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ADJUSTABLE TENSEGRITY ROBOT BASED ON ASSUR GRAPH PRINCIPLE

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ABSTRACT

The paper introduces a tensegrity robot consisting of cables and actuators. Although this robot has zero degrees of freedom, it is both mobile, and capable of sustaining massive external loads. This outcome is achieved by constantly maintaining the configuration of the robot at a singular position. The underlying theoretical foundation of this work is originated from the concept of Assur Trusses (also known as Assur Groups), which are long known in the field of kinematics. During the last three years, the latter concept has been reformulated by mathematicians from rigidity theory community, and new theorems and algorithms have been developed. Since the topology of the robot is an Assur Truss, the work reported in the paper relies on Assur Trusses theorems that have been developed this year resulting in an efficient algorithm to constantly keep the robot at the singular position. In order to get an efficient characterization of the desired configurations, known techniques from projective geometry were employed. The main idea of the control system of the device, that was also mathematically proved, is that changing the length of only one element, causes the robot to be at the singular position. Therefore, the system measures the force in only one cable, and its length is modified accordingly by the control system. The topology of the device is an Assur Truss – a 3D triad, but the principles introduced in the paper are applicable to any robot whose topology is an Assur Truss, such as: tetrad, pentad, double triad and so forth. The paper includes several photos of the device and the output data of the control system indicating its promising application.

INTRODUCTION

In recent years, there is a great interest in developing Deployable Tensegrity Structures due to its great potential for practical applications, such as: deployable bridges, space antennas and satellites [7], robots that can both deploy and fold and more. Tensegrity structures are well known in the literature. Tensegrity structures were first patented by R. Buckminster Fuller in 1962[1]. The analysis of a Tensegrity system requires a different approach from regular structures consisting of only rods, for example [2,3]. Tensegrity systems that can change their configuration were reported in the literature raising a problem of the difference between theoretical model and the actual system, for example, [4]. A further research with five modules and active shape control were discussed in [5]. The movement of a Tensegrity structure form one point to another along a prescribed path is presented in [6].

The approach adopted in this work is different. The work reported in this paper relies on the properties of Assur Trusses in general, and particularly on the singular configuration property of that guarantees the rigidity of the structure.

The mathematical foundation of this paper rests on different material, Assur Trusses [8], thus we do not give a comprehensive literature review.

The paper introduces the following sections; In section 3 the concept of Assur Trusses is introduced and their special properties, particularly their difference from regular determinate trusses. For the sake of clarity, the mathematical foundation of this work is explained in 2D systems but the results and the output data of the control system is taken from the 3D prototype robot that was built in our laboratory. In section 4 we introduce the unique geometrical property of Assur Trusses, which is the mathematical foundation of the control algorithm that was developed in this work. After the theory is introduced and explained in 2D, we proceed from section 5 and introduce the 3D robot that was built. In section 6 we introduce the Singular Configuration in the 3D robot and in section 7 the experimental results of the robot. In section 8 we discuss further research and conclusions.

3. ASSUR TRUSSES AND ITS UNIQUE PROPERTIES

In this section we introduce the concept of Assur Trusses. The idea of Assur Trusses (also known in the literature as Assur groups) raised from the mechanisms community, where it has been used in developing a systematic method for decomposing every linkage into kinematical components. There are several properties that exist in Assur Trusses, while in this paper, we use only two of them.

First, we clarify the difference between regular trusses and Assur trusses.

Definition of Assur truss: Let T be a determinate truss at a generic position, i.e., there is no algebraic dependence between its joints coordinates. T is an Assur truss IFF applying an external force at each joint results in forces in all the rods of the truss. For example, the truss appearing in Figure 1a is an Assur truss since applying a force at any of its joints: A, B or C yields forces in all the rods. This type of truss is called –'Triad'. The structure of the robot reported in this paper is a 3D Triad. The truss in Figure 1b is not an Assur Truss since applying a force at joint B does not yield forces in rods (AB) and (AO_3). Therefore, it is not an Assur Truss.

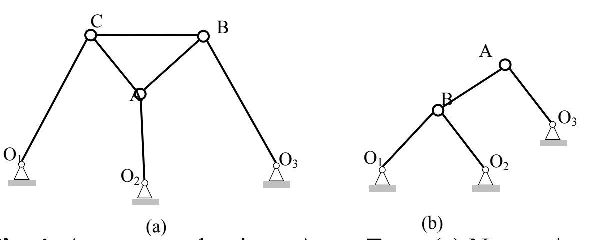

Fig. 1: A structure that is an Assur Truss (a) Not an Assur truss (b).

