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Lightweight Hyper-redundant Binary Elements for Planetary Exploration Robots

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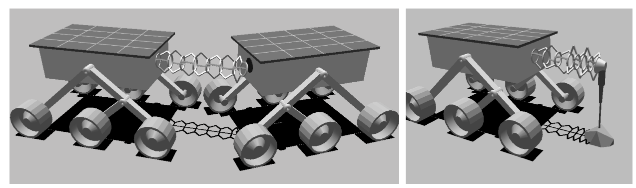
***Abstract*--This paper presents the design of a new lightweight, hyper-redundant, deployable Binary Robotic Articulated Intelligent Device (BRAID), for space robotic systems. The BRAID element is intended to meet the challenges of future space robotic systems that need to perform more complex tasks than are currently feasible. It is lightweight, has a high degree of freedom and a large workspace. The device is based on embedded muscle type binary actuators and flexure linkages. Such a system may be used for a wide range of tasks, and requires minimal control computation and power resources.**

***Index terms*—Binary robot, hyper-redundant, polymer actuator**

I. INTRODUCTION

Future missions to explore Mars will require robots to perform complex tasks such as scouting, mining, conducting science experiments, and constructing facilities, for human explorers and settlers [13]. To accomplish these objectives, future planetary robotic systems will need to work faster, travel larger distances, perform highly complex operations, and work with a higher degree of autonomy than today's technology would permit. New design concepts are required to meet these challenges. For example, robots will require devices for deploying communication antennas, rapid positioning of scientific sensors and facilitating assembly [13]. A single, yet lightweight and simple device that could perform a number of these tasks would be highly desirable. It would need to have fine motion resolution, a large motion workspace, multiple degrees of freedom, control simplicity, and have a small stowed volume.

This paper presents the design of an element that is intended to meet these requirements. This device, called a Binary Robotic Articulated Intelligent Device (BRAID), consists of compliant mechanisms with large numbers of embedded actuators. Figure 1 shows two potential application concepts of the BRAID element. In some ways it resembles deployable systems that have been used in the past for such space applications as: deployable booms, solar arrays, antennas, articulated masts and others [4, 7, 18, 22]. These devices can be deployed from a small package into relatively large structures. However, in general these structures are not controllable in terms of being able to assume different commanded configurations. Once deployed they are usually not retractable. They are also usually constructed from heavy and complex components, such as gears, motors, cables, etc., although there are some notable exceptions [3, 20].



(a) mating two rovers (b) coring rock samples
Figure 1. Two BRAID robotic potential applications

In the robotic research community, efforts have been made to develop concepts of simple manipulators with good performance. An interesting example is binary manipulators [5, 12, 15]. In this concept, a manipulator is controlled by activating the actuators that can assume only one of two states ("on" or "off"). The joint level control is very simple. By simply activating the given actuator in the system a discrete change in state is obtained. Often, the control does not require feedback sensors. The two states are the extreme positions of the actuator. Examples include pistons, solenoids or motors. This form of control has been classified as sensor-less manipulation [6, 10, 15].

As the number of binary actuators in the system increases, the capabilities of the device approaches that of a conventional continuous manipulator. This is analogous to the revolution of the digital computer replacing the analog computer. However, this leads to mechanisms with complex system kinematics. Studies of the kinematics and control of such "hyper-redundant" manipulators, both with and without binary actuation have been performed [2, 5, 11, 12, 14].

This paper presents the design of a new lightweight, hyper-redundant, deployable Binary Robotic Articulated Intelligent Device (BRAID) for space robotic systems. The BRAID element is made of a serial chain of parallel stages (see Figure 2). Each three DOF stage has three flexure-

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based legs, each with muscle type binary actuators. In the experimental system described in this paper these are shape memory alloy (SMA) actuators. As discussed later, more promising polymer actuators are now being implemented in this study. Muscle actuation allows binary operation of each leg. The flexures are simple and light weight. This type of structure could be used in space robotics as an instrument positioning device, a highly articulated manipulator, a deployable boom (for solar arrays and antennas), etc. The experimental BRAID built consists of five parallel stages, yielding 15 binary degrees of freedom. Thus it has 2^{15} (32,768) discrete configurations. Thus, the system can approximate a continuous system in dexterity and utility. By its polymer construction and binary actuation the design is very lightweight and simple, appropriate for space exploration systems.

