THE APPLICATIONS OF SHAPE-CHANGING RIGID BODY MECHANISMS IN ARTS AND ENGINEERING

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Article History: Received 3 August 2017; Revised 12 October 2017; Accepted 3 December 2017

ABSTRACT: Design of shape-changing or shape-morphing machines is an area of growing importance. Shape-change can potentially be applied soon to vary the cross section of a wing, create wind or liquid flow control by morphing shapes to locally influence downstream fluid behavior, or vary the size of a car seat to meet a wider array of human anthropometric needs. Rigid body shape-change mechanisms offer many advantages including the high capacity to endure substantial loads while achieving large displacements. Their design techniques are also well-established. The goal of this research project is to develop the synthesis theory to address planar rigid-body shape-change where significant differences in arc length define the problem. A MATLAB-based software was developed to facilitate visual assessment of the process and results. Lastly, this paper illustrates several mechanization examples that apply the segmentation process, and the fundamental mechanism synthesis to guide the motion of the chain of rigid bodies to progress to the subsequent positions.

KEYWORDS: *Shape-Changing; Rigid Body; Mechanisms; Machines; Design*

1.0 INTRODUCTION

Some machines must vary between specific shapes in a controlled manner in order to function. Even though there are various examples of conventional machines that exhibit shape-change capability to function, novel approaches are currently being developed to solve increasingly sophisticated problems. This section presents a summary of this research work in the context of similar shape-changing technologies.

One of the objectives of much study has been on shape morphing aircraft wings that increase performance over a range of flight conditions [1-2]. Most of the design work has revolved around changes between wing profiles of similar arc length [3-5]. The fundamentals of aerodynamics dictate, however, that lift and drag can be significantly altered with a change in camber and chord [6]. This means that for high lift situations like during an approach, landing, and climbing, a higher camber and longer absolute chord are preferable, while for efficient cruising, a lower camber and shorter chord are desirable. Kota et al. [5] synthesized early shape-changing wing mechanisms using rigid-links and fiberglass flex-panels. The application was for the wing's front slat and its rear flap of a fighter aircraft wing that resulted in superior aerodynamic performance.

Hydroplanes or oftentimes called "underwater wings" and ship rudders may benefit from shape-changing [6]. In surface vessels, active fin stabilizers or gyro fins are used to prevent capsizing due to rolling and pitching moments [7]. Figure 1 depicts the position of such wing on a submarine [8]. Gillmer [9] mentions that some underwater stabilizers can have rear flaps that result in the most effective vertical force. On a related note, Molland [10] explained that as a submarine navigates underwater at a speed beyond ten knots, its stability and control depend mostly on the hydrodynamic forces and moments on the hull and control surfaces like the fins and underwater wings. To solve these problems, at least two sets of hydroplanes are suggested.

Figure 1: The two front control surfaces of this Ohio-class ballistic missile nuclear submarine USS Tennessee are seen attached to its conning tower [8]

To control such flaps on underwater stabilizers, Garner et al. [11] experimented with a biomimetic active hydrofoil actuated by shape-memory alloy (SMA) technology. They tested the application of 0.58 mm diameter wires with its material containing nickel-titanium with 10% copper on the outside of the 2 m long gyro fin profile. Other researchers use compliant mechanisms that use single piece material that are optimized in shapes to bend at joints [12-13]. Traditionally, this technology is limited in terms of load capacity and displacement achieved [14]. This is partly due to the flexibility in material that is used in making such mechanisms.

2.0 METHODOLOGY

A shape-changing design problem is usually posed by specifying a set of desired profiles or 2D line shapes, such as wing profiles for loiter and attack modes. The synthesis process is initiated with a segmentation phase that creates segments, which are optimized in shape and length so that they approximate corresponding portions on each desired profile. To finish the design, a mechanization phase adds rigid binary links to each segment in order to achieve a lower degree-of-freedom (DOF) linkage. When conceivable, a 1-DOF system is preferred for ease in control. This presently obtainable design method discusses problems with profiles of roughly the same arc length [14], which is a severe drawback for general synthesis problems.

This short paper reviews a piece of the developments to the rigid-body shape-changing theory that allows design profiles to have substantial dissimilarities in arc length. These developments change the segmentation methodology to include prismatic joints into the chain of rigid bodies used to closely resemble a set of design profiles.

