structure’. This can be achieved with changing the cable tensions or the strut lengths. The selected method here for this product is to change the lengths of the main strut with telescopic system to desired new form. The main strut’s main shell kept stable in the space where the connection to the ceiling has been made. The movement of the arms of this main structure will determine the new orientation for remaining struts.

Overall, the dimming of the illumination and the movement of the struts will be in controlled at the same time.   These steps and the parts used to achieve this concept explained below in details.

Mechanical Input

The main body is covering the source of the motion. The motor inside the main case is turning the main gear. Occasionally, racks translate this turning motion to both sides. This designed rack & pinion mechanism creates 140 mm total displacement on the struts. This creates the shape change in overall system. This difference shouldn't be achieved so fast or so slow. The sense of movement should be preserved by the users but at the same time should not create risky instabilities to the general structure.

The main reason behind choosing stepper motor is explained above. This motor can be controllable with many systems like specific drivers or even Arduino. With these drivers, it can be integrated to smart systems. (wireless, remote controllers, phone & tablet applications). For mechanical properties, the stepper motor has advantage with low speeds(rpm) and high torque(T). This is exactly what this project requires for this unique movement.

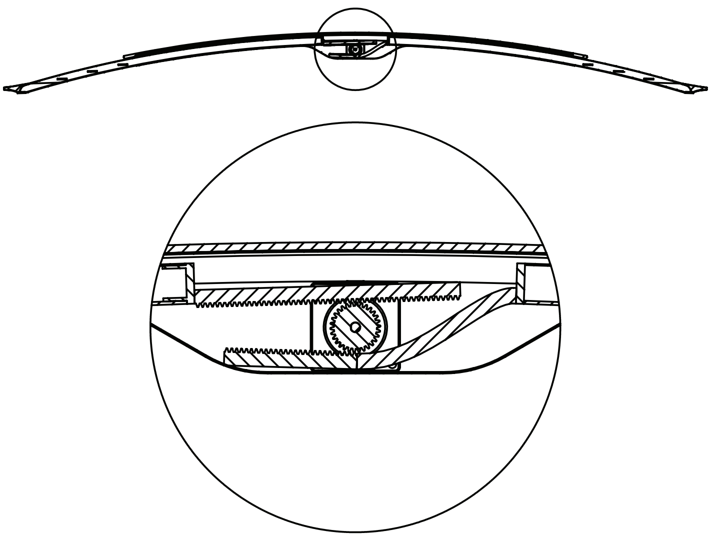


FIG 45. *Technical relation of mechanical input.*

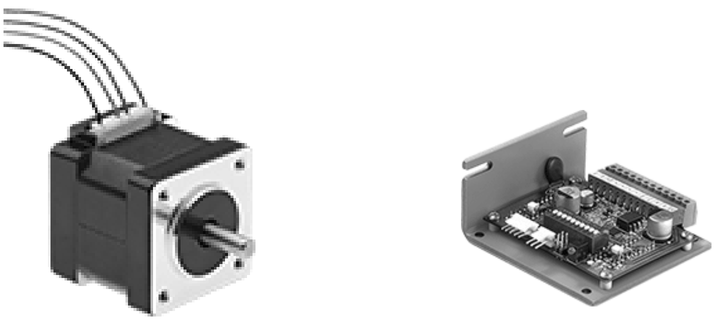
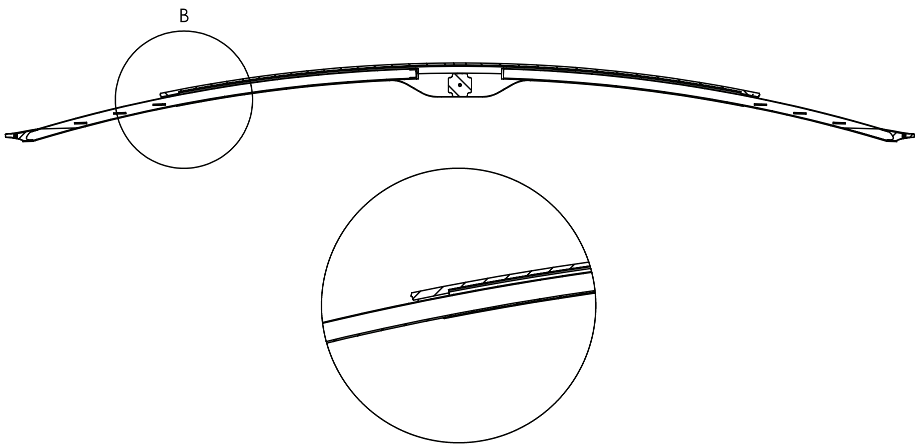


FIG 46. *Stepper Motor & Driver*

Telescopic Arms

To have a dynamic tensegrity system (configurable geometry) the struts lengths should be changed with time. The idea to have a telescopic mechanism has been deepened of this main brief. These arms are connected to the racks where the source of movement is coming from. These arms are sliding in the hollows of the main shell. The idea here to achieve a robust sliding effect without harming both of the structural elements. The frictions between these elements should be reduced with surface finish and coatings. The tolerances play critic role in this part. It should be durable for the life cycle of the product. The shape chosen here is for the aesthetic purposes and it comes with its own drawbacks of manufacturing and functioning. All the aspects will be mentioned in the next parts of this section.

FIG 47. *Telescopic Arms & Section view*



Cable System

The cables are essential parts for the tensegrity structure. With in the definition of the tensegrity the cables are the elastic elements which creates the tension and source of the overall structure. These elements should be selected carefully. In the previous proof of the concept section, the suggested cables are not sufficient enough for the real-life product due to aesthetic and functional purposes. The inspiration for the new cables comes from one of the most common used cables in our life's. Bike braking or museum hanging cables can be good solution for this new concept.

Resistance enough for long use and required tensions. Also, for the elastic requirements defined before leads the decisions to chose this already-made product. They can be installed to the system easily and create a strong structure as wanted. They can resist to the changes of the tensions as they designed for the bikes or hanging products. Moreover, adjusting the tensions can be done by already used maintenance tools on the market. For installing to the general system, they should be placed to their special cable holders before the general assembly made. From the practical results from initial prototype they should be able to move in their holes with small angles but not be displaced from their place.

