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Computer-aided manufacturing of spherical mechanisms

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Abstract

In this paper a computer-aided manufacturing methodology for spherical four-bar mechanisms is presented. First, the kinematics of spherical mechanisms are reviewed as they pertain to their manufacture. This is followed by a brief review of some of the current computer-aided design (CAD) software for spherical four-bar mechanisms, e.g., SPHINX, SPHINXPC, ISIS, and OSIRIS. These software packages provide the three-dimensional visualization and computational capabilities necessary to design spherical four-bar mechanisms. However, to date no tools exist to aid in the manufacture of spherical mechanisms. Finally, we present our implementation of this CAM methodology for spherical four-bar mechanisms called SPHINXCAM. SPHINXCAM, when used with the CAD tools mentioned above, facilitates the design, visualization, prototyping and manufacture of spherical four-bar mechanisms.

1. Introduction

Traditional one degree of freedom four-bar linkages are capable of generating only planar movements. Spherical four-bar mechanisms produce motion that is constrained to the surface of a sphere while still only having one degree of freedom (see Fig. 17). Having only one degree of freedom greatly simplifies the actuation and control of the mechanism. This complex motion is desirable since the mechanism can be designed to move a body through many positions while still being driven by a single motor. It is often stated that spherical mechanisms are challenging to design, visualize, prototype and manufacture. However, the design and visualization problems recently have been solved to some extent by the CAD programs such as SPHINX [1], SPHINXPC [2], ISIS [3,4], and OSIRIS [5–7]. Even though these packages facilitate the synthesis of spherical mechanisms they do not assist the important subsequent stages of prototyping, testing, and fabrication [8]. As stated by Laliberté et al. [9] "... the design and fabrication of a prototype using traditional techniques is rather long, tedious, and costly". The manufacturing methodology proposed here facilitates the prototyping and manufacturing of

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spherical mechanisms. The challenges of manufacturing spherical four-bar mechanisms that the methodology address are:

- Precise link arc lengths.
- Precise radial link placement.
- Accurate orientation of axes.
- Compactness of the mechanism.

The methodology presented here yields accurate axes location for the links and lays out the mechanism with compact circular arcs. Precise axis placement is vital to the manufacturing of spherical mechanisms since inaccuracies may result in the link not rotating at the proper radius, which may in turn lead to increased friction and/or binding of the mechanism. Circular arcs are used because they yield a compact mechanism and when machined permit the links to be spaced closely together which reduces internal loading and conserves material.

It is often stated that once a mechanism has been designed that it is desirable to construct a fully functioning prototype [10,11]. The methodology presented here can be used to layout the final design of a mechanism or the layout may be used to quickly manufacture a fully functioning prototype. SphinxCAM is an implementation of this methodology written in the high-level script programming language of AutoCAD called AutoLISP. AutoCAD is used because it is an industry standard and its data can be exported in many different formats that are compatible with computer-aided manufacturing (CAM) programs. CAM files can then be loaded into computer numerically controlled (CNC) machining centers for manufacture. Using these automated and accurate tools facilitates the manufacturing of spherical mechanisms with tight machining tolerances on the critical dimensions (e.g., link arc length, axis placement and orientation).

This paper begins with a review of spherical four-bar mechanisms. Next, the geometry and special cases of spherical four-bar mechanisms are discussed. This is followed by a look at current CAD programs for spherical mechanisms. The final section presents a case study demonstrating the utility of SphinxCAM.

2. Spherical four-bar mechanisms

Traditional planar four-bar mechanisms are a one degree of freedom closed kinematic chain connected by four revolute (R) joints. The joint axes are all parallel and the mechanism is modelled in a single plane. A spherical four-bar mechanism is also a one degree of freedom closed kinematic chain connected by four revolute joints. However, for spherical mechanisms the joint axes all intersect at a common point. This point is the center of the sphere that the mechanism moves about [12]. In both cases the mechanisms can be designed in two dimensions: on the plane or on the sphere (see Fig. 1(a)). However, when you need to manufacture and assemble the links of the planar four-bar they can no longer be coplanar. Instead they must lie in parallel planes (see Fig. 1(b)). Similarly, for spherical four-bar mechanisms the links must be manufactured and assembled to operate in concentric spheres. Manufacturing links to operate in concentric spheres with accurate link lengths and in a compact mechanism is facilitated by the CAM methodology presented here.

In spherical kinematics a link is characterized by the great circle arc subtended by its two joint axes. The two great circles associated with two adjacent links intersect at two points on the sphere. These two points define a line in space which is the R-joint axis that connects the two links. Note that this line passes through the center of the concentric spheres. Fig. 2(a) shows the intersection of four great circles and the resulting axes of rotation and Fig. 2(b) shows the spherical four-bar linkage axes and link nomenclature.

Most studies of planar four-bar linkages have been made on the kinematics of the connecting rod [12]. The connecting rod, or coupler link, performs general planar motion. Similarly, in the spherical four-bar mechanism case, the coupler link performs general spherical motion. Attaching a workpiece or tool to the coupler link usually requires additional parts. Here spherical mechanisms may require two parts, an extension and an attachment, to attach the workpiece to the coupler. The *coupler extension* is an arc length that lies in the same plane and has the same radius as the coupler, see Fig. 3. The *coupler attachment* is orthogonal to the coupler and it too has the same radius as the coupler. We refer to links that operate at the same radius as being in the same layer. Hence, the coupler, coupler extension, and the coupler attachment are all in the same layer.

