ON THE KINEMATICS OF PARALLEL MECHANISMS WITH BI-STABLE POLYMER ACTUATORS

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Abstract Binary robotic devices have been proposed to perform complex tasks. These systems do not require feedback and are very easy to control. Their kinematic performance approaches that of continuous devices as their degrees of freedom becomes large. To date, high DOF binary systems have not been demonstrated, largely due to actuator limitations. Recently, significant advances have been made with dielectric polymer actuators. Here it is shown that such actuators have the potential to make binary robotic devices practical. Two designs of a Binary Robotic Articulated Intelligent Device (BRAID) using dielectric polymer actuators are presented. The kinematic performance based on laboratory results and analysis is predicted.

Keywords: Parallel Mechanism, Binary, Bi-Stable, Dielectric Polymer Actuators, Double-Octahedral Variable Geometry Truss, BRAID

1 Introduction

Proposed future tasks for robotic systems such as for missions to Mars will require robot subsystems that are lightweight, inexpensive, and easy to control (Weisbin et al., 1999, Sujan et al., 2001). Conventional robotic technology does not meet these requirements. A key limitation is actuator performance. Recently, important progress has been made in two areas that have the potential to meet this challenge. The first is hyper redundant binary robotic devices, and the second is dielectric polymer actuators (Pelrine et al., 2001). Here these two technologies are brought together in a concept called BRAID – Binary Robotic Articulated Intelligent Device. The BRAID is a lightweight, hyper-redundant binary manipulator with a large number of embedded actuators (Sujan et al. 2001). The kinematic performance is predicted based on measured results of actuator prototypes. Performance is also shown for projected performance of these actuators. Analysis suggests that dielectric polymer actuators have the potential of overcoming current actuator limitations and serving as a key component for high degree of freedom binary element manipulators. Such systems have the potential to be important in future robotic systems

2 Background and Literature

In the 1960's and 70's the concept of binary and sensorless robotics was introduced (Anderson et al., 1967, Roth et al., 1973). More recently increased computation power made the analysis, control, and planning for binary robots feasible (Chirikjian, 1994, Lees et al., 1996). Some experimental work has been done on binary redundant manipulators (Chirikjian, 1994). An example is a large variable geometry truss (VGT) manipulator that was constructed using pneumatic actuators. This implementation, while acceptable for systems with few DOF, cannot readily be extended to develop practical systems with very large DOF. To date, little work has been done to develop simple, lightweight, robust binary design concepts.

Development of dielectric polymer actuators started in the late 1990s (Pelrine et al., 1997). These actuators are one of a large class of electro active polymers (EAP) that has been studied (Madden et al., 2000). Recent progress has resulted from the identification of new and more effective dielectric materials, making it one of the most promising new actuator technologies, with relative strains of up to 380% having been reported (Pelrine et al., 2000, Pelrine et al., 2001). Applications such as robots, acoustic speakers, and solid-state optical devices have been proposed, including a snake-like manipulator using a small number antagonistic pairs of dielectric polymers, controlled in a conventional analog fashion (Pelrine et al., 2001).

To date, very high DOF binary robotic systems implemented with polymer actuators have yet to be explored. This is the subject of this paper. The focus is on the expected system kinematic performance given the demonstrated and anticipated actuator performances.

3 The BRAID

Figure 1 shows the kinematics for two designs of 3 degree-of-freedom parallel platforms. The first one is a revolute-revolute- spherical (RRS) configuration. The second one is a double-octahedral variable geometry truss (DOVGT) with a revolute-spherical-revolute (RSR) configuration (Rhodes et al., 1985). Each degree of freedom is binary-actuated, allowing a single stage to reach $2^3=8$ discrete states. The combination of identical stages forms the BRAID.

