Metamorphic tensegrity structure for pipe inspection

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Metamorphic tensegrity structure for pipe inspection

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Abstract. This paper proposes a new concept of metamorphic tensegrity structure for pipe inspection. A new structural deformation technique is developed that can be employed to design a non-complex and lightweight robot or vehicle. This concept is to deform the cross-shaped tensegrity structure by using the cooperation of prismatic actuators (PAs) and passive joints with locking mechanisms called restrictor mechanisms (RMs). Two control levels are designed to control the structural deformation: A high-level controller for motion patterns and low-level controllers to locally control the PA lengths and restrict the cable lengths of four RMs. Experiments show that the proposed deformation technique can deform the shape and size of the tensegrity structures with the aim of creating a new generation of pipe inspection robots.

1. Introduction

Pipelines are the major equipment for transporting water, oils and gas from production sites to distribution sites. Most of them are installed in underwater or underground environments that are subjected to extreme conditions, for example, high temperature, dust, humidity and pressure. These lead to many problems in pipes such as cracks, corrosion, erosion, deposition, thermal cycling, pitting, shock loading and joint-failure [1]. Therefore, continuous inspection, maintenance and repair are strongly recommended. Often pipes are not easily accessed by humans, so effective equipment should be used to undertake the task instead. Several types of pipe inspection robots have been introduced to access the dangerous areas such as PIG type, wall-press type, wheel type, caterpillar type, Screw type, walking type, snake type, inchworm type and magnetic type [2]. The wall-press type of pipe inspection robots has high performance to negotiate vertical and curve pipelines because it can generate high traction forces between its track wheels and the inner wall pipes by using tension mechanisms that can extend and retract wheels. However, wall-press robots are generally heavy because of the rigid body and joints, leading to the need for high power actuators to generate high traction force for holding the robot during locomotion. High traction force is likely to damage the inner surface of the pipe. To alleviate these problems, we propose a new structure concept for a pipe inspection robot base on the tensegrity principle.

A tensegrity structure is one of the compliant structures. It consists of discontinuous compressive elements (struts) connected to a continuous network of tensile elements (cables) without any rigid joints to maintain a stable volume in space [3]. The tensegrity structure has unique and advantageous properties such as force distribution, lightweight mechanisms and compliant structure [4]. These properties are of interest in the field of robotics. The compliant capability to distribute external impact forces to their elements could be employed to design the compliant-structural robot to reduce or prevent the damage of robot when it faces high-external impact forces. Also, these structures would be safe for a human who works alongside or cooperates with the robot [5]. For these beneficial properties, if we can use the tensegrity structure to develop a lightweight pipe inspection robot, it would reduce the high traction force problem of existing wall-press pipe robots.

The basic locomotion of the tensegrity robot is to change the centre of gravity of the structure for rolling [6] and generate friction force between contact points for crawling [7]. There are several ways to deform the structure for locomotion. First, the use of actuator spooling the outer cables which are connected between struts generating high tension force to pull the strut close together resulting in rolling movement [8]. Another method is to make the robot rolling by adjusting the length of struts to unbalance the structure [9]. The adjusting strut length is also employed to design a duct inspection robot named DuCTTv2 [10] to move inside a pipeline. However, it can move only inside a straight pipe due to the limitation of the structural deformation. Therefore, this paper presents a new technique to deform the tensegrity structure by using the combination of the PAs and the RMs to find the new effective-deformable way of the tensegrity robot which can negotiate complex junctions in pipeline systems.

2. Conceptual design

2.1. Metamorphic tensegrity structure

The proposed concept of the metamorphic tensegrity structure is to deform the structure by using two linear motion types. The first type is the prismatic actuator (PA) that can exert forces in two directions ($F_{P1}$and F_{P2}) through actuation by a motor. The second type is the restrictor mechanism (RM) that can only exert restrictive force in one direction (F_R) by locking a cable as illustrated in figure 1. This basic tensegrity structure comprises of one PA and two RMs. They are connected by using inelastic cables. For the purpose of this investigation, one end side of the PA and RMs are fixed on a mounting plate. In this case, the PA will rotate to the left or right side as shown in figure 2 (depending upon the state of the RM).

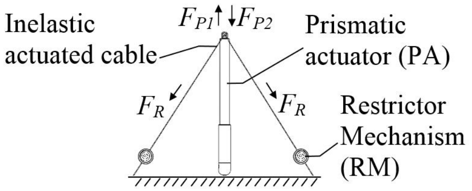


Figure 1. The basic tensegrity structure.