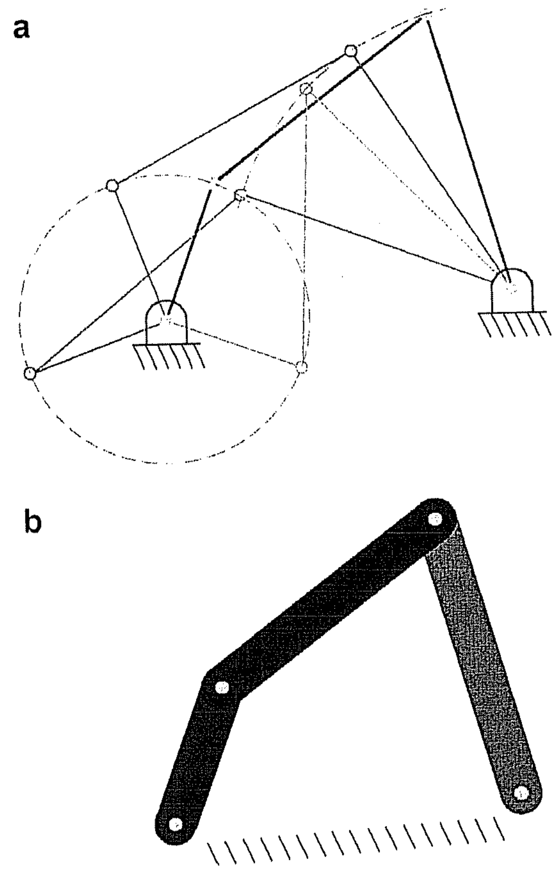

Fig. 1. Planar mechanism design. (a) Planar four-bar synthesis and analysis, (b) planar four-bar assembly.

3. Link geometry of spherical four-bar mechanisms

The links of a spherical four-bar mechanism are described by their angular length along great circles. This produces purely circular links which make machining the holes for their axes difficult (see Fig. 4(a)). Proper placement of the axes in spherical four-bar mechanisms is vital. If the locations of the axes are not accurate, then the resulting links will not rotate about the center of the concentric spheres. This will prevent the mechanism from moving as desired. A link geometry that will facilitate precise link arc lengths, placement of link axes, and compactness of the mechanism is circular arcs with rectangular ends called *feet*. The feet eliminate all the above problems. The feet provide a flat surface, the geometric center of which can be easily found, that facilitates the locating and machining of the axes (see Fig. 4(b)). The orientation of the axis is also simpler since the link can be laid on the flat of the foot and the axis drilled normal to the plane of the foot. A jig or fixture could be used to assist in locating and machining the axes since all the feet of the mechanism are identical. The design addition of the feet on the links facilitates the accurate machining of spherical mechanisms. The circular arcs connecting the feet ensure that the link moves on a thin layer of the concentric spheres. By incrementing the link radii, the links can be designed to operate on different layers of the concentric spheres. This geometry solves the manufacturing and assembly problems of axis location while still keeping the mechanism compact.

To complete the design process, the geometry of each link needs to be described. An arc length, radius, foot size and link width describe each link of the mechanism. The foot size and link width can be considered constant for all the links of the mechanism. The radius of each link can be determined by declaring the radius of the outer most link and then stepping in at increments of link width, cutting tool diameter and offset distance

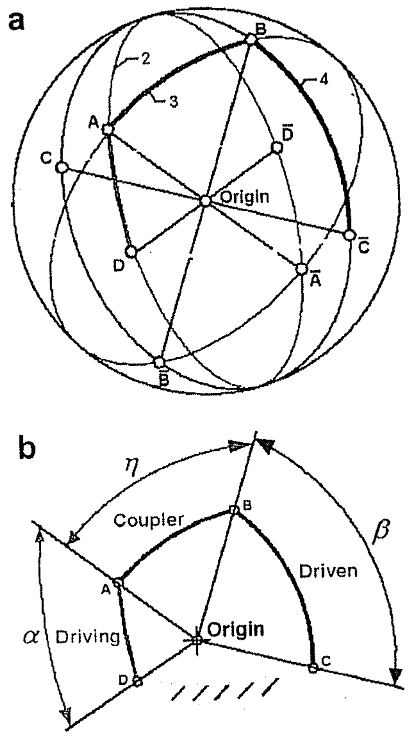

Fig. 2. Spherical mechanism design. (a) Great circles, (b) spherical linkage nomenclature.

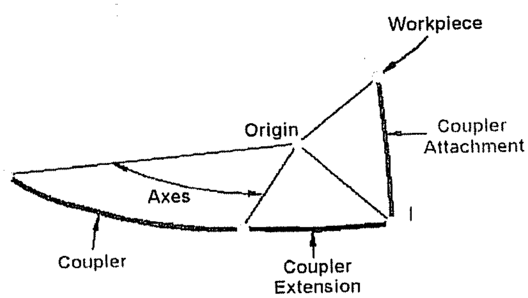

Fig. 3. Attaching the workpiece to the coupler.

for each subsequent link. For reference the links are referred to by their radius, i.e. the largest radii link or link 1, the second largest radii link or link 2, the second largest radii link or link 3 and the smallest radii link or link 4. Additionally, the coupler extension and attachment angles used to attach a workpiece are needed.

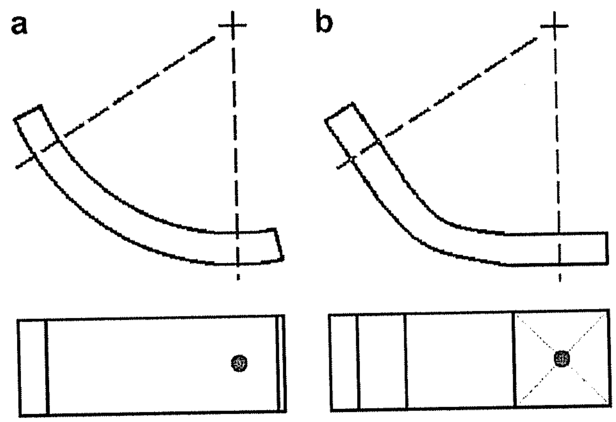

Fig. 4. Link geometry. (a) Circular link, (b) link with feet.

