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# ON SYSTEMS OF CIRCULAR WEDGES FOR SERPENTINE ROBOTS APPLICATIONS

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**Key words:** Biomimetic systems, biologically inspired robots, serpentine robot, space based maintenance, robotic workspace.

**Abstract.** *Previous work showed that duplicate circular wedges might be used to achieve repeatable, accurate, precise and versatile alignment of mechanical components. This paper further explores the versatility and application of circular wedges in robotics. Of particular interest are dissimilar circular wedges, i.e., circular wedges that differ in wedge angle, in the number of circumferential divisions, and in offset angle. Several applications are highlighted: the use of circular wedges as the basis for a new robotic joint; the utilization of circular wedges in implementing a robotic end-effector; and, the configuration of a serpentine robot from circular wedges.*

## 1 INTRODUCTION AND OBJECTIVES

Alignment of mechanical components needs to be performed in varied applications, e.g., in vehicular wheel alignment. Previous work[1] shows that the use of a duplicate pair of wedged discs to achieve alignment of surfaces is an approach that satisfies the need for repeatable, accurate, precise, versatile and inexpensive alignment of mechanical components. A natural extension is to use a large number of circular wedges to structure a highly versatile and flexible serpentine robot. Potentially this novel robot would be used for space based maintenance, which involves periodic inspections of enclosed areas which are difficult to examine. The quality, cost and time involved in these inspections could be reduced by use of a snake-like device which could be programmed to look for certain types of damage, and carry a small camera, ultrasonic device or some other tool. This robot-snake would move through small ports in the craft and maneuver through tight spaces without a human guide and would therefore need to move in a manner similar to the way a real snake moves. Serpentine robots offer advances over traditional mobile robots and robot arms because they have enhanced flexibility and reachability, especially in convoluted environments. These mechanisms are especially well suited for search and rescue operations where making contact with surviving victims trapped in a collapsed building is essential. Another application would be exploring a rough terrain, in an area where wheeled vehicles could not travel. Robot-snakes could also be sent into fluid and “swim” to explore contaminated water or slither in to do inspections in places too dangerous for humans. Beyond their adaptability to the environment, serpentine robots offer a variety of advantages over mobile robots with wheels or legs. They are robust to mechanical failure because they are modular and highly redundant. This technology could be applied on several levels: Macro-snakes for planetary surface exploration, mini-snakes for inspection and repair of aerospace structures with limited access, micro-snakes for exploration within the human body.

The same flexibility that makes serpentine robots incredibly useful also makes them difficult to design and control. Another drawback is the difficulty in analyzing and synthesizing snakelike locomotion mechanisms, which are not as simple as wheeled mechanisms. The objective of this paper is to establish a mathematical framework for modeling, analysis, and synthesis of serpentine locomotion with a multi-circular wedges robotic snake. We do apply some existing knowledge from biological study of snakes, but our focus will be on a robotic realization theory of snakelike locomotion rather than the biomimetic aspect of the problem. We restrict our attention to the general three-dimensional motion of the robot-snake. The kinematics of the serpentine robot is studied for combined two-, three-, five-, and ten-circular-wedge structures. This sequence of increasing complexity is chosen to gain insight into the kinematical workings of this serpentine robotic scheme so as to better appreciate its potential for practical applications. Use is made of an object oriented programming approach in a MATLAB© environment. Of additional interest are dissimilar circular wedges, i.e., circular wedges that differ in wedge angle, in the number of circumferential divisions, and in offset angle.

## 2 SYMMETRICAL AND ASSYMETRICAL CIRCULAR WEDGES

Typical front and back views of a circular wedge may be represented as in Figure 1. The axis of symmetry of the disc is labeled A-A, which splits the disc into two equal halves. Also shown is a set of same size circular holes, equidistantly distributed around the periphery of the disc that serves to define the number of rotational disc divisions. These can be labeled according to the total number of disc divisions, e.g., from 1 to 10, if the disc is arbitrarily divided into 10 parts. The relative location of these holes can be changed to reflect the fact that these holes do not have to correspond to the symmetric geometry of the disc. In particular, the figure to the right of the edge view of the disc shows that an offset angle has been defined between the location of the center of the hole labeled with the number 1 and the axis of symmetry.

