PROPOSAL FOR A NEW DESIGN FOR CONTINUUM ROBOTS SUITABLE TO MANIPULATE TOOLS IN HIGHER POSITIONS

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Abstract.*Continuum robots do not contain rigid links and identifiable rotational joints. Their structure bend continuously along their length via elastic deformation and produce motion through the generation of smooth curves, similar to the tentacles or tongues of the animal kingdom. One technique to construct lightweight continuum devices with many degrees of freedom is to utilize remote actuation, and transfer motion into the structure via groups of antagonistic tendons. Independent tendon pairs or triads control the orientation of the backbone. Usually, continuum robots have a small working volume due to the fact that they need to bend their backbone in order to reach the aimed positions. This work proposes a new design for continuum robots with increased working volume by replacing the continuous backbone with a telescopic structure driven by wires and electric motors. Using this kind of design, it is possible to change the length of the robot. When attaching cable pairs to the end of the telescopic structure, it is possible to provide two axis bending using two mechanisms to exert tension on the cables in two horizontal orthogonal directions. To control the robot, a PLC was used, using an open loop control. The open control scheme works with the relation to he number of cycles of the DC motor that makes the end pole extremity reach a determined displacement. Applying such changes in the structure of a continuum robot, it is possible to build robots that could reach higher positions. This feature makes the robot more suitable for operations in inaccessible places, such as inspections of electric power transmission and distribution networks. To verify the efficiency of the proposal, a study case was adopted and a prototype was constructed, designated for wood cross-arms inspection. As a consequence, a robot was developed, much longer than any other continuum robot proposed, up to 9 meters high. Bearing in mind the importance of studying the deformation of the robot once the structure will bend in order to promote movements, it was analyzed, using the finite element method. The aim of the analysis is to find out how the structure would react to an external load caused by the tensile cables and to determine the amount of force that the mechanisms need to promote a specific displacement in the pole extremity. Finally, in order to validate the proposed design, a prototype has been developed, constructed and submitted to tests.*

Keywords. *Continuum robots; Telescopic mechanism; Robot design; Electric power network inspection*

1. INTRODUCTION

Over the last several decades research in robotic manipulators has focused mainly on designs that resemble the human arm, and can be best described as discrete manipulation (Robinson, 1999). The design of discrete manipulators is based on a small number of single degree of freedom joints that are serially connected by discrete rigid links. This kind of design has proven to be effective for many tasks; however, it may present some limitations (Chen, 2000) (Walker, 2000). Their structure is based on stiff links and large sections, which are passive supporting structures; the result is a heavy robot mechanism that is suitable for most industrial applications, where speed of operation and accuracy are essential (Robinson, 1999). In spite of being very efficient for open environments, when constraints are added to the environment, the manipulator may fail to reach its desired endeffector position. This failure is due to the lack of degrees of freedom in the robot to meet both the environmental constraint conditions and the desired endeffector position requirements (Walker, 2005).

In this way, traditional robot manipulators are essentially "vertebrate" structures. However, traditional robots, like humans, encounter difficulties operating in highly congested environments, or in manipulating objects with parts of their arm other than their specialized endeffector (Walker, 2005). These problems have been effectively addressed in nature by structures such as elephant trunks, mammal and lizard tongues, and octopus arms. These highly successful muscular structures can produce motions from their appendages or bodies that allow the effective manipulation of objects even though they are very different in structure compared to the human arm (Kier, 1985).

Even among these appendages, i.e. trunks, tentacles, tongues, etc., the physical structure can vary, but all share the trait of having a relatively large number of degrees of freedom (Walker, 2005). In order to best describe manipulators with a large number of degrees of freedom, Robinson (1999) classified robots in three different categories, as can be seen in Fig. 1.

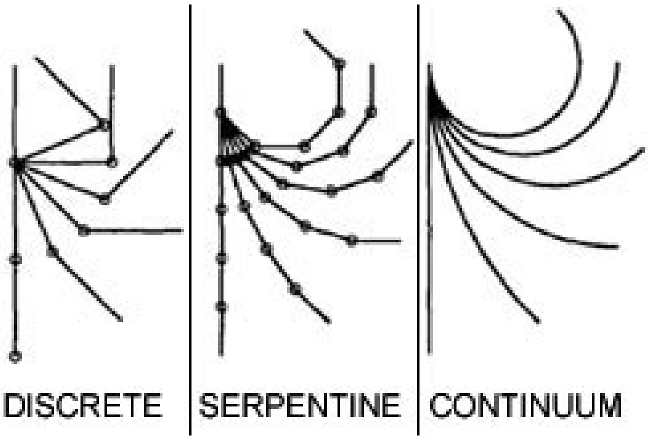

Figure 1 Manipulator motion of three classifications (Robinson, 1999)

The first of them is known as conventional discrete robots. As the number of discrete joints increases the redundancy or maneuverability of the manipulator also increases, moving the manipulator into a second classification known as serpentine. Serpentine robots also utilize discrete joints but combine very short rigid links with a large density of joints (Robinson, 1999). This creates highly mobile mechanisms, which appear to produce smooth curves, similar to a snake. This classification most often includes robots and manipulators that are described as hyper-redundant (Chirikjian, 1992).

The third classification for robots and manipulators is known as continuum. Continuum robots do not contain rigid links and identifiable rotational joints (Robinson, 1999). Their structure bends continuously along their length via elastic deformation and produces motion through the generation of smooth curves, similar to the tentacles or tongues of the animal kingdom (Kier, 1985).

2. CONTINUUM ROBOTS

Considering that research into continuum structures has spawned several different designs that can be broadly classified as intrinsic, extrinsic, or hybrid, it is possible to separate continuum robots by method and location of mechanical actuation. According to the type of motion produced these categories can also be sub-divided into ‘planar’ and ‘spatial’. Planar devices move in a single plane of bending and spatial devices can bend in any direction perpendicular to their longitudinal axis (Robinson, 1999).