The extension and attachment of the coupler have the same radii as the coupler link and move in the same layer as the coupler. This ensures that the extension and attachment do not interfere with adjacent links on neighboring layers.

3.1. Link layout and spacing

The spacing between the drawn links is set at the cutting tool diameter plus the offset distance. This spacing is required so that each link can be properly machined. If the space between links was the cutting tool diameter then machining problems could arise. Fig. 5(a) shows how the inner arc of the next link would be improperly machined and may result in poor axis placement. By using additional spacing as shown in Fig. 5(b), the links have sufficient spacing to prevent machining problems such as over cutting at the link ends. The corners of the feet, at the end of each link, are needed to locate the axes and verify that they are orthogonal to the feet. Larger than necessary offset distance can be added but that would increase the radii of the other links and make the final mechanism larger and heavier. By adding the offset distance the links can be properly spaced so the feet are not over cut and the mechanism remains compact.

Although the mechanism can be designed so that the outer most link can move on any radius layer, there is a minimum size that the mechanism can be. This minimum size must leave space for all the links and their manufacturing parameters in order to maintain the integrity of each links feet. The maximum link radius is the outer radius of the outermost link. The minimum value for the outermost radius needs to allow space for the remaining three links. The maximum radius takes into account the link arc length (θ_i), link width (l_w), the cutting tool diameter (c_t), offset distance (o_d), stock thickness (s_t), and link number, see Eq. (1). The minimum inner radius IR_i of each link is calculated, which maintains the links feet, and the corresponding mechanism minimum maximum radius is calculated. The mechanism minimum maximum radius is the largest

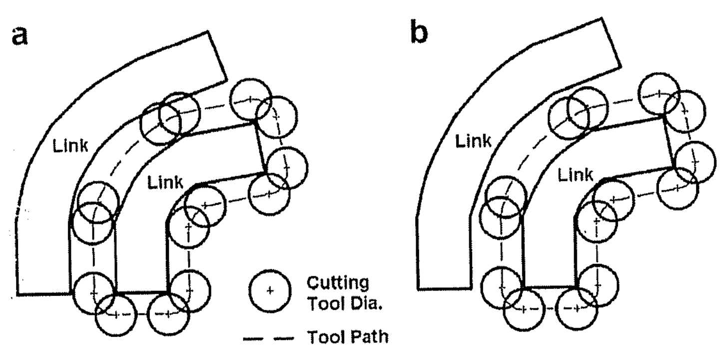

Fig. 5. Spacing between links. (a) Without offset, (b) with offset.

of the four link minimum maximum radius calculated. Fig. 6 shows the layout for two different link numbers with their required minimum radius

$$\begin{array}{l}\text{Minimum}\\ \text{Maximum}\\ \text{Radius}_i\end{array} = \mathrm{IR}_i + l_\mathrm{w} + (i-1) * (l_\mathrm{w} + c_\mathrm{t} + o_\mathrm{d}) \qquad (1)$$

$$\text{where } \mathrm{IR}_i = \begin{array}{c}\text{Inner}\\ \text{Radius}_i\end{array} = \frac{\frac{s_\mathrm{t}}{2}}{\tan\left(\frac{\theta_i}{2}\right)}$$

$$\text{and } i = \begin{pmatrix} 1 & \text{Largest Radii Link} \\ \vdots & \vdots \\ 4 & \text{Smallest Radii Link} \end{pmatrix}$$

