New Joint Design for Enhancement of Mobility of Spacesuits for Planetary Exploration

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Abstract

A new joint design for next-generation spacesuits is proposed. The next-generation spacesuits will support the moon exploration missions, where low weight, high mobility and functionality will be the main requirements. We proposed design of joint based on flexible “origami” parts supported by artificial muscles to realize spacesuits working under relatively high operating pressures. The conceptual design of the joint and calculations on the origami parts are shown.

Keywords: Spacesuits, extravehicular activity, mobility, joints, and artificial muscles

1. Introduction

Investigations on spacesuits for the coming exploration missions to the moon and Mars have been carried out according to the specific mission requirements, where essential factors such as savings of weight and volume, suits universality, size-adjusting capability, fast donning and doffing, high functionality, easy maintainability, reliability and safety can play key roles in the spacesuits performance and mission’s success. Current extravehicular activity (EVA) spacesuits, which are used on the low earth orbit, have been designed for the microgravity environment, where the weight of spacesuit is not a crucial factor for the astronaut mobility and performance efficiency. Current EVA spacesuits can difficultly answer to the tasks of the future space missions.

The National Aeronautic and Space Administration (NASA) of the United Stated has initiated a new Constellation Program, which will carry human back to the moon and beyond. Using the Ares and Orion rockets NASA plans to return human to the moon by 2020 and set up there a lunar outpost. International participation in the moon exploration has been expected, and as a first step toward establishing an international cooperation NASA and 13 other space agencies have been discussing their opinions on an approach to the exploration of solar system.

In October 2007 as a part of the Constellation program NASA released a request for proposals (RFP) for the Constellation Space Suit System (CSSS) acquisition (the details could be found in NASA procurement website for the CSSS requirements http://procurement.jsc.nasa.gov/csss/). The CSSS will be a single space suit system to provide intravehicular activity and EVA on the moon and in zero-weight environment.

Development of a next-generation spacesuit for the planetary exploration represents considerably complicated technical tasks, where conflicting demands such as enhancement of mobility without additional weight penalties should be met. Modern science and technology have made great progress from the times when the present spacesuits design was basically decided (1970s) in various fields including information, energy and materials technologies, therefore effective solutions can be provided to the tasks raised in the spacesuits design.

In the present work, a new joint design has been proposed for the next-generation spacesuits. The present joint design is based on combination of fixed and flexible “origami” parts supported by artificial muscles to provide a required spacesuit’s mobility.

2. Spacesuit’s concept (1)

A proposed spacesuit (**Fig. 1**) is designed for supporting EVAs in microgravity conditions on the International Space Station, as well as for EVAs on the lunar and Martian surfaces. The spacesuit design is based on the next principles:

1) The present model belongs to the full pressure type and provides donning and doffing without assistance,
2) As an essential starting point of the present model, a high operating pressure to eliminate prebreathe procedure is considered. In case of cabin pressure of 1 atm, the operating pressure would be set up at 0.6 atm,
3) Universality and adaptability to various environmental conditions are realized by means of interchangeable parts and additional garments,
4) Flexibility is provided by advanced joints design and power assist systems,

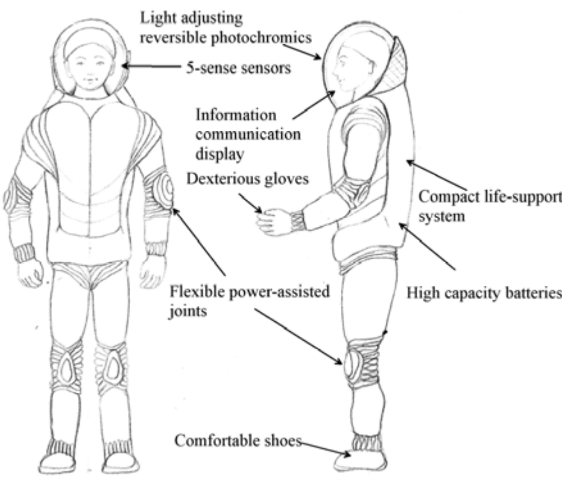

Fig. 1 Spacesuit model.

5) Regeneration technologies and in-situ environmental utilization are included for highly effective life-support system realization,
6) Low weight is achieved by gaining weight economy with advanced garment and life-support system, and
7) Real time communication and wide informational support provide high safety and work efficiency.

3. Spacesuit's mobility

Main factors of the spacesuit's mobility in the conditions of gravity (surface of the moon and Mars) are considered to include the weight of spacesuit, weight distribution (position of the center of weight, for example), and flexibility provided by spacesuit's mobility systems, which incorporate joints and bearings. The joints are applied at the positions of bending (wrists, elbows, knees, shoulders, etc.) to secure the mobility of hands, arms, and legs. The bearings are applied at the places where twisting and rotation is necessary. For example, the arm assembly of the current EMU includes the shoulder joint and upper arm bearings, as well as the elbow joint and wrist bearing. Combination of joints and bearings ideally can provide full range of motions. However, application of bearings adds an additional weight and decreases crew comfort.

