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Zhiping Wang, Yicha Zhang, Gaofeng Li, Guoqing Jin, Alain Bernard. Stiffness modulation for soft robot joint via lattice structure configuration design. 31st CIRP Design Conference 2021 (CIRP Design 2021), Jun 2021, Enschede, Netherlands. pp.732-737, 10.1016/j.procir.2021.05.149 . hal-03323285

HAL Id: hal-03323285

<https://hal.science/hal-03323285v1>

Submitted on 13 Jun 2023

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31st CIRP Design Conference 2021 (CIRP Design 2021)

Stiffness modulation for soft robot joint via lattice structure configuration design

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Abstract

Soft materials have been applied on the soft robots built with high deformation and compliance. Additive manufacturing (AM) technology has the ability to fabricate functional soft materials or structures. However, soft robots generally have shortages in strength to manipulate relatively heavy objects. This paper proposes a novel concept on the application of lattice structure configuration for the lightweight functional spherical joint of soft robotics with variable stiffness modulation. A novel active spherical joint driven by air pressure is mainly composed of a rigid ball and soft porous socket. The stiffness can be adjusted by changing air pressure in the soft socket. In order to obtain a high-speed response performance and large-scale linear stiffness, the socket is divided into inner and outer layers. Parametric uniform strut-based lattice structures are populated within the inner layer of the socket to guarantee the flow of air. Trimmed TPMS-based lattice structures are infilled within the outer to keep the stable external shape of the socket. The manufacturability for two lattice structure configurations is also analyzed. In order to achieve a linear variable stiffness, the type and size of lattice unit cells and the thickness of lattice struts can be changed parametrically.

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Peer-review under responsibility of the scientific committee of the 31st CIRP Design Conference 2021

Keywords: Additive manufacturing; Lattice structure configuration; Soft robotics

1. Introduction

Additive manufacturing (AM) technologies have the potential to fabricate significantly complex and lightweight structures with a layer-by-layer printing strategy enabling to achieve a non-linear relationship between the complexity and manufacturing cost [1-3]. The complexity causes lightweight lattice structure to be candidates for energy absorption [4], tissue engineering scaffolds [5] and lightweight structural components [3]. Lattice structure can exhibit unique functional properties by controlling its geometric parameters, which has attracted much research attention [6]. With the development of new materials/actuators in robotics, many researchers are paying more attention to investigate soft robots due to their potential advantages in safe interaction, adapting to uncertain

and complex environments [7]. Soft robots are defined as systems capable of autonomous behavior that are exclusively composed of soft materials which are inspired by animals [8]. Generally speaking, smart shape and material properties play a key role for a successful design of soft robotics [9]. Different types of stimuli-responsive materials are used to achieve actuation, the conversion of any types of input energy into mechanical movement, when building soft robots or bio-inspired artificial muscles [10]. However, it is usually hard to manipulate relatively heavy objects for soft robots with high deformability and compliance. Therefore, to fully exploit the potential of soft actuators, new design principles and manufacturing routes should be developed to generate functional multi-material structures with higher flexibility and heavier load bearing capacity. Parametric functional lattice

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structure can provide soft materials with controllable deformation and activation for building soft robots or systems. Hence, this paper proposes a novel design method by using a parametric lattice structure configuration on soft functional robots with the ability of stiffness modulation.

The remainder of this paper is organized as follows. Section 2 will review related work on lattice structures. After introducing some research problem on soft robotics, a novel pressure-driven soft robot is developed in Section 3. Then, the overall methodology of the proposed lattice structure configuration method is introduced in Section 4. Finally, the paper ends with conclusion and future work in Section 5.

2. Related work

Due to the geometry complexity of AM, lattice structure got more attention recently, especially when AM becomes more mature. Lattice structure typically can be categorized as strut-based and triply periodic minimal surface (TPMS). The most common strut-based lattice cells are body-centered cubic (BCC), face-centered cubic (FCC), octet-truss, dodecahedron units, etc. [6]. Maxwell criterion can be described as a sufficient condition to characterize the mechanical response of a strut-based structure. The Maxwell rule in 3D is given by [11]:

$$M = s - 3n + 6 \quad (1)$$

Where s and n are the number of struts and nodes, respectively. If $M < 0$, the strut-based cell will exhibit a bending-dominated behavior. Whereas if $M \geq 0$, it can make the struts stretch-dominated [12]. Bending-dominated structures have a relatively low strength and high compliance and stretch-dominated structures play a strong and stiff performances [13].