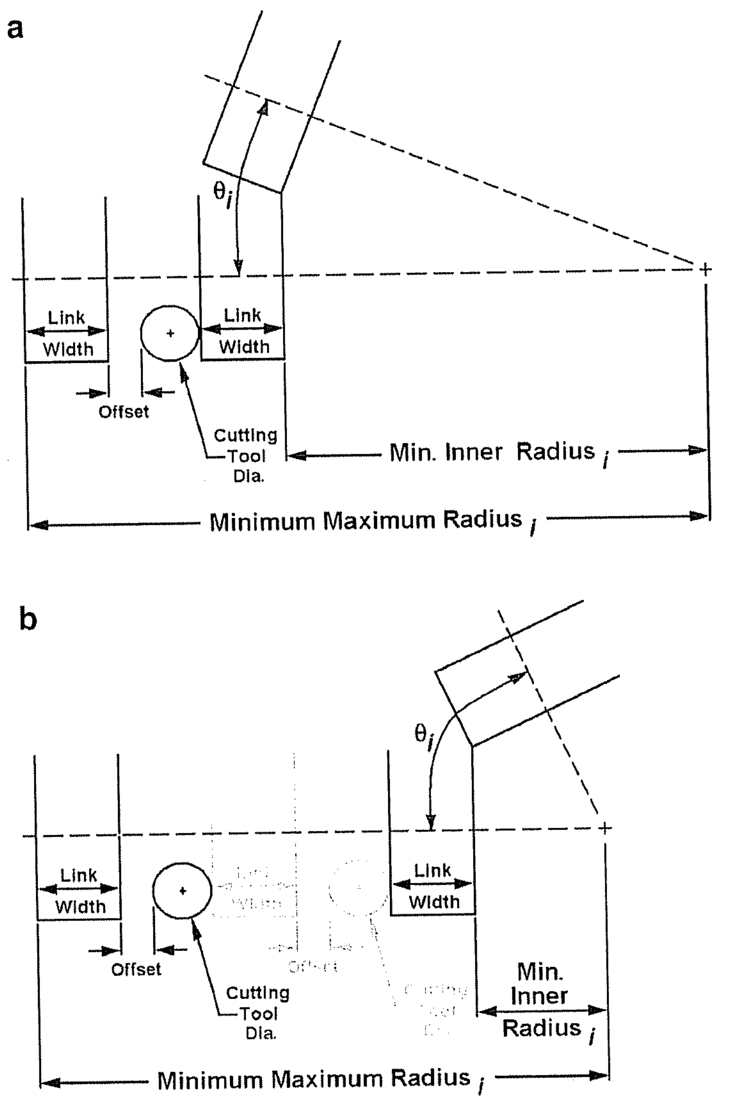

Fig. 6. Minimum maximum radius. (a) Link 2 ($i = 2$), (b) Link 3 ($i = 3$).

$$\begin{bmatrix} X \\ Y \end{bmatrix} = [R_x(\theta)] \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} + \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \tag{2}$$

where $[R_x(\theta)] = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$

Knowing the radius and the angle of the link, Eq. (2) can be used to determine the location of the points of the rotated foot. The X–Y coordinates of points are compared to determine their relation for the design cases of the coupler extension and coupler attachment. This rotation can be used to see if, when moved, the link's extension foot will overlap determining how the extension should be drawn. This is done by simply comparing the X-value of the right side of the rotated foot to the rotated value of the link's extension left side of foot. The Y-values of the points are used to determine which design case occurs for the coupler attachment link.

3.2. Coupler extension

The coupler extension has the same radii of the coupler link so that it moves on the same layer of the concentric sphere. The coupler link has the feet necessary for axial location and manufacture, it may require that the link be extended to attach the workpiece to the mechanism. If the coupler has an extension that does not lie completely within the coupler link another foot or partial foot is added to the link. This additional foot can be used to locate and mount the coupler attachment to the coupler link.

In what follows we address the five possible extension cases listed in Table 1 and shown in Figs. 7–10.

3.2.1. Case 1

This case, seen in Fig. 7(a), occurs when the coupler extension does not overlap the coupler link's rotated foot (see Table 1). The extension's foot is drawn as specified. The foot is connected to the coupler link's foot with arcs drawn from A to a and B to b, seen in Fig. 7(b), with radii equal to the coupler link's. Arcs are used to connect the extension to the coupler link for two reasons. The first one is that the link thickness will be maintained using arcs. If lines are used to connect the extension and the extension angle is large then the link may narrow. The second reason is that using arcs maintains the spacing between the links. This prevents the cutting tool from over cutting adjacent links when machining the coupler extension link.

3.2.2. Case 2

This is a rare case, seen in Fig. 8(a), that occurs when the coupler extension inner radii foot overlaps the links rotated inner foot but their outer radii feet do not overlap (see Table 1). The extension's foot top and end are drawn as normal. The foot is connected to the couplers foot by an arc drawn from A to a and a line from B to c, seen in Fig. 8(b).

3.2.3. Case 3

The next case occurs when the extension is slightly smaller. Both legs of the extension foot overlap the coupler's rotated foot legs. If the overlap distance from B to c is greater than $\frac{1}{4}$ of the stock thickness, then the case in Fig. 9(a) occurs (see Table 1). The coupler's extension end, $\overline{\text{cd}}$, is drawn as specified. The extension is attached to the coupler link by connecting the top of the extension to the top of the coupler with a line, $\overline{\text{Ad}}$, and the same is done for the bottom of the extension and coupler link, $\overline{\text{Bc}}$, as shown in Fig. 9(b).

Table 1
Coupler extension design cases

Case	Criterion 1	Criterion 2
1	$b_x > B_x$	
2	$b_x \leqslant B_x$	$A_x < a_x$
3	$b_x < B_x < c_x$	$\overline{\text{Bc}} > \frac{s_1}{4}$
4	$b_x < B_x < c_x$	$\overline{\text{Bc}} \leqslant \frac{s_1}{4}$
5	$B_x \geqslant c_x$	

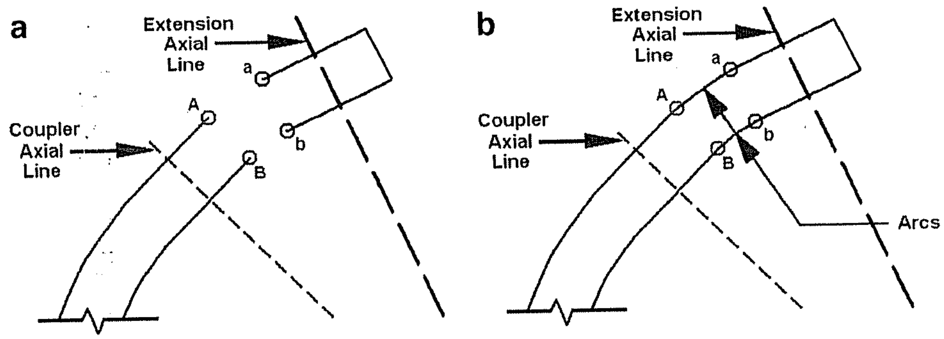

Fig. 7. Case 1: Complete extension of coupler link. (a) Coupler extension no overlap problem, (b) coupler extension no overlap solution.