As mentioned earlier, the shape-change problem begins by forming a set of j design profiles that represent the different shapes to be achieved by the machine. Murray et al. [14] defined a design profile j as a curve stated by a well-arranged set of n_j points where the arc length between any two such points can be calculated. As in the much earlier rigid-body shape-change initiatives, each design profile is seen as a piecewise linear curve. The i^{th} point on the j^{th} design profile is labeled $\{a_{j_i}, b_{j_i}\}^T$. Hence, the length of the i^{th} segment of the j^{th} design profile is

$$c_{j_i} = \sqrt{\left(a_{j_{i+1}} - a_{j_i}\right)^2 + \left(b_{j_{i+1}} - b_{j_i}\right)^2} \tag{1}$$

while the arc length of the entire j^{th} design profile is

$$c_j = \sum_{i=1}^{N_j - 1} c_{j_i} \tag{2}$$

The design profiles can be constructed by any number of points spaced at various intervals, resulting in a wide range of c_{j_i}. To proceed with the mechanism synthesis, the design profiles are converted to target profiles that have more common features. This is important so that comparisons can be conducted and a chain of rigid-bodies can be designed that, if repositioned correctly, would approximate all the original design profiles. In earlier work [6], the design profiles were presumed to be of approximately equal arc lengths, C1 ≈ C2 ≈ … ≈ Cp. In that easier case, the design profiles could be converted to target profiles that all have the same number of defining points n dispersed equally along the design profiles so that each segment has about the same length, C11 ≈ C12 ≈ … ≈ C1n ≈ Cpn.

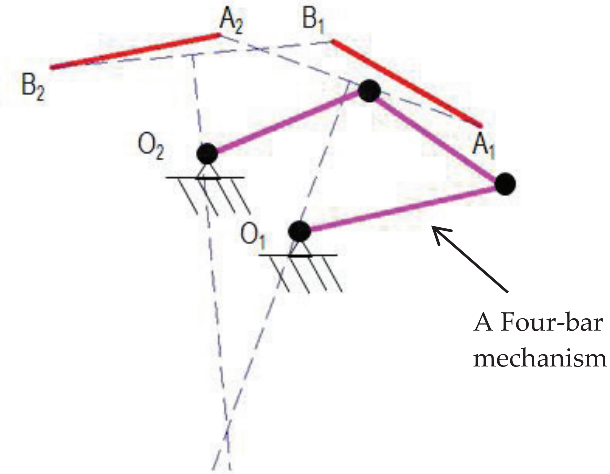


Figure 2: Two-position mechanism synthesis

In short, the next step is segmentation where the developed MATLAB program divides the profiles into rigid-body segments. Mostly, the segments can be of fixed mean length (M-segments), constant-curvature length-changing segments (C-segments) or the fusion of M and C-segments. Then, a chain of these segments were formed by connecting the segments by revolute (R) joints. The M-segment has prismatic (P) integrated in them. Mechanization may follow long-established techniques for two or three positions as explained in detail by many authors such as [15-16]. Figure 2 shows a common graphical technique in mechanism synthesis for known two positions.

3.0 RESULTS AND DISCUSSION

3.1 Artwork Application

As part of a moving sculpture, a machine that changes between the letters "U" and "D" has been designed [17]. The target profiles and the set of rigid body segments that morph between the two letters are shown in Figures 3 and 4, respectively. The design vector for the segments is [C C M M M] which is the result from a search by the MATLAB program. The selection of this design is based on the distance error between the points on the rigid bodies and the corresponding points on the design profiles. A sample of the error matrix EM is shown in equation (3) for a four-segment chain approximating three profiles.

$$EM_{joined} = \begin{bmatrix} 0.26 & 0.15 & 0.25 & 0.11 \\ 0.38 & 0.06 & 0.27 & 0.19 \\ 0.26 & 0.33 & 0.39 & 0.36 \end{bmatrix} \tag{3}$$