Recently, a great amount of investigations has been concentrated on nature-inspired TPMS structures. This kinds of surface-based structures are represented by mathematical formulations according to level-set functions [14]. Three common TPMS structures, Schwarz P, Diamond and Gyroid, are widely used. Their mathematical expressions can be described by the following equations.

$$\begin{aligned} \phi_P(x, y, z) &= \cos(\omega x) + \cos(\omega y) + \cos(\omega z) = C \\ \phi_D(x, y, z) &= \cos(\omega x) * \cos(\omega y) * \cos(\omega z) \\ -\sin(\omega x) * \sin(\omega y) * \sin(\omega z) &= C \\ \phi_G(x, y, z) &= \sin(\omega x) * \cos(\omega y) + \sin(\omega y) \cos(\omega z) \\ + \sin(\omega z) * \sin(\omega x) &= C \end{aligned} \quad (2)$$

Where x, y, z are the spatial coordinates, $\omega = 2\pi / l$ and l is applied to define the length of lattice cell, and C can control the expansion of the surface in three dimensions.

At a Meso-level, the configuration of lattice structure can be divided into two main types: uniform and conformal [15]. The uniform lattice structures, called as periodic lattice structures, are described as those kinds of lattice structures which repeat the unit cells in 3D space. Due to the periodic properties, all unit cells have the same size and topology. For the conformal lattice structure [16], known as pseudo-periodic lattice

structure, the shape and size are designed to conform to the original geometry of a part hull. Fig. 1 shows the two types of lattice structure configurations in 2D. In order to optimize the material distribution, such as the lattice, shape, size and topology, topology optimization is usually used to address the structural design problem. A heuristic optimization method, called as the augmented size matching and scaling (SMS) method, was proposed to optimize the thickness distribution of conformal strut-based lattice structure [17]. Other optimization methods are applied to optimize the shape, orientation and parameters of lattice structure configuration [3, 18].

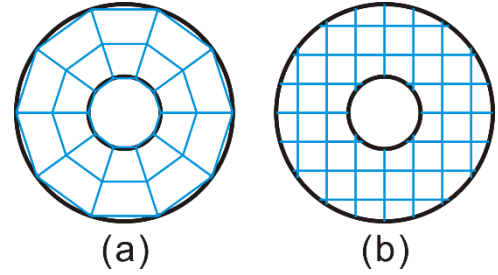


Fig. 1. (a). conformal lattice configuration; (b). uniform lattice configuration.

The success on design and optimization for lattice structures configuration has significantly accelerated and expanded the application of lattice structure. Lattice structures with functional graded characteristics can be easily fabricated by controlling fabrication parameters layer by layer without increasing the manufacturing cost. However, most applications for lattice structure still focus on lightweight structural design.

This high flexibility on the material distribution of lattice structure has a great possibility to provide a broad platform for development of different types of stimuli-responsive soft robots [9]. Some researchers [19, 20] have designed auxetic metamaterials and proved that simple lattice unit cells can exhibit robust mechanical responses. However, 3D parametric complex lattice structure configuration is rarely used in the field of soft robotics. Therefore, this paper proposes a novel hybrid lattice structure configurations method for a 3D spherical joint of soft robots. It can broaden the application of functional lattice structures.

3. Research problem

To explore a wider application on soft robot, a pressure-driven soft robot is proposed to achieve a variable stiffness output in different manipulator configurations. The stiffness of the whole robot is determined by the stiffness of all spherical joints. This flexible configuration can be achieved by design and optimization on lattice structure configuration. Fig. 2 shows a conceptual schematic of the soft robot with spherical joints. A ring is fixed on the bar connecting with the rigid ball. The rotation of ball can be controlled by driving the cables. A series of spherical joints are embedded into a soft elastomer body and serve as a backbone. A soft and elastic pipe, as a container, is designed to avoid damage to the soft elastomer body. The cable can drive the ring to generate relative motions to the socket. After the motion, the air pressure on the soft porous structure is increased to gain the stiffness. At any specific configuration,

the stiffness of each spherical joint can be adjusted separately to achieve the control coupling of motion and stiffness.