FIG 48. *Suggested Cables*

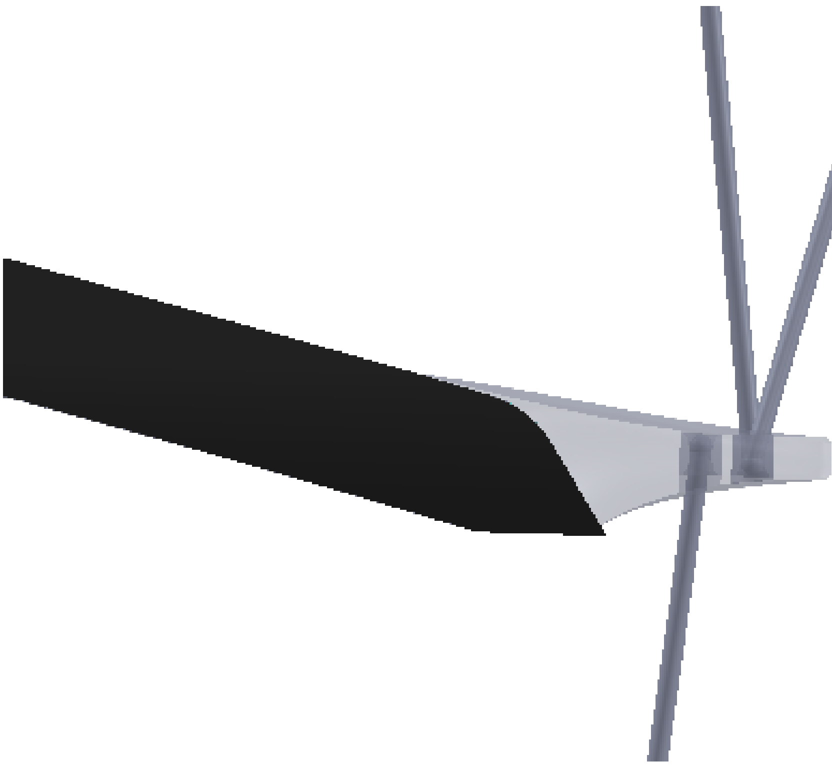


FIG 49. *Cable Connection*

LED System

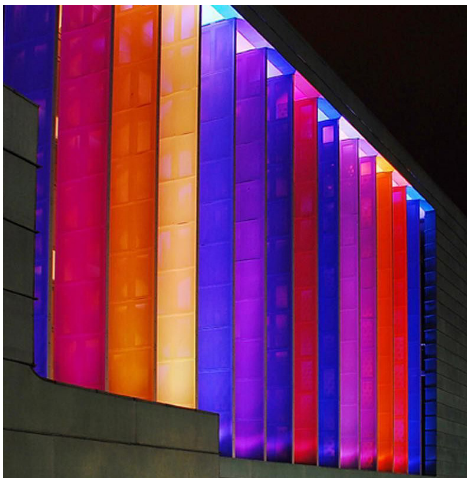
To achieve an amazing and unforgettable experience for the lightening units, the light source itself plays an important role. Although the sense of dimming with the movement can create a unique effect, the right choice of lights can expand the overall experience. In this manner the source of illumination is the key factor for success of this product. When we consider the environments where this product will be used, it is more usable to have more than monochrome colors. Also, when we say the lightening, the efficiency and the maintenance will be an important issue for life cycle. This main criteria's leads the selection for RGB flexible LED's.

Currently this type of source is used almost everywhere. It easy to build up and set up these lightening sources. The most important part for these setups is the selection of the diffuser material and locations. The effect will change dramatically with this diffuser. The source of LED's shouldn't be visible directly and should be concealed correctly.

When we consider the form, shape and materials used in this product, these light sources should give the sense of technological excellence of the tensegrity. To sum up, the lightening system should be considered as a whole and should be investigated with all the materials illuminated with the RGB LED's.

To stress the design language of high-tech elegancy, the arms have been selected to locate the LED strips. This will create a focus on the functioning parts and expand the feeling of the movement.

FIG 50. *RGB LED's*



6.5. Material Selection

After a careful research on the possible materials that can be introduced in the lighting design market, material selection will be introduced for the main components selected. With transforming the limitations into design requirement through the use of CES Ashby software, it was possible to obtain an initial material selection. After this initial step, the selection will be done due to manufacturing, design requirements and for most importantly aesthetic purposes.

General Requirement of the TEN-X:

The first aim of TEN-X that the overall structure should be stiff enough to carry the tensions and forces created by tensegrity itself. Components that are in contact must be investigated carefully due to the frictions and for long life cycle. They have to be durable with desired functions.

The aesthetic elements should be transparent enough to give the effect of illumination but at the same time not to show the source of the lights. To achieve high performance in suggested environments, the product should be protected from the sun,dust and moisture. The protection standards for this lighting unit have been decided as IP65.

Following the design development, it was decided to use commercial parts for cables, stepper motor, gear and LED lights, which will be the buy components. The selection of these buy components explained before.

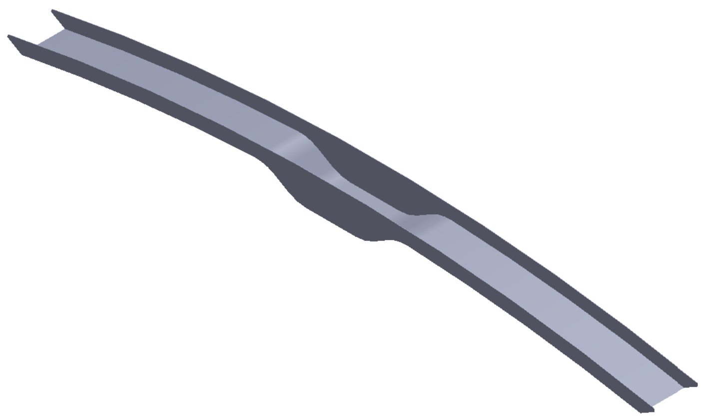
The other critical elements decided to be produced will be explained detailed below.

6.5.1. Main Shell

The main shell of the struts is the case for the telescopic arms and the base for the stepper motor. It must be rigid, stable and robust enough. Should be able to suitable for welding, forming, and drilling operations. Generally, metal family is well suited to these requirements. For most of the metals, contact with other part are critical and dangerous. In this manner the selected material shouldn’t be that abrasive. They are easily producible and have a relatively low material cost.

Thanks to post-processing such as coating, painting it is possible to obtain different finishes, colors. It will be preferable to have the aesthetically beautiful and decorative due the sector it used and the requirements of the defined design language.

FIG 51. *Main Shell*



	Costraint
Functional Costraint	Rigid Stable Robust Not Brittle Surface Finishing Forming,Welding,Drilling
Aesthetic Costraint	Painting, Coating
Free Variable	Material

CES Requirements

After identifying the requirements for the recognition of the material, it was necessary to introduce these parameters into the CES Ashby software and try to merge them.

The material for this component needs to be robust enough to resist the forces of the general product. Considering also the heat resistance to guarantee the correct functioning of the product due to the source of lights. The shape also brings limitations to the manufacturing methods.

Requirements:

- Formability
- Weldability
- Heat Resistance
- Robustness

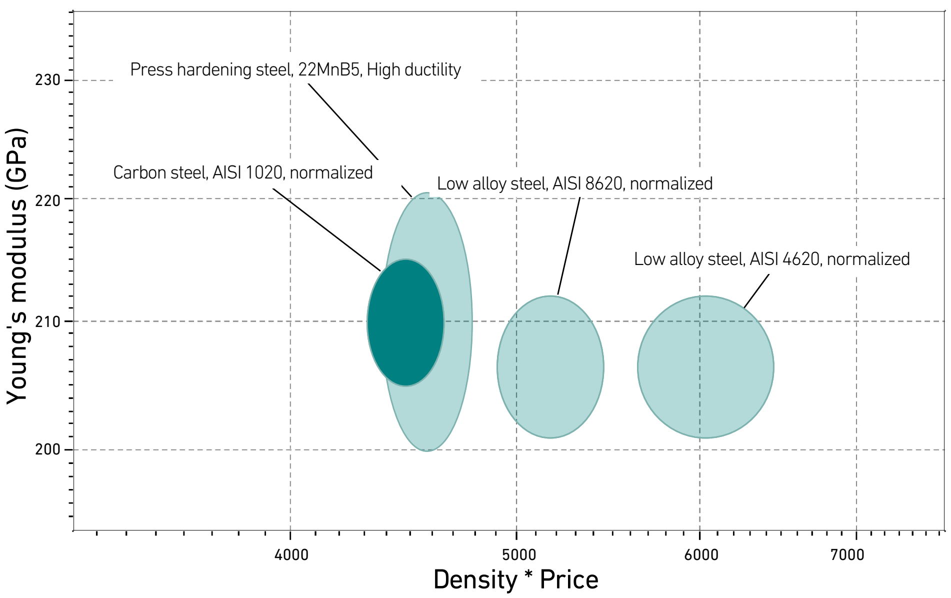


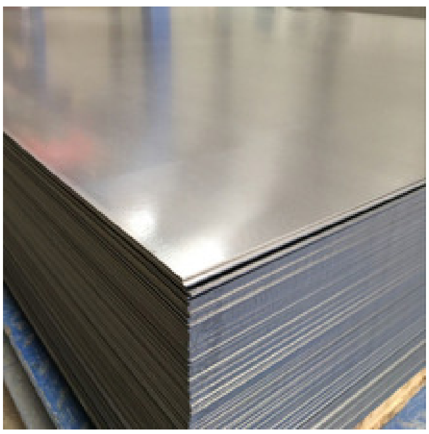
FIG 52. *CES Software Results*

Results

It has been decided the choose carbon steel sheet, because this material not only presents advantages for its density and its price, but as the limits shown, it is suitable to support the forces that are applied. Having the aesthetic requirements, the coating should be added to get the maximum decorative effect, to give the idea of high-end product.

