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Topology Optimization of a 6-DOF Arm-Z Modular Robotic Manipulator

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Abstract

This contribution considers the problem of topology optimization of modular structures. A bionic trunk-like robotic "Arm-Z" manipulator is considered. The manipulator is modular, that is, it is composed of a sequence of identical modules. In geometric terms, each module is essentially an obliquely cut section of an elliptical pipe, so in the cutting plane it forms a circle. With respect to the previous module, it has a single degree of freedom: the relative twist. Therefore, the total number of the degrees of freedom of the entire manipulator equals the number of its modules. Such a manipulator belongs to the family of Extremely Modular Systems. The advantages of such systems are the economization (due to the possible mass production of modules) and robustness (replacement of a failed module instead of a complex repair).

Keywords: topology optimization, modular manipulator, multiple loadings, geometric transformations, kinematics, stress constraints.

1 Introduction

Biological snakes are very well adapted for different environments. This is mostly the result of the high redundancy of the snake mechanisms. In many instances of irregular environments the bio-inspired robots outperform conventional wheeled, legged or tracked robots.

The snake-resembling robots are researched already for a few decades. This type of locomotion has been studied already in the 1940s [3], and a half century later, its rigorous mathematical model has been developed. In the late 90's, a trunk-like locomotors and manipulators have been introduced in [4].

A number of various snake-like robots have been built [5]; most of the designs were intended for crawling on ground [6, 7, 8, 9, 10], some of them for swimming [11, 12], and even fewer for both swimming and crawling on the ground [13, 14].

Alike biological snakes or bionic trunks, in various environments the characteristic type of motion gives this type of manipulators certain advantage over conventional robotic manipulators.

They can operate in geometrically complicated environments which are not accessible by other approaches.

Depending on the required task, various working heads can be installed on such manipulators, e.g. for: welding, cleaning, monitoring, etc.

Extremely Modular Systems [2] are comprised of as few types of modules as possible and allow for creation of free-form objects not constrained by regular tessellations. Arm-Z [15] is the concept of an Extremely Modular robotic manipulator. In Arm-Z each module is identical, and the links between modules have exactly one degree of freedom (1-DOF) - the relative twist. Arm-Z manipulator has as many degrees of freedom as the number of modules less of one. This redundancy allows it to perform complicated movements, but also may improve its robustness and fault tolerance [16].

Despite this extreme modularity, provided sufficient number of modules, it allows for creation of practically any three-dimensional shapes, e.g., prime mathematical knots.

In principle, each module is defined by the following parameters: size r, offset d, and ζ that is the angle between upper (***T***) and lower (***B***) faces of the module, as shown in Fig. 1.

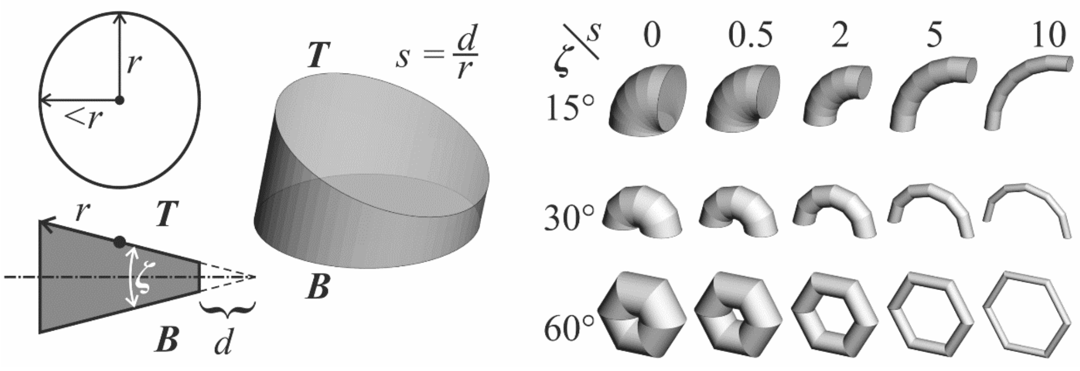

Figure 1: On the left: visualization of the Arm-Z unit defined by three parameters: r, d and ζ. On the right: simple examples of assemblies of units for various values of ζ and s (slenderness), which is an additional parameter, a d to r ratio.