This paper is divided as follows: Section 2 describes the parallel link stage design of the BRAID element. Section 3 presents a discussion of its actuators and the actuator control. Section 4 explains the forward kinematics of the BRAID. Section 5 presents two approaches for solving its inverse kinematics.

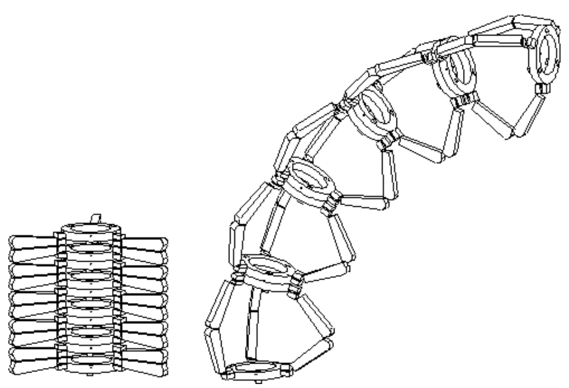
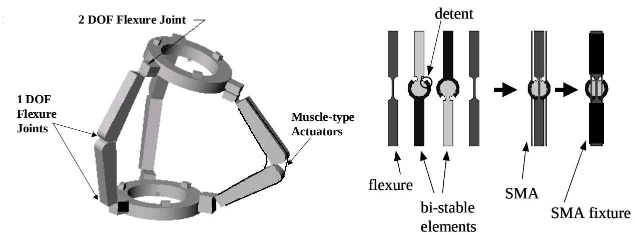


Figure 2: Basic design of the BRAID element

II. MANIPULATOR PARALLEL LINK STAGE DESIGN

Figure 3(a) shows one stage of the BRAID element. Each parallel link stage has three legs and actuators. Each leg has three flexure joints—two one DOF joints and one two DOF joint. This results in four non-intersecting axes per leg: three in parallel and a fourth orthogonal to the first three. Coupling the three legs together (symmetrically 120° apart) gives the parallel link stage three DOF mobility (vertical translation, pitch, and yaw). If each leg has only one actuator (an SMA wire in tension) the restoration force to change the binary states is provided by the elastic flexure joints. A pair of antagonistic actuators does not require the elastic effect. Detents help lock each binary leg into a discrete state (see Figure 3(b)) and provide more accurate and repeatable positioning. They also eliminate the need for power while the BRAID is stationary.



(a) parallel link stage (b) detent based binary joint

Figure 3: Parallel link stage of BRAID

The concept of using flexures to replace hinges and bearings is not new. Short plastic hinges can commonly be seen in commercial applications such as cabinet doors, tool box lids, shampoo bottle caps, etc. Their design requires careful attention to their structure mechanics. In the BRAID application large range of motions and low stiffnesses are desired, and fatigue strength proves to be critical. Repeated bending of a flexure can cause fatigue failure. The relationship between performance and fatigue life can be seen by considering a simple beam of thickness t, with Young's modulus E, bent elastically to a radius of R. The surface strain and maximum elastic stress is given by:

$$\varepsilon = \frac{t}{2R} \quad \text{and} \quad \sigma = \mathrm{E}\frac{t}{2R} \tag{1}$$

This stress must not exceed the fatigue yield strength of the material, σ_f. Hence, the minimum bend radius is given by:

$$R \geq \frac{t}{2}\left(\frac{E}{\sigma_f}\right) = \frac{t}{2}\left(\frac{1}{M}\right) \tag{2}$$

Materials that can be bent to the smallest radius or the ones where M (defined in Equation 2) is maximized are desirable because they give the largest range of motion. Literature suggests the best choices are polymeric materials and elastomers with M equal to $3\text{x}10^{-2}$ [1]. Materials such as polyethylene, polypropylene and nylon fall into this category. For comparison, for spring steel M equals $0.5\text{x}10^{-2}$ (which would be appropriate when high stiffness and small range of motion is desired). An ultra high molecular weight polyethylene was chosen here, based on its machinability, fatigue life, stiffness, weight, and cost.