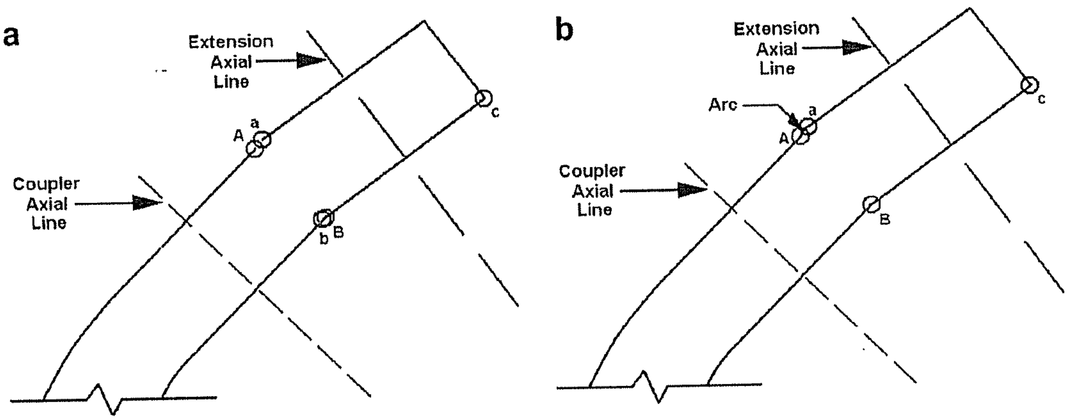

Fig. 8. Case 2: Complete extension of coupler link. (a) Coupler extension one leg overlap problem, (b) coupler extension one leg overlap solution.

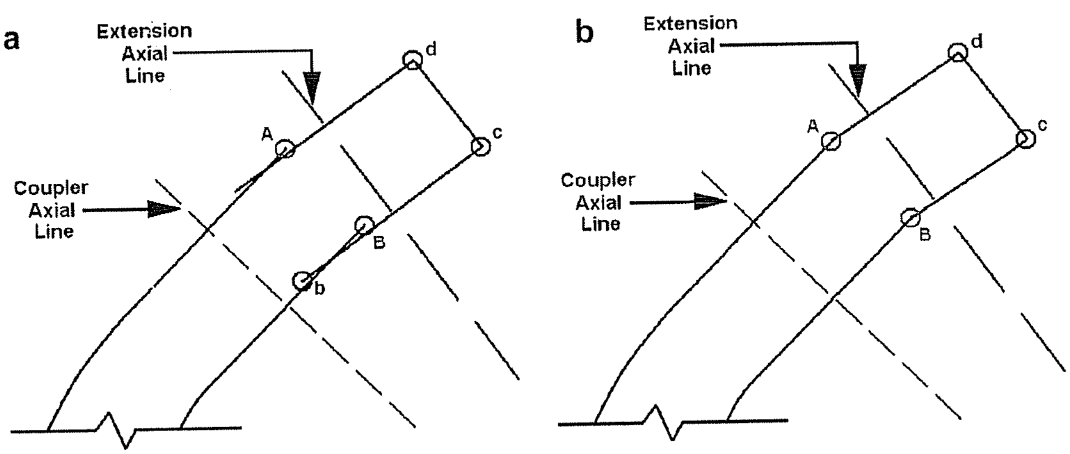

Fig. 9. Case 3: Small extension (>1/4 stock thickness). (a) Coupler extension >0.25 stock thickness overlap, (b) coupler extension >0.25 stock thickness solution.

3.2.4. Case 4

This case occurs when both legs overlap as in case 3 but the distance from B to c is $\leqslant \frac{1}{4}$ of the stock thickness as shown in Fig. 10(a) (see Table 1). For this case the link extension is laid out by drawing the end of the extension, $\overline{cd}$, where it needs to be. The top of the extension is connected to the coupler link with a line between the upper edge of the link and the top of the extension end, shown as $\overline{Ad}$ in Fig. 10(b). The bottom of the exten-

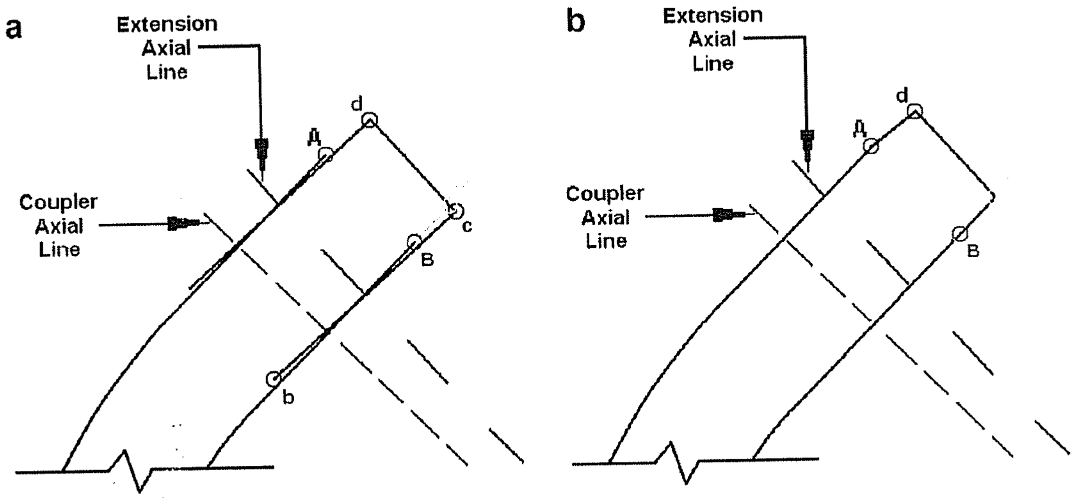

Fig. 10. Case 4: Small extension (<1/4 stock thickness). (a) Coupler extension ⩽0.25 stock thickness overlap problem, (b) coupler extension ⩽0.25 stock thickness solution.

sion is connected to the coupler differently. The bottom line of the foot of the coupler link is extended to intersect the extension end, $\overline{Bc'}$, and the bottom of the extension end is trimmed, see $\overline{cc'}$ in Fig. 10(b). This was necessary because if the bottom of the link foot was attached to the bottom of the extension end it would be jagged and difficult to machine. By extending the bottom of the link's foot the contour can be more easily machined. Note that if this case occurs, the convex side of the link's foot is used to find the location of the axis. Extending the bottom of the link's foot results in the concave side of the foot being unsuitable for locating the axis.