According to these application requirements, the spherical joint needs to have a wide range of stiffness output. Hence, how to configure functional lattice structures is the key to obtain a lightweight spherical joint with the ability of stiffness modulation. Traditional methods, e.g. using smart material with external stimulus [9], used in soft robot development can hardly meet the needs. To solve the lattice structure configuration problem, this paper proposes a novel hybrid lattice structure configurations method with an aim to achieve enough strong and adjustable stiffness for the 3D spherical joint structure. The stiffness output can be tuned by changing the shape, size, thickness of unit cell parametrically. Moreover, manufacturability is analyzed to guarantee the self-supporting of lattice structure.

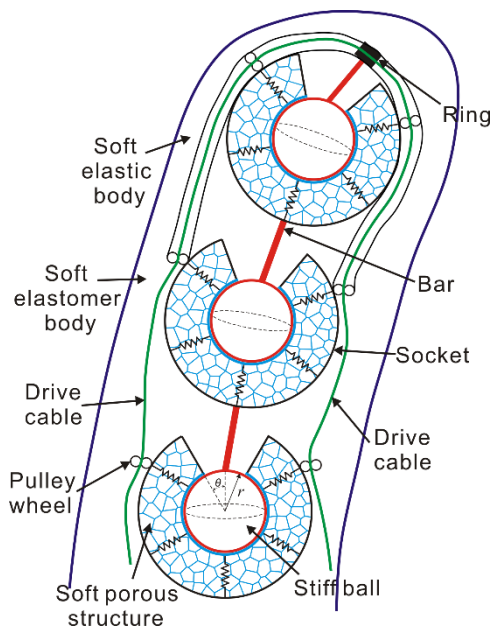


Fig. 2. Conceptual schematic of a soft robot.

4. Proposed method

The spherical joint with the ability of stiffness modulation is separated as shown in Fig. 3(a). It is composed of active stiff joints and soft deformable socket. The stiff ball is embedded into the soft deformable socket. The change of inner surface radius of the socket can achieve different preload force between outer surface of the spherical joint and inner surface of the socket. With a smaller inner radius, the socket can provide a bigger preload force to the ball. The stiffness modulation can have a wide range of the possible stiffness outputs. Hence, the radius of the socket’s inner surface can be set as a control input. The design should follow the rule that applied preload force is linear with the radius. To control the inner radius, a possible solution is to use air pressure [21]. The radius of the socket’s inner surface is tuned by controlling the air pressure via the pneumatic pipe. In this design, the stiffness of the whole robot is determined by the stiffness of all spherical joints. Moreover, it brings an additional benefit that the robot can share different stiffness in different parts.

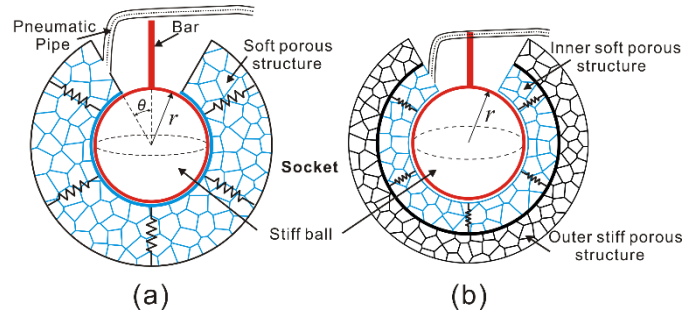


Fig. 3. (a). the spherical joint design with the ability of stiffness modulation; (b). a modified design using double-layer lattice structures.