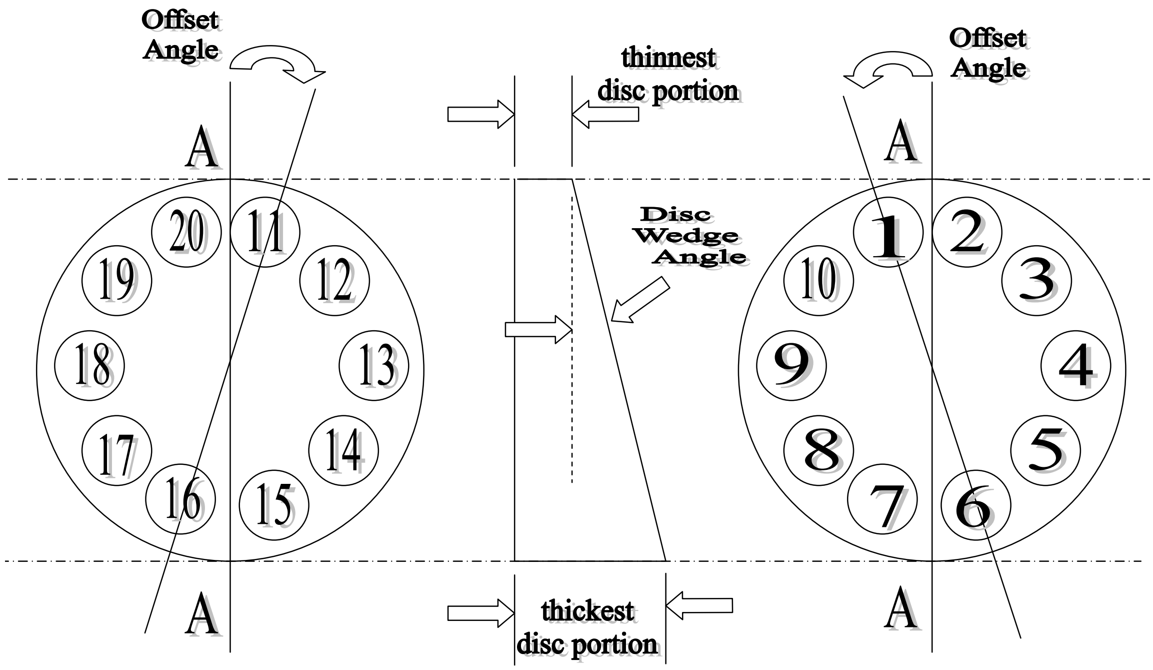



Figure 1: The Disc Geometry (adapted from [2])

This maximum offset angle is obtained by dividing 360-degrees by the number of disc divisions (N) or holes around the periphery of the disc. The offset angle defines the range of values for which the distribution of the holes is asymmetric relative to the location of the axis of symmetry. For multiples or half-multiples of this maximum offset angle the location of the holes remains symmetric with respect to the disc axis of symmetry. For fractions of this maximum offset angle, other than those cited above, the location of the holes is asymmetric with respect to the disc axis of symmetry. The main significance of the offset angle is to transform a single disc into two discs. This occurs because we can flip the disc over, as shown in the figure to the left of the edge view of the disc. The asymmetry created by the offset angle, produces a duplicate number of disc combinations, all of which might be unique when compared to the first. In summary, for no offset angle, the two sides of the disc are the same. For a disc with some existing offset angle, less than the maximum possible offset angle and not equal to one-half this maximum possible offset angle, has twice the number of combinations than a disc without such an offset angle. This unique characteristic resulting from an appropriate offset angle allows for greater versatility when combining two duplicate circular wedges to achieve repeatable, accurate, precise and versatile alignment and positioning of mechanical components. An added level of complexity involves consideration of dissimilar circular wedges, i.e., circular wedges that differ one from the other in wedge angle, in the number of circumferential divisions, and in offset angle. The initial objective of this paper is to explore the impact of these changes on a system of two dissimilar circular wedges.

## 3 MODELING OF THE DISC PAIR USING ORTHOGONAL TRANSFORMATIONS

Modeling of the disc pair is done by means of orthogonal transformations[2]. Figure 2 shows the 2D geometry of a single disc, and the associated coordinate systems used in this analysis[1]. Defining the local $x_2 - y_2 - z_2$ coordinate axes shown in the figure makes it easy to assess local vectors such as $\mathbf{P}_L$ and $\mathbf{P}_L^{'}$, lying on the disc top surface.