Fig. 2 shows the prototype of Arm-Z.

Figure 2: A photograph of the prototype of Arm-Z

The related previous research revolved around the kinematics, geometric transformations, and path planning of such manipulators [15]. This contribution is the first to consider structural optimization of the modules. This is a challenging task due to the possible loading states of a single module, arising from its different positions along the arm and different global geometric configurations of the manipulator. Essentially, it is a multi-load structural optimization problem with a very large number of loads. As it is computationally infeasible to consider all possible loading states, this contribution first determines a limited number of the most unfavourable configurations (with respect to module twist, bending, axial loading, etc.) and then optimizes the topology of a module only with respect to the few determined borderline loading states.

For the purpose of topology optimization, each module is represented by a section of a pipe. The walls of the pipe are meshed using a single layer of 3D finite elements. Consequently, the process of topology optimization [17, 18] effectively corresponds, in terms of its result, to perforating the cylindrical wall of the module and determining the optimal location and shape of the holes.

2 Methods

Before proceeding with topology optimization of a 6-DOF Arm-Z modular manipulator (Figure 3) one has to determine internal forces present in various configuration of this robotic system. For that purpose, we start our consideration with brief description of manipulator kinematics (section 2.1) then we calculate axial and transverse forces and twisting and bending moments in every module of the manipulator (section 2.2).

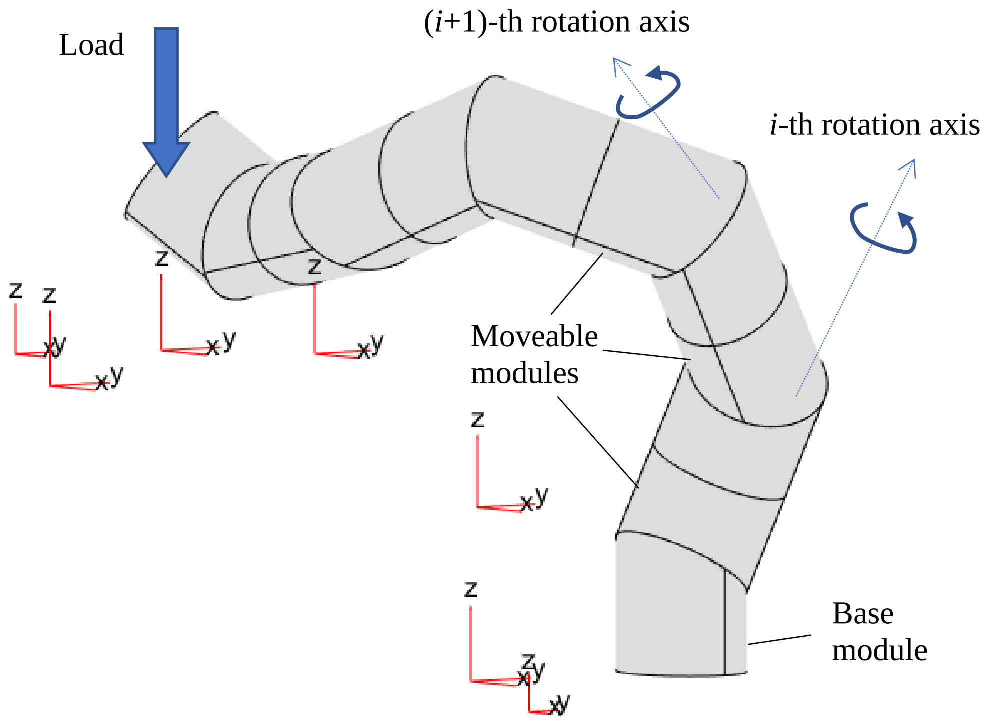

Figure 3: Robotic manipulator with six degrees of freedom, loaded at the free end.