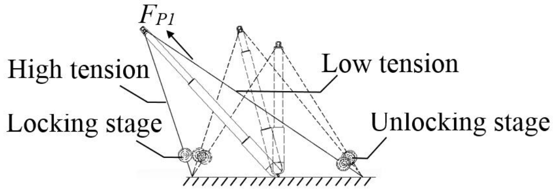


Figure 2. The structural deformation concept.

In order to change the PA position, the length of the PA and the cables will be controlled simultaneously. For example, to tend the PA on the left-hand side (see Figure 2) the RM on the left-hand side is locked, and the RM on the right-hand side is unlocked. Then, the PA length is extended. In this stage, the PA movement will rotate left side until either the cable length on the right-hand side reaches the target length and is locked or the actuator reaches its maximum length. To return to the starting position, the PA will retract its length to the initial length (minimum length), and then the cable on the right-hand side will be reeled inside the RM with the tension force (F_R).

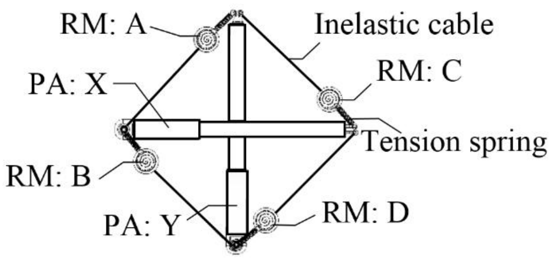


Figure 3. The cross-shaped tensegrity structure.

Table 1. The procedure design for shape changing.

PA:Y motion	RM				PA:Y action
	A	B	C	D	
UP	UL	L[a]	UL	L	E[c]
DOWN	L	UL[b]	L	UL	E
LEFT	L	L	UL	UL	R[d]
RIGHT	UL	UL	L	L	R
CW	UL	L	L	UL	E
CCW	L	UL	UL	L	E

[a] Lock, [b] Unlock, [c] Extend and [d] Retract

To thoroughly understand the movement behaviour of the proposed technique, we design a cross-shaped structure which is put on the backplane as illustrated in figure 3. It comprises of two PAs placed in X axis and Y axis, and four RMs (A to D) mounted between two PAs with inelastic cables to provide tension forces between them to form the symmetry structure. The one side of the RM is connected to the PA tip, and the opposite side of the RM is connected to an extension spring before connected to the other PA tip. The extension springs provide a structure compliant to prevent the RM and cable damage in case of over tension.

For the structure deformation analysis, we design control procedure of the locking stage of four RMs and the length of the PA in Y-axis (see in table 1) while the PA in the X-axis is fixed on the backplane because it is suitable for comparing with experimental results. The movement analysis of the proposed structure is shown in figure 4. For example, in figure 4 (a), the structural shape is changed to the top because the PA(Y) length is extended while the cables of RM (B) and RM (D) are restricted. It can be considered that the motion of the structures in figure 4 (a) and (b) could be used to make the structure moving inside a pipe like an inchworm robot. The structures in figure 4 (c) to (f) could be used to make the structure turning to the left and right directions which are useful to access complex junctions in the pipe.

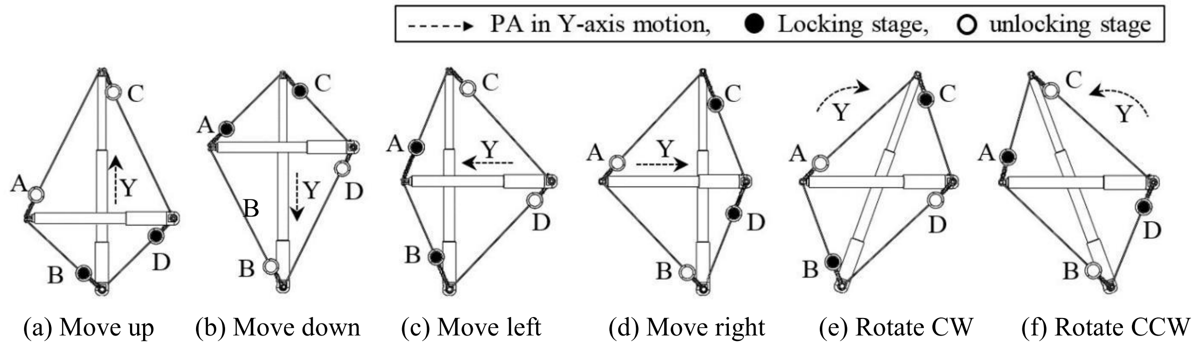


Figure 4. The shape-changing concept of the cross-shaped tensegrity structure.