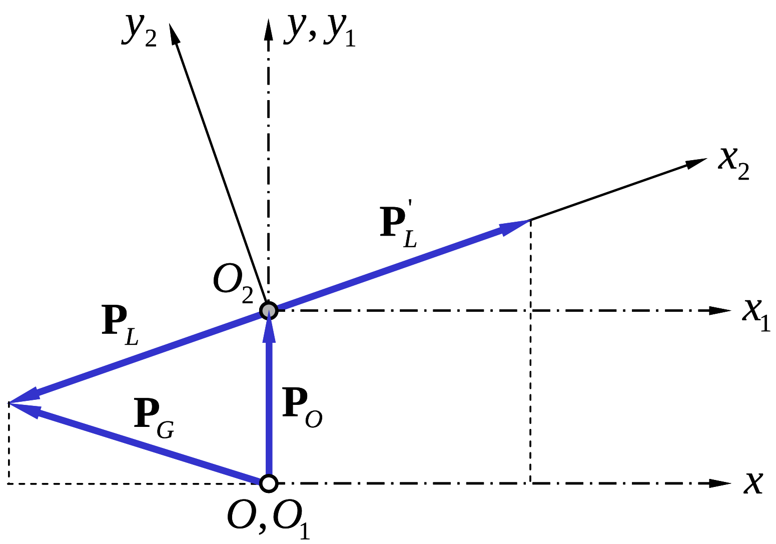



Figure 2: The Coordinate Systems of the Single Disc (adapted from [2])

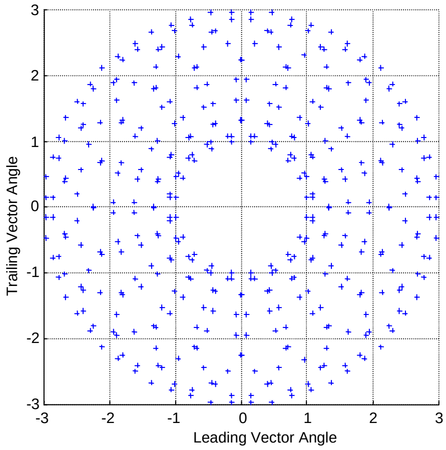
Similar vectors may be used to define the orientation of the top disc surface relative to its base surface. Notice that $\mathbf{P}_L$ and $\mathbf{P}_L^{'}$ point in opposite directions, yet have the same inclination. Vector $\mathbf{P}_L^{'}$ defines a positive inclination, while vector $\mathbf{P}_L$ has a negative inclination with respect to a horizontal reference. The following relationship exists between local and global coordinates,

$$\mathbf{P}_G = \mathbf{T}(h)\mathbf{R}(\theta_z)\mathbf{R}(\theta_y)\mathbf{P}_L \tag{1}$$

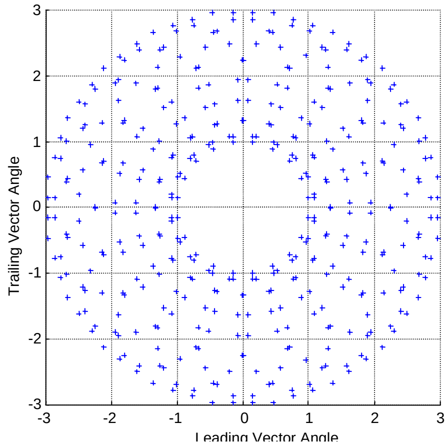
The global position vector set $\mathbf{P}_G$ is obtained by transforming the local position vector set $\mathbf{P}_L$, defined in the local $x_2 - y_2 - z_2$ coordinate system, by multiplying it by a sequence of matrices that denote rotation and translation: $\mathbf{R}(\theta_z)$, $\mathbf{R}(\theta_y)$, and $\mathbf{T}(h)$. Subtracting vector $\mathbf{P}_O$ from $\mathbf{P}_G$ yields the vector, which defines the absolute orientation of the top surface of the disc. The angle between this vector and its projection onto a horizontal surface can then be calculated using the concept of the dot product between two vectors. What is of interest to us in this geometry is being able to define the orientation of the top disc plane. In general, a plane may be defined by the specification of three non-collinear points. By defining two vectors, normal to each other, lying on the plane of interest we are able to achieve this. It is then straightforward to make the calculation of the required angles as outlined above. We will call these vectors that are normal to each other the leading vector and the trailing vector. The leading vector leads the trailing vector by 90 degrees if these vectors are assumed to rotate counterclockwise when looking down at them along the $y_2$-axis. Knowing the components of the leading vector and the trailing vector allows calculation of the angles that these vectors make relative to a horizontal plane. When considering the orientation of the top surface of a second disc, with known configuration and capable of independent motion, stacked on top of the first one, it is straightforward to apply this same approach to assess the absolute orientation of that top disc surface with respect to the horizontal surface of the bottom disc.