In the last three years, a work has been done to mathematically prove the existence of special combinatorial and geometrical properties in Assur Trusses [9]. The main geometrical property, upon of which the control algorithm reported in this paper is based on, was proved, and is given in the following theorem.

Theorem 1: Let T be a determinate truss.

T is an Assur Truss IFF there is a configuration in which there exists:

a. A unique self-stress in all the rods.

b. All the joins are mobile with one degree of freedom.

Example of a singular configuration of the 2D Triad appears in Figure 2, where the characterization is that the continuations of the three rods: (O_1,C), (O_2,A) and (O_3,B) intersect at the same point, denoted by O. Note that the latter point is the absolute instant center of the body {A,B,C}.

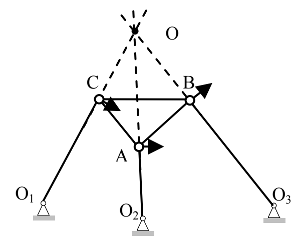

Fig. 2: The singular configuration of the Assur Truss- 2D Triad.

4. THE MATHEMATICAL FOUNDATION OF THE CONTROL ALGORITHM OF THE ROBOT

The main idea behind the control algorithm is as follows:

Theorem 2: Let T be an Assur Truss in an arbitrary configuration.

It is guaranteed that the singular configuration will be reached by changing the geometrical condition of **only** one link.

The scheme of the Deployable Tensegrity robot in 2D appears in Figure 3. In 2D, the robot consists of three struts (actuators) and three cables. In one of the cables, in this case cable (BO_3), there is a length control element which changes the length of the cable to assure that the system is constantly at the singular position state.

The struts (actuators) are operated to expand and sustain the compression forces while the cables sustain the tension forces.

A unit that measures the tension forces is attached to cable O_3B. If the cable becomes loose, its length will be shortened by the length control element (Figure 3) which will retrieve the cable's tension. Thus, according to theorem 2, it is guaranteed that this change will bring the system into its singular positions.

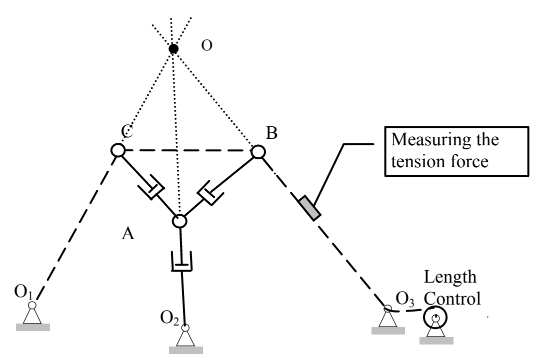

Fig. 3: Scheme of the Adjustable Deploying Tensegrity Triad.

5. INTRODUCTION OF THE 3D ROBOT

In Figure 4 appears one floor of the Adjustable Deployable Tensegrity 3D prototype robot that was built in our laboratory. The components of the robot depicted bellow are indicated in Figure 4 with the letters A-E.

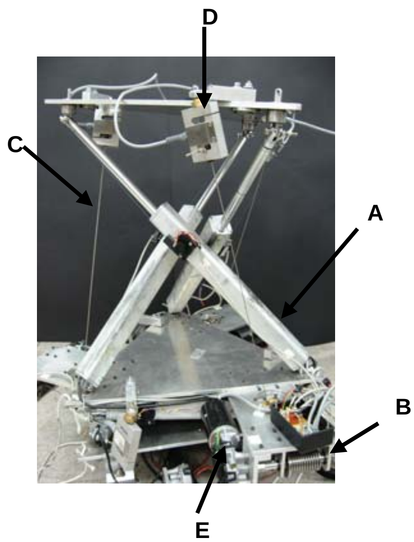

Fig. 4: One floor of the robot and its components.
(A) - An electric actuator (three overall) (B) -A coiling system for the cables (C) - Cables
(D) - Load cells measuring tension (E) - Electric motors (three overall)