2.1. INTRINSIC, EXTRINCT AND HYBRID DESIGN

In an intrinsic design, bending occurs by increasing the internal pressure in an elastic actuator, which has different axial stiffness in its internal walls. One of the most common designs consists in using parallel actuator chambers placed at equal intervals about a central longitudinal axis, as shown in Fig.3 (a). In order to operate the actuator, internal pressures are controlled to generate extension forces, which will move the actuator to determined positions, as shown in Fig.3 (b) (Robinson, 1999).

Extrinsic design use remote actuation; consequently, motion is transferred into the mechanism via mechanical linkage. Independent cables pairs, that can be called tendons, control the orientation of rigid plates placed at intervals along the structure. Continuum structures connect successive plates, working as springs, ensuring that the tendons remain in tension. Spatial continuum motion occurs since the springs bend according to sequential plate orientations (Robinson, 1999). The most popular design uses a central structure known as backbone structure, which is actuated by sets of cables. This kind of design has many potential applications in dexterous manipulation for manufacturing and space environments (Chen, 2000). The design of these robots requires specification of a stiff bendable backbone, selection of cable support heights and spacing, and development of a cable drive system (Changquing, 2002). The robot arm divides into sections that are subdivided into segments bounded by cable supports. Cable pairs are attached to the end of each section to provide two-axis bending. Expanding this concept to many sections, the arm can be bent into complex shapes to allow redundant positioning of the endeffector payload, (Changquing, 2002) as shown in the manipulators proposed by Anderson (1967) in Fig.3 (c) and Hannan (2001) in Fig.3 (d).

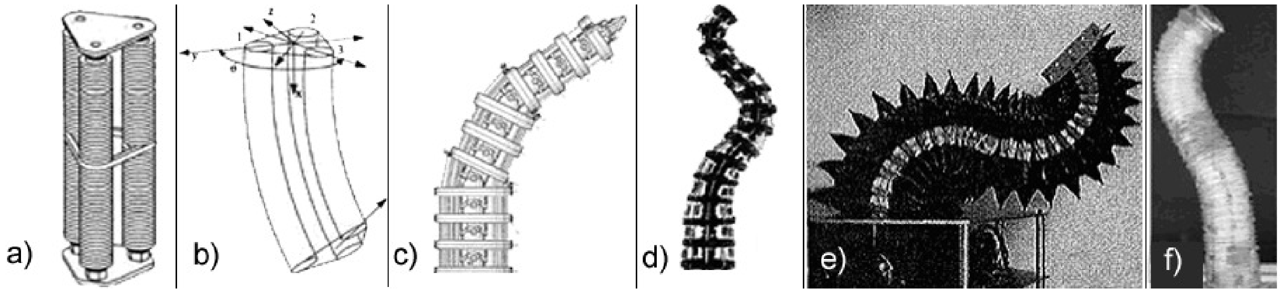

Figure 3 – a) Intrinsic Design b) Intrinsic working principle c) Extrinsic manipulator proposed by Anderson (1967) d) Extrinsic manipulator proposed by Hannan (2001) e) Hybrid manipulator proposed by Immega (1995) f) Hybrid manipulator proposed by McMahan (2005)

The hybrid design uses a similar working principle to the extrinsic approach. The main difference is that instead of the passive springs the hybrid design uses actively controlled bellows. The internal bellows pressure opposes the operation of the tendons, ensuring they always remain in tension.(Robinson, 1999) To control the structure it is possible to vary the tendon lengths and the bellows pressure. As a result, the length and stiffness of the structure can be controlled, as proposed by Immega (Immega, 1995) shown in Fig. 3(e) and McMahan (2005) shown in Fig.3(f).

3. PREVIOUS WORKS

After doing a bibliographic revision it is possible to affirm that several recent works have examined the design, control, and properties of continuum robots and manipulators. Such devices have unique qualities that set them apart from traditional “rigid, vertebrate” robots; their continuous structure can, in theory, bend at arbitrary locations down the “backbone” (Blessing, 2004). Designs for tentacle robots are typically highly modular, enabling kinematic redundancy and hyper-redundancy. They typically have a large number of degrees of freedom, making them much more maneuverable than conventional robots (Blessing, 2004).

Another common characteristic of continuum manipulators is their passive compliance to external contacts; at the presence of an unexpected object, the manipulator inherently bends and yields (Blessing, 2004). On the contrary, when discrete manipulators find an object obstructing their path, often they damage the object and, depending on the case, they can damage themselves. It happens due to the fact that discrete manipulators are designed to be stiff while continuum manipulators have a structure that allows them to successfully interact with soft materials and living organisms with a reduced risk of causing injury (Chen, 2000) (Blessing, 2004). In addition, continuum robots commonly do not contain any actuators in the manipulator structure itself, making them relatively compact and lightweight.

Consequently, these manipulators are comparatively strong, with a significantly higher payload to weight ratio than traditional manipulators (Blessing, 2004). These properties give tentacle robots the potential for novel applications in various fields. Their compliance allows them to be used in medical fields, because there is less of a threat of them harming a patient. Similarly, military applications have been proposed, where a tentacle flexibility would allow it to carry payloads into hostile situations. The option of using dielectric materials in its structure makes them more suitable for operations near electric power networks. The combination of strength and compliance allows tentacles to be applied in search and rescue situations, to search for survivors from collapsed buildings, as well as exploring hazardous environments (Blessing, 2004).

Analyzing the previous works, it is possible to say that the majority of the robots proposed would expand their potential application if they could vary the length of their bending segments. The impossibility of varying the length of the bending segments severely restricts the range of curvatures that the robot can achieve (Walker, 2003). While much works characterize the kinematics of continuum robots, little has been done in the direction of examining the inherent limitations caused by fixed bending segment lengths (Blessing, 2004).