MATERIAL	AISI 1020
PRICE	0,55 - 0,59 EUR/kg
DENSITY	7,8 e^3 - 7,9 e^3 kg/m^3
YOUNG'S MODULUS	205 - 215 GPa
YIELD STRENGHT	295 - 365 MPa
POISSON'S RATIO	0,285 - 0,295

FIG 53. *Galvanized Steel*



6.5.2 Telescopic Arm Diffuser

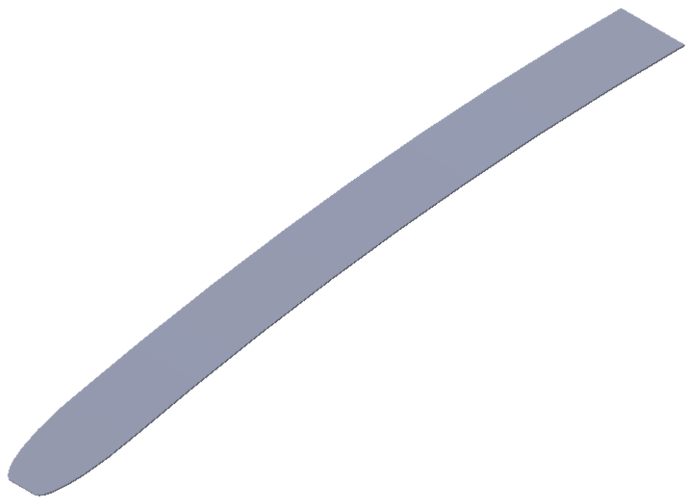
The telescopic arms of the struts are the parts that are moving inside the main shell. They are formed as the extensions of the general shape and they are connected to the main gear. They also have to be rigid and lightweight. This part are the covers for the RGB LED strips that will be the source of illumination.

The main structure of these element has been assigned the same with the main shell because of considering friction but with different coating to achieve different aesthetic purposes. The sheet metal will have a laser cut operation and bended as the form defined.

The critical part here is the selection of the diffuser, which is so important to translate the illumination to the place. The idea here is to cover the source of the LED's and also achieve clear and uniform illumination all inside the telescopic arm. Generally, thermoplastic family is well suited to these requirements. They are easily producible and have a relatively low material cost. But more important some of them have the most critical feature "transparency". The heat resistance also plays critical role for these parts. The heat of the light source shouldn't harm these covers.

This part doesn't have any mechanical functions, there is no need to achieve stiffer materials for these parts. It will be preferable to have the aesthetically frosted glassy look to achieve aesthetic function.

FIG 54. *Diffuser*



	Costraint
Functional Costraint	Rigid Not Brittle Surface finishing, Coating Formability Vacuum Forming Heat Resistance Protectection
Aesthetic Costraint	Transperency
Free Variable	Material

For this part identifying the requirements for the recognition of the material, it is considered not to use CES Ashby software. The market and the common materials for this type of applications analyzed deeply and selected for practically. Transparency is the main key feature for this part. The main idea to hide the light source directly but at the same time keeping the light passing through for illumination.

Heat resistance also is an another issue, to guarantee the correct functioning of the product due to the source of lights the part should not be effected from the heat.

The shape also brings limitations to the manufacturing methods. The unique shape is forcing to manufacture special methods. The manufacturing step of this shape determined as vacuum forming.

Requirements:

Transparency
Heat Resistance
Vacuum forming

Results

It has been decided the choose Polycarbonate, PC as selected material. The Polycarbonate (PC) is mostly used engineering thermoplastic due to its transparency toughness, thermal stability and a very good dimensional stability. PC is an extremely clear plastic and can transmit over 90% of light as good as glass. PC sheets are available in a wide range of shades which can be customized depending on the end-user application. Also in practical sense, it is still the best application material for lighting design sector.

MATERIAL	Polycarbonate, PC
PRICE	2.6–2.8 €/kg
DENSITY	1.15-1.2g/cm3
YOUNG'S MODULUS	2.2-2.5GPa
YIELD STRENGHT	61-69MPa
POISSON'S RATIO	0,375 - 0,400

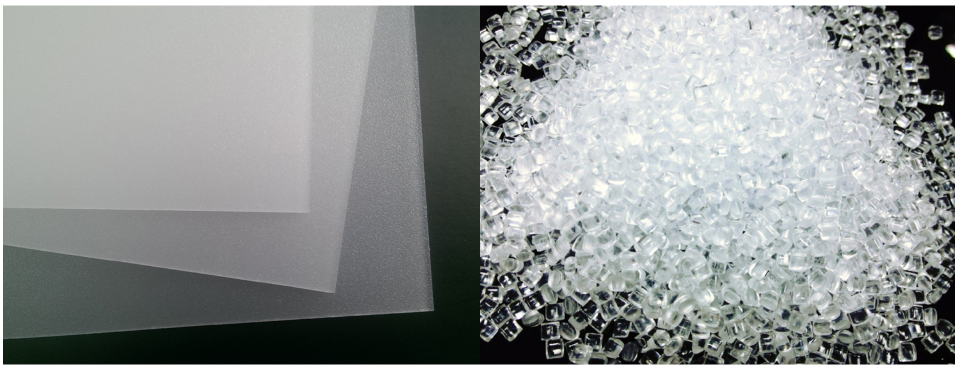


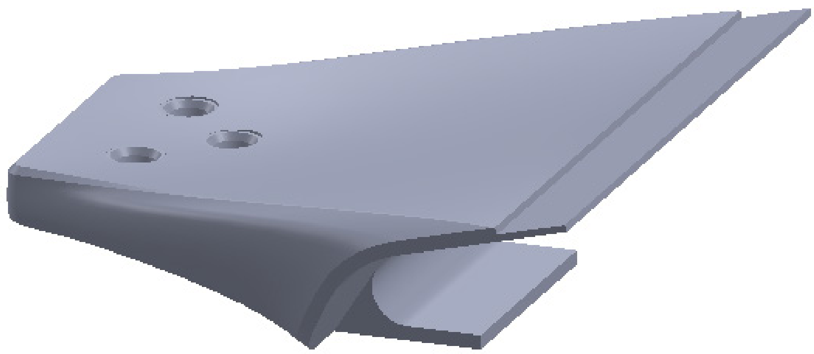
FIG 55. *PC* Polycarbonate

6.5.3 Cable Holders

The cable holders are critical part for defining the final shape as aesthetically and functional element for holding cables. This part is designed to have a unique shape for a purpose. Offsetting the cable holes from the main body and having the planar surface for the holes. This functional element is the first contact point where the cables are connected. The tension translates with this part to the telescopic arms. This unique shape requires detailed manufacturing methods. Should be able to suitable for milling, drilling, CNC operations.

