(#40) In-Situ Pipeline Inspection with A Soft Robotic Manipulator Using PneuNet and SMA Springs

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Abstract

Soft robotics has emerged as a trending field recently due to the traditional rigid robotics failure in their applications requiring flexibility and adaptability in constrained environments. One of the crucial parameters that defines a soft robot is its material and the redundant degrees of freedom. The use of soft materials allows for continuous deformation which in turn, enables structures with ranges of motion limited only by the properties of the material [1]. Such materials that are used for the fabrication of the soft manipulators are Silicone Rubber, Elastomers (PDMS), SMAs, Thermoplastic Elastomers, etc. Among the applications that require flexibility one significant scenario is the inspection of pipelines in water sprinkler systems, which often involves navigating through pipelines with diameters as narrow as 4-8 inches. This research aims to design and analyse a soft robotic manipulator specifically for in-situ operations within these confined spaces. The manipulator incorporates a Shape Memory Alloy (SMA) spring, actuated by voltage, and a pneumatically actuated PneuNet structure to facilitate precise and flexible movements. The main focus of this research is on detailing the design process of the manipulator and highlighting the customization of the SMA spring. The manufacturability and material selection for the PneuNet structure are also discussed, alongside simulations are also performed using Abaqus CAE to ensure the validity of the manipulator design.

Keywords: *soft robotics, bio-inspirations, confined space, continuum robots, manipulators*

Introduction

Soft robotics has emerged as a trending field since recently due the traditional rigid robotics failed in their applications requiring flexibility and adaptability in constrained environments. One of the crucial parameters that defines a soft robot is its material and the redundant degrees of freedom. The use of soft

materials allows for continuous deformation which in turn, enables structures with ranges of motion limited only by the properties of the material [1]. Such material that are used for the fabrication of the soft manipulators are Silicone Rubber, Elastomers (PDMS), SMAs, Thermoplastic Elastomers, etc. Among the applications which require flexibility one significant scenario is the inspection of pipelines in water sprinkler systems, which often involves navigating through pipelines with diameters as narrow as 4-8 inches. These inspections are mostly done as in-situ inspections where the system is isolated and then the pipelines are cut through from the welding seems to check for the damages. This research aims to design and analyse a soft robotic manipulator specifically for in-situ operations within these confined spaces. The manipulator incorporates a Shape Memory Alloy (SMA) spring, actuated by voltage, and a pneumatically actuated PneuNet structure to facilitate precise and flexible movements. The manipulator designed thus would be able to extend lengthwise utilizing the SMA spring properties and then bent to inspect the inside of the pipeline using the pneumatic bending rib. The main focus of this research is on detailing the design process of the manipulator and highlighting the customization of the SMA spring. The manufacturability and material selection for the PneuNet structure are also discussed, alongside simulations are also performed using Abaqus CAE to ensure the validity of the manipulator design. The novelty of this research is though the Pneumatic rib incorporated manipulators are extensively explored this scientific study incorporates two basic actuation principles Shape Memory Alloy and Pneunets which are still nearly unexplored, in the same design for a successful operation of the manipulator.

Methodology

The design inspiration for the manipulator comes from the tentacle of a jellyfish, which is bendable at the end for precise operations. The design process began by selecting Nitinol (NiTi) for the spring due to its superior shape memory properties and its widespread acceptance in the industry. The initial and most crucial step involved determining the operating state of the SMA coil, as the phase transition of SMA significantly impacts the design calculations; 100% Austenite state or 100% Martensite state. A summary of the designing process of the SMA spring is carried out as explained in [2]. The design process of the SMA spring involved obtaining properties like shear

modulus in both austenite and martensite states, maximum residual stress, and critical stresses. The desired maximum shear stresses were then obtained for both states so that the values are not too close to the marginal stresses as the second step. These values were considered for 100% martensitic and 100% austenitic states as constant loading condition and constant deflection condition where in this research we considered both cases in the calculations. As the third step some of the calculation parameters were preselected and they were the initial pitch angle to be 0^0 and the coil index to be 9. And thus, all the other parameters were calculated accordingly and reselected for industry manufacturable standards. The final pitch angle and the maximum stroke was calculated as the next step and finally, the no. of active coils and the total number of coils were calculated. After verifying manufacturability, the process was finalized.

The next step involved designing the PneuNet structure, consisting of 10 units of two different sizes with hollow chambers to facilitate air passage. This structure was simulated using Keyence AR G1L, Reynolds Ecoflex 00-10, and Ninjaflex, chosen for their flexibility and manufacturability.It should also be specified that according to [3] the softness of the material for soft robotics cannot be described with the classical concept of modulus of elasticity except it must be considered a primary finding when selecting a material and must have a Young's modulus of greater than 100Pa for structural support, controlled deformation and to be compatible with traditional manufacturing processes. Also, the tangent modulus of the material must be less than 1000 MPa to offer greater flexibility and the strain capacity to undergo deformation must be within the range of 10% to 100%. The PneuNet structure is attached to the SMA spring via a custom-designed holder, enabling it to reach and inspect local points within the pipeline effectively. The components were designed in SOLIDWORKS and assembled, with each part validated through simulations in Abaqus CAE.