## 4 EFFECT OF SYMMETRIC AND ASSYMMETRIC DISC COMBINATIONS

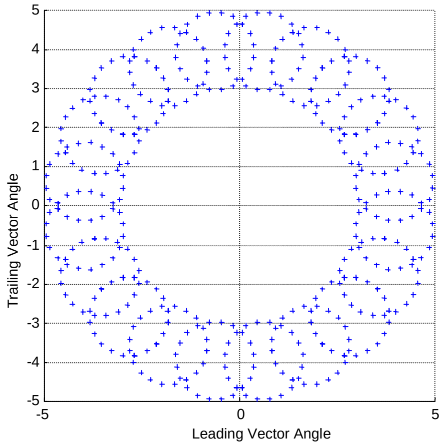
To show the effect of using circular wedges that differ in wedge angle, number of circumferential divisions, and in offset angle, plots of leading vector angle versus trailing vector angle are used. The graphs represented in Figure 3 show the effect of using two circular wedges in which the circular wedge angle is changed.




(a) Combination of 1- and 2-degree circular wedges




(b) Combination of 1- and 3-degree circular wedges

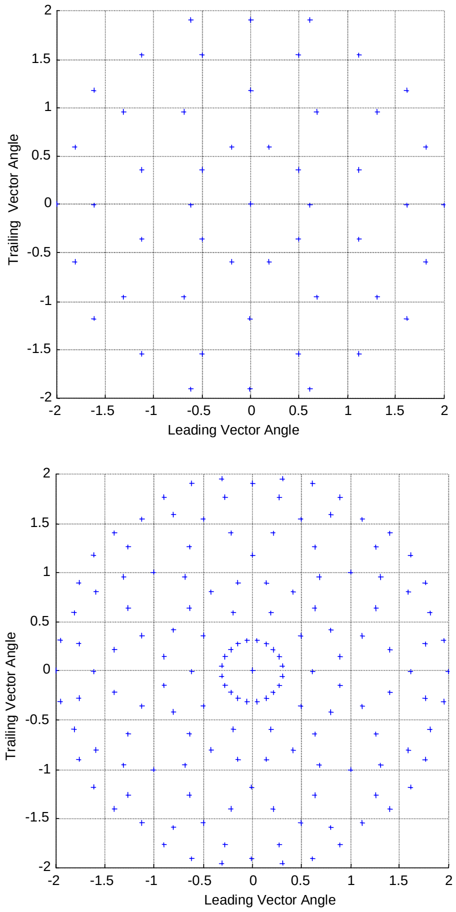



(c) Combination of 1- and 4-degree circular wedges

Figure 3: Leading Vector Angle versus Trailing Vector Angle Plots for Wedge Angle Changes

It demonstrates the effect of all combinations and permutations of two discs with the same number of peripheral divisions (10 disc divisions), the same offset angle (25% of maximum offset angle), but different wedge angle combinations: (a) 1 and 2 degrees, (b) 1 and 3 degrees, and (c) 1 and 4 degrees. It is useful to note that any particular combination of two wedges with different circular wedge angles defines a work range given by upper and lower bounds. The lower bound is given by the subtraction of the smaller wedge angle of the first from the larger wedge angle of the second; and, the upper bound is obtained by adding the smaller wedge angle of the first to the larger wedge angle of the second.

Figure 4 shows the effect of increasing the number of disc divisions in one of the discs: (a) disc division combinations of 10 and 10, and (b) disc division combinations of 10 and 20. The wedge angle for both circular wedges is the same (1-degree), as is the offset angle, which has been set to zero. It is clear that positive changes in the number of peripheral divisions of the disc, augments the possible combinations of leading vector and trailing vector angles, increasing their versatility.