4. A TELESCOPIC STRUCTURE AS A BACKBONE

Considering that manipulators can expand their working volume by varying their length and consequently improve the number of applications, this work proposes the replacement of the continuous backbone for a telescopic structure driven by wires and electric motors. Using this approach, it is possible to develop continuum robots with increased working volume and capable of reaching higher positions. These features expand the application of continuum robots, making them suitable for operations in inaccessible places, such as inspections of electric power transmission and distribution networks.

A telescopic structure comprises an innermost member, a plurality of intermediate tubular sections, and an outermost tubular member, each nested together; the arrangement from a stowed position is ensured, commencing with the innermost member, progressing with the next outer member and so on. Each intermediate member includes latching which serve to lock the next inner member in an extended position (Meston, 1983). Using a telescopic arrangement it is possible to vary the length of a structure without causing deformation. Even having some mobile parts, once the structure starts to bend, the friction between the components of the structure increases and it works as a continuum structure, even in intermediate positions.

As shown in Figure 4, the working principle of a telescopic structure consists on lifting the first stage till it reaches its maximum length, then the second stage starts to move till it reaches its full length and so on. Expanding this concept for more stages, it is possible to create a structure that reaches several higher positions. However, it is important to observe that as the length of the structure increases, the slenderness ratio also increases. The structure gets more and more slender; when analyzing a slender continuum robot, it is important to consider the geometric nonlinearity of its structure due to the fact that it affects its stability. As will be seen in the next topic, in some cases the weight of the structure itself can generate second order loads and make the robot collapse. Bearing this in mind, the need of using auxiliary mechanisms in order to promote a pre-loading the structure arises. A traditional solution to increase the stability of slender structures is to use tension cables; the working principle is similar to the cable-stayed tower. Fig.5 depicts most usual designs for cable-stayed towers. Combining the stabilization strategy by tensile cables depicted in Fig.5 (c), with the concept of extrinsic actuation shown previously, it is possible to obtain a new design for continuum robot that could use slender structures to reach high positions without losing stability.

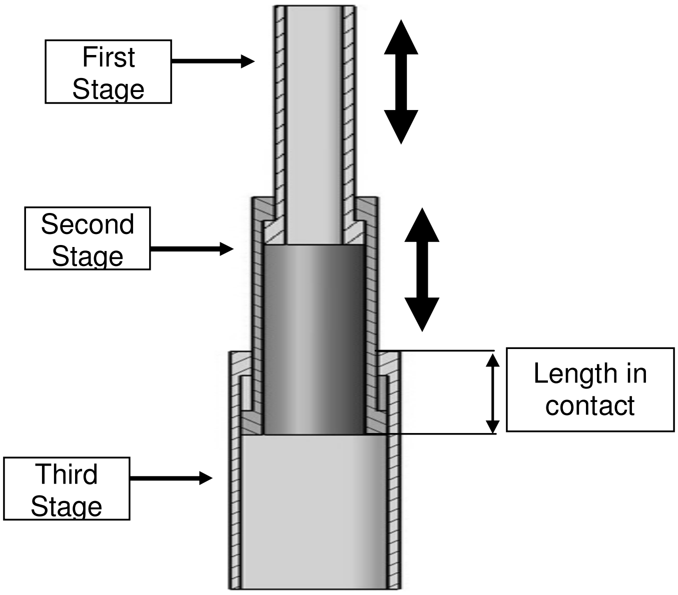

Figure 4- Telescopic structure working principle

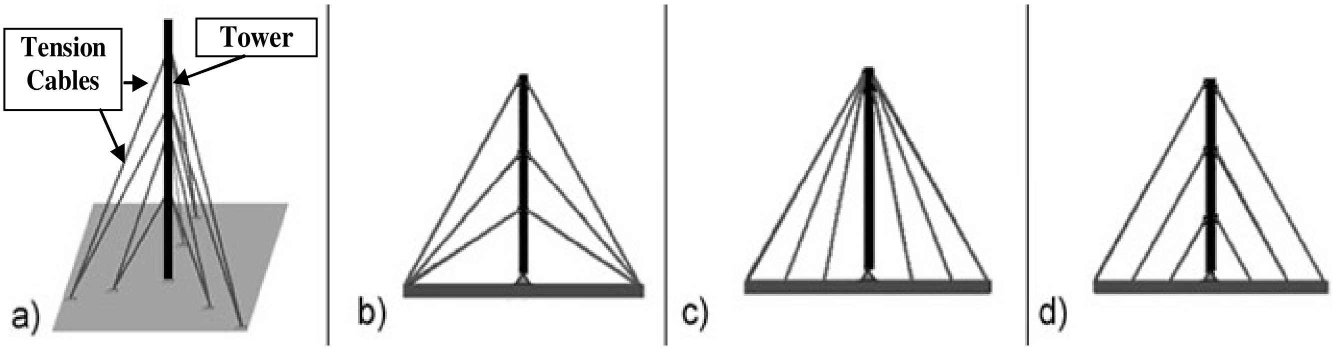

Figure 5 – a) Cable-stayed Tower working principle, b) c) and d) - Main designs for cable-stayed towers