2.1 Kinematics of the chain manipulator

As it is shown in fig.1. the robotic system under consideration consists of one fixed (base) module and 6 movable modules. Motion of such a system can be uniquely described by creating a rotation matrices between individual modules, for which module tree is presented in Fig. 4.

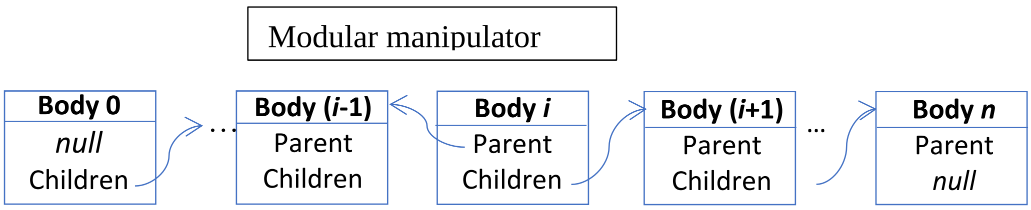

Figure 4. Connections between individual modules of the Arm-Z manipulator.

As we can see in Fig. 4 the module tree for our manipulator degenerated to doubly linked list in which a parent of module i is module i-1 and its child is module i+1.

The whole kinematics of such a system can be implemented in a form of following pseudocode:

```
θ = π * rand( 1, n)
for i = n:-1:1
    for j = n:-1:i
        rotate( module{j}.Geometry, θi*180/π, Pstart(i,:),
Pend(i,:));
    end
end
```

Computational complexity of the above algorithm allowing generate the kinematics of the *n*-module chain manipulator is $O(n^2)$ and manipulator working space is show in Fig. 5.

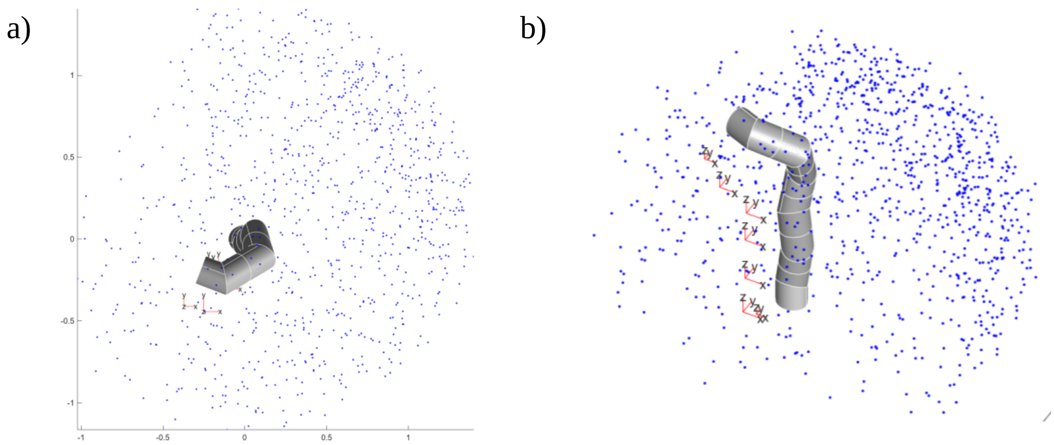

Figure 5. Working space of Arm-Z manipulator: a) 2D top view, b) 3D view

2.2 Statics of the chain manipulator

After describing the kinematics of the modular system one can determine internal forces in the individual modules of manipulator. The module with highest internal forces will be used in the topology optimization step.
There are many approaches to find configuration of the manipulator giving the highest internal forces in its modules such as random search. However, for the sake of simplicity in this study we selected two of such configurations based our engineering judgement. These configurations are shown in Fig. 6.