2.2. Restrictor mechanism (RM)

One of the important parts of the proposed deformation technique is the RM because it is used to restrict the cable length which is spooled by the PA, and it can also passively roll the cable back to cable storage which is a useful feature to prevent the cable becoming stuck with objects surrounding them. The RM composes two main parts: a retractable part and a locking part. The spiral power spring is employed for the retractable part because it can generate a rotational force to reel the cable automatically without an actuator. A friction-based locking is used for the locking part because it can generate a high-frictional force to stop the rotational part, and it completely decouples between the frictional part and movable part leading to has a zero friction during rotational movements [11]. The conceptual design of the locking part is illustrated in figure 5.

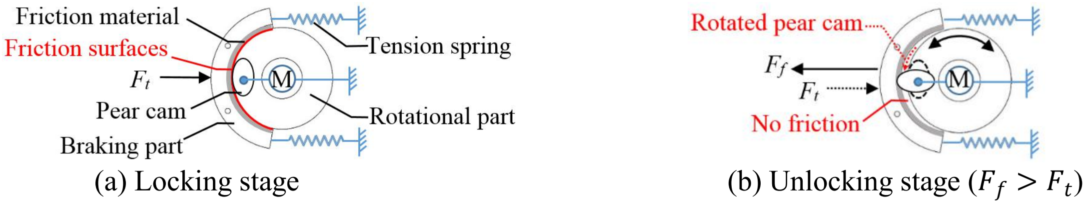


Figure 5. Locking part conceptual design; F_f is the forward force generated by a cam and F_t is the tension force generated by tension springs.

The locking part consists of a braking part, friction material, tension springs, pear cam and actuator. The braking part is designed to be curved to increase the friction force of the surface areas between the friction material and rotational parts as much as possible during locking stage as illustrated in figure 5 (a). The friction force values depend on two main factors: a tension force (F_t) relates to the spring constant of the tension springs and the material contact property of the friction material associated with the coefficient of friction (COF). For the unlocking stage, the friction surfaces between the friction material part and the rotational part are entirely decoupled (see in figure 5 (b)). The pear cam is rotated to push the breaking part out the rotational part. The pear cam is driven by the actuator to generate forward force (F_f) that must be higher than the spring tension force (F_t). Therefore, the selection of the tension springs and the actuator for the locking part should be proper.

3. Hardware design

The property requirements of the restrictor mechanism (RM) are to restrict cable lengths by using locking parts, to reel the cable keeping in the cable storage automatically and to measure the cable length accurately. Therefore, mechanical design of the RM consists of two main parts; locking parts and retractable parts including a cable length sensor.

3.1. Locking parts

The locking parts are designed by using the friction-based method. The design of the 3D model of the locking parts is illustrated in figure 6. A high-frictional force to stop rotational parts is generated by using two tension springs gripped between braking parts and a fixed base to create a pressing force. The moveable braking part is attached to a rubber sheet 1mm thick called a friction material that contacts to the rotational part surface in the locking stage. This braking part can be linearly moved in two directions (passively forward and actively backwards) via a slide guide attached to the fixed base. A miniature DC motor with 287:1 geared head is employed to generate the forward force against the pressing force through a hard coupling. This coupling is attached to a ball plunger mounted at the front surface. This ball plunger will push an unlocking guide during the unlocking stage to separate the friction material from the rotational part.

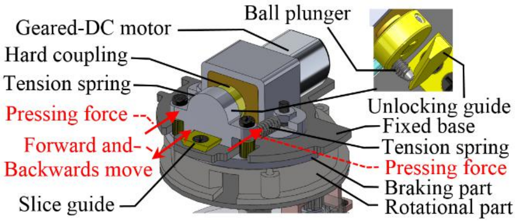


Figure 6. The 3D model of the locking parts.

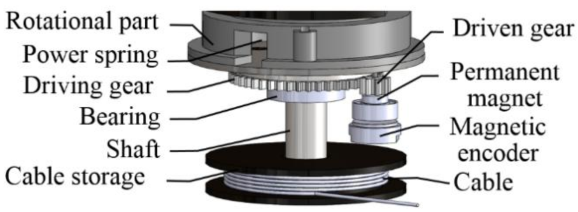


Figure 7. The 3D model of the retractable part and the magnetic encoder installation.