A modification modulation is designed to improve the response rate of the stiffness modulation by dividing the soft porous structure into inner soft and out stiff porous structures. To guarantee the flow of the air in the inner soft porous structure, a strut-based lattice structure is configured via parametrized conformal design. Considering the impact of air pressure from the inner layer, the outer layer is built by using TPMS structure to keep the shape of the socket. This is because the TPMS structure can display a relatively uniform stress distribution under compressive loading [4]. Fig. 3(b) shows the modified double-layer lattice design of the spherical joint. Based on the double lattice structure configurations, the general workflow is presented in Fig. 4. Lattice configurations for two types of lattice structures will be introduced in the next subsection.

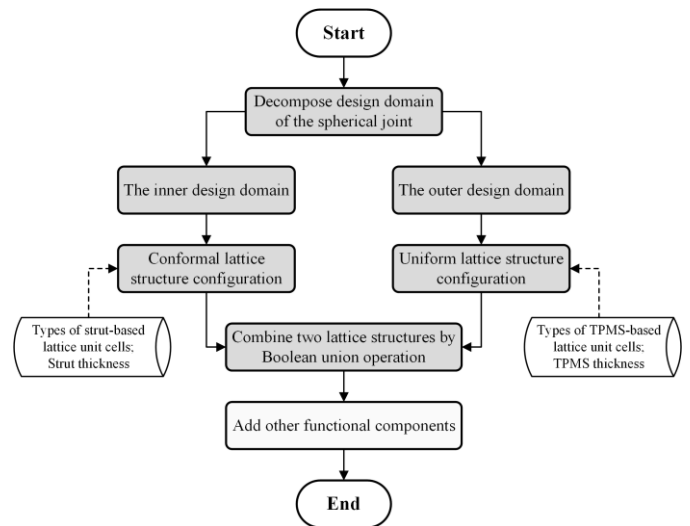


Fig. 4. General workflow of lattice structure configuration.

4.1. Inner parametric conformal lattice structure configuration

The inner layer is responsible for converting air pressure into mechanical work. Due to the high deformable properties of the inner layer, strut-based structure with negative Maxwell value are used to infill the inner structure. Fig. 5 shows the main steps of a parametric conformal strut-based structure configuration process.

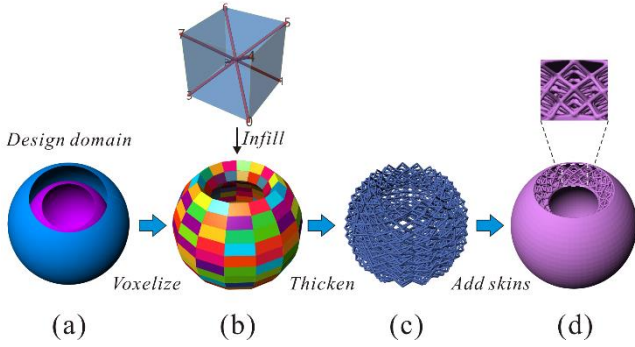


Fig. 5. Workflow of the inner parametric voxel-based lattice structure configuration: (a). design domain defined by two untrimmed surfaces; (b). conformal fill of voxels between the two surfaces and the BCC unit cell; (c). thickness definition for strut-based unit cells; (d). final inner lattice configuration with skin structures and partial lattice enlargement.

Firstly, two untrimmed surfaces are constructed to define the inner design domain. Then, the design domain is divided into many voxels parametrically. Body-centered cubic (BCC) unit cell is used to fill within the conformal voxels. After that, the lattice structures obtained are supplied a thickness value to form a solid lattice structure. Finally, two skin structures are used to perform a union operation with the solid lattice structures. The lattice structures are covered by the two skin structures. Because the thickness of the inner skin has a direct impact on the inflatable deformable performance, the coupling relationship between unit cells and thickness should be tested.