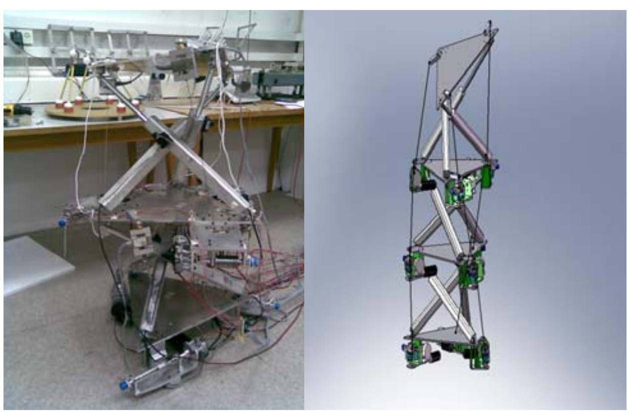

Fig. 4a: The two floor prototype robot (left) and a model of the three floor prototype (right)

6. SINGULAR CONFIGURATION OF THE 3D ROBOT

Each floor (module) is a 3D triad consisting of two plates. A top plate and a bottom one. In each there are three important points: T_i and H_i for i=1,2,3 where T_i and H_i are points in the bottom plate and in the top plate respectively (Figure 5).

It is well known that three points define a plane, thus applying the following equation, we derive the three planes, with which we define the singular position. Every plane is defined by three points, thus we define the following three planes through the six points mentioned above, as defined by the following equation (1). Note, the index numbers in the equation are modulo three, thus 4 becomes 1, and the symbol 'v' stands for joint operation.

$$\boxed{\Pi_i = T_i \vee T_{i+1} \vee H_{i+1} \quad i = 1,2,3} \quad (1)$$

Since the intersection between two planes is a line, the intersection of each of the three planes Π_i, i = 1,2,3 with the top plane creates three lines, with which we define the singular position as follows:

Conclusion 1: The 3D Triad is at a singular position when the three lines of the intersection between the three main planes and the top plane intersect at the **same point**.

Thus, in order to maintain the stiffness of the device, that allows it to sustain external loads, the control system guarantees that the intersection of the three lines is constantly at a one single point.

It is interesting to notice that the singular position of a 2D Triad is also an intersection of three lines at a single point.

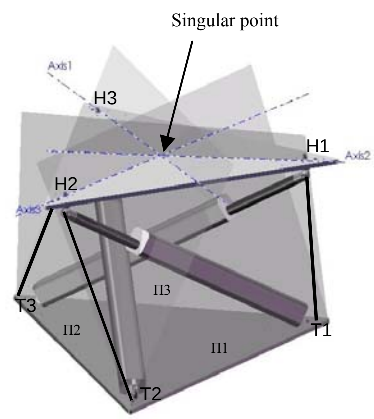

Fig. 5: Description of the singular configuration of the device.

7. EXPERIMENTAL RESULTS

The algorithm that was based on the theoretical work appearing in the previous section was implemented on a single stage system described in chapter 4. The shape changes, which are described in the following results, include the deployment of the stage from a distance of 310 mm to 520 mm between the upper and lower plate and back to 310 mm. The duration of the deployment and the folding process was set to fifteen seconds. During the reported experiments, the tension in cable no. 1 was maintained around 20 Kilograms using an impedance control algorithm. The tension in the other two cables was monitored, and compared afterwards with the required tension value. The latter determines the rigidity of the structure. The tension values in the three cables are depicted graphically in Figure 6. Another important feature that was measured, was the trajectory tracking of the struts and the cables.

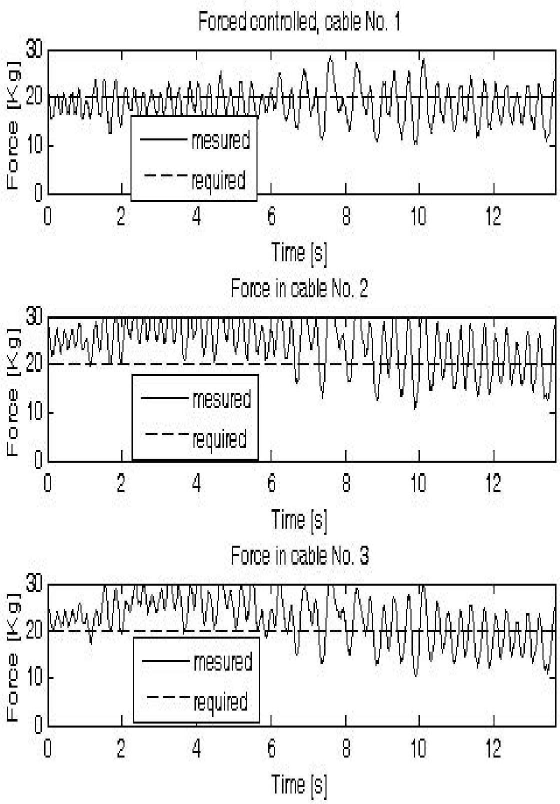

Fig. 6: The force developed in the three cables, while only cable 1 (first graph) was force controlled during the deployment process. Note that the other two cables reach the 20 Kg value of the force controlled cable.

