Mechanism and Machine Theory 121 (2018) 563–582

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmachtheory

Research paper

Conceptual configuration synthesis of line-foldable type quadrangular prismatic deployable unit based on graph theory

Chuang Shi[a], Hongwei Guo[a,*], Meng Li[b], Rongqiang Liu[a], Zongquan Deng[a]

[a] State Key Laboratory of Robotics and System, Harbin Institute of Technolo gy, Harbin, Heilongjiang, China
[b] Qian Xuesen Laboratory of Space Technology, China Academy of Space Technology, Beijing, China

ARTICLE INFO

Article history:
Received 5 June 2017
Revised 10 November 2017
Accepted 13 November 2017
Available online 1 December 2017

Keywords:
Structural synthesis
Line-foldable
Quadrangular prism
Graph theory
Deployable mechanism

ABSTRACT

This study proposes a conceptual configuration synthesis method based on graph theory to obtain a series of quadrangular prismatic deployable units (QPDUs) which can be folded into a straight line. Firstly, according to graph theory, graphs of statically determinate QPDUs are synthesized. Secondly, in order to establish the conceptual configuration of QPDUs, weighted graph, weighted adjacency matrix and some rules are analyzed. Combined with graph properties, a procedure for synthesizing conceptual configuration of QPDUs is obtained. Finally, all 78 kinds of QPDUs are discovered by using synthesis approach mentioned above. These QPDUs are then used to build large deployable space mechanisms, such as mast, planar and hoop mechanisms, in different construction methods. This study expands the deployable unit configuration library, and the method can provide experience for the theoretical research in aerospace deployable mechanisms.

1. Introduction

With the development of the aerospace industry, more and more large and light space structures are required to meet the needs of space missions. The size of the space structure has a large effect on the resolution level of earth observation, the distance of space communication, the capacity of sending and receiving data, the capability of precision strike, etc. [1–3]. So, space structures have been one of the hot spots in the field of the space research. As the transport rockets used today have limited storage space, large space structures must be designed as deployable mechanisms which can be folded into a compact configuration before launch and be deployed into a predetermined shape in the orbit [4–6]. Many large deployable structures have been constructed by connecting numbers of modules which are composed of several deployable elements. For example, a deployable mast composed of four prismatic units has been used in the America's SRTM mission [7,8], a deployable mechanism which is made up of hexagonal prismatic modules has been used in Japan's satellite ETS-VIII launched in 2006 [9,10], a deployable mechanism constructed by rectangular pyramid units has been used in Canada's satellite RADARSAT-1/2 [11,12], a deployable antenna structure which consists of a circle of parallelogram units has been used in America's satellite AstroMesh [13], etc. So, the deployable unit becomes a key to build new large deployable structures which satisfy the demand of small folded volume while maintaining stability.

* Corresponding authors.
E-mail addresses: guohw@hit.edu.cn (H. Guo), liurq@hit.edu.cn (R. Liu).

https://doi.org/10.1016/j.mechmachtheory.2017.11.010
0094-114X/© 2017 Elsevier Ltd. All rights reserved.