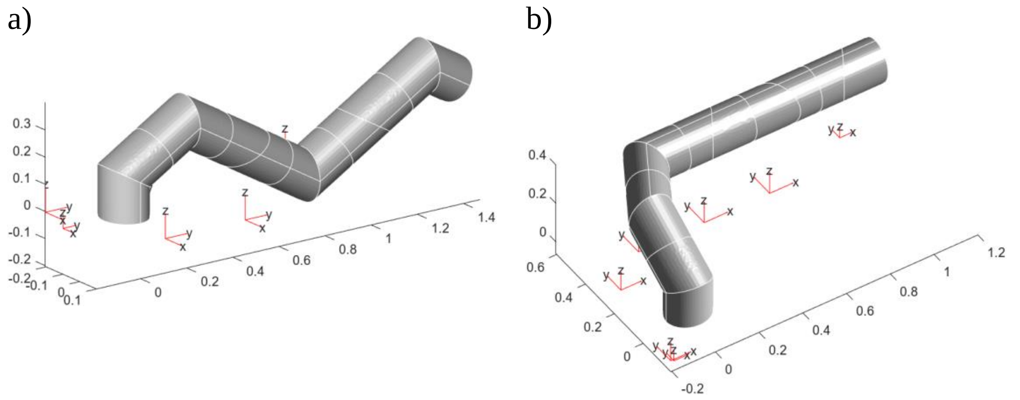

Figure 6. Configurations used for calculation of extreme internal forces:
a) maximum bending moment, b) maximum twisting moment

2.3 Topology optimization

The formulation of the stress constrained topology optimization problem is presented in Eq. (1)

$$\begin{aligned} \min_{\boldsymbol{\rho}_e \in S} \quad & \sum_{i \in \Omega^e} \rho_i A_i \\ \text{s.t.} \quad & \mathbf{K}(\boldsymbol{\rho})\mathbf{u}(\boldsymbol{\rho}) - \mathbf{f} = \mathbf{0} \\ & \rho_j \left(\frac{|\boldsymbol{\sigma}_j|}{\sigma_0} - 1 \right) \leq 0, \quad j \in \Omega^e \end{aligned} \tag{1}$$

Where ρ_i is design variable being density of the finite element, A_i, is volume of the element, $\mathbf{K}(\boldsymbol{\rho})$ is stifness matrix, $\mathbf{u}(\boldsymbol{\rho})$ is displacement vector, $\sigma_0$is stress limit, $|\boldsymbol{\sigma}_j|$ is norm of the Huber Mises stress and **f** is load vector.

3 Results

Using basic loading conditions i.e. shear forces, or bending and twisting moments acting on the single module allowed for determining the optimal material distribution in the whole robot arm. Obtained topologies determined separately for above mentioned basic cases are presented on Figure 7.
To obtain the topologies shown in fig.7. linear 8-node Lagrange finite elements have been used. Loads have been equally distributed along inclined faces of the module. The stress constrained topology optimization approach described in previous Authors' work [17] has been used to determine final topologies. The main concept of this approach is based on sequential removal of the redundant material from the module.