The released in 2007 by NASA RFP for CSSS acquisition in its basic requirements for the spacesuit mentions that a soft upper torso will be used, that is different from current EMU, and bearings will be applied more widely. The operational suit pressure will be at least 30 kPa, which is higher than that value used in the Apollo EMU (25.5 kPa). High operating pressure is known to influence negatively the mobility of soft spacesuits, in which laminated fabric layers are used, because they have a tendency to become very stiff and hard to bend when inflated. Therefore, for the next-generation space suits for the moon and Mars exploration the design of mobility systems, including joints and bearings, will play an especially important role in the total mobility of spacesuits.

In the present work the approach to design of mobility systems is based on combination of joints, providing bending, and solid-lubricant assisted rotational elements. The joints are designed according to the following considerations:

1) Preservation of constant volume of the joint during motion.

If the joint motion (flexion, rotation, abduction, etc.) leads to the decrease of the volume of the joint, then additional physical efforts are required to overcome the gas pressure increase. Thus, to keep the joint volume constant is one of the essential points of the joint design.

2) Control of an elongation force (a kind of spring force) during flexion.

Any volume with soft walls filled with a gas tends to adopt an equilibrium shape that in case of arm garment, for example, would be a stretched cylinder; therefore when flexed at elbow, this cylinder tends to return to a straight position and elongate. As a result flexing of the arm and keeping it at a flexed position requires considerable physical efforts.

To illustrate the mechanics of joints we calculated the distribution of stress for a simplified model of an arm assembly. For a complete analysis of stress distribution we should consider a joint action of internal pressure and bending moment, however in the present work we assume that the model is subjected to the action of only internal pressure. The model is considered as a thin-walled shell consisting of two cylindrical shells connected through a toroidal shell. Its geometry and nomenclature is given in **Fig. 2**(a), where a is the radius of cross-section and h is the wall thickness. Assume that the shell is subjected to the action of the internal pressure P. Then the meridional σ_1 and circumferentional (hoop) σ_2 membrane stresses (Fig. 2 (a)) can be calculated according to the following formulae[(2)]:

Cylindrical part: $\sigma_1 = aP/2h$ (1)

$\sigma_2 = aP/h$ (2)

Toroidal part: $\sigma_1 = aP/2h$ (3)

$\sigma_{2max} = aP/2h(1+b/(b-a)$ (4)

$\sigma_{2max} = aP/2h(1+b/(b+a))$ (5)

where *b* is the curvature radius (See Fig. 2 (a)).

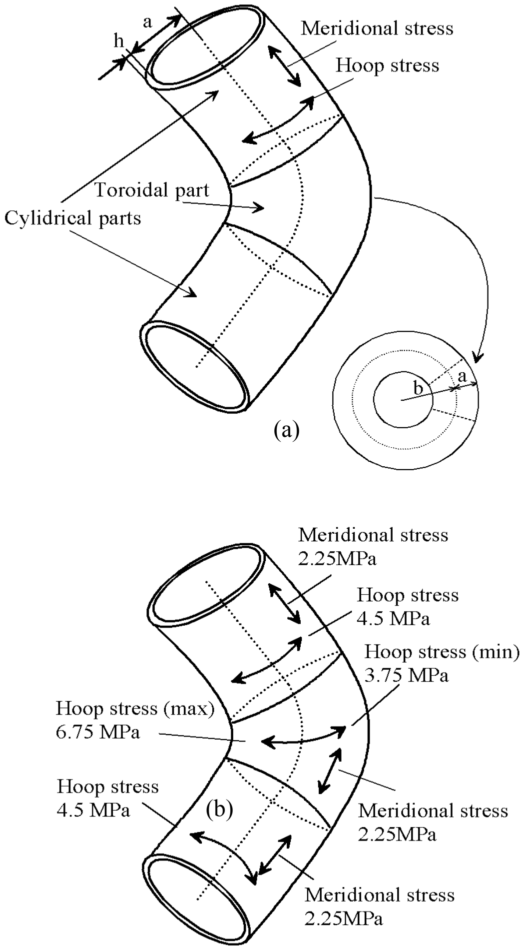

Fig. 2 The model of the arm assembly for the calculation of the membrane stresses and the inner and outer radii of the toroidal part (a) and the results of the calculation (b).

Table 1 The membrane stresses calculated for the model of arm assembly.