Many scholars have studied the configuration design of deployable units extensively and have achieved significant progress. The deployable units can be divided into three types in accordance with the form of themselves. First of all, due to the simple structural form and reliable movement, the scissor mechanism is widely used in the construction of deployable structures. You and Pellegrino presented a set of two dimensional and three dimensional deployable structures consisting of scissor mechanism [14,15]. Akgün, et al. presented a novel adaptive spatial scissor-hinge for convertible roofs [16]. Tanaka, et al., proposed a planar radial type deployable structure with single DOF using 8-bar-jointed scissor mechanisms [17]. Zhao et al. constructed a foldable stair by using scissor mechanisms [18]. Lu et al. developed a deployable network on the basis of Sarrus linkages and scissor joints [19]. With the size of the space deployable structure increasing, the mass of the scissor mechanisms becomes very large, which cannot meet the mass requirement of the spacecraft. Therefore, the scissor mechanisms are not suitable for large-scale space deployable structures. Secondly, in past decades, much attentions have been paid to the polyhedral deployable structures which are made by planar linkages. A series of polyhedral over-constrained linkages are proposed by Wohlhart K by inserting planar links on the surfaces of regular polyhedra [20]. Taking 1-DOF planar polygonal linkages as units, Gosselin and Gagnon–Lachance developed a set of polyhedral deployable mechanisms [21]. A family of polyhedral deployable mechanisms are obtained by Kiper [22,23]. Ding, et al. developed a novel prismatic deployable mechanism and an evolved deployable ball mechanism by using polyhedral linkages [24,25]. With a large-scale, deployable mechanisms cannot be implemented by only one polyhedral deployable structure, therefore, they are always constructed by connecting numbers of polyhedral deployable structures. However, the networking method of them is still lacking. Besides, these polyhedral deployable structures can't be folded into a straight line, which is not suitable for large-scale deployable mechanisms. Thirdly, the spatial overconstrained linkages with the advantage of high deployment ratio and good stiffness are investigated in the past few years to construct large deployable mechanisms, and many theoretical achievements have been obtained. Chen and You first attempted to utilize spatial overconstrained linkages such as Bennett linkages [26–28], Myard linkages [29,30], and Bricard linkages [31] as units to bulid large deployable mechanisms. Dai and Wei have performed a number of studies on overconstrained deployable polyhedral mechanisms in recent years [32–37]. Ding proposed a deployable mast using eight-bar overconstrained linkages [38]and some deployable networks composed of type III Bricard linkages [39]and Bennett linkages [40]. At present, the application of spatial overconstrained linkages on deployable mechanisms is still hindered by their complicated configuration and motion path. They can move only when it follows specific geometric requirements, which is not conducive to the structural design of deployable mechanisms. According to the above analysis, when the scale of deployable mechanisms is expanded to 100 m or more, the existing deployable units cannot meet the required stiffness and deployment ratio. As a result, it is urgent to put forward a new line-foldable type QPDU with high stiffness and deployment ratio.

In the research field of deployable mechanisms, much attentions have been paid to the construction of deployable units in past decades. However, little attention has been given to the synthesis and design process for deployable units. The construction methods depend on the personal experience of researchers. Therefore, it is very important to propose a theoretical method of building deployable units. Configuration synthesis is the most effective method for mechanism innovation design, but attentions of configuration synthesis for spatial linkages are mainly focused on parallel mechanisms and spatial single loop overconstrained linkages. In the past ten years, the synthesis method has been divided into three groups [41]: In 1978, Hervé listed all 12 types of displacement subgroups, which laid the foundation of synthesis methods based on displacement subgroups [42]; The synthesis method based on the constraint spiral is developed by Huang, which is applicable to the general and non-restrictive mechanisms [43]; The motion synthesis method which includes the comprehensive method based on the orientation feature set is proposed by Yang [44], the Gf synthesis method proposed by Gao [45] and the linear transformation method proposed by Gogu [46]. Kong and Fang combined a series of single closed-loop mechanisms based on screw theory [47,48]. Li, et al. presented a synthesis approach for single loop deployable linkage using Lie group theory [49–51]. Deployable unit is a complex spatial mechanism which is multi-looped and highly flexible, so, it has some unique topological properties different from parallel mechanism and spatial single loop overconstrained linkages. Therefore, the construction methods mentioned above are not fully applicable to deployable units. Graph theory uses the weighted matrix to describe the topological relations between the mechanism components and the kinematic pair, which is convenient to perform the structural synthesis of deployable units. Based on graph theory, a series of new deployable units can be obtained automatically. However, the studies in the literature related to configuration synthesis of deployable units using graph theory are generally on planar linkages [52–54], while spatial linkages are very rare. Warnaar, et al. obtained many new types of spatial deployable units through a synthesis approach using graph theory [55,56]. Although some studies are available on the establishment of synthesis approach of spatial deployable units, little work has been published on the establishment of synthesis approach of the QPDUs which can be folded into a straight line. The large deployable space mechanisms can be composed of multiple structures with the same repeating QPDUs which are very suitable to use the structural synthesis method based on graph theory mentioned above.

According to the requirement of large deployable space mechanisms, this paper puts forward a series of Line-Foldable type QPDUs which have high stiffness and big deployment ratio by applying the conceptual configuration synthesis method presented in this article. Based on graph theory, a conceptual configuration synthesis method is obtained to acquire a set of QPDUs. Firstly, graphs of statically determinate QPDUs are synthesized. Then, a weighted graph and adjacency matrix are established to realize the topological description for QPDUs. The establishment process of the conceptual configuration for QPDUs are then proposed. Finally, all 78 conceptual configurations of QPDUs are discovered using the method mentioned above.