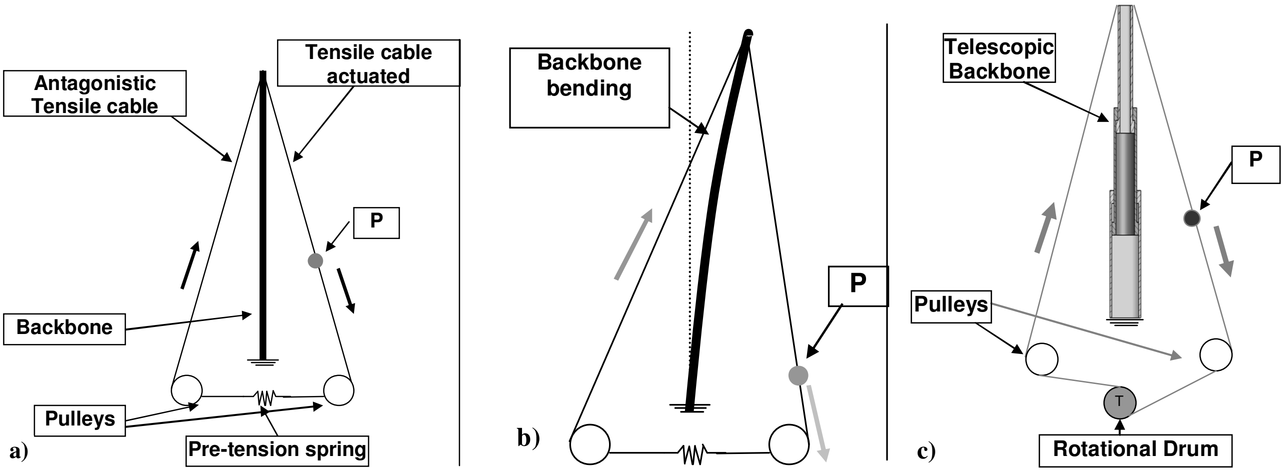

Figure 6 – a) and b) Tension cables actuating the structure, c) Telescopic Backbone proposal

To move the structure without loosing the stability, a pre-load must be applied constantly to the structure. Fig.6(a) illustrates how to achieve this. The spring, at the bottom of the picture, represents the pre-load that the tension cables will provide. Consider the fixed point *P* in the figure. Once *P* moves, the tension in one cable increases and the backbone is deformed as shown in Fig.6(b); at the same time, the tension cable of the antagonistic side is relaxed in the same amount. Thus, the structure bends and reaches a new equilibrium position.

In order to keep the structure always pre-loaded, the spring is replaced with drums that wind up or down the cables keeping a constant tension in the cables, as shown in Fig.6(c). Thus, it is possible to obtain a telescopic continuum robot, which can be bended according to an extrinsic approach and vary its length. To bend the backbone moving its extremity, it is necessary to add auxiliary mechanisms to promote movement to the mentioned point *P* and to pre-load the structure. It is important to remember that in case of need more stiffness more tension cables can be used in different parts of the telescopic structure.

5. CASE STUDY – CROSS ARMS INSPECTION

To validate the proposal, a study case was adopted and a prototype designated for wood cross-arms inspection was developed. Usually, cross-arms are located at 9 meters in height and are 3 meters long (Fig.7(a)). Consequently, the inspection robot to be developed should be much longer than any other known continuum robots. Besides, the robot has to be capable of displace its upper end by 1.5 meters in both horizontal directions.

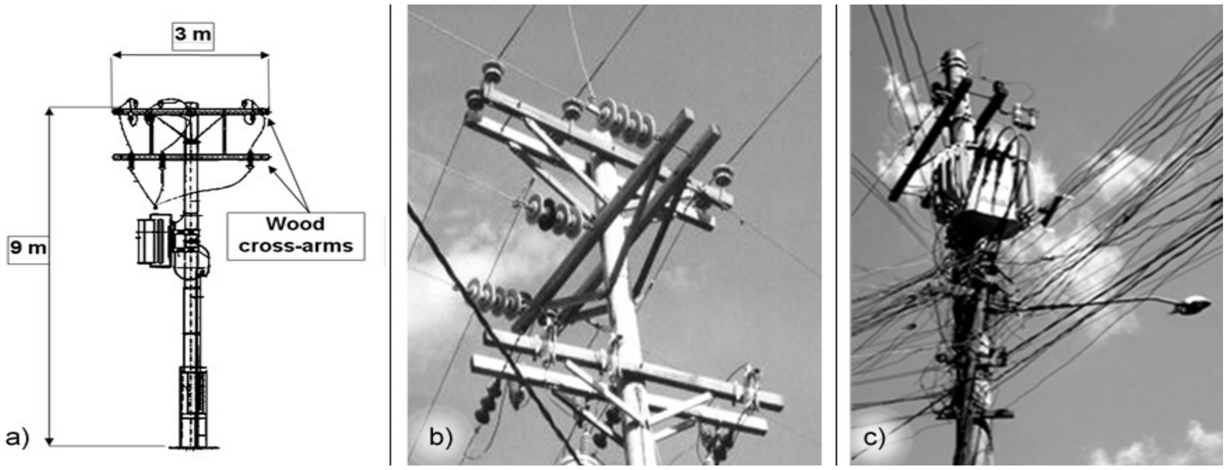

Figure7 – Wood cross-arms a) main dimensions b) location and function c) Dangerous environment due to the density of cables

Electric power distribution networks are formed by a large number of systems that have a huge amount of devices that can present problems. Considering that this system provides electric energy to industries, hospitals, residences etc., it is important to have strict plans of maintenance, due to the fact that a simple shortcut can just let one residence without power or stop a whole industry for an entire day or even compromise the operation of equipments in a hospital. In most cases, maintenance procedures are high risked operations due to the fact that they occur close to the high voltage power lines. The tools used in this kind of procedures are in most cases entirely mechanical, demanding human effort and long work periods that increase the risk of accidents (Fiedler, 2006).

In a vast group of devices to be analyzed in an electric power distribution network, wood cross-arms have a vital importance due to the fact that they support other devices, as shown in Fig.7(b). In the inspection of wood cross-arms, the electrician stays on the ground and using a binocular analyzes the state of the device. This procedure is inefficient because most frequent problems occurs at the top surface of the cross-arm; the common problems presented are burned marks caused by the sun or deterioration due to wetness.