(a) Combination of 10- and 10-circumferential division circular wedges

(b) Combination of 20- and 10-circumferential division circular wedges

Figure 4: Leading Vector Angle versus Trailing Vector Angle Plots for Circumferential Division Changes

It is clear from comparing the various leading angle versus trailing angle plots that a changing offset angle affects the total number of independent alignment possibilities and their distribution on each of these plots. Clearly the distribution of alignment possibilities and versatility change with choice of offset angle.

## 5 ROBOTIC APPLICATIONS

The circular wedge as a robotic joint is first proposed by Bejczy[3], as reported by Hirose[4], when he defines the oblique rotation joint shown in Figure 5. The objective that Hirose pursues, by combining several of these joints, is the assembly and use of an Active Cord Mechanism (ACM) that resembles a snake, or serpentine robot. The result is that he built and tested an "ACM of oblique rotation type", as well as a serpentine arm to be used in the "grinding and inspection of water turbine runners" for "hydroelectric power production". Hirose points to several advantages to the use of the oblique rotation joint: (a) improvement of the output per unit weight of the actuator system; (b) since it has no natural orientation because of its cylindrical shape, it can be used to penetrate into narrow spaces; and, (c) its hollow interior may provide an advantage in making it airtight and as a conduit for power and control signals. The main disadvantage that concerns Hirose is that the mobility range is restricted due to his intent of using oblique rotation joints with inclination angle close to 30-degrees, in alternating combination with rolling joints which allow rotary motion about its longitudinal axis. Thus one of his ACMs uses eight rolling joints and seven oblique rotation joints, while another serpentine arm is composed of two oblique rotation joints and three rolling joints. The use of oblique rotation joints permits the design of a lightweight, compact and highly rigid system, e.g., one robot is able to carry a weight of 300 Newtons, producing a deflection at the end of 5-mm, while maintaining a repeatability of ±0.5-mm.