Generally, metal family is well suited to these requirements. The unique shape requires a precise manufacturing method. With the advantage of CNC milling this part can be produced as defined. And holes can be done with drilling. In this manner the selected material should be suitable for metal processing operations. It will be preferable to have the aesthetically beautiful and well-suited with the other parts used in this product.

FIG 56. *Cable Holder*



Requirements:

CNC milling
Stiff and Strong Enough
Drilling Operations

	Costraint
Functional Costraint	Rigid and Stiff Enough Not Brittle Surface finishing Milling, Drilling
Aesthetic Costraint	Painting, Coating
Free Variable	Material

After identifying the requirements for the recognition of the material, the selection has been considering mainly the manufacturing method for realistic approach. Manufacturing method assigned as CNC milling to guarantee the correct functioning of the product due to the precision.

Results

It has been decided the choose Aluminum Alloys. The 6061 aluminum alloy is one of the most common and versatile for extrusion. It is generally referred to as structural aluminum. Due to its well processability, very good surface finish ing, and dimensional precision with the suggested manufacturing method lead to this decision.

MATERIAL	6061 Aluminum Alloy
PRICE	1,52 - 1,57 EUR/kg
DENSITY	2.70 g/cm3
YOUNG'S MODULUS	68.9 GPa
YIELD STRENGHT	83-110 MPa
POISSON'S RATIO	0.33

6.6. Manufacturing Method

It is essential to suggest manufacturing process and assembly steps for this concept. Considering materials,the geometrical constraints and market need reasonable methods for manufacturing suggested below. For each critical make-parts design rules listed.

MATERIAL / QUANTITY	IRONS	STEEL (carbon)	STEEL (tool, alloy)	STAINLESS STEEL	COPPER & ALLOYS	ALUMINIUM & ALLOYS	MAGN & ALL
VERY LOW 1 TO 100	[1.5] [1.6] [1.7] [4.M]	[1.5] [1.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.1][1.5][1.7] [3.10] [4.M] [5.1] [5.5] [5.6] [5.7]	[1.5] [1.7] [3.7] [3.10] [4.M] [5.1] [5.5] [5.6]	[1.5] [1.7] [3.10] [4.M] [5.1]	[1.5] [1.7] [3.7] [3.10] [4.M] [5.5]	[1.6] [3.10] [5.1]
LOW 100 TO 1,000	[1.2] [1.5] [1.6] [1.7] [4.M] [5.3] [5.4]	[1.2] [1.5] [1.7] [3.10] [4.M] [5.1] [5.3][5.4][5.5]	[1.1][1.2][1.7] [4.M] [5.1] [5.3] [5.4] [5.5][5.6][5.7]	[1.2] [1.7] [3.7] [3.10] [4.M] [5.1] [5.3][5.4][5.5]	[1.2] [1.5] [1.7][1.8][3.5] [3.10][4.M][5.1] [5.3] [5.4]	[1.2][1.5][1.7] [1.8][3.7][3.10] [4.M] [5.3] [5.4] [5.5]	[1.6] [1.8] [[4.M]
LOW TO MEDIUM 1,000 TO 10,000	[1.2] [1.3] [1.5] [1.6] [1.7] [3.11] [4.A] [5.2]	[1.2][1.3][1.5] [1.7][3.1][3.3] [3.10] [3.11] [4.A][5.2][5.3] [5.4] [5.5]	[1.2][1.5][1.7] [3.1][3.4][3.11] [4.A][5.2][5.3] [5.4] [5.5]	[1.2][1.5][1.7] [3.1][3.3][3.7] [3.10] [3.11] [4.A][5.2][5.3] [5.4] [5.5]	[1.2][1.3][1.5] [1.8][3.1][3.3] [3.10][3.11][4.A] [5.2][5.3][5.4]	[1.2][1.3][1.5] [1.8][3.1][3.3] [3.7][3.10][3.11] [4.A][5.3][5.4][5.5]	[1.3] [1.8] [3.3][3.4 [4.A]
MEDIUM TO HIGH 10,000 TO 100,000	[1.2] [1.3] [3.11] [4.A]	[1.9][3.1][3.3] [3.4] [3.5] [3.11] [3.12] [4.A][5.2][5.5]	[3.1][3.4][3.5] [3.11][3.12] [4.A] [5.2]	[1.9] [3.1] [3.3] [3.4] [3.5] [3.11] [3.12] [4.A]	[1.2][1.4][1.9] [3.1][3.3] [3.4][3.5][3.11] [3.12] [4.A]	[1.2][1.3][1.4] [1.9][3.1][3.3] [3.4][3.5][3.11] [3.12][4.A][5.5]	[1.3] [3.1] [3.4] [3.12]
HIGH 100,000+	[1.2] [1.3] [3.11] [4.A]	[1.9] [3.1] [3.2] [3.3] [3.4] [3.5] [3.12] [4.A]	[4.A]	[1.9] [3.2] [3.3] [4.A]	[1.2][1.9][3.1] [3.2][3.3][3.4] [3.5][3.7][3.8] [3.11][3.12][4.A]	[1.2][1.3][1.4] [1.9][3.1][3.2] [3.3][3.4][3.5] [3.8][3.12][4.A]	[1.3] [[3.1][3. [3.8][3.1
ALL QUANTITIES	[1.1]	[1.1] [1.6] [3.6] [3.8] [3.9]	[1.6] [3.6]	[1.1] [1.6] [3.6][3.8][3.9]	[1.1] [1.6] [3.6] [3.8] [3.9] [5.5]	[1.1] [1.6] [3.6] [3.8] [3.9]	[1.1] [[3.8] [

KEY TO MANUFACTURING PROCESS PRIMA SELECTION MATRIX:

CASTING PROCESSES
[1.1] SAND CASTING
[1.2] SHELL MOULDING
[1.3] GRAVITY DIE CASTING
[1.4] PRESSURE DIE CASTING
[1.5] CENTRIFUGAL CASTING
[1.6] INVESTMENT CASTING
[1.7] CERAMIC MOULD CASTING
[1.8] PLASTER MOULD CASTING
[1.9] SQUEEZE CASTING

PLASTIC & COMPOSITE PROCESSING
[2.1] INJECTION MOULDING
[2.2] REACTION INJECTION MOULDING
[2.3] COMPRESSION MOULDING
[2.4] TRANSFER MOULDING
[2.5] VACUUM FORMING
[2.6] BLOW MOULDING
[2.7] ROTATIONAL MOULDING
[2.8] CONTACT MOULDING
[2.9] CONTINUOUS EXTRUSION (PLASTICS)

FORMING PROCESSES
[3.1] CLOSED DIE FOR
[3.2] ROLLING
[3.3] DRAWING
[3.4] COLD FORMING
[3.5] COLD HEADING
[3.6] SWAGING
[3.7] SUPERPLASTIC F
[3.8] SHEET-METAL SH
[3.9] SHEET-METAL FO
[3.10] SPINNING
[3.11] POWDER METALL
[3.12] CONTINUOUS EX (METALS)

The lighting design is a massive field within combination of architecture, interior design and electrical engineering to serve human needs. Nowadays there are various solutions with different shapes, sizes and colors. The current trend is to apply smart products to smartphone applications, control support and dimming/color changing options as desired.