The experimental system constructed is shown in Figure 4. It consists of five parallel link stages coupled serially, giving a 5 DOF end-effector. This device has yet to have its detents installed. With binary control this structure has $2^{3\text{x}5}$ (or 32768) possible states giving the device suitable freedom for a number of applications. For other applications this could be extended to 10 or 20 stages giving $2^{3\text{x}20}$ (approximately 10^{18}) possible states. While this closely approximates a continuous workspace, it leads to some interesting inverse kinematic problems due to the hyper-redundancy of the system, see Section 5.

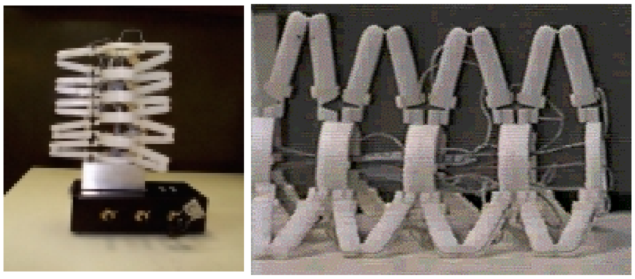
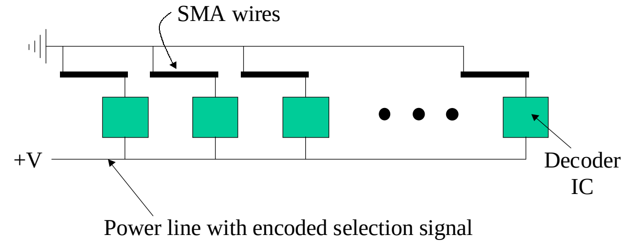


Figure 4: Experimental platform of BRAID

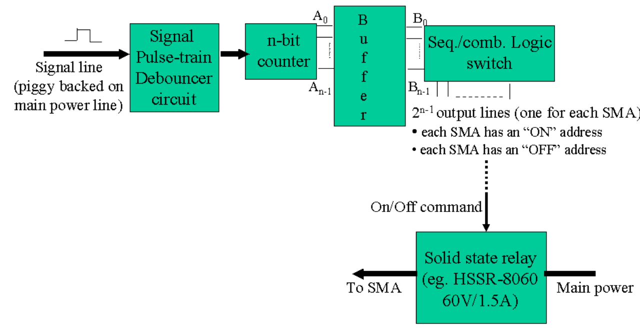
III. Actuator and Actuator Control

For some applications, a hyper-redundant BRAID would need a large number of actuators. The actuators are assumed to be polymer-based smart materials. These materials include conducting polymers and electrostrictive polymers [17, 21]. However, while these materials are anticipated to meet the needs of the concept in the future, they have not yet reached a sufficient state of development to perform practical experimental demonstrations in devices today. In the near term, shape memory alloys (SMAs) are being used for the muscle actuators. SMAs are a class of alloys which are able to remember their shape and are able to return to that shape after being deformed, given a certain temperature change [8]. These alloys can be used as actuators, as the ratio of the deformation stress to the actuated recovery stress can be higher that 10 to 1. It is proposed that each link be actuated by a pair of antagonistic SMA wires, which open and close the link. Appropriate wire length and thickness are easily determined based on the range of motion and the force output desired. For this laboratory demonstration, the payload is assumed to be a sensor such as a CCD camera weighing less than 50 grams. The stiffness of the antagonistic pair and the flexures must also be accounted for. However, the design of the SMA actuators is not a serious challenge.