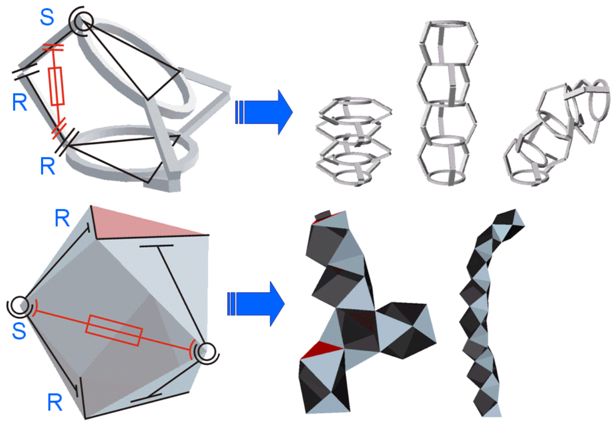

Figure 1 BRAID kinematics; top) RRS; bottom) RSR

As the number of stages of the BRAID increases, its performance approaches that of a continuous system (Lichter et al., 2002). The major advantage over conventional systems is that due to the on/off nature of each actuator and the two-state latching no feedback is required, which greatly simplifies control. The device also has good disturbance rejection and graceful failure modes. Figure 2 shows potential applications for space exploration of a 7-stage BRAID, such as a manipulator and a 6-legged walking rover.

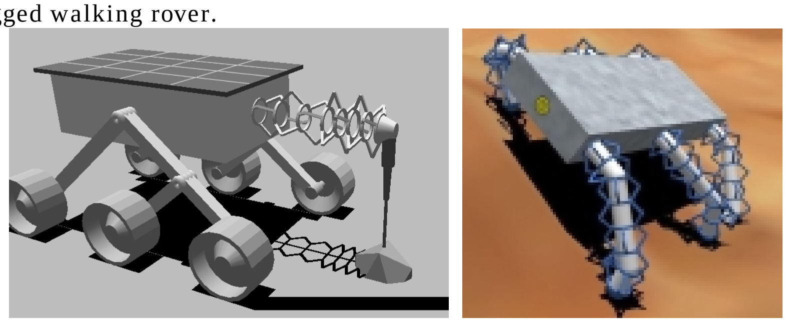
Figure 2 Application of the BRAID as a manipulator and as limbs of a walking robot

Implementing such systems as the BRAID with conventional actuators is not practical (Lichter et al., 2000, Chirikjian, 1994).

A first generation BRAID was built that used electromagnetic actuators (Hafez et al., 2002). It was found that the low force to weight ratio of the electromagnets greatly limited the number of stages, and hence the number of DOF. It is shown that dielectric polymer actuators have potential to be effective for this application. Figure 3 shows a sketch of how these actuators can be used into an RRS-BRAID.

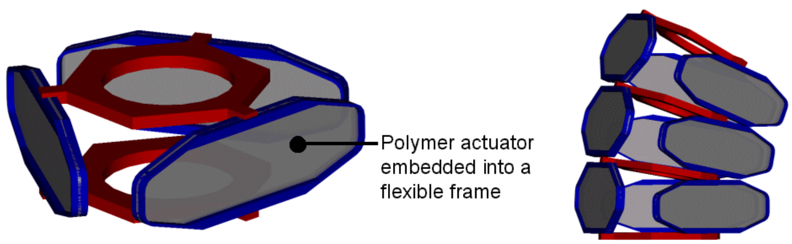

Figure 3 Polymer-actuated BRAID

4 Actuator Design

4.1 Dielectric polymer actuators

The operating principle of the dielectric polymer actuators is simple. An elastomeric film is coated on both sides with compliant electrodes. As a voltage is applied across the electrodes, the electrostatic charges will force the film to compress in thickness and expand in area (Pelrine et al., 1997). This expansion in area can be used to actuate mechanical systems.