3.2. Retractable part

The retractable part is designed for retracting the inelastic cable (stainless steel 0.5 mm diameter, length 400 mm with 0.12 kN) into cable storage passively. Figure 7 shows the design of the retractable part. It composes of a spiral power spring which is installed inside the rotational part. This part is attached to the stainless-steel shaft (¼ inch diameter) impaled through an enclosure case. The miniature magnetic encoder (model: RM08ID0009B02L2G00, 512 counts per revolution, IP68) and a permanent magnet (4mm diameter) generating magnetic fields are employed. The magnetic encoder is placed on the bottom of the enclosure case. It senses the magnetic field variation generated from the permanent magnet mounted over the magnetic encoder. This magnet can be rotated by using a driven gear (8 teeth) which is driven by a driving gear (46 teeth) attached to the shaft. From these mechanisms, the magnetic encoder can sense the variation and direction of the magnetic field depending on the shaft rotation.

4. Control system design

In this section, the design of a simple control system for the cross-shape tensegrity structure will be described. It is divided into two levels; a high-level controller (HC) which is a master board and a low-level controller (LC) which is a slave board. The HC is used to send control procedures to six LC including two prismatic actuators and four restrictor mechanisms. To control the structure, the HC sends cable length target and prismatic actuator length target to the LC. The HC also receive data from the LC to process data and generate control signals. The PI controller is used to control the prismatic length. The PI parameters are found by using a trial and error method while the ON/OFF control is used to restrict the cable length of each RM. A serial communication I2C is used to communicate between the HC and the LCs.

5. Hardware integration and implementation

This section describes the assembly of the custom RM, the RM performance test, control board development and the implementation of a cross-shaped tensegrity structure. The RMs are made of two material: PLA material with 3D printing technology for non-frictional parts and metal material including aluminums, brass and stainless steel for frictional parts which must withstand the high-frictional forces between a rotational part and fixed part during rotating and braking process. The assembly process of the RM is illustrated in figure 8, and the physical specifications of the RM are summarised in table 2.

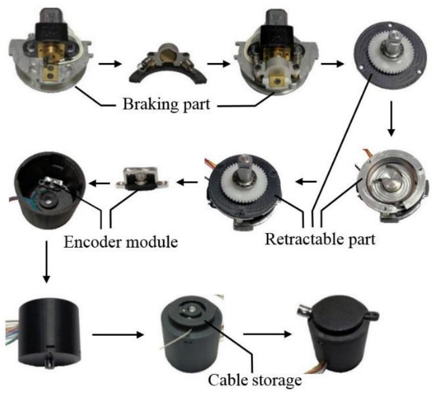


Figure 8. The RM assembly process.

Table 2. Physical specifications of the RM components.

Components	Values
Maximum cable length	400mm
Maximum power spring turn	Six revolutions
RM strain	8
Torsion spring	0.92N
Torsion spring constant	0.13 N/mm
Geared motor torque	0.23 Nm
Geared motor maximum speed	40rpm
Magnetic rotary encoder	512 counts per revolution

In order to evaluate the locking performance, a spring balance was employed to measure the rotational force of the RMs. The experimental result shows that RM can withstand the pulling force of 10N as illustrated in figure 9, and the relationship between cable lengths and the rotation force of four RMs are shown in figure 10. This experiment helps us to calibrate the rotational forces of each RM equally which improves the shape-changing performance.

One HC control board and six LC boards are developed to control the length of PAs and restrict the cable of four RMs. Each LC control board consists of a microcontroller (Arduino Nano V4), a motor driver (MAX14870 for the RM modules and VNH5019 for the PA modules) and an encoder counter (Counter click with LS7366R) to gather the encoder signal before sending to the microcontroller.

Figure 9. The locking performance test.

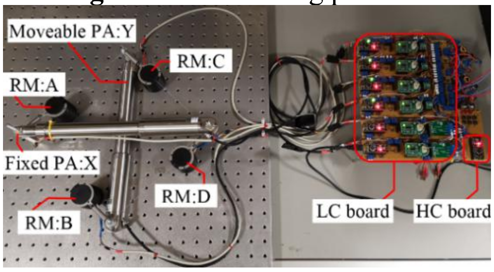


Figure 11. The experimental setup.