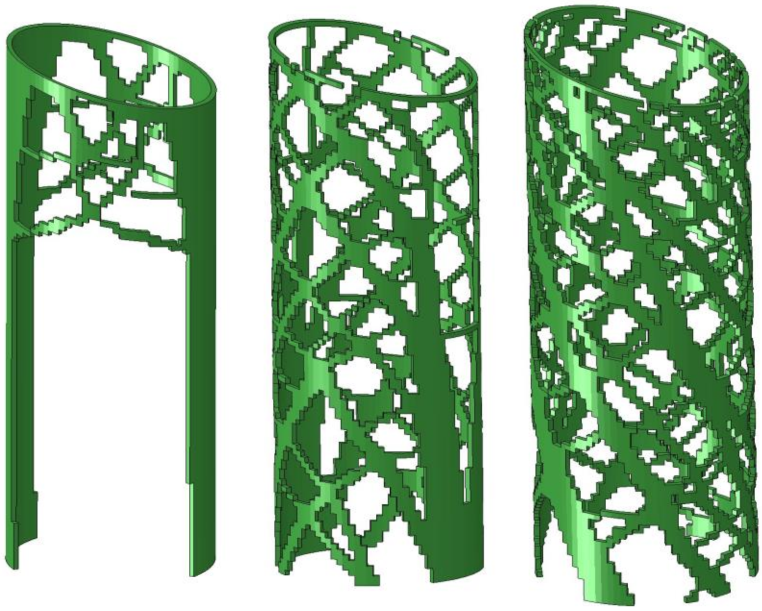

Figure 7: Bending, shear and torsional topologies of single module

Conclusions

In this paper the Authors have shown preliminary results concerning optimal topology of the single module of the discrete-type elephant trunk manipulator. In particular, three special cases of loading conditions have been considered, namely: shear, bending and twisting.
It is assumed that optimal topology for arbitrary loading conditions can be approximated using superposition of these basic topologies.

Acknowledgments

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References

[1] Zawidzki M., Nagakura T. "*Arm-Z: a modular virtual manipulative*." Proceedings of the Sixteenth International Conference on Geometry and Graphics, 2014, pp. 75-80

[2] Zawidzki M. “*Discrete Optimization in Architecture – Extremely Modular Systems*.” SpringerBriefs in Architectural Design and Technology, 121 pages, 2016. Springer.

[3] Gray, James. "The mechanism of locomotion in snakes." *Journal of experimental biology* 23.2 (1946): 101-120.

[4] Hirose, Shigeo. "Biologically inspired robots." *Snake-Like Locomotors and Manipulators* (1993).

[5] Ijspeert, Auke Jan, and Alessandro Crespi. "Online trajectory generation in an amphibious snake robot using a lamprey-like central pattern generator model." *Proceedings 2007 IEEE International Conference on Robotics and Automation*. IEEE, 2007.

[6] Chirikjian, G. S., and J. W. Burdick. "Design, implementation, and experiments with a thirty-degree-of-freedom ‘hyper-redundant’robot." *ISRAM 1992* (1992).

[7] Klaassen, Bernhard, and Karl L. Paap. "GMD-SNAKE2: a snake-like robot driven by wheels and a method for motion control." *Proceedings 1999 IEEE international conference on robotics and automation (Cat. No. 99CH36288C)*. Vol. 4. IEEE, 1999

[8] Miller, G. "Snake robots for search and rescue, neurotechnology for biomimetic robots." *Proc. Int. Conf. Robotics and Automation (ICRA)*. 2002.

[9] Choi, H. R., and S. M. Ryew. "Robotic system with active steering capability for internal inspection of urban gas pipelines." *Mechatronics* 12.5 (2002): 713-736.

[10] Tsakiris, Dimitris P., et al. "Polychaete-like undulatory robotic locomotion." *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*. IEEE, 2005.

[11] Melsaac, K. A., and James P. Ostrowski. "A geometric approach to anguilliform locomotion: modelling of an underwater eel robot." *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C)*. Vol. 4. IEEE, 1999.

[12] Wilbur, Cricket, et al. "A lamprey-based undulatory vehicle." (2002).

[13] Yamada, Hiroya. "S. development of amphibious snake-like robot acm-r5." *The 36th international symposium on robotics (ISR 2005), Tokyo*. 2005.

[14] Crespi, Alessandro, et al. "AmphiBot I: an amphibious snake-like robot." *Robotics and Autonomous Systems* 50.4 (2005): 163-175.

[15] Zawidzki M., Szklarski J. “*Transformations of Arm-Z modular manipulator with Particle Swarm Optimization*.” Advances in Engineering Software 126, 2018, pp. 147-160

[16] Zawidzki, Machi. "Deployable pipe-Z." *Acta Astronautica* 127 (2016): 20-30.

[17] Błachowski B., Tauzowski P., Lógó J., “*Yield limited optimal topology design of elastoplastic structures*.” Structural and Multidisciplinary Optimization 61, 2020, pp. 1953-1976.

[18] Tauzowski P., Błachowski B., Zawidzka E., Zawidzki M., “*MorphoGen: Topology optimization software for Extremely Modular Systems”*, SoftwareX, ISSN: 2352-7110, Vol.27, 2024, pp.1-10