It should be noticed that the size of lattice unit should respect AM capability to guarantee the manufacturability of each unit cell. Here the maximum size of voxel (L_{max}) is set as 4 mm. In this design, the parameter of the inner layer is defined as $r_1 = 15\text{ mm}$, $r_2 = 23\text{ mm}$, $\theta = \pi / 6$. Fig. 6 gives section views of the spherical joint from the top and front views. Therefore, the minimum number of lattice cells in the x , y and z direction should be set as:

$$\begin{aligned} n_x &= \frac{2\pi r_2}{L_{max}} \approx 36; \\ n_y &= \frac{r_2 - r_1}{L_{max}} = 2; \\ n_z &= \frac{(\pi - \theta)r_2}{L_{max}} \approx 15; \end{aligned} \quad (3)$$

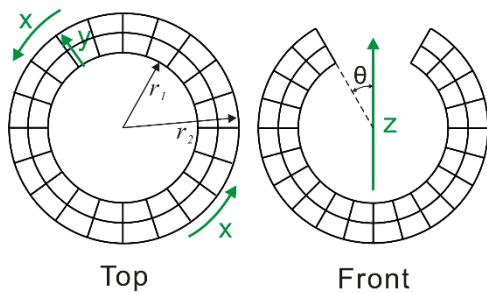


Fig. 6. Manufacturability analysis for the inner lattice structure.

4.2. Outer rigid uniform TPMS-based trimmed lattice structure configuration

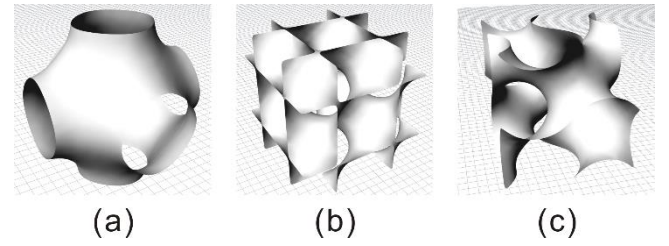


Fig. 7. Three common TPMS unit cells: (a). Schwarz P surface; (b). Diamond surface; (c). Gyroid surface.

The outer layer acts as an auxiliary layer to prevent inner air pressure from deforming the sphere joint. Therefore, TPMS structures are chosen to infill this layer due to stable mechanism and good energy absorption performance under compressive loading [4]. Fig. 7 displays three common TPMS structures in the literatures. They can be populated into the outer layer.

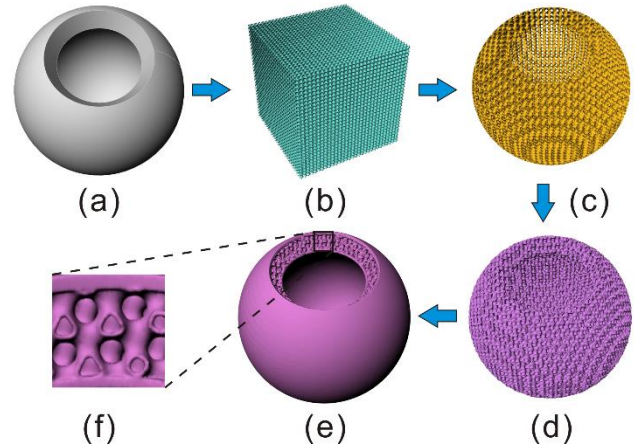


Fig. 8. Workflow of the outer trimmed-based TPMS structure configuration: (a). design domain; (b). populate Schwarz P unit cell into the bounding box; (c). trim the lattice mesh surface; (d). thicken the trimmed surface; (e). final outer TPMS structure configuration with skin structures; (f). Partial TPMS structure details.

Fig. 8 introduces the workflow of outer uniform lattice configuration by using Schwarz P unit cell. At first, a closed design domain of outer lattice layer is built. A bounding box is applied to cover the whole design domain. Within the bounding box, Schwarz P unit cell is populated to finish the lattice configuration. Then, the TPMS structure is trimmed by using the boundary of the design domain to obtain the lattice mesh surface inside the design domain. After that, the trimmed surface is thickened to obtain the desired TPMS structure. At last, two skin structures are coupled with the final TPMS structure through Boolean union operation. Fig. 8(e) gives the TPMS structure configuration process of the outer design domain. It should be noticed that the size of TPMS unit cell should also respect the manufacturability of AM capability to avoid any surface collapse in printing. In this example, the size of TPMS unit is also 4 mm. The critical size should be set as different values in practice to fit any AM process capability.

Because the TPMS-based lattice structure configuration mainly serves as a buffer for air pressure, it can be replaced by other non-TPMS unit cell configuration.