Considering that elevating the electrician to inspect the wood cross-arm is a high-risked operation, which will demand great costs to power supply companies and with the aim of optimizing the current inspection, robotics can be applied. In this case, it seems to be more suitable to use a robot made of dielectric material, which needs to have a passive complaint behavior to external contacts, as can be seen in the Fig.7(c) this is an important feature due to the fact that in case of hitting the cables, the robot can deform instead of cause accidents, and could position a wireless camera to take pictures or record videos of the wood cross-arm. During the inspection, the electrician would be situated on the ground analyzing the pictures, and deciding if the word cross-arm is in good or bad conditions.

Analyzing the main dimensions of the wood cross-arms shown in Fig.7(a) and the busy and dangerous environment shown in Fig.7(c), a telescopic continuum robot is proposed, that is about 9 meters high and deforms its structure by 1.5 meters from the base in both orthogonal axis, as shown in Fig.8.

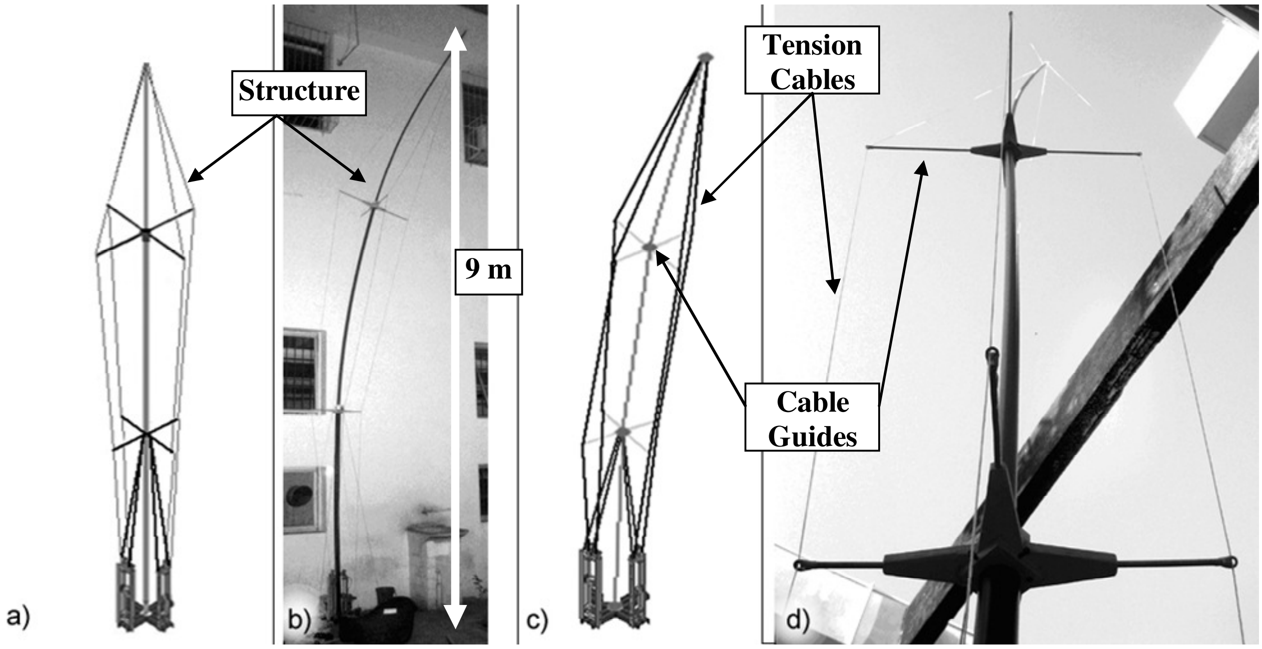

Figure 8– Proposed telescopic continuum robot

Considering the need of using a lightweight, dielectric and portable structure to reach the cross-arm, three PVC tubes is used. Three tubes which an external diameters of 58mm, 40mm and 26mm consecutively, are assembled in a telescopic structure. As said previously, depending on how slender the structure is and depending on its material, the structure may collapse due to its own weight. In fact, this occurs with the structure used in this robot, as will be shown in the structural analysis section. As a consequence, tensile cables (multi-filament nylon cables) are used to stabilize the structure. To lift up the tubes, another cable (multi-filament nylon cable) is used. This cables passes through pulleys 1 and 2 (Fig.9) in a manner that, as the cable is tensioned, the inner tube moves upwards. The same mechanism is applied to the other stages.

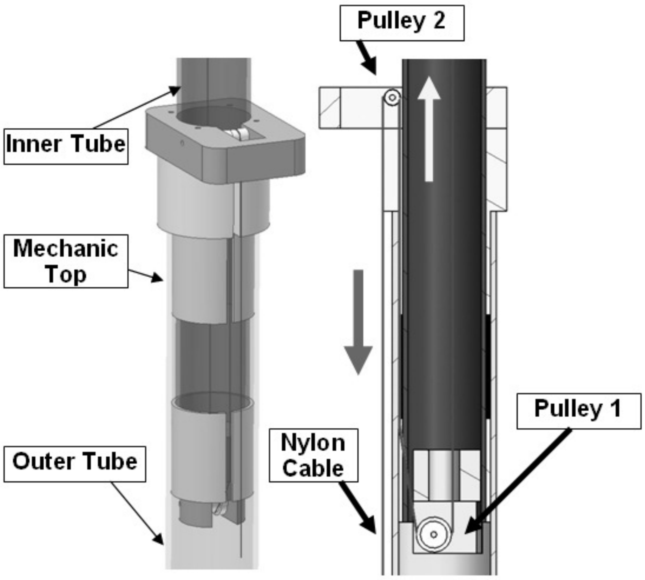

Figure 9 – Working Principle to extend the telescopic structure

Besides the mechanism to extend the structure, another mechanism is developed to use the tension cables not only to pre-tension the structure but also to actuate, as shown in Fig.8(a). The mechanism uses a single actuator to bend the structure in one direction by pulling the cable of one side of the structure and relaxing the complementary cable, as shown in Fig.8(c). To bend the structure in two orthogonal planes, two mechanisms are used, as shown in Fig.10. Combining the bending produced by both mechanisms it is possible to achieve the working volume mentioned previously. The mechanism is composed basically by a DC motor that rotates a screw, moving a gripper that, when reaching a ramp, closes the grip, holding the cable. The cable of one side is held and pulled in one direction while the complementary, is relaxed in the same amount.