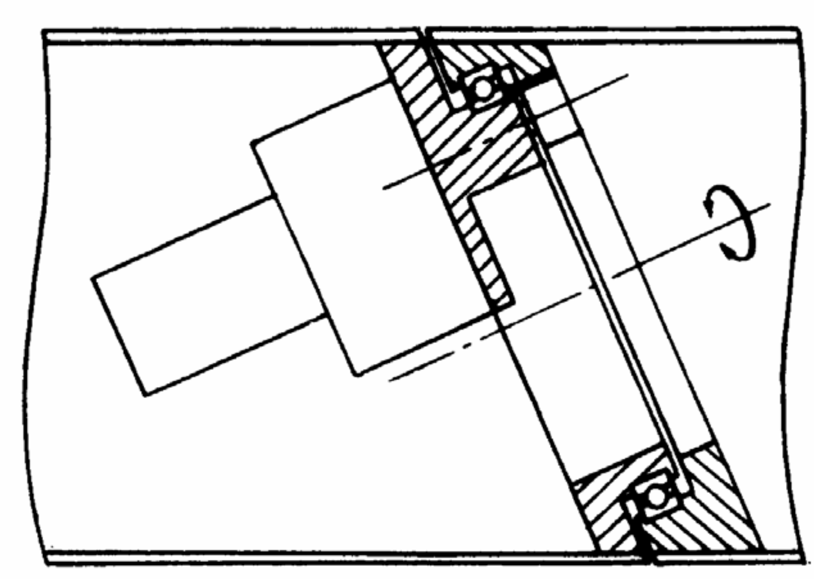
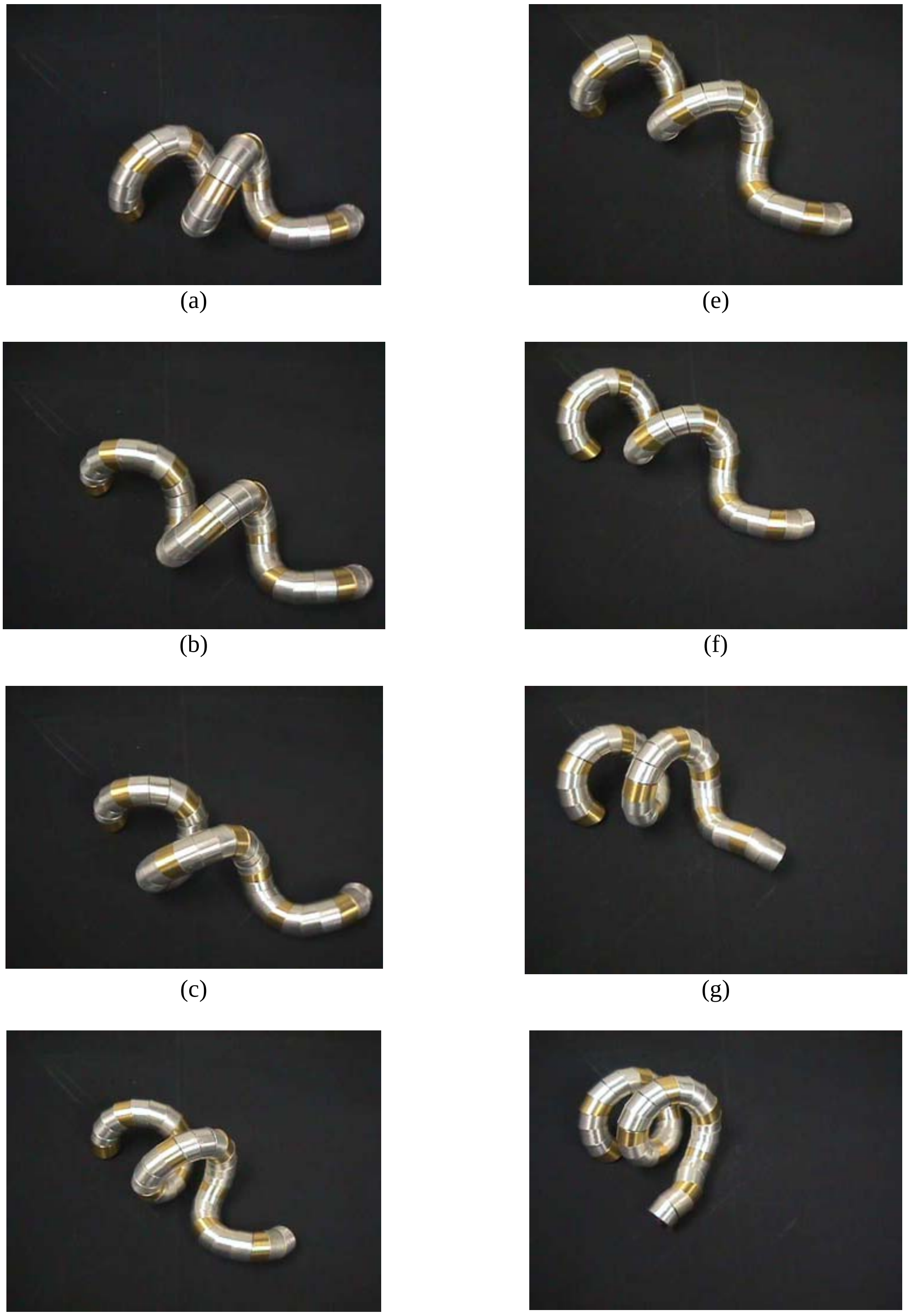


Figure 5: Oblique rotation joint (adapted from [4])

Figure 6 shows the versatility of a further refinement of the oblique rotation joint to implement a serpentine robot or Intelligent Rope (IR) using the circular wedges described above as interchangeable modular elements. Modularity is attractive for this IR design for ease of configuration, redundancy, and versatility. An IR configured robotic end-effector design currently under development is shown in Figure 8. The IR robotic end-effector consists of extended circular wedges housing stepper motors making up six rotation joints whose mechanical design are shown in Figures 7 (a)-(c). The stepper motors (Pacific Scientific, Sigmax Series 802), driven by a hybrid step motor driver (Intelligent Motion System Inc, IB462H), achieve relative motion between end-effector joints with a resolution of less than one degree. A LabView program controls the set of stepper motor drivers by means of a digital I/O card (National Instruments, PCI-DIO-96). Figure 7(d) shows the robotic end-effector at its rest position (without power), while Figures 7(e)-(g) show the end-effector at the same spatial location achieved by different joint combinations.