4.2 Actuator implementation

For most elastomeric film materials, the response is much larger if the film is pre-stretched in both planar directions (Kofod et al., 2001). For application in the BRAID, the film is placed between two flexible frames, which have a degree of freedom in the intended direction of motion. The frame ensures the desired boundary conditions on the film. It further supplies a restoring force to the stretched film, forming an actuator that can work under both tension and compression. The restoring force is also tuned by a passive bi-stable element, which effectively cancels the stiffness of the film and frame over a certain range. This increases the range of motion and ensures a nearly constant force throughout the actuator stroke. Figure 4 shows an actuator assembly before and after actuation. The relative strain of the active film is about 50%. The actuator assemblies serve both as actuator and structural components when integrated into the RRS-BRAID (Figure 3).

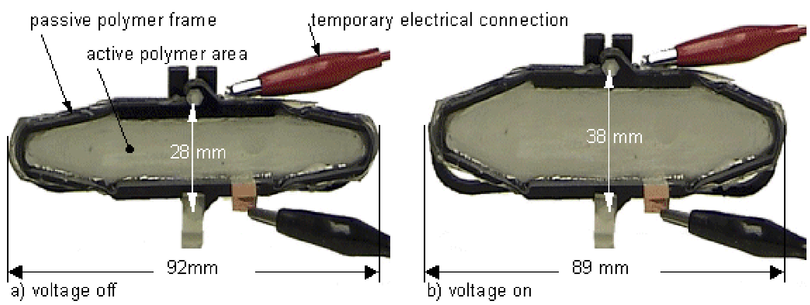

Figure 4 Photograph of embedded polymer actuator before and after actuation

4.3 Actuator Performance

The actuation forces are proportional to the cross sectional area of the film and can therefore be increased by combining multiple layers of the actuator material. Since a single layer of stretched dielectric material is only about 50μm thick, adding additional layers increases the actuation forces without significantly changing the geometry of the actuator. For an actuator with the same geometry shown in Figure 4, the actuation force is about 0.75N per layer.

The mass of a complete actuator unit is approximately 8 grams. Most of this mass is due to the frame and bi-stable element. For a double-layer actuator, the mass of the dielectric polymer actuator itself is less than 0.1 grams, only a fraction of what the actuator is capable of lifting. The performance of the actuator material is also independent of scale. In contrast to voice-coil actuators, which have poor performance on small scales, these actuators lend themselves for miniaturization (Pelrine et al., 2001). This suggests that the proposed BRAID can find applications on the micro- scale.

The actuator requires high voltage (5kV), but only draws currents of about 50μA, hence they can be powered by conventional miniature batteries. New thinner films will result in lower voltages.

5 BRAID Kinematics and Workspace

To illustrate the current and predicted capabilities of a dielectric polymer powered BRAID, a 4-stage (12 DOF) device is considered. The workspace is a function of the geometry of the individual stages as well as the strokes of the actuators.

Figure 5a shows the workspace cloud of an RRS-BRAID that can be achieved readily with actuator performance demonstrated in laboratory experiments (Figure 4) (Wingert et al., 2002). The actuator overall length changes from 28mm to 38mm.

The size of the workspace is on the order of a single stage of the BRAID. The high density of the workspace would make such a design suitable for a micro-positioning device where high resolution is required rather than a large range of motion.

Dielectric polymer actuators have shown strains that are much larger under laboratory conditions than in the self-contained modular frame design described above. This suggests that the dominant limitation to system performance is not the actuator material itself. Optimization studies currently being performed on the frame and passive elements suggest that actuator strokes that are double those cited above will be demonstrated shortly. Figure 5b shows the significantly larger workspace, using an actuator that expands from 28mm to 48mm. The workspace diameter would then be on the order of the stowed RRS-BRAID height. Such a system lends itself to a variety of applications, such as a camera placement device for planetary exploration, see Figure 2.