Simulation and Results

The following Table 1 depicts the results obtained through the mathematical modeling of the Shape Memory Alloy coil spring (SMA spring). This spring is a tension spring which is a very compact spring and will actuate lengthwise only when given a tensile force.

Table I: SMA numerical data

		Martensite	Austenite
G	Shear Modulus	$8x10^9$ Pa	$25x10^9$ Pa
d	Wire diameter	0.75mm	0.75mm
α_i	Initial pitch angle	0º	0º
D	Spring diameter	6.75mm	6.75mm
n_a	Active no. of coils	21	21
N_t	Total no. of coils	23	23
F_R	Required force	2.45N	2.45N
v	Poisson's ratio	0.33	0.33
δ_{max}	Maximum stroke	8.16mm	8.16mm
D_m	Mean diameter	6mm	6mm
α_f	Final pitch angle	1.07º	0.02º
C	Coil index	9	9
$\varepsilon_{s\tau}$	Detwinning martensitic factor	1	1

To confirm the reliability and effectiveness of the design, simulations were conducted using Abaqus CAE. The simulations involved setting up appropriate boundary conditions and parameters to mimic the operation of the manipulator under different loading conditions.

PneuNet simulations involve the bending of the actuator under gravity while having one end of the rib fixed under Encastre boundary condition as shown in Figure 1. The spring was simulated for tension under loads. The primary focus was on the mechanical behaviour of the spring and the simulation results provided critical insights into the performance of both the components guiding necessary adjustments such as the wire diameter of the spring, diameter of the wire, and parameters of the PneuNet such as the length and the chamber occupancy.

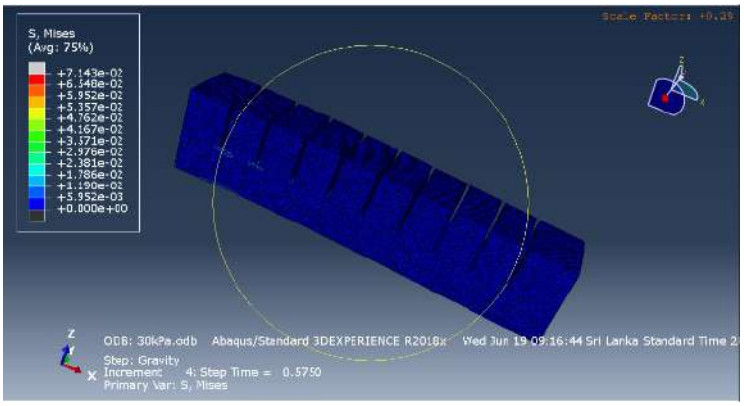


Figure 11: PneuNet structure simulation bending under 30kPa pressure

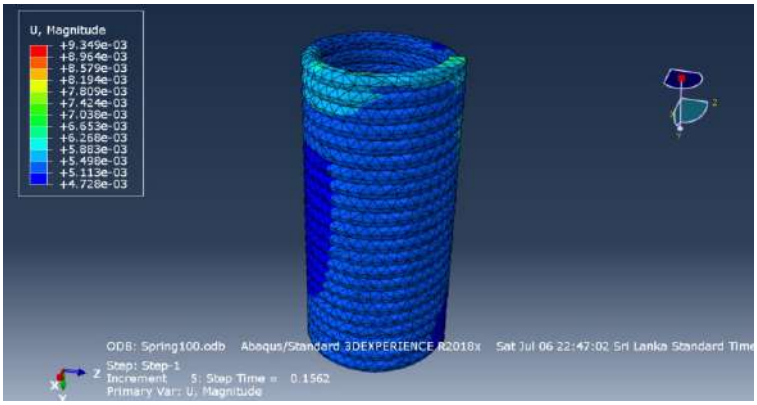


Figure 12: SMA Spring under 100N load

Discussion

The design process of the soft robotic manipulator highlights the importance of material selection and parametric decision-making for precise actuation of the SMA spring and the PneuNet structure. While the manipulator components met most of the expectations to be feasible to employ it in a confined space of a pipeline further research should be carried out to simulate the complete manipulator via a suitable simulation tool and to explore alternative materials to address the limitations.

Conclusion

This research was focused on designing a soft robotic manipulator for in-situ operations within pipelines of water sprinkler systems; integrating an SMA spring and PneuNet structure for effective movements. The simulations

performed in Abaqus CAE provided insights into the design and limitations that must be addressed. Future work will explore further enhancements to the manipulator's performance and broader the application of the manipulator.

References

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