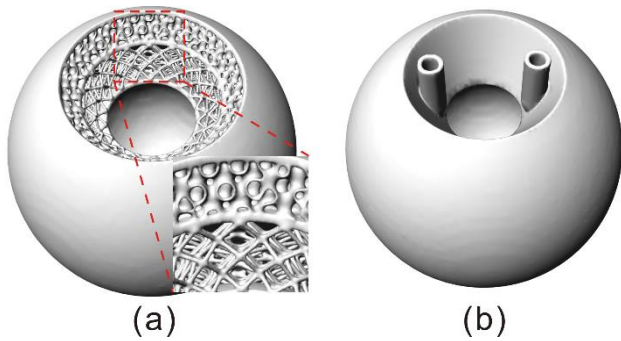


Fig. 9. (a). final hybrid lattice structure configurations; (b). the hybrid lattice structure configurations with stomata.

A Boolean union operation is used to obtain the final spherical joint using the hybrid lattice structure configurations method. Fig. 9 shows the final lattice structure obtained. Regarding build orientation optimization and support design for the surface of the socket, readers can find an AI-based build orientation determination method in [22] and a bio-inspired support design & optimization method in [23].

4.3. Graded lattice design and other lattice unit cell configurations

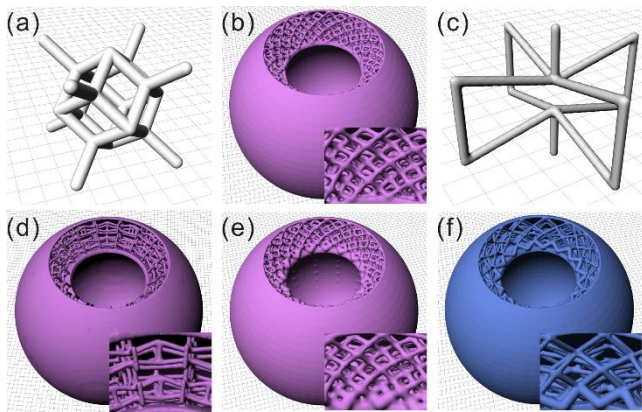


Fig. 10. Different types of lattice unit cells and graded lattice unit cells: (a). Dodecahedron unit cell; (b). uniform Dodecahedron units; (c). auxetic unit cell; (d). uniform auxetic units; (e). graded Dodecahedron units; (f). graded BCC units.

In our modified design, the robot can achieve high-speed response performance by adjusting the thickness of inner design domain. However, the robot should also provide different stiffness values in different manipulator configuration. To solve this issue, different types of lattice unit cell can be populated within the inner and outer layers. Moreover, uniform lattice structures can be transformed into gradient structures. Fig. 10 shows different types of lattice structure and graded lattice configuration. In Fig. 10(c), an auxetic structure [19] with negative Poisson's ratio is used to populate the inner layer. In addition, the size of both inner and

outer design domains can be seen as variables to optimize the range of stiffness output.

According to the functional properties of the spherical joint, multi-material AM techniques can be applied to print the design structure. Soft and hard material can also be used for the inner and outer lattice structure configuration, respectively. Hence, multi-material direct writing and jetting AM techniques can be used to print the functional spherical joint.

5. Discussion and Conclusion

In this paper, a novel design method of combining uniform and conformal lattice configurations is proposed to achieve a variable stiffness modulation applied to soft robots. The stiffness can be controlled by tuning the air pressure on the inner socket. It has the potential to provide a new actuation in deformable arm, hand manipulation or exoskeleton field. However, to verify the feasibility of the concept design, in the next step, direct writing and jetting AM processes will be used to print a set of joint samples for performance characterization. Numerical simulation experiments will also be implemented. In the future, experiment results will drive a design optimization method to optimize the lattice configuration according to performance requirements and experiment results. Further investigations will be carried out to study the influence of different lattice unit cells, gradient distribution of thickness and even different inner and outer design domain divisions on stiffness modulation.

Acknowledgements

This research work is supported by China Scholarship Council (first author), under Grant No. 201806950079.

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