Membrane stress		Cylindrical part	Toroidal part
Meridional σ_1, MPa		2.25	2.25
Hoop σ_2, MPa	Average	4.5	4.5
	Min	-	3.75
	Max	-	6.75

The parameters for the equations (1)-(5) were fixed as following: P=0.6 atm =60 kPa, a=7.5 cm, b=15 cm, h=1 mm. The results of the calculations are shown in **Table 1** and in **Fig. 2** (b). The obtained values are not absolute, however they can help to understand the effects of inside pressure on the mobility of spacesuit.

As can be seen from the calculated data for the toroidal segment, the hoop stress varies from the highest value in the inner part (6.75 MPa) to the lowest in the outer part (3.75 MPa), while the meridional stress does not depend on the curvature. It means that total resulting stress distributes unevenly during the bending when the cylindrical shape changes to the toroidal. The information about stress distribution in the shell can be useful for understanding the mechanics of the joint and for the development of requirements to the materials of spacesuits and power assist systems.

4. New joint design

A new joint design is proposed in the present work, where Fig. 2 shows an elbow joint for example. The key conditions are shown in the following:

1) To prevent excessive elongation of the arm assembly an x-shape of the joint is proposed,
2) Upper and lower parts do not change their shape during flexion,
3) Right and left parts stretches and shrinks during flexion,
4) Volume change of the joint during motion is controled by flexible parts,
5) Flexible parts are patterned using origami structure, and
6) Control of flexion is realized with power assist systems based on artificial muscles.

The purpose of artificial muscles is to control the range of elbow joint flexion angle and to eliminate the spring force. As candidate materials for the artificial muscles electroactive polymers, dielectric elastomers, conducting polymers and shape-memory alloys are

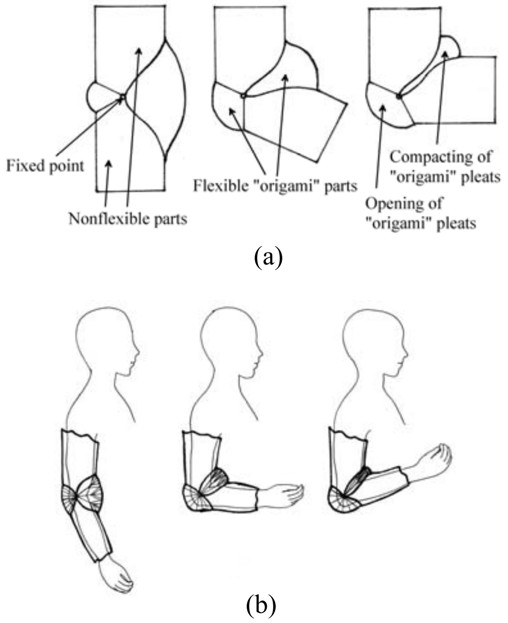

Fig. 3 Illustration of the new joint design: (a) Schematic view of the joint model, and (b) The arm assembly model.

selected; their possibilities for selection are evaluated from the standpoints of stress, strain, reproducibility, and response rate, as well as specific requirements to materials for application in spacesuits.

With the help of origami structure a compact and simultaneous folding/ unfolding capability can be realized. Moreover, origami structure can control flexibility depending on direction of applied force. Such sensitivity to the direction of applied force can make power assistance very effective.

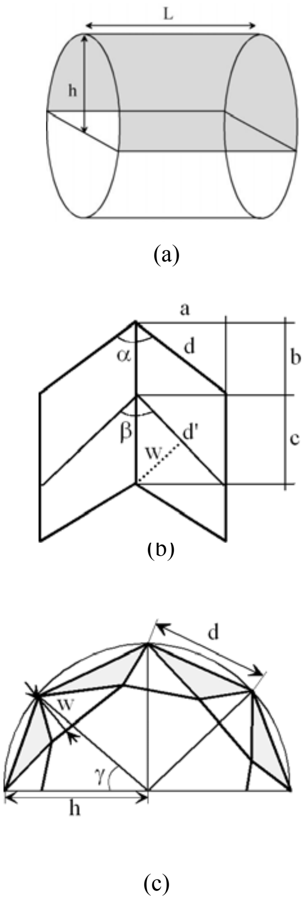

Fig. 4 Illustrations to the calculation of the origami arch:

(a) cylindrical segment, where L is length and h is radius;
(b) origami pattern unit;
(c) cross-section of the folded origami arch with number of origami units N=4, where d is edge of the unit, and w is the thickness of the arch.

5. Calculations of the origami parts

As a basic shape for the origami parts of the design shown in **Fig. 3** a cylindrical segment, which is a half of cylinder in our case, was selected (**Fig. 4** (a)). The length of the cylinder L and the radius h of the cylinder are different for the inner and outer “origami” parts of the arm assembly, shown in Fig. 3.