...ESIUM ...LOYS	ZINC & ALLOYS	TIN & ALLOYS	LEAD & ALLOYS	NICKEL & ALLOYS	TITANIUM & ALLOYS	THERMOPLASTICS	THERMOSETS	FR COMPOSITES	CERAMICS	REFRACTORY METALS	PRECIOUS METALS
[1.7] [4.M] [5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]	[1.1] [1.7] [3.10] [4.M] [5.5]	[1.1] [3.10] [4.M] [5.5]	[1.5] [1.7] [3.10] [4.M] [5.1][5.5][5.6]	[1.1] [1.6] [3.7] [3.10] [4.M] [5.1] [5.5][5.6][5.7]	[2.5] [2.7]	[2.5] [5.7]	[2.2] [2.8] [5.7]	[1.5] [5.1] [5.5] [5.6] [5.7]	[1.1] [5.7]	[5.5]
[1.7] 3.10] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.7] [1.8] [3.10] [4.M] [5.5]	[1.1] [1.8] [3.10] [4.M] [5.5]	[1.2][1.5][1.7] [3.10] [4.M] [5.1] [5.3] [5.4] [5.5]	[1.1][1.6][3.7] [3.10][4.M][5.1] [5.3][5.4][5.5] [5.6] [5.7]	[2.3] [2.5] [2.7]	[2.2] [2.3]	[2.2] [2.3] [2.8] [5.7]	[5.1] [5.3] [5.5] [5.6] [5.7]	[5.7]	[5.5]
[1.6] [3.1] 4][3.10] [5.5]	[1.3] [1.8] [3.3] [3.10] [4.A] [5.5]	[1.3] [1.8] [3.3] [3.10]	[1.3] [1.8] [3.3] [3.10]	[1.2][1.3][1.5] [1.7][3.1][3.3] [3.11][4.A][5.2] [5.3][5.4][5.5] [3.10]	[3.1] [3.7] [3.10] [3.11] [4.A] [5.2] [5.3][5.4][5.5]	[2.3] [2.5] [2.6] [2.7]	[2.2] [2.3] [2.4]	[2.1] [2.2] [2.3]	[5.2] [5.3] [5.4] [5.5]		[5.5]
[1.4] [3.3] [3.5] [4.A]	[1.3] [1.4] [3.3] [3.4] [3.5] [3.12] [4.A]	[1.3] [1.4] [3.3] [3.4] [3.12]	[1.3] [1.4] [3.3] [3.4] [3.5] [3.12] [4.A]	[3.1][3.3][3.5] [3.4] [3.11] [3.12] [4.A] [5.2] [5.5]	[3.1][3.4] [3.11] [3.12] [4.A][5.2][5.5]	[2.1] [2.3] [2.5] [2.6] [2.9]	[2.1] [2.3] [2.9]	[2.1] [2.3]	[3.11]	[3.12]	[3.5]
[1.4] 3][3.4] 2][4.A]	[1.4] [3.2] [3.3] [3.4] [3.5] [4.A]	[1.4] [3.3] [3.4] [4.A]	[1.4] [3.2] [3.3] [3.4] [4.A]	[3.2] [3.3] [4.A]	[4.A]	[2.1] [2.6] [2.9]	[2.1] [2.3] [2.4] [2.9]		[3.7] [3.11]		[3.5]
3.6] 3.9]	[3.6] [3.8] [3.9]		[3.6]	[1.1] [1.6] [3.6] [3.8] [3.9]	[3.8] [3.9]				[5.5]	[1.6]	[1.6]

FIG 57. *PRIMA Table*

S
RGING

FORMING
HEARING
ORMING

LURGY
TRUSION

MACHINING PROCESSES

[4.A] AUTOMATIC MACHINING
[4.M] MANUAL MACHINING

(THE ABOVE HEADINGS COVER A BROAD RANGE OF MACHINING PROCESSES AND LEVELS OF CONTROL TECHNOLOGY. FOR MORE DETAIL, THE READER IS REFERRED TO THE INDIVIDUAL PROCESSES.)

NTM PROCESSES

[5.1] ELECTRICAL DISCHARGE MACHINING (EDM)
[5.2] ELECTROCHEMICAL MACHINING (ECM)
[5.3] ELECTRON BEAM MACHINING (EBM)
[5.4] LASER BEAM MACHINING (LBM)
[5.5] CHEMICAL MACHINING (CM)
[5.6] ULTRASONIC MACHINING (USM)
[5.7] ABRASIVE JET MACHINING (AJM)

Market share of high-end products in modern lighting family keep growing in the general market for this sector. With the product suggested in this project the aim of the market has been identified for exclusive users. This means that the target will be very unique and special to the users and places. The geometrical constraints, material and the annual batch sizes investigated together to make reasonable and strong hypothesis.

Considering the market need and planned product specifications, annual batch size assigned to less than 100 which refers to "very low"

As seen from the PRIMA table, this product will compose of two main material families. These are Steel (Carbon) family for structural elements and Thermoplastic family for parts for functional and aesthetic elements.

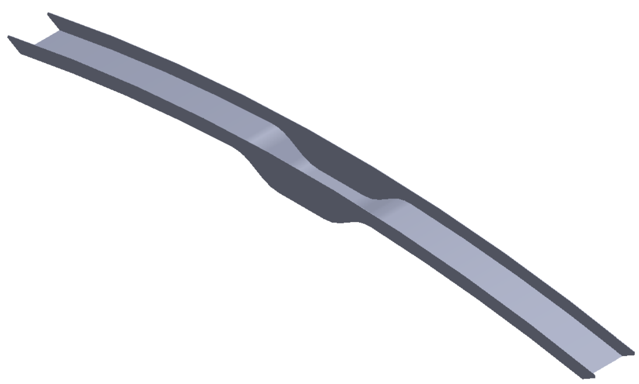
As shown in PRIMA table with the determined annual batch size of very low selected manufacturing operations and reasons behind of these choices listed below.

6.6.1. Investigated Critical Make-Parts

Main Shell

This part is designed to carry the weight of the overall structure and to serve a base function for the step motor. The channel will be the way for telescopic arms. Sheet Metal Steel is used make this part. The required form will be given by Laser Beam Machining operations and then welding will be applied to create this part.

FIG 58. *Main Shell*



Laser Beam Manufacturing (LBM)

A pulsed beam of coherent monochromatic light of high power density, commonly known as a laser s focused on to the workpiece surface causing it to vaporize locally. The material then leaves the surface in the vaporized or liquid state at high velocity.

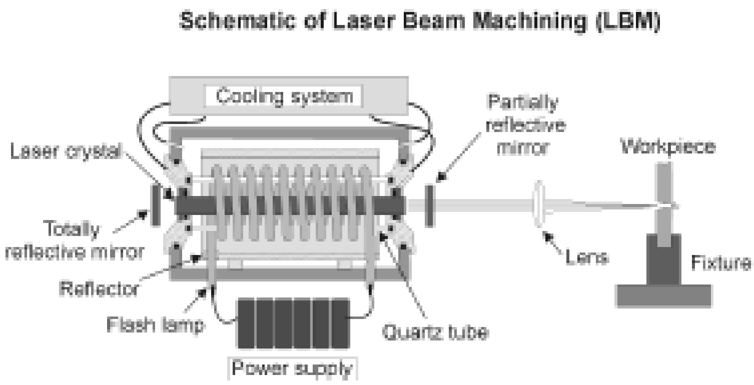


FIG 59.*Laser Beam Machining*

The laser cutting process is a very precise technique that utilizes a special technique and precision tools and give a shape with lasers to produce parts that are more nearly complete and ready for assembly. Standard thickness of the sheet metals can be formed with laser cut.