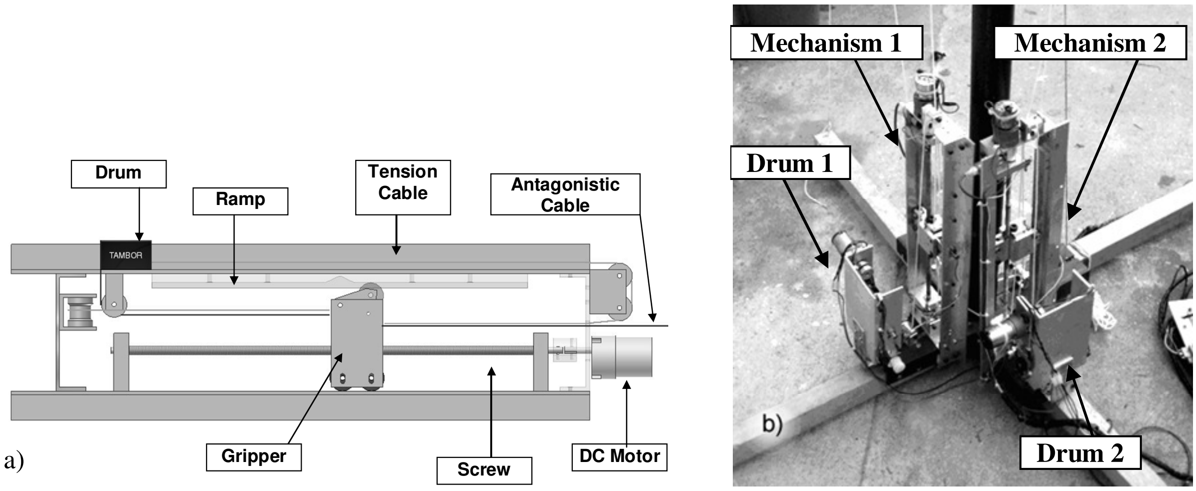

Figure 10 –Auxiliary mechanism a) Main parts b) Orthogonal assemblage

6. STRUCTURAL ANALYSIS

In the robot presented in this work, the structure bends in order to promote movements. Therefore, the behavior of the structure in terms of deformation is analyzed using the finite element method. The aim of the analysis is to find out how the structure would react to an external load caused by the tensile cables considering nonlinear effects, and to determine the amount of force that the structure needs to promote a specific displacement in the pole extremity.

In the analysis, a 3D beam element was used that provides suitable answers for simple structures and is more adequate to be programmed using commercial softwares such as MATLAB. The initial mesh assumed was composed by seven elements and then, adopting a unitary load, the mesh was refined, by analyzing if the results of the analysis had significantly modifications when increasing the number of elements, as shown in Fig.11.

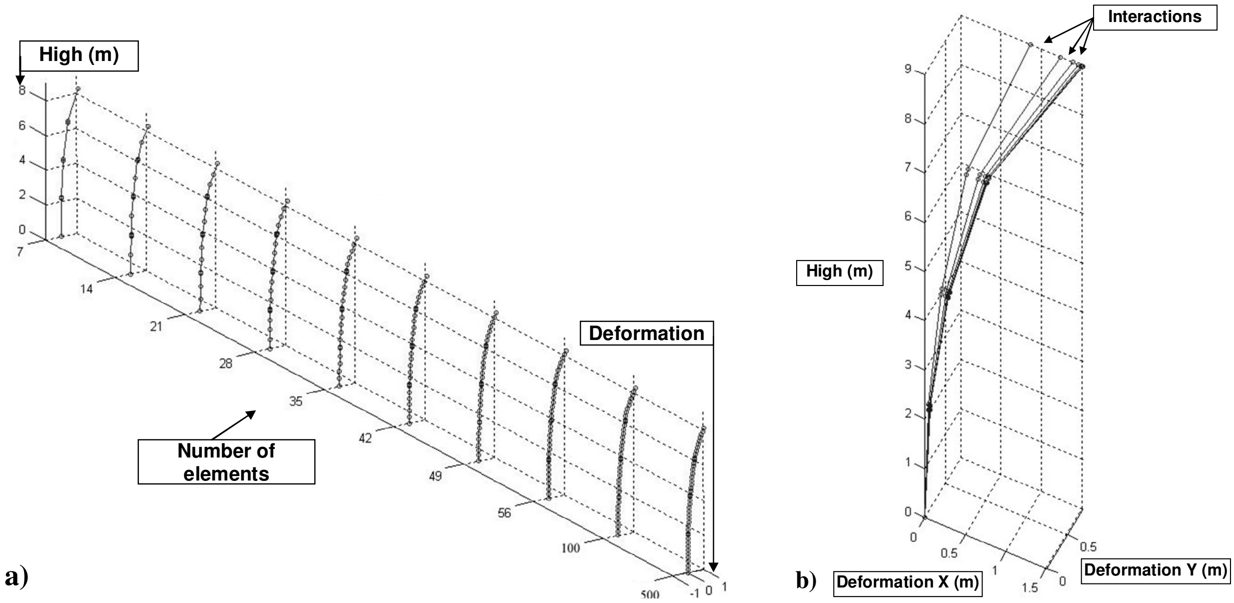

Figure 11 – a) Linear analysis and meshing b) P-Delta Analysis

After this analysis, it was concluded that the initial mesh suits the structural problem because even working with 500 elements the results did not change significantly. As a second step, a non-homogeneous analysis (Bathe, 1996) is conducted and then, a displacement of 1.5m is applied at the end of the pole extremity. The result of the linear static analysis shows that the force necessary to impose such displacement is of 0.8531N.