(a) (e)

(b) (f)

(c) (g)

(d) (h)

Figure 6: Versatility of Intelligent Rope (IR)

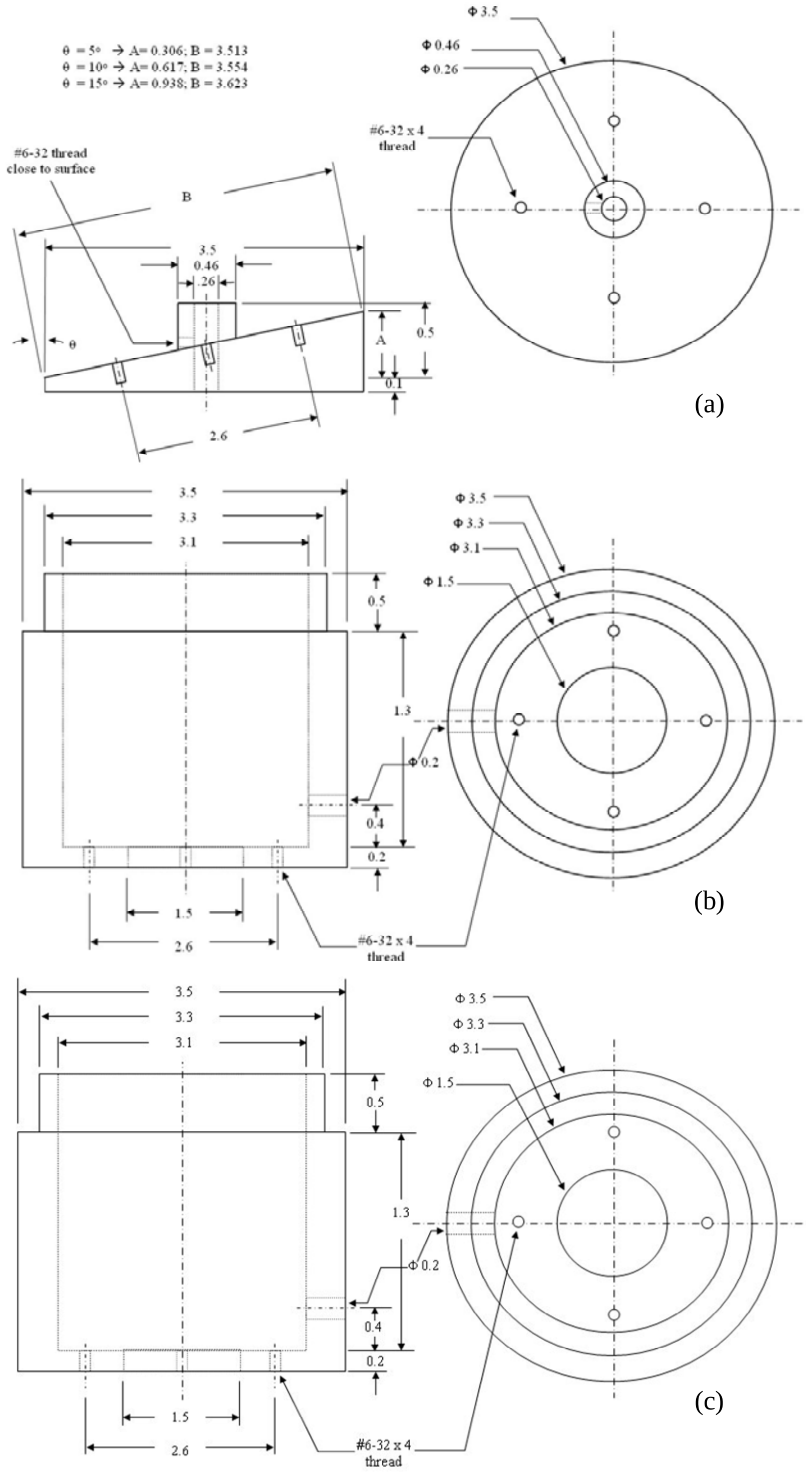



Figure 7: Intelligent Rope (IR) configured robotic end-effector

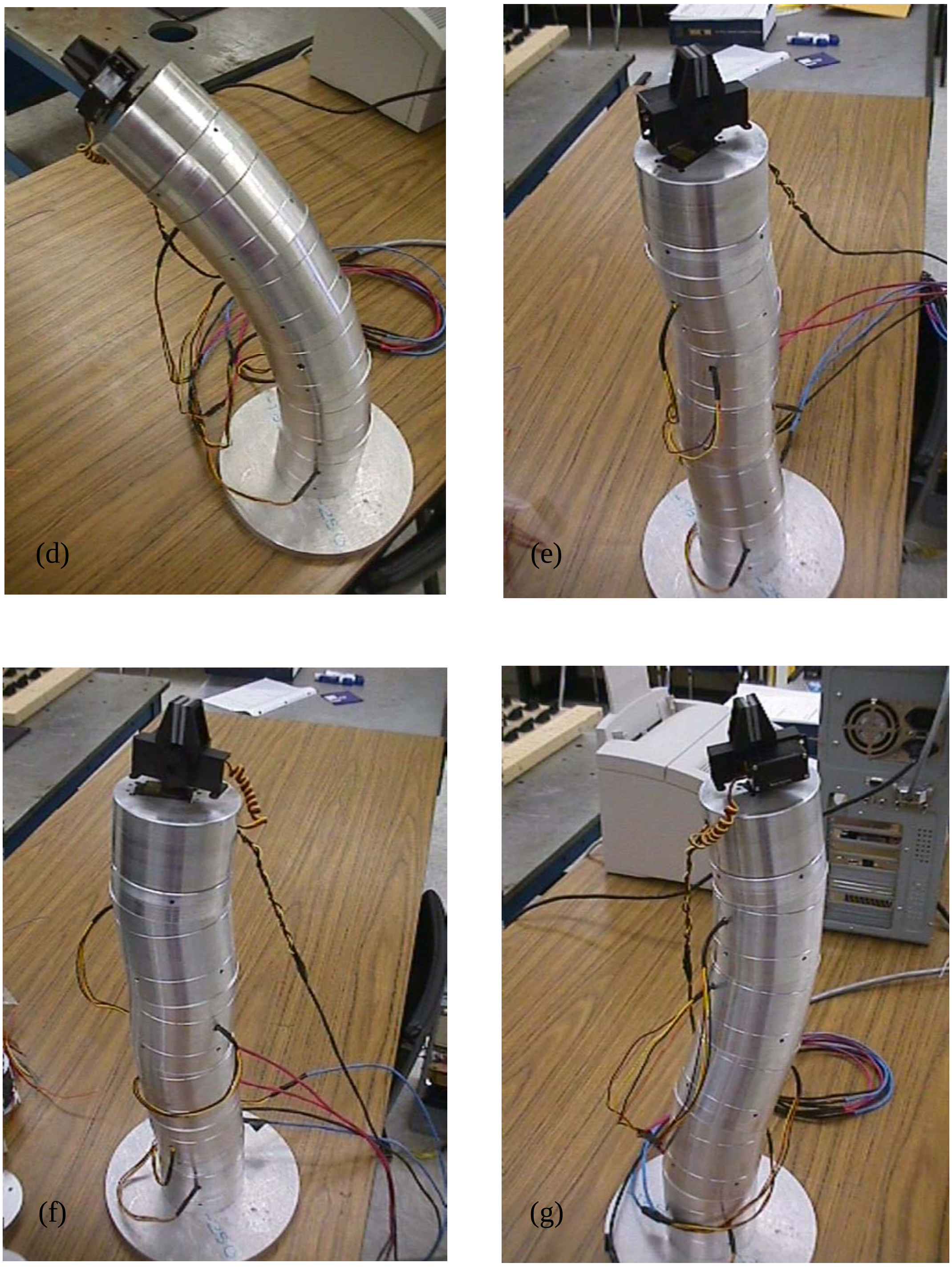



Figure 7: (Continuation) Intelligent Rope (IR) configured robotic end-effector

## 6 SUMMARY AND CONCLUSIONS

A principal objective of this paper has been to examine the use of dissimilar circular wedges, i.e., circular wedges which differ in wedge angle, the number of positions or increments along the circumference of the circular wedge, and changes in the offset angle. Changing the circular wedge parameters permits the development of systems of circular wedges allowing even greater versatility in the alignment of mechanical components. The approach used in this paper, i.e., the use of kinematic transformation matrices, permits an accurate assessment of the leading and trailing angles and guarantees better than ±0.001 degrees accuracy. In summary, the accuracy, precision and versatility of the circular wedges is shown to be a function of wedge angle, the number of positions or increments along the circumference of the circular wedge, and changes in the offset angle, which defines the asymmetry of the discs. Additionally, consideration of circular wedges as an extension of the notion of an oblique rotation joint leads to the configuration of serpentine robots that may have use as robotic end-effectors or as Intelligent Rope (IR) for potentially multiple uses.

## 7 REFERENCES

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