The reasons for considering laser cut include the need for higher dimensional accuracy. For this project this part will be used to achieve the general form. Geometric accuracy is the biggest concern in this part. That's why laser cut method has been selected.

Applied Design Rules

. This part especially divided for to 3 parts to manufacture.
. Radius used generously ,avoided sharp edges.
. Maximum thicknesses not exceed 25mm which is the limit for steels.
. Minimum hole size not exceed 0.005 mm.
. Size is not exceeding the common machines and tools on the market

Laser Beam Welding

Welding minimizes building of complex shapes in certain applications, which reduces waste and cost. There are a lot of welding operations on the market. Welding methods are generally inexpensive and make use for the permanent assembly for metals. When welding this type of precision needed project, the welding operations should be at right angles with right fixtures. The welding cavities should be reduced as much as possible.

The selection for this type of welding is depend on reducing the initial tool cost. The same machine can be used both for cutting mentioned before and here for welding.

Applied Design Rules

The weldings will be inside the channel and designed to be not visible for the users. This also allows the aesthetic errors can not be visible . The welding joint determined as corner joints. It is preferable to avoid cavities and errors. The side parts should be 90 degree to base plate.

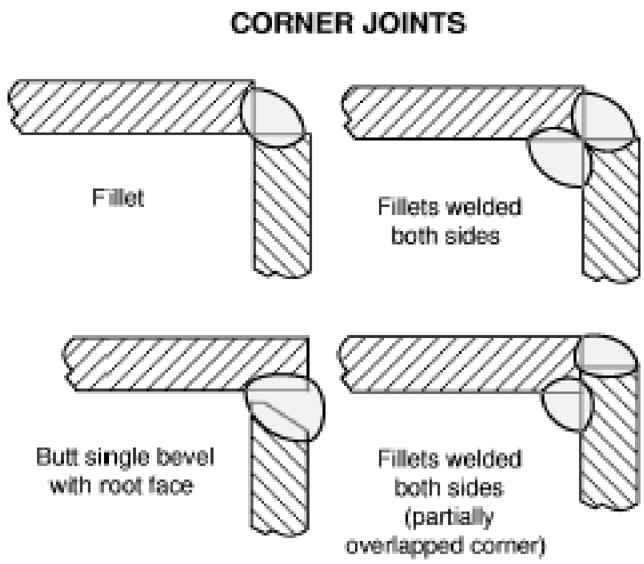


FIG 60. *Design Rules for welding operations.*

Telescopic Arm Diffuser

Vacuum Formed PC used to create a semi-transparent diffuser for LED units. This part will be fixed to frame with mechanical joining (Screws,Bolts,Nuts...).The required form will be given by vacuum forming operation.

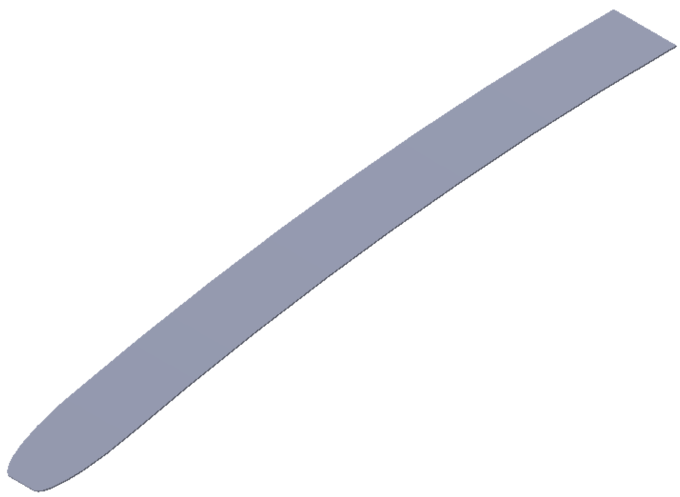
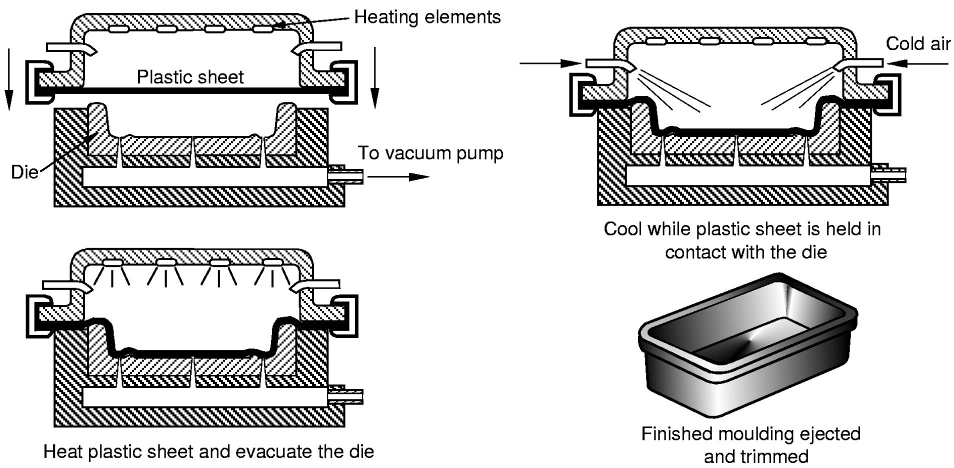


FIG 61. *Diffuser*

Vacuum Forming

Vacuum forming, as the term is normally used, involves the shaping of a thermoplastic sheet softened by heating elements and pulled under vacuum on to the surface form and cooling in the mold, taking the mold's shape. Then it is removed from the mold and trimmed as necessary. Surface finish good and related to the condition of mold surface.

FIG 62. *Vacuum Forming*



Due to plastic memory of the sheet material and high temperatures , there are possibilities to turn back to original shape. The shape should be considered for this drawback. Operating temperature should be controlled all the time. Other important thing is to having a uniform sheet material for better results.

Applied Design Rules

. One plane molding has been selected. Shape complexity reduced to basic geometery with large curvature.
. Constant thickness.
. Surface area keep small as possible.
. Corner radii has been setted to be large compared to thickness of material.
. Sharp corners avoided.
. Maximum section is not bigger than 3 mm.
. Minimum section is not exceed 0.05–0.5 mm
. Size considered to be fit in common machines on the market nowadays.

6.7. Assembly Process

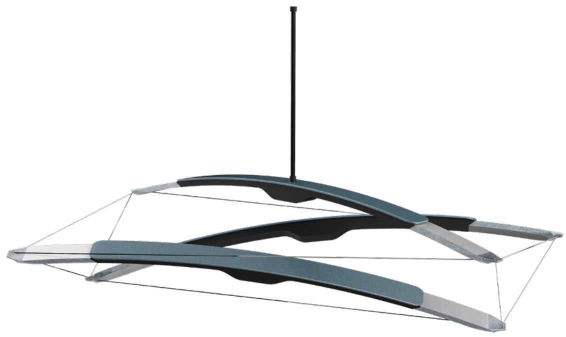
• Assembly operations starts with the attaching the gear to stepper motor and these parts to top cover for further operations. Main ceiling cable holder added from the hole in the center.

• To create a telescopic arm, the bended sheet metal frame, LED strips, rack, cable holder and diffusers assembled externally.

• Externally assembled telescopic arms will be added to system from their contacting point with the gear assembled before. They will able to move in the main shell.

• To cover the struts, main shell will be added from the bottom and cover overall struts.

• Last step for assembling this product is to create the tensional forces with elastic elements(cables) to achieve a tensegrity structure. This requires a practice and knowledge mentioned in this thesis before.



