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Topological principle of strengthened connecting frames in the stretchable arm of an industry coating robot

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ABSTRACT

This paper researches on a stretchable coating robot arm for extremely large parts. It has high enough lateral and vertical stiffnesses within the reachable workspace to keep the required spraying accuracy. According to the functional independence principle, the vertical stiffness is kept by screw driving mechanism working in the vertical direction while the lateral stiffness is safeguarded by an overconstrained stretchable arm. In this paper, the focus is put on the stiffness synthesis of the stretchable arm's strengthened connecting frames by discussing both their lateral stiffness and unit-stiffness under different topologies. The stretchable arm consists of a four-sided scissor-form structure of pivoted links interconnected by strengthened connecting frames at each deployable layer, forming a multi-planar laterally overconstrained structure. Different frames have different stiffnesses and self-weights because of their different topologies. Therefore, the unit-stiffness, which is the ratio between the lateral stiffness and self-weight, is applied as it proved to be a resourceful design index in evaluating the planar stretchable arm. This paper proposes a topological design solution for the strengthened connecting frames, positively influencing the stretchable coating robotic arm's mechanical performance in engineering application.

1. Introduction

A stretchable arm is a kind of mechanism that can be deployed from one form to another and bear a certain load. These can be classified as either one-, two- or three-dimensional stretchable arms. Iqbal et al. proposed a type of stretchable arm that is stable in two different configurations [1–3]. Equivalent mechanisms were initially proposed by Dai and Jones [4, 5]. In fact, there are many applications of stretchable arms in engineering, for example, NASA developed an Astro-mast deployable lattice column in 1967 [6], Qi investigated large stretchable arms constructed by plane-symmetric Bricard linkage [7], Shaker produced folding articulated square truss in 1994 [8].

However, there are also many problems in their process of application, hence many researchers have been paying enormous attention to solving them. Mikulas introduced several rigid concepts and developed a design methodology, which permits a rational comparison between any two alternative concepts [9]. Professor You proposed a new concept of self-locked expandable cylinders, which is ideal for deployable booms [10]. Crawford proposed formulas to describe the mass, bending stiffness and yield stress of certain stretchable arms [11]. Inflatable rigidizable isogrid booms also attracted attention from many researchers [12–14].

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A scissor-form structure of pivoted links, as constitutive part of any kind of stretchable arm, has many advantages. It can be driven by a single motor fixed at the base of the stretchable arm, which confirms that there is no electric equipment on the distal platform, largely improving the equipment's susceptability and the overall operational safety. It also allows a larger foldability ratio, broadening its range of application to encompass even ampler workspaces, such as air handling and large equipment manufacturing. As a result, it is widely used in many industries [15–19]. However, recent studies also show that deployable structures have poor stability during transformations. They can either gain structural stability under external loads [20, 21], or fall into bifurcations along the motion paths [22–24].

Going back to its applications, there are in fact many in aerospace structures [25, 26]. Georgian produced a space antenna for symmetric and non-symmetric radio telescopes with scissor-form pivoted links [27]. The kinematics of foldable arms in space engineering was investigated by Nagaraj in 2009 [28]. The kinematics of a one-degree-of-freedom network of Bennett linkages was investigated by Lu in 2016 in geometry, the influence of the geometric parameters and procedure for connecting the unit mechanisms [29]. In nature, scissor-form pivoted links are also widely used by some biological organisms with the purpose of retaining their exterior shapes [30–33]. Zhao proposed a deployable structure for a morphing wing. It had the merits of high structural stiffness, strength of a truss frame and motion flexibility [30]. Lu proposed a network of type III Bricard linkages by linking the units either using scissor linkage elements or hinged parallelograms [33]. In infrastructural applications, Zhao proposed a foldable stair and investigated its structure synthesis and static analysis [34]. Nagaraj presented an approach, based on constraint Jacobian matrix, to obtain the stiffness matrix of widely used deployable pantograph masts with scissor-like elements [35]. Recently, Sun studied the vibration through an n-layer scissor-like structured vibration isolation platform. In the platform, the scissor-like structure proved to be an interesting design solution, as it beneficially contributed for a better nonlinear stiffness and damping characteristics in vibration control [36].

The accuracy of a stretchable arm depends on its vertical and lateral stiffness. In a coating robot's stretchable arm, its vertical stiffness is kept by a screw driving mechanism working in the vertical direction, while the lateral stiffness by the overconstrained mechanism, consisting of scissor-form pivoted links and strengthened connecting frames. However, single scissor-form pivoted links have poor stability in the lateral direction, particularly when there is an unexpected side-force exerted on them during operation. It was Zhao who proposed the method of connecting strengthened frames in three sides to form an overconstrained mechanism in the lateral direction, thus increasing its lateral stiffness [37]. Zhao analyzed and proposed two types of strengthened connecting frames to connect scissor-form pivoted links by comparing their lateral stiffnesses. However, no principles were presented on how to get a frame able to satisfy demands such as required stiffness, minimum cost, etc.

Therefore, this paper focuses on various topological designs of strengthened connecting frames, which are pivoted with identical scissor-form pivoted links in four sides to increase the stability and lateral stiffness in deployment. In this process of design, not only are the frames projected to meet the required lateral stiffness in order to sustain any unexpected side shock exerted on them, as also a cost-efficient design ought to be attained. Hence, this paper investigates several different strengthened connecting frames in order to find out a practical design which meets the requirements mentioned above. The principle will be discussed in detail in Sections 2–7.

2. Synthesis of coating robot system

In this section, we introduce the synthesis of the complete coating robot system, comprising an orthogonal three-dimensional space system, a coating system of two degrees of freedom, a paint transporting system and an electric control system, which are shown in Fig. 1.

In Fig. 1, the orthogonal three-dimensional space system's constitutive elements are well captioned, namely, linear guide rail in x-direction, 1, linear guide rail in y-direction, 2, and stretchable arm in vertical/z- direction, 3. The described system is responsible for adjusting the position of the entire coating robot, however, its three constitutive parts are decoupled from each other. The stretchable arm, which is the element being investigated in this paper, only rules the motion along the vertical direction. In particular, the topological design of its strengthened connecting frames is the main focus of research. At the distal extremity of this stretchable arm is the spraying head, which consists of an end effector with two degrees of freedom responsible for adjusting the orientation of the spraying gun. This end effector includes two orthogonal rotational joints.

On the other hand, the paint transporting system is mainly responsible for paint supply, demanding an exact start-stop controlling strategy, adequate measurement procedures, accurate pressure flux, maintenance, etc.

Most of the controlling effort put into the coating robot system, as a whole, is obviously related to its trajectory control. To do so, pre-saved trajectory data needs to be iteratively processed on a feedback-based closed control loop, in order to constantly make the necessary subtle adjustments to counteract any unsatisfactory parameter reading coming from installed sensors. The stretchable arm's stability plays an integral role in guaranteeing as good readings as possible. Several strengthened connecting frames, involved by four columnar scissor-form chains of pivoted links, comprise the innovative design herein proposed, as shown in Fig. 2. All pivoted links composing the scissor-like chains are equally sized, exception made for the last two links of each extremity, which are shorter, as can be seen in Fig. 2(b). That being said, Fig. 2(a) illustrates a section of the proposed solution for the stretchable arm, with a full network of four columnar chains of four layers with a strengthened connecting frame each.