3.2.5. Case 5

This case occurs when there is no extension or the extension lies completely within the link (see Table 1). For this case the link is drawn normally and the axial line is drawn for reference purposes only.

3.3. Coupler attachment

The geometry of the coupler attachment link differs from the other links. The base end that attaches to the workpiece has just half of a foot. The center of the end of the half foot is the point where the workpiece is attached so that the mechanism produces the desired motion. The other end of the link has no foot. This is because it will be attached to the coupler link. The thickness of the coupler link acts as the foot of the attachment link. There are three different cases that are encountered when laying out the coupler attachment link listed in Table 2 and shown in Figs. 11–13.

3.3.1. Case 1

The first case (Fig. 11(a)) occurs when the attachment link angle is large enough that there is no overlapping of the coupler link's foot and the attachment's end (see Table 2). When this happens the base half foot is

Table 2
Coupler attachment design cases

Case	Criterion
1	$C_y < b_y$
2	$B_y \leqslant b_y \leqslant C_y$
3	$b_y < B_y$

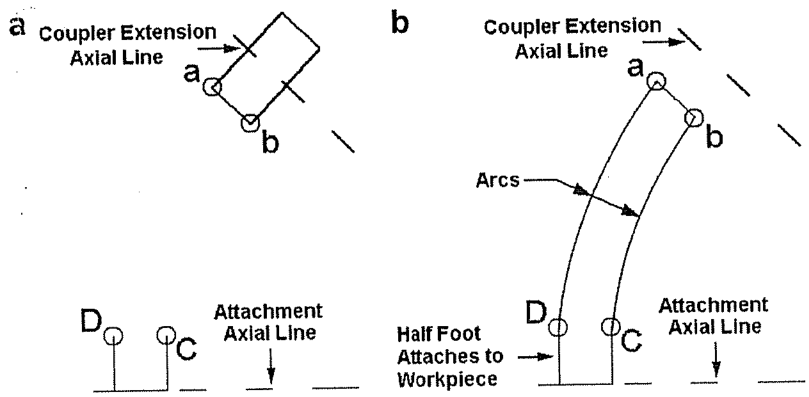

Fig. 11. Case 1: Geometry with no overlap of extension link. (a) No attachment overlap, (b) no overlap solution.

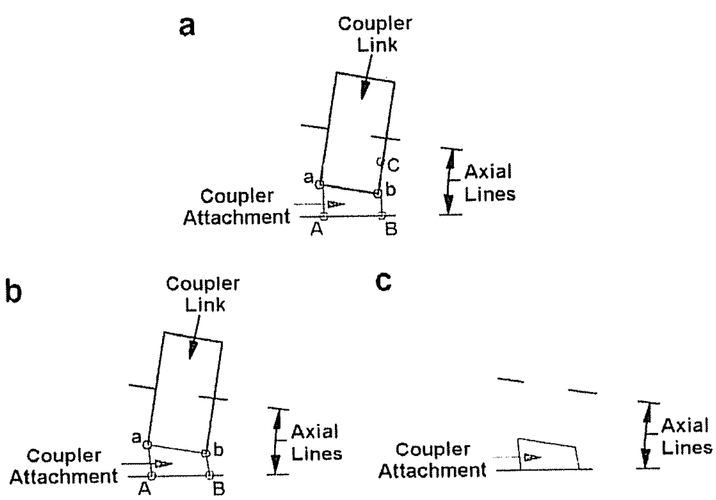

Fig. 12. Case 2: Small overlap of extension link. (a) Partial attachment overlap, (b) partial overlap solution, (c) coupler attachment link.

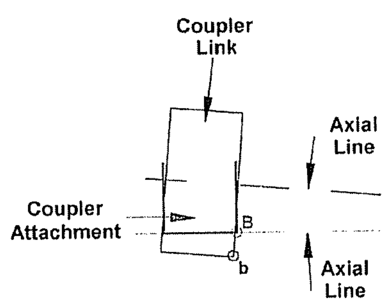

Fig. 13. Case 3: Overlap of extension link.

drawn normally. Arcs are drawn from D to a and C to b and the link is closed by connecting a and b (Fig. 11(b)).

3.3.2. Case 2

If the attachment angle is small, causing the attachment foot to intersect with the coupler link's foot as seen in Fig. 12(a), then an attachment link is drawn. In this case the attachment end does not intersect with the coupler foot but is not far enough away for it to be connected with arcs (see Table 2). Instead the attachment end is connected to the coupler foot with straight lines from A to B to b to a to A. Fig. 12(b) and (c) shows the solution to the small overlap problem and the resulting coupler attachment link, respectively.

When the inner legs overlap and the outer legs do not it is treated as this case.