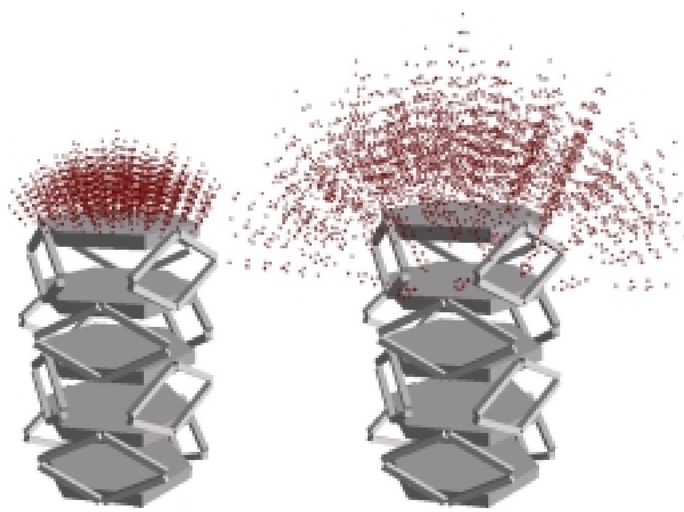

Figure 5 4-stage RRS-BRAID a) workspace with current actuator performance b) workspace with predicted actuator performance

A single stage of the RSR-BRAID has 14 faces, 8 of which have a fixed triangular geometry. The remaining 6 faces form diamond shapes that are occupied by dielectric polymer actuators (Figure 1). The RSR-stage is actuated by changing the diagonal lengths of the diamond-shaped areas with the dielectric polymer. Actuators enclosed in a diamond-shaped frame have been successfully demonstrated.

One advantage of the RSR-BRAID over the RRS-BRAID is that the actuators are directly integrated into the structure, reducing the number of components. This comes at the cost of adding some complexity to the design process, as actuators and structure can no longer be tuned independently. The joints of the RSR-BRAID could be designed to provide the desired restoring forces. As with the previous design, the actuation forces can easily be increased by adding layers of actuator film.

Taking the currently achieved performance of the frame actuators and applying them to the RSR-BRAID results in a workspace shown in Figure 6a. If the effective motion of each actuator were to be doubled, a significantly larger workspace would be achieved (Figure 6b).

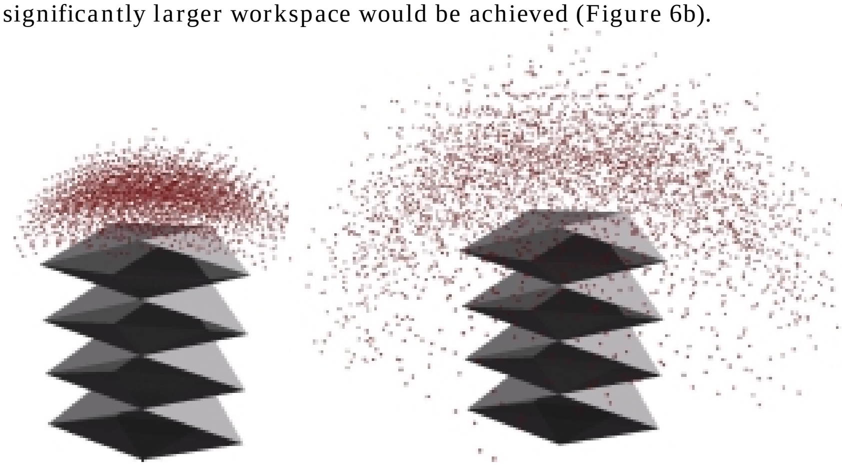

Figure 6 4-stage RSR - BRAID workspace cloud a) with current actuator performance b) with predicted actuator performance

6 Conclusion

It has been shown that dielectric polymer actuators have the potential of overcoming the key limitations of traditional actuators in making high-degree of freedom binary parallel robots practical. The simplicity of the actuators allows for a BRAID design that is virtually all-plastic, inexpensive, lightweight, and easy to control. Research in this program is continuing to develop devices that fully exploit the dielectric polymer actuators in very high DOF practical binary systems.

7 Acknowledgements

The support of the NASA Institute for Advanced Concepts (NIAC) for this research is acknowledged.

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