However, the linear analysis does not consider the influence of axial loads in the beam bending. To consider second order effects, the P-Delta analysis is used. This consists on an interactive method that assumes a fictitious transversal load based on the axial load and the displacement occasioned by the first order effects (Cook, 1989). When running the non-linear analysis and not considering the use of tensile cables, the structure loses the stability and the deformation tends to infinite. On the other hand, when considering the use of tensile cables that will support the weight of the structure, the non linear analysis shows that, after a number of interactions, the structure reaches an equilibrium position, as shown in Fig.11(b). The nonlinear analysis shows that the force necessary to bend the structure by 1.5m is of 0.26N, that is significantly smaller than the force shown in the linear analysis, that is, if the load shown in the linear analysis were applied in the structure, it would probably collapse.

In order to build a dynamic model of the structure, a modal analysis is performed and the first natural frequencies and vibration modes determined. One of the advantages in using this numerical method is that it is possible to come up with different dynamic models of the system (Borges, 2006). In experimental tests, it is possible to perceive that the first mode is more influent on the dynamics of the structure. So the dynamic model can be simplified to a model of one degree of freedom, in which, the lumped mass, stiffness and damping are respectively $k^*=0.6$, $m^*=2.2$ and $c^*=0.0575$, assuming a damping ratio of 0.05.

7. CONTROL SYSTEM

Continuum devices present a novel control problem in which, the entire structure undergoes elastic deformation. There are no joints to control or measure and those methods of direct measurement of the device end-point are required for reliable position control (Robinson, 1999). Facing these difficulties and as a first step in the development of the robot, this work assumes a sequential control and does not consider the time that the structure takes to establish once it is actuated, i.e. the dynamics of the robot is not considered.

Therefore, in this work, an open-loop control scheme is adopted. A PLC is used in this task. The control scheme, illustrated in Fig.12, is based in a relationship between the number of turns completed by the screw (Fig.12(a)) and the displacement of the end pole extremity. In a fist step, a calibration is executed. This consists on experimentally measuring the relation between the number of turns of the screw and the displacement of the structure extremity. An inductive sensor, installed near the motor coupling, counts the number of turns of the screw and the displacement of the structure extremity is measured visually using a scale. The calibration data is stored in the PLC memory and when commanding a determined displacement, the PLC control algorithm look up the calibration table, determines the necessary number of turns of the screw and finally, activates the motor the drives the screw.

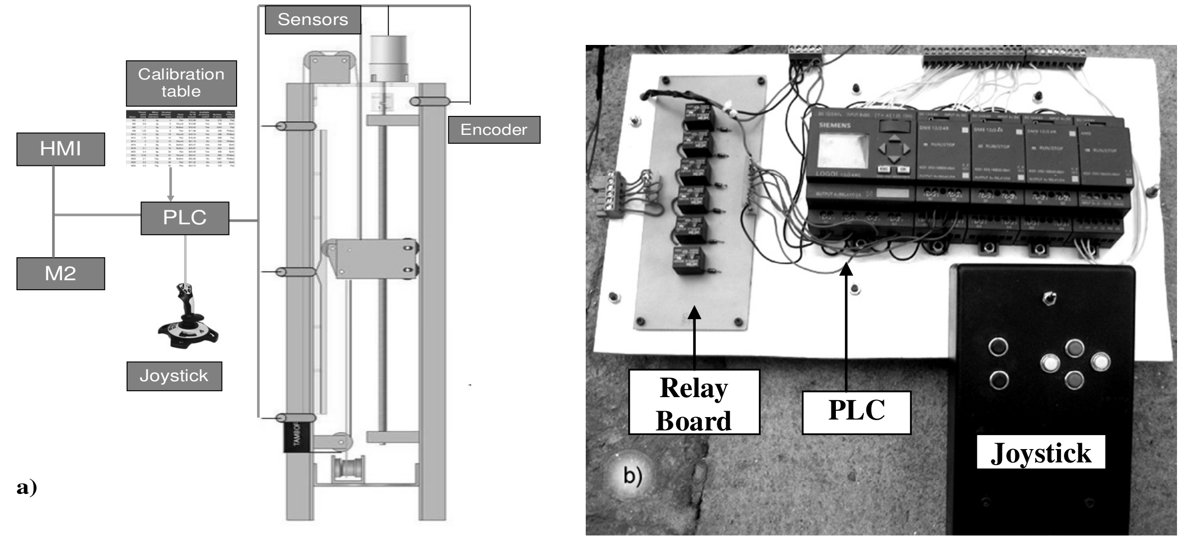

Figure 12 – a) Control Scheme b) Control Panel

8. EXPERIMENTAL TESTS

As mentioned, the calibration of the robot consists on finding out the relation between the number of turns of the screw and the displacement amount of the robot extremity. As Fig.13(a) shows, in order to calibrate the system, a reference structure is used; then in a second step, the repeatability of the prototype is verified by repeating the calibration process 10 times. In Fig.13(b), Y axis is the number of turns and X axis is the measurement. At the right side of the graph, it can be seen the displacement achieved and the standard deviation of the number of turns. The repeatability of the positioning in terms of standard deviation is less than 4.29 turns. The variance occurred mainly because the gripper did not clumped perfectly the cables, thus the cable slips relative to the gripper. In each positioning procedure, the structure was brought back to the zero position manually.