3.3.3. Case 3

No attachment link will be drawn if the attachment angle is too small or a zero value is entered. The attachment angle is too small for an attachment link to be drawn if the angle is not large enough for the attachment foot end not to intersect the coupler link. Using Eq. (2) the Y value of the coupler link's foot lower right corner b is compared to the inner right corner of the half foot B (see Fig. 13 and Table 2). If this case occurs then the attachment lies within the coupler link's foot and no attachment is drawn. Fig. 13 shows the end of the coupler link and the coupler attachment. The coupler link is drawn only as the link width and stock thickness, since the coupler attachment lies on the great circle that is orthogonal to the coupler link.

3.4. Spacer sizes

The last information to be determined is the spacer sizes needed to construct the mechanism. The spacer lengths are set so as to maintain the proper interlink distance along the connecting axes. This distance makes the links move on their corresponding layers such that they do not interfere with adjacent links. The spacer sizes, shown in Fig. 14, correspond to the distance required between the links to ensure that they move on concentric spheres. Four spacers, of two different sizes, are needed to assemble a mechanism: Spacer Size_1 for links that are adjacent, and Spacer Size_2 for the links that are nonadjacent. Eqs. (3) and (4) are used to calculate the two spacer sizes,

$$\begin{matrix}\text{Spacer}\\ \text{Size}_1\end{matrix} = c_t + o_d \begin{pmatrix}\text{Adjacent}\\ \text{Links}\end{pmatrix} \tag{3}$$

$$\begin{matrix}\text{Spacer}\\ \text{Size}_2\end{matrix} = 2 * c_t + l_w + 2 * o_d \begin{pmatrix}\text{Nonadjacent}\\ \text{Links}\end{pmatrix} \tag{4}$$

3.5. Assembling the mechanism

To assemble the drawn mechanism the links may be connected to form a closed chain as follows. Remember that the links move on layers of concentric spheres so the outer edge of the smaller radius link will always be attached to the inner edge of the larger radius link. The smallest link is attached to the second smallest link with a Size_1 spacer being used to maintain distance between the links. The other end of the second smallest link is attached to the largest link using the Size_2 spacer. The other end of the coupler link is attached to the second largest link with the Size_1 spacer keeping the distance. The chain is closed using the final Size_2 spacer to attach

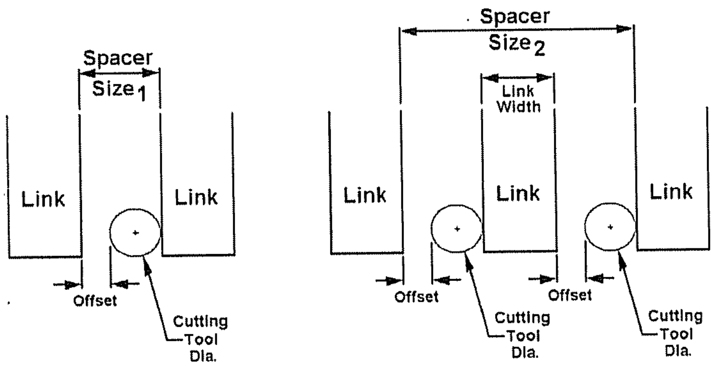

Fig. 14. Spacer sizes.

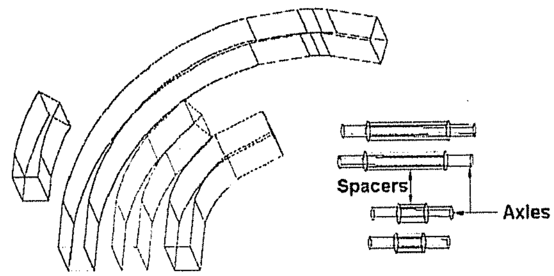

Fig. 15. The sample mechanism-part layout.

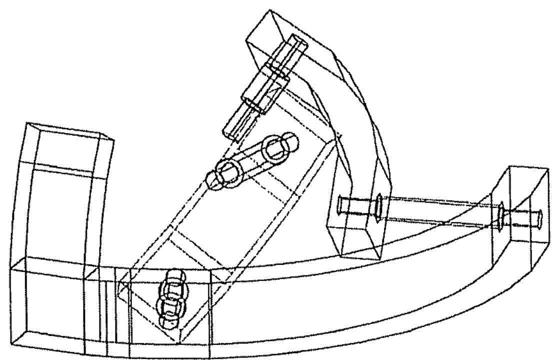

Fig. 16. The assembled sample mechanism – wire frame.

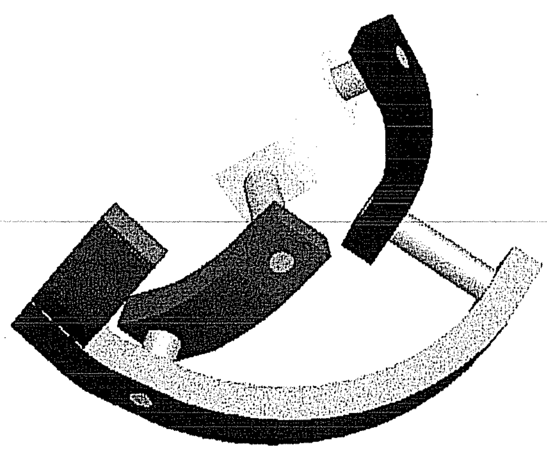

Fig. 17. The assembled sample mechanism – solid.

the remaining ends of the second largest link and the smallest link together. The parts of a spherical mechanism are shown in Fig. 15 and the assembled mechanism is shown in Figs. 16 and 17.