To actuate the BRAID element, the actuators need to be triggered selectively, as required by the inverse kinematics. Conceptually, such a binary control is simple requiring no sensor feedback. However, the large number of actuators can rapidly make the physical realization of such a system difficult, if each actuator requires unique power supply lines. A multitude of wiring introduces possibility for error and would result in additional weight and volume, large external forces, and complexity. The BRAID concept uses a more compact and efficient form of supplying power and control (see Figure 5). A common power line and ground are provided to all the actuators. Each actuator has a small "decoder" chip that can be triggered into either binary state by a carrier signal "piggybacked" on the power line. The carrier signal is a sequence of pulses that identifies a unique address in the form of a binary word for the actuator that requires toggling. This architecture reduces the wiring of the entire system to only two wires (see Figure 5). This can easily be implemented in the form of conducting paint/tape (on the non-conducting polyethylene substrate). This bus architecture is currently being implemented.



(a) Overview of actuator control electronics



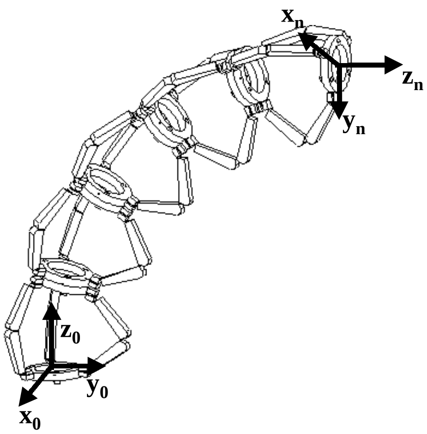
(b) Power/Control Bus Decoder Architecture

Figure 5: SMA Power and Control Bus

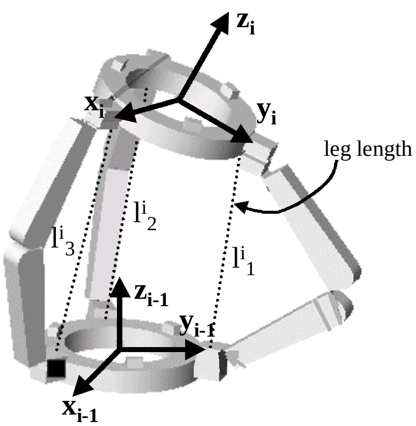
IV. Forward Kinematics

Binary devices present a number of challenges not found in conventional continuous systems. For example, a continuous robot can reach an infinite number of points within its workspace while a binary robot can only reach a finite number of points. A binary robot's workspace is thus a discrete point cloud. A BRAID based system adds further challenges, due to the complexity of its kinematics. A typical four by four homogeneous transformation matrix is formulated as a combination of a rotation matrix and a translation vector of one coordinate frame with respect to another. The kinematic variables are then three rotational and three translational variables (six DOF). In a single parallel link stage of the BRAID system, the three legs are positioned about the vertices of two equilateral triangles. Additionally, based on the joint configuration of each leg, the single stage has only three degrees of freedom—pitch and yaw rotations and a vertical translation. In general, given the four by four transformation matrix $A_{i-1,i}$, of the i^{th} coordinate frame with respect to the i-1^{th} coordinate frame (see Figure 6(b)), one can derive the forward kinematics of the entire n-staged system. A_{0n} defines the forward kinematics from base to end-effector of the entire system and is simply given by:

$$A_{0n} = A_{0,1} A_{1,2} A_{2,3} \cdots A_{n-1,n} = \prod_{i=1}^{n} A_{i-1,i} \qquad (3)$$



(a) BRAID system frames



(b) i^{th} parallel link stage

Figure 6: Critical parameter representation of BRAID system

In this formulation the leg lengths (see Figure 6) are the control variables. The relationship between these leg lengths and the pitch, yaw, and vertical translation of the i^{th} coordinate frame with respect to the $i\text{-}1^{th}$ coordinate frame (see Figure 6) can be formulated. This relationship does not have a closed form solution. Hence, $A_{i-1,i}$ is only a function of the variable leg lengths of the i^{th} stage ($l^i_{1,2,3}$). Since every leg in the system can be in only one of two states (binary), each leg length can have only one of two values (defined as l_{min} and l_{max}). Hence, each term of $A_{i-1,i}$ can have only 8 different discrete values.