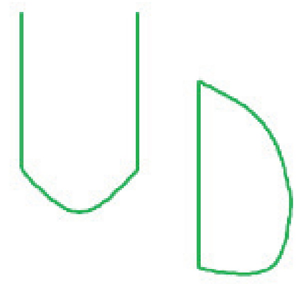


Figure 3: The original design profiles

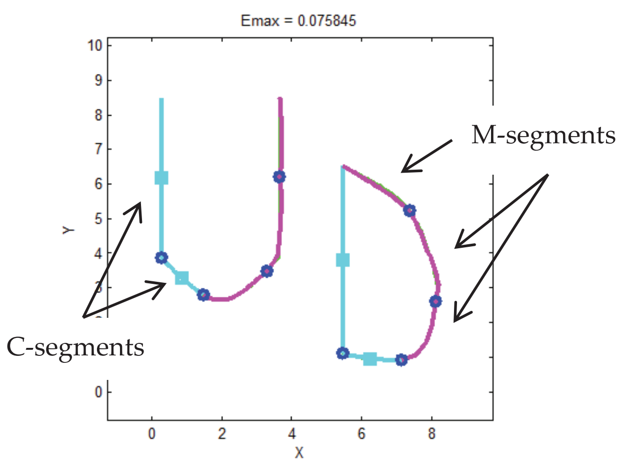
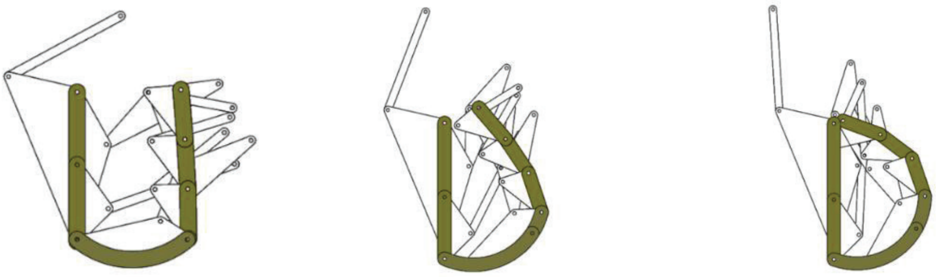


Figure 4: The set of rigid body segments

A single input shown in Figure 5, actuates the mechanized chain since this is synthesized to be a single degree of freedom (DOF) system.

3.2 Engineering Application

Shamsudin [18] studied the possibility of applying the rigid-body shape-changing mechanism on aircraft wing. Although the normalized data of the airfoils are available from sources such as the University of Illinois at Urbana-Champaign (UIUC) Airfoil Database, the actual sizes are not known. Here, the E420 high-lift airfoil is scaled-up in order to have longer camber that helps to attain higher lift. The resulting target profiles have dissimilar arc lengths (C1 = 2.02 and C2 = 2.4).



(a) (b) (c)

Figure 5: Mechanization result for the mechanism that changes from 'U' to 'D'

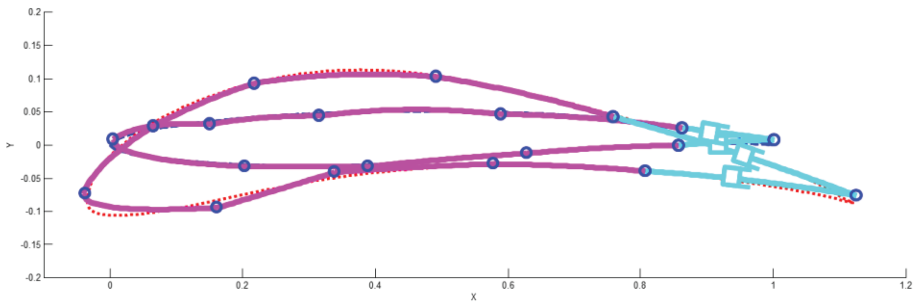


Figure 6: The wing with 10 segments approximating two profiles

Figure 6 shows the segmentation results for the wing after the process was executed in the developed MATLAB codes. As in the previous example, the result is based on the distance errors of the corresponding points. Here, the design vector is [M M M M C C M M M M] and the maximum error after connection is Emax = 0.015 units.

Figure 7 also exhibits the chosen profiles and the progression from high-lift airfoil to high-speed airfoil. The two profiles are positioned as such in hope to have all mechanism dyads placed within the common region. The system produced is one DOF and may be driven by an actuator or a motor on a dyad link that progresses monotonically, as shown in Figure 7(d). Any other dyad would also work well to actuate this mechanism.

