

Optimization of retractable structures utilizing bistable compliant mechanism



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ABSTRACT

An optimization approach is presented for a retractable structure consisting of bistable compliant mechanism. The structure is modeled using truss and beam elements, and snapthrough behavior is utilized to generate large deformation under small input displacement and recover the initial shape by application of a small reversal force. The parameters such as nodal locations and cross-sectional areas of members are optimized to minimize the error of nodal displacements from the specified target values. It is shown that the deformed shape, required input force, and stiffness against lateral loads can be controlled independently by modifying nodal locations and stiffnesses of different sets of members. It is also shown through an example of roof model that the maximum load required for shape transformation can be effectively reduced by utilizing the flexibility and self-weight of structure.

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1. Introduction

Mechanisms are used in variety of fields of engineering including robotics and mechatronics. The direction of motion is modified and a large output displacement is generated from a small input displacement utilizing mechanisms. In order to reduce input force, it is conventional to employ an unstable bar-joint model called link mechanism. However, when an unstable mechanism is used for a retractable roof in architectural engineering, the structure cannot have required stiffness against long-term and short-term design loads. A constraining force should also be applied to ensure stability of structure in the process of shape transformation, and a force in reverse direction is needed to recover the initial shape.

Mechanisms are extensively utilized for deployable structures in architectural engineering [1,2]. The shape of a pin-jointed truss can be controlled by placing some actuators instead of truss members. A flexible truss consisting of bars and actuators is called variable geometry truss (VGT), which is used for robot arms, deployable structures in space, etc. Senba and Furuya [3] developed an approach to optimizing the geometry of a VGT considering its vibration modes. Optimization methods for robot arms to avoid obstacles are also presented [4]. However, many actuators are generally needed for shape transformation of a VGT.

The mechanisms including VGT are also used for small deployable structures and shape transformation of long-span retractable roofs in civil and architectural engineering. However, very limited types of mechanisms such as scissors mechanism are used in this field [5,6]. Furthermore, the parameters to realize the desired kinematic relations are adjusted manually using explicit geometrical formulas [7–9]. Vu et al. [10] carried out parametric study on locations of cables and struts for deployable tension-strut structures.

In contrast to conventional unstable link mechanisms, a compliant mechanism utilizes elastic deformation of structural parts to produce large output displacement in different direction from the input displacement [11]. It can also store strain energy utilizing bistability and flexibility of the structure. In the initial definition of compliant mechanism, the structure is designed as continuum [12,13], because it is aimed to be a single-piece product in micromechanics, and to have less frictional noise than a link mechanism. However, for large structures in civil and architectural engineering, the compliant mechanism can be modeled as a flexible bar-joint structure incorporating deformation of members. A bar-joint mechanism can be easily re-modeled to frame mechanism utilizing flexibility of joints [14,15].

Optimization methods have been extensively developed for generating compliant mechanisms. Ohsaki and Nishiwaki [16] presented an optimization approach to generating multistable compliant bar-joint mechanisms that have multiple stable self-equilibrium states at both deformed and undeformed states utilizing snapthrough behavior and contact to an obstacle. The bar-joint structure enables us to eliminate the difficulties due to

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local member buckling in the optimization process considering geometrical nonlinearity. Oh and Kota [17] categorized the behaviors of bistable mechanisms. Ohsaki et al. [18] optimized clamping members of frame-supported membrane structures utilizing the flexibility of frame model. Huang and Xie [19] optimized a bridge-type structure considering geometrical nonlinearity.

A bistable structure that has two self-equilibrium states can also be utilized to shape transformation of structures. Gantes and Konitopoulou [20] investigated constructability of a bistable deployable arch through geometrically nonlinear analysis and physical model. Kabadze et al. [21] discussed basic properties of a bistable shell unit.

In this paper, an optimization approach is presented for designing retractable structures consisting of bistable compliant bar-joint mechanisms. Each mechanism is controlled by only single input force to generate large deformation through snapthrough behavior. Therefore, due to geometrical nonlinearity, it is not straightforward to achieve the target deformation through optimization of nodal locations and member stiffnesses. The parameters of a column-type mechanism are optimized using a heuristic approach called tabu search. It is shown that the deformed shape, required input force, and stiffness against lateral loads can be controlled independently by modifying nodal locations and stiffnesses of different sets of members. The characteristics of a roof-type bistable compliant mechanism are next compared with those of unstable link mechanism. It is shown that the maximum required force for deformation can be effectively reduced utilizing the flexibility and self-weight of structure.

2. Bistable compliant mechanism

In this section, we summarize, for completeness of the paper, the properties of bistable compliant mechanism modeled as a flexible bar-joint system using truss elements. Snapthrough behavior is utilized to realize a bistability of structure, which has a deformed stable self-equilibrium state in addition to the initial undeformed state; see, e.g., Refs. [16,22] for details.