The required tension in the force controlled cable was 20 Kg, the mean tension error (difference between the required tension and the actual one) in cable 1 was -1.3(3.5) Kg, in cable 2 - 4.47(5.2) Kg and in cable 3- 2.52 (4.87) Kg. The overall fluctuation in the cable tension is given by the STD written in the brackets. While folding the structure, the mean forces in the cables were lower than during the deployment process. The mean tension error in cable 1 was -2.17(2.35) Kg, in cable 2- 2.94(3.4) Kg and in cable 3- 0.62 (3.3) Kg. The results of the cables' tracking are depicted in Figure 7.

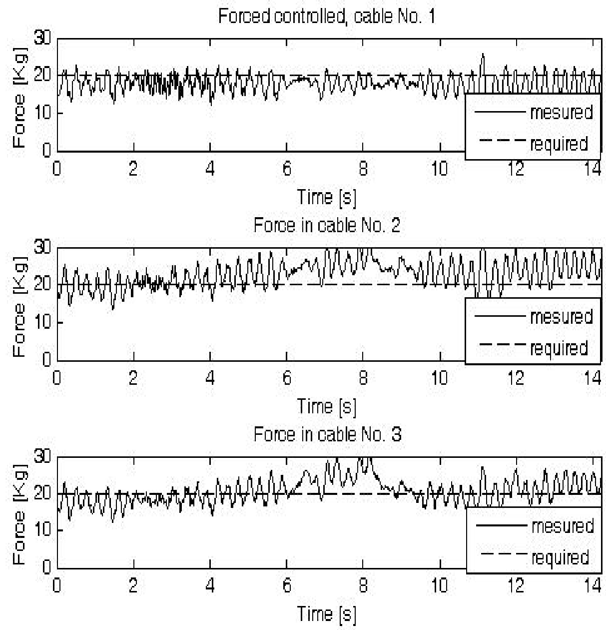

Fig. 7: The force developed in the three cables, while only cable 1 was force controlled during the folding process.

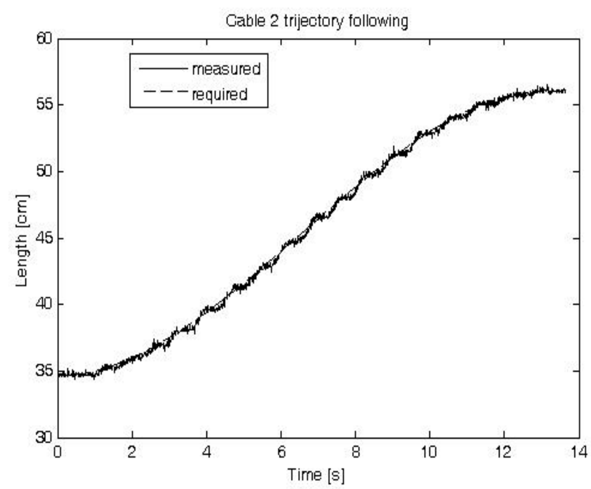

Fig. 8: Length change of cable 2 related to time.

The important result is that applying a force control in only one cable, maintains the rigidity of the structure while changing its configuration from one position into another. There is a clear difference between the deployment and the folding processes. After exploring these phenomena, we concluded that it is due to the difficulty to maintain a certain tension in the cable while loosening it. Another conclusion that stems from the experiments' results is that the response time of the winch system used for the length control of the cable is too long. As a result there is a delay between the measurement and the response. This might explain the relatively large overshoot in the force response graphs.

8. CONCLUSION AND FURTHER RESEARCH

In the paper we introduced the prototype of the Adjustable Deployable Tensegrity Robot including its underlying theory and some of the experimental results. The performance, as can be seen in the paper, impressively meets the theoretical conclusions. The result is a new device that can be both very loose and very stiff, and capable of sustaining massive external forces at any configuration.

We intend to proceed and develop an algorithm that will find the best process for the shape changes of the robot in order obtain the desired configuration. Moreover, the intension is to create a smooth movement which is often disturbed by the equipment and the design of the prototype.

Another direction that we are working on is developing another type of a Tensegrity Deployable robot using a different topology, for example, a Tetrad. The mathematical foundation remains the same and relies upon the Assur trusses, but the variety of the configurations is expected to extremely increase.

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