The cylindrical segment is tessellated with an origami pattern in such a way to allow folding and unfolding in axial direction. Thus obtained structure is called an origami arch. The length of the cylindrical segment L depends on the size of the flexible origami parts and on allowed degree of folding and unfolding. The radius h is determined by the diameter of the arm assembly and position of a point of rotation (see Fig. 3).

As a basic element for the origami pattern we selected a Miura-ori pattern(3), shown in Fig. 4(b). Miura-ori represents geometrically and elastically coupled arrays of mountain and valley folds, which can fold and unfold simultaneously. Geometrically the Miura-ori pattern is a tessellation formed by regular tiling of trapezoids with sides d, c, d’ and b.

$$d = b/\cos(\alpha/2) = a/\sin(\alpha/2) \qquad (6)$$

$$w = c\sin(\beta/2) = a\cos(\beta/2) \qquad (7)$$

If α=β, then we obtain a flat Miura-ori pattern. Otherwise, the pattern repeats the shape of cylinder. If α>β and angle β fixed at 90^0, then vertexes at angle α lye on a straight line when the origami pattern is completely folded. A cross-section of a folded into half-cylinder origami pattern is shown in Fig. 4 (c). The length of the edge of origami unit d represents a dimensional characteristic of the origami unit in a folded state. Sector angle γ is connected with α and β by the following formula:

$$\alpha - \beta = \gamma \qquad (8)$$

From the other side, α-β is connected with the number of origami units N (Fig. 4(c)):

$$\alpha - \beta = \pi / N \qquad (9)$$

Formula (10) reveals connection between radius of the cylinder h and edge of origami unit d:

$$h\sin(\frac{\alpha - \beta}{2}) = d/2 \qquad (10)$$

If we substitute β=π /2 into formula (7), then we obtain that thickness w is:

$$w = 0.707c = 0.707a \qquad (11)$$

The number of units N, necessary to construct cylindrical segment with given parameters can be calculated using equation (12):

$$\cos(\pi/N + \pi/4) = 0.707 - a/h \qquad (12)$$

Since the value N should be integer, we take the nearest integer number as the solution of equation (12).

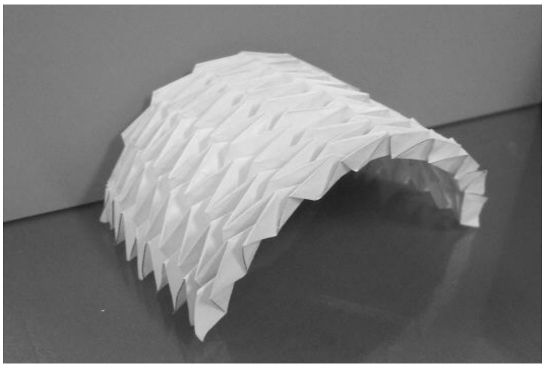

Fig. 5 Paper model of the origami arch.

Hence, we can obtain value of angle α by substituting the number of units N:

$$\alpha = \pi / N + \pi / 2 \qquad (13)$$

and thereafter b:

$$b = a / \tan(\alpha / 2) \qquad (14)$$

In that way it is possible to connect the dimensional characteristics of the cylindrical segment with the parameters of a single origami unit.

To construct the cylindrical segment with given L, h, and w the angles α and β, number of origami units N, as well as a, b, and c parameters were calculated. As a result we designed two origami arches for the inner and outer origami parts that can perfectly fit to the model shown in Fig. 3.

For example, if we fix the thickness w at 1 cm, and the height of the segment h as 5 cm, then by substitution of the given values into the formulas (11)-(14) we can obtain a=c=1.14 cm, number of units in the arch N=9, $\alpha = 110^0$, b=1 cm, and d=1.73 cm. The length L can be easily adjusted by adding origami units in an axial direction. The paper model of the origami arch constructed using these calculated data is shown in **Fig. 5**.

The origami arch is stiff in a radial direction and flexible in an axial one. It can be compactly folded and easily unfolded with retaining of an arch shape, thus providing shrinking and stretching of the inner and outer parts of the joint shown in Fig. 3 (b).

The origami arch allows bending of the elbow joint. Concerning twisting, an additional system should be designed, that would correspond to the bearings applied in the current spacesuits. As a possible alternative to the bearings, a solid-lubricant based system can be proposed, however application of solid lubricants in spacesuits requires an additional feasibility study.

6. Summary

The proposed design provides realization of a constant volume joint, where flexibility and volume change control are achieved with origami structure. The x-shape of the joint keeps the length of arm assembly constant and prevents an undesirable elongation. Origami structure proposed for the flexible parts of the joints has the advantages of characteristic tailored flexibility and compact folding/ unfolding capability. The origami arch was calculated to construct the flexible origami parts of the elbow joint with given parameters such as curvature and thickness.

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