Figure 7 shows the workspace generated for a 5 stage BRAID element. The workspace for this example consists of 2^{15} unique states. However, the workspace is clearly non-uniform in its distribution. Optimization of this workspace in terms of density of reachable states is an area of continuing research.

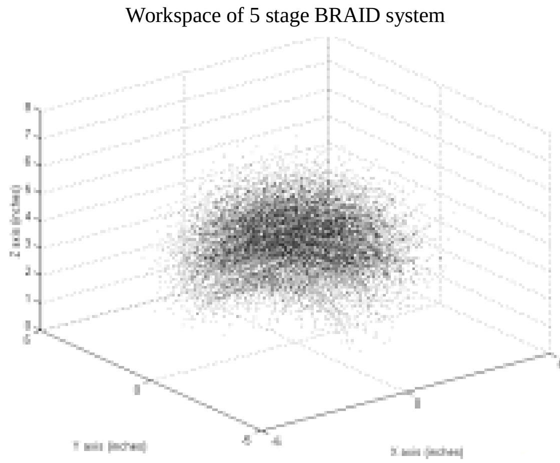


Figure 7: Workspace of 5 stage BRIAD element (BRAID element base center=origin)

V. Inverse Kinematics

Once the forward kinematics of the system have been developed, the problem of executing practical tasks requires the solution to the inverse kinematics problem. While the hardware costs and control complexity of a binary manipulator are lower than those of a continuously-actuated manipulator, there is a tradeoff in the complexity of the trajectory planning and inverse kinematics software. As expected, the inverse kinematics problem cannot be expressed in a closed form solution. Brute force or exhaustive search methods may prove appealing for systems with few stages (less than 5), but become impractical for larger systems. As the number of degrees of freedom increase, the complexity of the workspace grows exponentially. For every additional stage there is about an order of magnitude increase in the number of states in the workspace. Hence, for large systems more efficient search methods are required to find "optimum" solutions. This section presents two possible search methods for the inverse kinematics problem. The first is a genetic search algorithm and the second is a combinatorial heuristic search algorithm. The search metric for both algorithms is to minimize the distance between the end-effector and desired position. Both algorithms will be briefly described and their results will be presented.

A. Genetic Search Algorithm

Here a classical genetic algorithm approach for finding an optimum solution is used, where each generation consists of m-bit binary words describing the manipulator state (where m is the number of actuators). A full description of genetic algorithms can be found in [9].

B. *Combinatorial Heuristic Search Algorithm*

This algorithm was first described in [15]. In order to avoid exponential growth of the search space as the number of actuators grow, the inverse kinematics are solved by changing the state of only a few actuators at any given time. This is perceived as a k-bit change to the given system state, where any system state is defined by an m-bit word (m is the number of actuators). At any state all possible changes (up to k-bits, where $k \le m$) are evaluated to determine the one that optimizes the search metric (i.e. reduces the error between the end-effector position and the desired position). This optimal change forms the new state of the system and the search procedure repeats until convergence. This search method reduces the computational complexity from $O(2^m)$ to $O(m^k)$ or from exponential computational time to polynomial computational time. This is seen through the following observation. For the binary robot being considered with m actuators, moving towards its target by changing up to k-bits requires a search through $\binom{m}{0}+\binom{m}{1}+\cdots+\binom{m}{k}$ possible states, where $\binom{m}{k}=\frac{m!}{k!(m-k)!}$. Expanding these terms, the highest power of m is found to be k. An exhaustive search of same system would require exactly 2^m search states.

C. *Search Algorithm Results*

Figure 8 shows the performance of the BRAID with different number of stages (n), using the genetic search algorithm, attempting to reach a desired position from an initial position. The actuated leg length was normalized to one inch. Figure 8 shows that, the steady state error decreases with increasing n. Note that the absolute error difference (after convergence) for 12 stages and 17 stages is 0.015 inches. Thus, although the number of reachable points increases with the number of stages, the accuracy to reach a given point might not increase. As expected of a genetic algorithm, the average error across a given population decreases with increasing generation.