In order to explain the basic concept of bistability, consider a two-bar shallow truss, as shown in Fig. 1, subjected to vertical load P_1 , where solid and dotted lines represent deformed and undeformed shapes, respectively. The vertical displacement of the center node is denoted by U_1 .

Fig. 2(a) illustrates the sequence of deformed shapes against vertical load P_1 . The thick lines denoted by 'a' correspond to the undeformed initial shape. We suppose that the deformation is controlled by a nodal displacement using, e.g., an actuator clamped to the node. Fig. 2(b) illustrates the relation between the input displacement U_1 and the associated input force P_1 . The points 'a', 'b', ..., 'e' in Fig. 2(b) correspond to the shapes 'a', 'b', ..., 'e' in Fig. 2(a), respectively. When U_1 is increased from 0, the force P_1 reaches the local maximum at 'b', which is called limit point. By further increasing U_1 , P_1 reduces to 0 at 'c', where two bars are located horizontally between the supports. The shape 'c' is a self-equilibrium shape that is retained without external force. However, it is unstable if the vertical displacement is not restrained, because a slight disturbance to the node leads to a

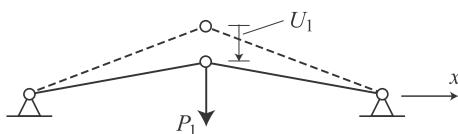


Fig. 1. A two-bar truss subjected to a vertical load; dotted line: undeformed shape, solid line: deformed shape.

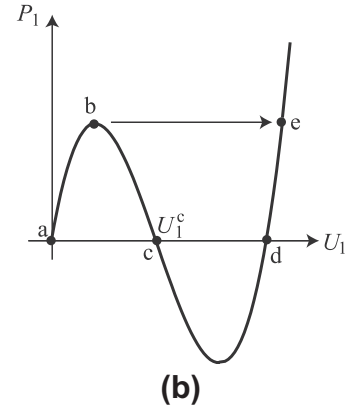
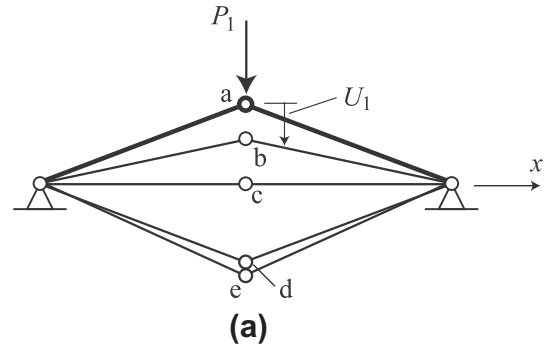


Fig. 2. Relation between input force P_1 and input displacement U_1 of the two-bar truss exhibiting snapthrough; (a) sequence of deformed shapes; thick line: undeformed shape, thin lines: deformed shapes (b) relation between P_1 and U_1 .

dynamic vertical displacement. By increasing U_1 beyond 'c', the truss reaches the shape 'd' corresponding to an unstressed state that is reverse (reflection symmetric) to the initial shape with respect to x -axis. Obviously, this shape is stable and retained without external force.

If the deformation is controlled by the force P_1 , it is possible to increase P_1 stably until reaching the limit point 'b', where the equilibrium state jumps dynamically to 'e' exhibiting snapthrough. Consider the self-equilibrium point 'c' in Fig. 2(b) at $U_1 = U_1^c$ satisfying $P_1 = 0$, and suppose a horizontal rigid plate is placed slightly below the line between the two supports, as shown in Fig. 3, to terminate the deformation slightly beyond 'c' and stabilize the structure by contact to the plate. A bistable mechanism with two self-equilibrium states $U_1 = 0$ and $U_1 \simeq U_1^c$ thus have been generated. Furthermore, the initial state can be recovered by simply adding a small upward force or disturbance at the final state. The stable unstressed state 'd' in Fig. 2(a) is not utilized here to generate a bistable structure, because we assign the requirement such that the initial state can be recovered by a small reverse force at the final state.

Fig. 4 illustrates a bistable compliant mechanism generating specified displacement at output node 'B' as a result of input

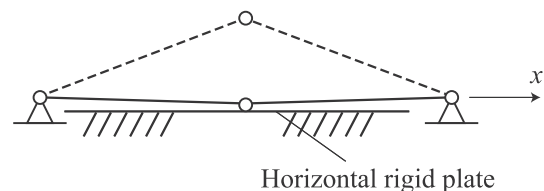


Fig. 3. Termination of deformation and stabilization of the truss by contact to a horizontal rigid plate; dashed line: initial shape, solid line: deformed shape.

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