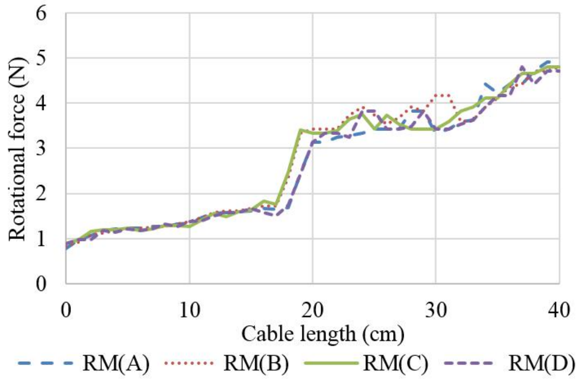
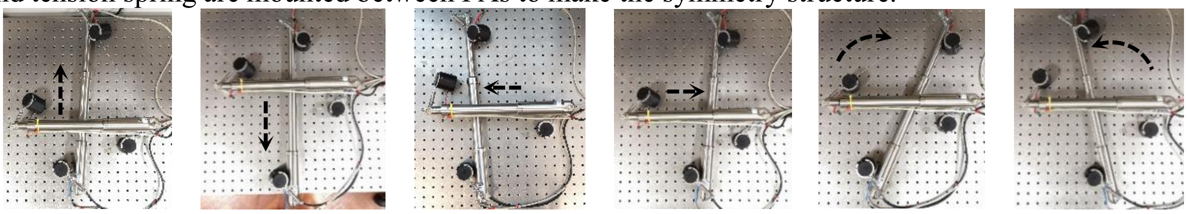


Figure 10. The relationship between the cable length and the rotational force of four RMs.

The cross-shaped tensegrity structure is constructed as illustrated in figure 11. Two PAs (LA35 series with 150 mm stroke, 350mm original length, 400N, 16mm/s and 0.1429mm/pulse) are placed on a backplane by fixing one PA in X-axis and another one in Y-axis which is moveable. The four RMs and tension spring are mounted between PAs to make the symmetry structure.



(a) Move up (b) Move down (c) Move left (d) Move right (e) Rotate CW (f) Rotate CCW

Figure 12. The experimental result of the cross-shaped tensegrity deformation.

In order to deform the cross-shape tensegrity structure, the control procedure in table 1 is utilised to generate control signals sending to each LC control boards. The experimental results in figure 12 (a) to (f) showed that the structure shape could be deformed similarly to the cross-shaped structure analysis. The custom RMs could restrict and reel the cables suitably, and the PA could be moved to the desired position resulting in the change of overall sizes. The PA movement behaviours could be used to design a robot which would be able to change its shape getting into different sizes of pipelines by extending and retracting its length against a pipe wall. Besides, the RM features could be employed to turn the structure in different angles to negotiate complex junctions in the pipelines.

6. Conclusions and future works

In this paper, we have presented the concept of a tensegrity structure deformation by using the cooperation between the RMs and the PAs. Unlike any other known tensegrity robot deformation technique, the proposed technique is to restrict the cable length by the RMs while the cable has been spooling by PAs leading to the design of a non-complex structure and control algorithm to deform the structure. The experimental results showed that the custom RM performed efficiently to restrict the cable lengths in order to deform the cross-shaped tensegrity structure, and it is sufficient to use the RMs and the proposed technique to design a pipe inspection robot based on tensegrity structure in the future.

References

[1] Shukla A and Karki H 2016 Application of robotics in onshore oil and gas industry—A review Part I, *Robotics and Autonomous Systems* vol. **75** pp. 490-507.
[2] Mills G, *et al.* 2017 Advances in the Inspection of Unpiggable Pipelines *Robotics* vol. **6**, p. 36
[3] Pugh A 1976 *an introduction to tensegrity* United States of America: University of California

[4] Skelton R E and de Oliveira M C 2009 *Tensegrity systems* vol. **1**. University of California USA: Springer.
[5] Kim, *et al.* 2014 Rapid prototyping design and control of tensegrity soft robot for locomotion *Robotics and Biomimetics (ROBIO) 2014 IEEE Int. Conf.* pp. 7-14.
[6] Sabelhaus A P, *et al.* 2015 System design and locomotion of SUPERball, an untethered tensegrity robot *IEEE Int. Conf. on Robotics and Automation (ICRA)* pp. 2867-73.
[7] Tietz B R, *et al.* 2013 Tetraspine: Robust terrain handling on a tensegrity robot using central pattern generators *IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics* pp. 261-67
[8] Chen L H, *et al*. 2016 Soft spherical tensegrity robot design using rod-centered actuation and control *ASME 2016 Int. Design Engineering Techical Conf. & Computers and Information in Engineering Conf. (IDETC/CIE 2016)* Charlotte North Carolina.
[9] Luo A, *et al*. 2016 Motion simulation of six-bar tensegrity robot based on Adams *IEEE Int. Conf. on Mechatronics and Automation* pp. 264-69.
[10] Friesen J M, *et al.* 2016 The second generation prototype of a Duct Climbing Tensegrity robot, DuCTTv2 *IEEE Int. Conf. on Robotics and Automation (ICRA)* pp. 2123-28.
[11] Plooij M, *et al*. 2015 Lock Your Robot: A Review of Locking Devices in Robotics *IEEE Robotics & Automation Magazine* vol. **22** pp. 106-17.