07
Conclusions

7. Conclusions

This Master thesis has presented a new approach to use a tensegrity structure in product design field. This work differs from existing approaches by designing lighting product that changes its shape with given input with using advantageous of tensegrity. There are several outcomes in both fields in dynamic tensegrity and for future lighting applications.

The use of a suggested mathematical model that converts the form finding methods into a dynamic tensegrity solution allows tensegrity principles to be designed in real-world applications. To understand the overall structure behavior, initial prototype has been developed and tested. Moreover, the simulations setup has been done with this initial prototype setup. These concept proof steps tackled the challenges faced during mathematical modeling and create a great basic for the real product.

More importantly, the suggested lighting product also enables the new ways of interactions for lighting design field. From the beginning of the ideation, this product is designed to achieve an unique experience. To achieve this, key features and design decision explained in the product section. Overall, all the design procedure steps have been introduced to make this product real with material selection and manufacturing methods. Both theoretical and practical results show that the product is able to achieve a new kind of interactions by using the tensegrity structure as a source of technology.

The theoretical ideas presented in this article have been applied to real-world lighting design product which can be defined as the main goal of this master thesis. It has been demonstrated how mathematical model of tensegrity can be applied to create a deployable tensegrity structure and dynamic lighting unit. In addition to mathematical modeling , the idea generation of having a interactive lighting unit can achieve new performances in lighting products. Even this is not a new topic in design field, using tensegrity structures can be new approach for developing trend in this field. In the future, this system can have a significant importance in the lighting design sector.

The approach that has been used to develop TEN-X can also be applied to another fields of product design where there is a need for lightweight, deployable and dynamic structures such as furniture, toy, packaging or transformation design.

7.1. Future Work

This thesis covers all the aspects of design to make this product work in real-life scenarios, however there are still some improvements should be addressed both practically and theoretically. The results that gathered from this overall design process can lead designers and engineers to study together on this unique, complex structures to create valuable products for people.

On the theoretical side, the mathematical model for tensegrity structure should be investigated more deeply for better results. The assumptions and the decisions made for the calculations can be extended for real-life scenarios. The suggested method here is used for 3-Prism tensegrity structure which is the most basic and relatively not complex one. The reason for choosing this geometry explained in this thesis before. For additional work, new methods and their applications should be studied further for more complex structures. This work hopes to be a first step toward further understanding this important issue.

On the practical side, workability of this designed concept should be proved with prototyping process. The design decisions cannot be shaped without this process. From starting with the initial prototype, it is understood that this unique concept has unique outcome when it comes to application. Even the mathematical and computer aided design can be nice representation for the concept, the real understanding and the inspiration of the concept has been done with several prototypes. The next step here is to achieve a working prototype to show the key features and possibilities of this product. The manufacturing methods for this concept are suggested for conventional methods. For prototyping, 3D printing can be the best solution for demonstration. With the capabilities of 3D printing, using transparent materials can achieve a several advantageous to experiment the illumination affects. For the functioning parts like rack pinion mechanism it can be helpful to understand the capabilities of telescopic mechanism with 3D printing. This will be next step for this work and its essential for proof of concept.

To finalize, it is required to make further investigation more theoretically and practically. This thesis is giving the basis for who are interested about the tensegrity structures and its application to product design. This work will continue with the prototyping and the finished product.

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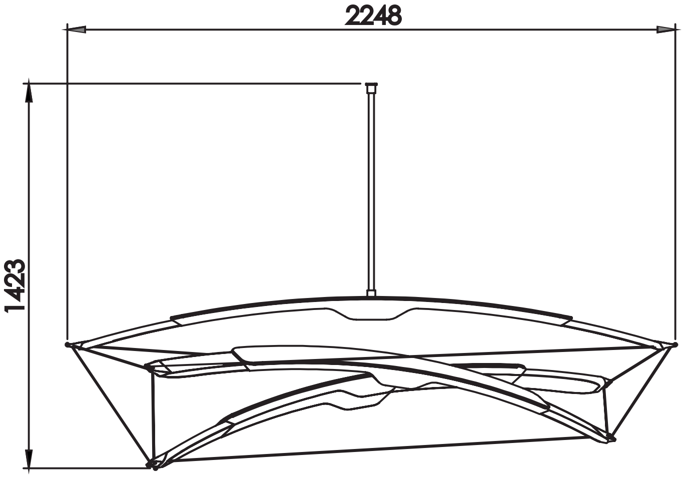
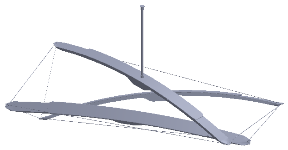
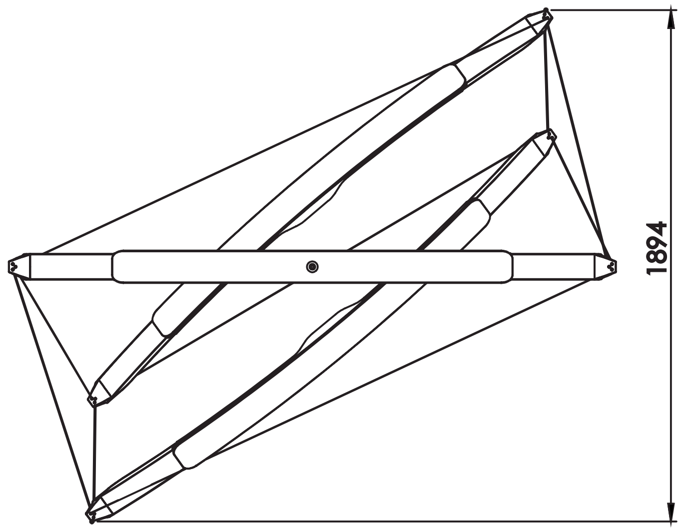
Appendix A