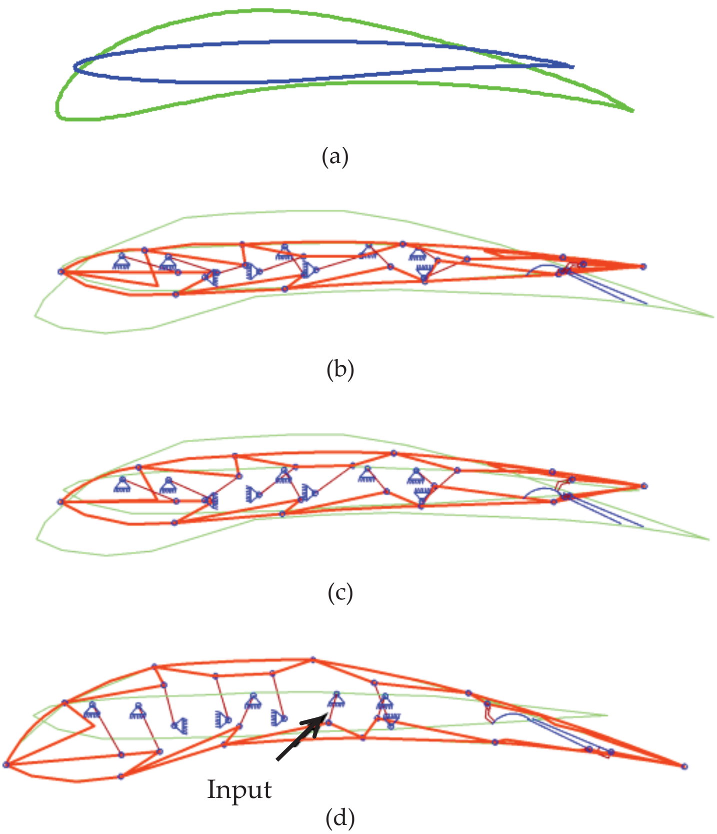
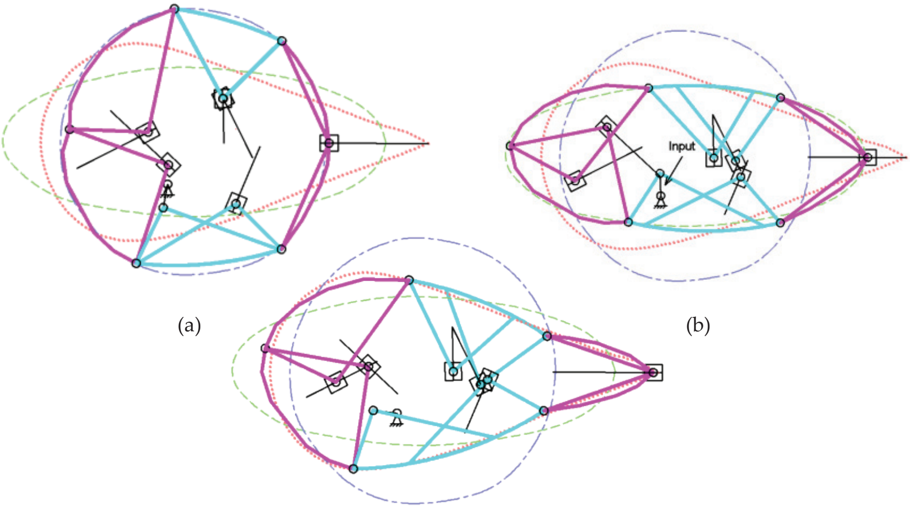


Figure 7: (a) Thin E850 high-speed airfoil and thick E420 high-lift airfoil and (b)-(d) Progression of the morphing wing between E850 and E420 airfoils [18]

Currently, the MATLAB code has been upgraded so that the two-dimensional synthesis of the mechanisms can be done. In previous work, this is done graphically in the computer-aided design (CAD) environment. The synthesis process to find the fixed and moving pivots can be modeled mathematically and this is then turned into MATLAB code. However, in this article, another application of the shape-changing mechanisms can be seen in a turret that can shift the machine profiles between several shapes. Figure 8 displays the capability of such a machine.



(c)

Figure 8: (a) A turret approximating a circle, (b) the turret in an ellipse shape and (c) the turret in a tear-drop formation

4.0 CONCLUSION

The "U" to "D" examples demonstrated the ability to transform between the two letters when their arc lengths are significantly different. The closed profile example was of a wing that transformed between E420 and E850 airfoils. This example displayed that shape-change was possible even when the constraints dictated that all mechanism links must be inside the wing compartment.

ACKNOWLEDGMENTS

The authors are grateful for the support given by UTeM and the Ministry of Higher Education, Malaysia.

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