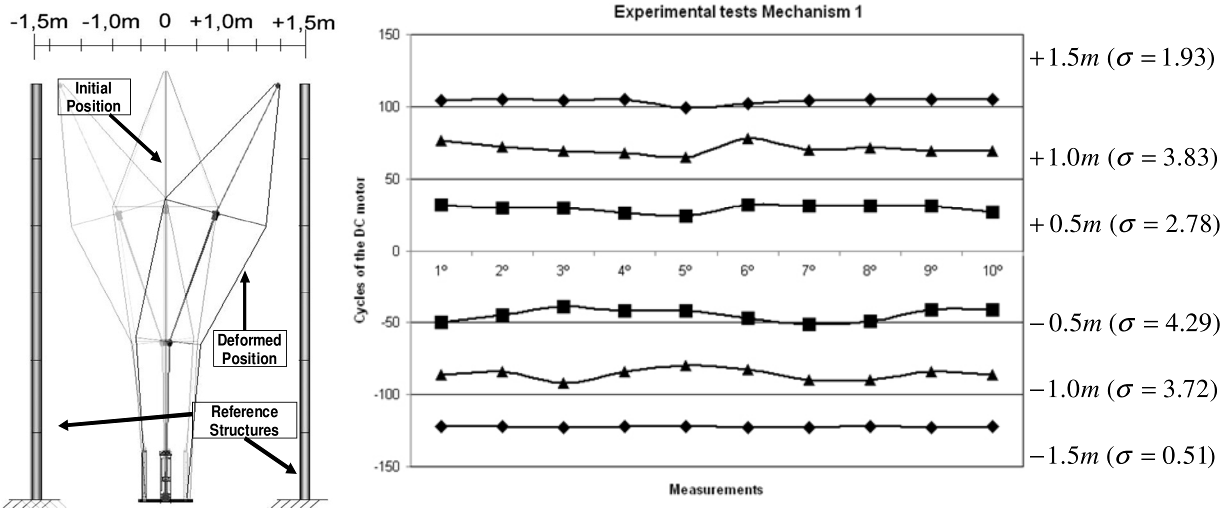

Fig. 25 – Experimental measurements a) Testing scheme b) Results of experimental tests

9. RESULTS AND CONCLUSIONS

By a bibliographical revision, the continuum robot is identified as the most suitable approach to develop a design for position tools in high positions. Based on the continuum robot concept, a telescopic based backbone is proposed together with mechanisms based on tensile cables to move change the robot height and move the robot extremity, always keeping the robot stable. A case study is adopted and a prototype developed to meet the working needs. By structural analysis, it is shown how to determine the instability, that depending on the material, the design proposed could have and the need of tensile cables to support and actuate the structure. Finally, the mechanisms are designed and a prototype is constructed. Tests demonstrated the validity of the proposed robot architecture. Although a considerable variance is repetitive positioning tests is observed, this problem can be minimized improving the design of constitutive elements, specifically, the gripper mechanism. In this work a fully automatic operation of the robot is not demonstrated but the final adjustments to achieve the automatic operation will be concluded soon and presented in future works.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

Anderson, V.C., Horn, R.C.,1967, Tensor Arm Manipulator Design. ASME paper, pp.1-12, 67-DE-57.

Bathe,K.J.,1996, Finite Element Procedures Englewood Cliffs: Prentice-Hall.

Blessing, M., Walker, I.D., 2004, Novel Continuum Robots with Variable-Lenght Sections, Proceedings of the 3rd IFAC Symposium on Mechatronic Systems, pp.55-60.

Borges A.S., 2006, Análise Modal Baseada Apenas na resposta- Decomposição no domínio da frequencia. Dissertação de mestrado, Unesp, São Paulo, Ilha solteira.

Changquing, L., Rahn, C. D., 2002, Design of Continuous Backbone,Cable-Driven Robots, Journal of Mechanical Design, JUNE, Vol.124, pp.265/272.

Chen G.,2005, Design modeling and control of a micro-robotic tip for colonoscopy, Phd Thesis, INSA of Lyon.

Chirikjian, G.S.,1992, Theory and Applications of Hyperredundant. Robotic Mechanisms. Ph.D. thesis, Department of Applied Mechanics California Institute of Technology.

Cook, R. D., Malkus, D. S. and Plesha M. E., 1989, Concepts and Applications of Finite Element Analysis, Third Edition, John Wiley & Sons, Inc, ISBN 0-471-84788-7.

Fiedler, N.C., et al., 2006, “Avaliação dos riscos de acidentes em atividades de poda de arvores na arborização urbana do distrito federal”, Revista Árvores, Vol.30, Sociedade de Investigação Florestais Viscosa, Brasil pp.223-233.

Hannan, M.W., Walker, 2001, I. D. Analysis and Experiments with Elephant´s Trunk Robot. International Journal of the Robotics Society of Japan, Vol. 15, No. 8, pp.847-858.

Immega, G., Antonelli, K.,1995, "The KSI Tentacle Manipulator", IEEE International Conference Robotics and Automation, Japan, pp.3149-3154.

Kier, W.,Smith, K., Tongues,1985, tenacles and trunks; the biomechanics of movement in Muscular Hydrostats, Zoological Journal of the Linnean Society, Vol.83, pp.307-324.

McMahan, W., Jones, B.A, and Walker, I.D., 2005, “Design and Implementation of a Multi-Section Continuum Robot: Air-Octor”, Intelligent Robots and Systems (IROS 2005) IEEE/RSJ, pp.2578-2585.

Meston, S.D.,1983, "Telescopic Mechanism", US Patent No.4406097.

Robinson, G., Davies, J.B.C.,1999, Continuum Robots - A State of the Art, IEEE Conf. on Robotics and Automation, Detroit, USA, pp.2849-2854.

Walker, I.D.,2000, Some Issues in Creating "Invertebrate" Robots. In the Proceedings of the International Symposium on Adaptive Motion of Animals and Machines, Montreal, Canada, pp.564-574.

Walker, I.D., Carreras, C.,2003, “Variation of the Bending Locations Within a Robot Manipulator,” Proc. IEEE International Conference on Advanced Robotics (ICAR), Coimbra, Portugal, pp.556-561.

Walker, I. D., et al.,2005, Continuum robot arms inspired by cephalopods Proc. Unmanned Ground Vehicle Technology VII, Proc. of SPIE Vol.5804 314, pp.595-596.

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