Technical Drawing - General Dimension

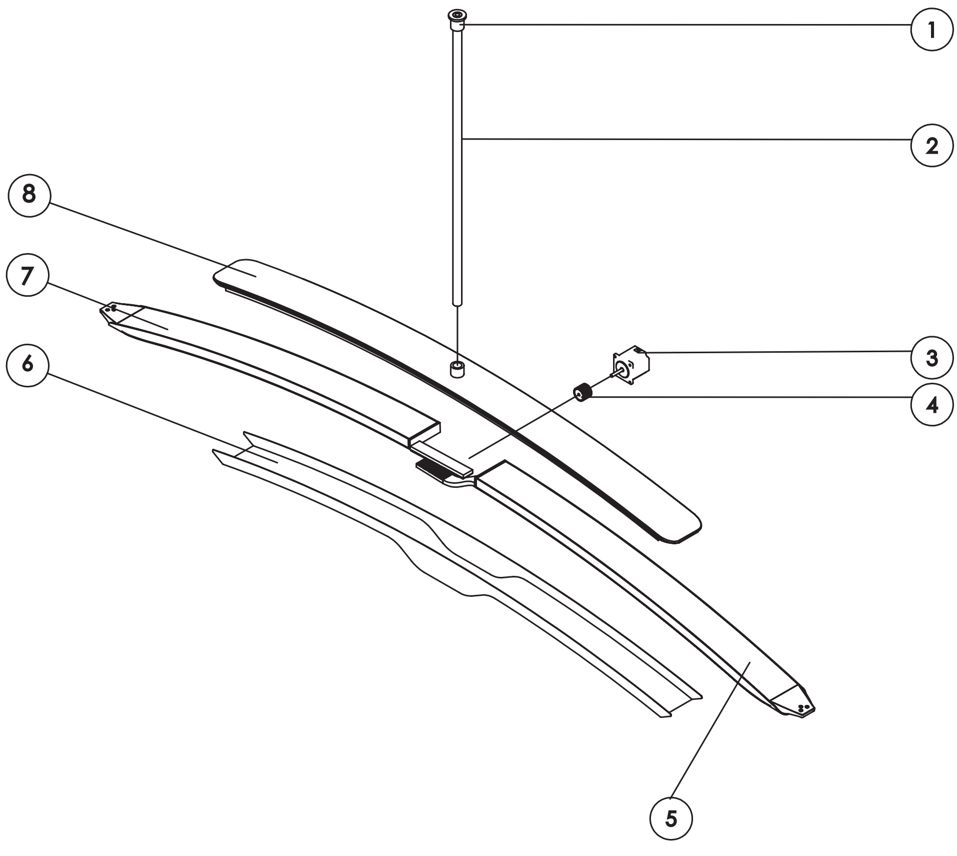


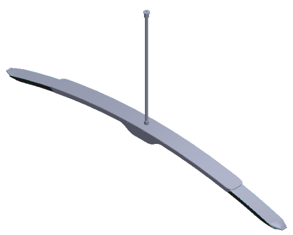




Appendix B

Technical Drawing - Exploded View





POSIZIONE Part Reference	LIV. Level	PEZZI Qty	CODICE Part number	DENOMINAZIONE Part name	MATERIALE - DATI TECNICI Technical data, designation	PESO UN. Unit Wt., kg	NOTE Notes
8	2	2	1.07.03.0	Ball Bearing		-	
7	2	4	1.07.01.0	Nut M8	SO 12125 - M8x1 - C	-	
6	2	8	1.07.02.0	Washer M8	8 ISO 7090	-	
5	2	4	1.06.01.0	Screw M8	ISO 4162 - M8x40x22-C	-	
4	2	1	1.01.04.0	Thermoformed base plate	P	1,26	4.0
3	2	2	1.01.05.0	External fork	AISI 1020 steel	0,09	
2	2	1	1.02.02.0	Fork plate	AISI 1020 steel	0,33	
1	2	1	1.02.01.0	Base frame	AISI 1020 steel	-	

AUTORE Created by: Ahmet Oguz
VERIFICATO DA Approved by:
DATA DI EDIZIONE Date of issues:

TIPO DI DOCUMENTO Document type: Assembly Drawing
PROGETTO Project:
INSIEME Assembly: General Exploded
GRUPPO Sub-assembly drawing: Assembly - Frame
SOTTOGRUPPO Sub-assembly drawing:
PARTICOLARE Part:

Rev	App'd	Date
01		
02		
03		
04		

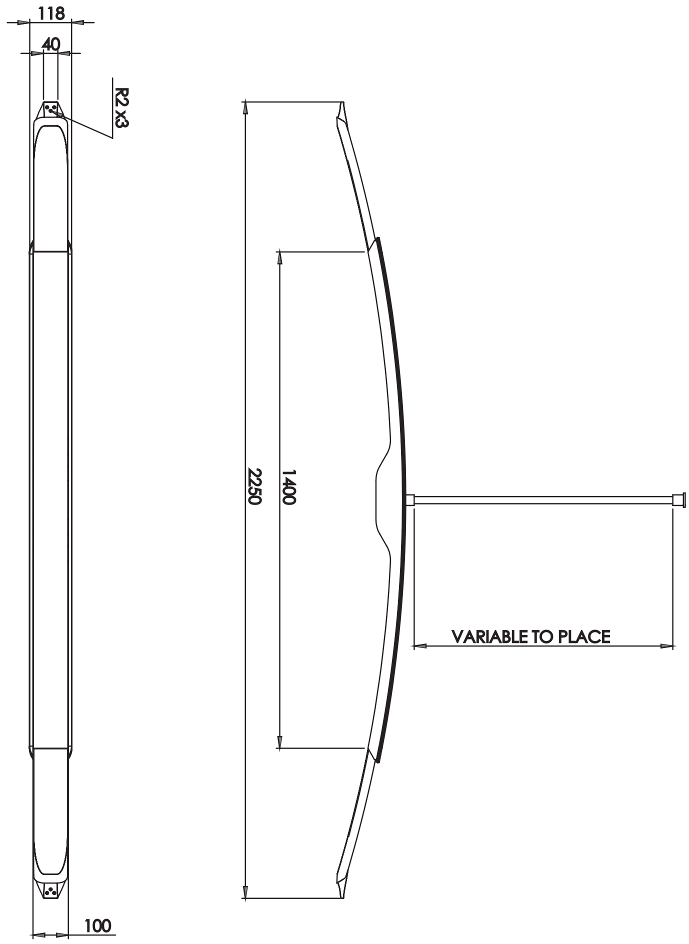
CODICE - Part number: 000560
SCALA Scale: 1:10

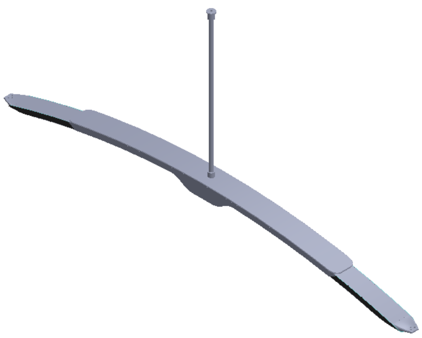
POLITECNICO DI MILANO
Scuola del Design
Corso di Laurea in
Design & Engineering
A.Y. 2018/ 2019 - Final Project Work

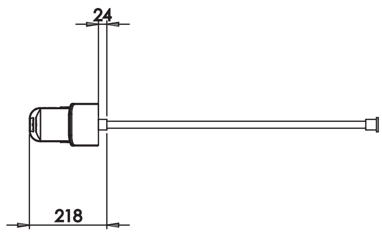
DIS. N. - DWG. N.: 2.1
Rev.: 00
FOGLIO Sheet: A3

Appendix C

Technical Drawing - Main Element Dimension







Appendix D

Technical Drawings - Bill of Materials

BILL OF MATERIALS TEN-X							
LVL 0	**LVL 1**	**LVL 2**	**LVL 3**	**Qty.**	**Part No**	**Part Name**	**Material**
0				1	1.00.00.0	**Assembly - Main**	
	1			3	1.01.00.0	**Assembly - Strut**	
		1.01		1	1.01.01.0	Main Shell	AISI 1020 Steel
		1.02		1	1.01.02.0	Top Frame	AISI 1020 Steel
		1.03		1	1.01.03.0	Top Frame Cover	
		1.04		1	1.01.04.0	Main Cable	AISI 1020 Steel
		1.05		1	1.01.05.0	Main Cable Connection	
		1.06		3	F02	ISO 4162 - M8 x 40 x 22 -C	
	2			2	1.02.00.0	**Assembly - Telescopic Arms**	
		2.01		2	1.02.01.0	Cable Holders	Al Alloy
		2.02		1	1.02.02.0	Top Difusser	PC
		2.03		1	1.02.03.0	Bottom Diffuser	PC
		2.04		1	1.02.04.0	Diffuser Shell	AISI 1020 Steel
		2.05		1	1.02.05.0	Rack 1	
		2.06		1	F08	Rack 2	
	3			1	1.03.00.0	**Assembly - Electonics**	
		3.01		1	1.03.01.0	Stepper Motor	
		3.02		1	1.03.02.0	Driver	
	4			9	F17	**Cables**	
	5			9	F18	**Cable Heads**	