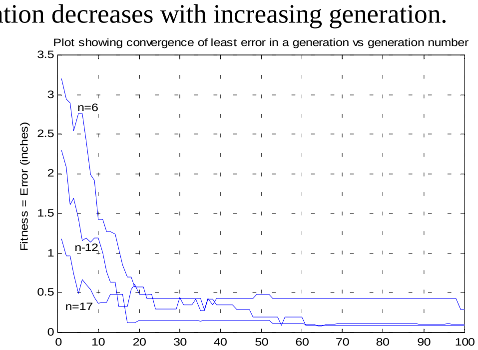


Figure 8: Results of genetic search algorithm for n-staged BRIAD element (population size = 30, probability of crossover = 0.6, probability of bit-wise mutation = 0.02)

Figure 9 shows the performance of the combinatorial heuristic search algorithm, attempting to reach a desired position from an initial position. The algorithm was tested on the BRAID, with variable number of stages. Again, the actuated link length was normalized to one inch. At every search step, a search through $\binom{m}{0}+\binom{m}{1}+\cdots+\binom{m}{k}$ states was performed (where k=3), giving a new end-effector position with less error. From figure 9, it is seen that the error convergence rate stays fairly constant with increasing system complexity (increasing n, the number of parallel link stages). However, each step needs more computation as $\binom{m}{0}+\binom{m}{1}+\cdots+\binom{m}{k}$ increases with increasing n. Additionally, in general the steady state error decreases with the increasing n. This is expected intuitively since there are more finite solutions in the workspace. Note again, that the absolute error difference (after convergence) for 10 stages and 12 stages is 0.019 inches. Thus, although the number of reachable points increases with the number of stages, the accuracy to reach a given point might not increase

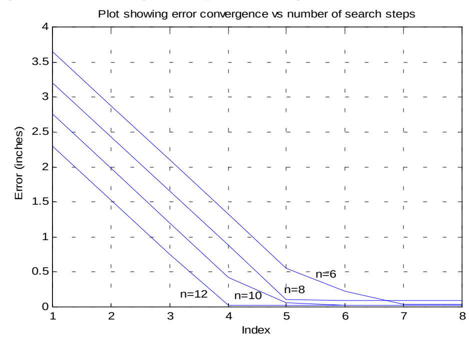


Figure 9: Results of combinatorial heuristic search algorithm for n-staged BRAID element (maximum allowable bit changes = 3)

VI. Conclusions

A new lightweight hyper-redundant binary device with potential application to space robotics systems has been presented. Such a system may be used for the deployment of booms and antennas, rapid and accurate positioning of sensors, and manipulation requiring simple and highly articulated onboard manipulators, all while maintaining a small stowed volume. This device is comprised of a serial chain of parallel stages and can collapse to a small stowed volume. Each stage is composed of three flexure-based elements, each with muscle type actuators, permitting only binary operation of each link. Each parallel link stage has 3 DOF. By coupling these parallel stages in series, a 5 DOF end-effector pose is obtained. With a large number of actuators, this system can approximate a continuous system in dexterity and utility. In such a system, only a binary word command signal is needed to control the motion of the entire system. Controller feedback and the corresponding computational load is completely eliminated. Further, the system power bus structure can be implemented so as to eliminate the need for individual power wires to the large array of actuators. This scheme eliminates all but one power and one ground line in the system. The system does not have a closed form solution of its forward kinematics. Numerical solutions to the BRAID inverse kinematics problem (or trajectory planning), are also presented. These search techniques were based on a genetic algorithm and a combinatorial heuristic algorithm. Both methods prove to be highly efficient as compared to exhaustive search methods. The workspace of such manipulators and the actuator triggering sequence are areas of current study. Such optimizations would allow for better distributed workspaces, allowing good dexterity throughout a region. Preliminary experimental results show good promise [16]. A detailed discussion of these results are beyond the scope of this paper.

VII. Acknowledgements

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