4. CAD/CAM for spherical four-bar mechanisms

SPHINX [1], SPHINXPC [2], ISIS [3,4], OSIRIS [5–7] and SPHINXCAM are software packages for designing and laying out spherical four-bar mechanisms. SPHINXCAM takes the output from SPHINX, SPHINXPC or ISIS and draws the links of the selected mechanism. SPHINXCAM is an AutoLISP program that can be run on any platform that operates AutoCAD. SPHINXCAM draws the links accurately, compactly, and quickly by simply entering the output data from SPHINX, SPHINXPC or ISIS. One advantage of working in the AutoCAD environment is that the finished drawing can be saved in several different formats which allow the user to import it into computer-aided manufacturing packages. CAM programs are highly accurate tools that assist with machining the links. This high degree of accuracy helps to precisely locate and machine the axes of the links.

5. SphinxCAM

SphinxCAM asks the user to enter geometric data about the mechanism to be drawn. The program asks for the stock thickness, cutting tool diameter, an offset distance, the links width, largest links' radii and the arc lengths of the mechanism. SphinxCAM requires positive nonzero values for all the geometric data, except the coupler extension and attachment. The program uses Eq. (1) to ensure the minimum maximum radius is acceptable and Eq. (2) to ensure that the arc lengths do not allow the feet to overlap. If overlapping occurs, the program informs the user and prompts for another value to be entered. If the feet were allowed to overlap, the location of the axes would be inaccurate. The foot would no longer be square and this would cause the axes to be misplaced.

After an acceptable arc length has been entered the program asks if the user desires a link extension. The program will continue to ask for link extensions until one is entered or all four links have been drawn. Only one link can have an extension. If any of the links have an extension then the program will also ask if a coupler attachment will be needed. If there is a coupler attachment then it will be drawn with the same radius as the link that had the extension. Both the coupler extension and coupler attachment need to be the same radius as the coupler.

SphinxCAM uses this data to layout the links accurately and compactly, see Fig. 18.

5.1. Drawing the mechanism links

SphinxCAM lays out four or five links with their axial lines, depending on the data entered. If there are four links, they are laid out with one axis of each link lined up along the bottom of the screen. They are arranged, left to right, from largest to smallest radii, with their common center lying to the right. The links' arcs extend clockwise, around the common center. If there are five links, the additional link is the coupler attachment. The first four links are drawn as in the four link case and the fifth link is offset to the left and raised relative to the other links so that as it is extended clockwise, its tool paths will not interfere with the adjacent link, see Fig. 18.

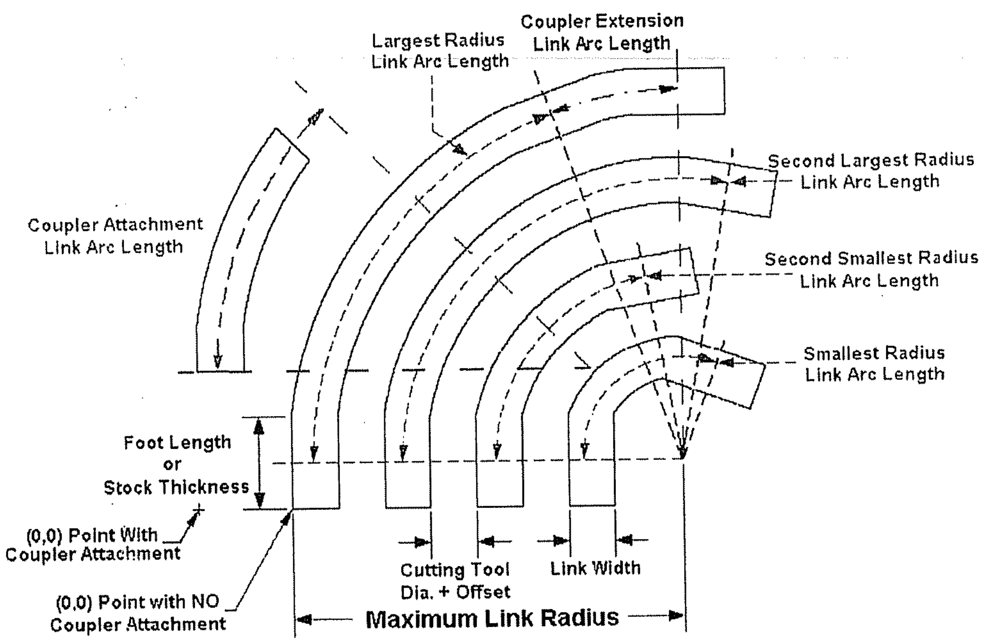

Fig. 18. General layout of links.

It has the same radius as the link that had the coupler extension. The radius of the coupler attachment link may be different from the outer-most link, which creates problems for drawing the attachment link without entering the toolpath region about the outer-most link. In order to avoid this problem the coupler attachment link is drawn offset to the left at the same spacing as the other links, and is positioned vertically according to which link has been extended and the size of the attachment angle. The vertical offset distance is a function of the stock thickness, link number, link width, cutting tool diameter and the offset distance (see Eq. (5))

$$\begin{array}{l}\text{Vertical}\\ \text{Offset}\\ \text{Distance}\end{array} = 1.5 * s_t + \frac{n}{2}(l_w + c_t + o_d) \tag{5}$$

$$\text{where } n = \begin{pmatrix} 0 & \text{Coupler has Largest Radii} \\ \vdots & \vdots \\ 3 & \text{Coupler has Smallest Radii} \end{pmatrix}$$

If the coupler attachment link arc length is ⩽30(deg) the vertical offset distance is set to $\frac{s_t}{2}$ regardless of which link is the coupler. This prevents a small radius attachment link from being drawn high up, which would waste material.

The general layout of the links, including the coupler attachment case, is shown in Fig. 18. SphinxCAM uses colors and linetypes to show the axial lines of the various links. The axial lines of the regular four links have a common origin and are drawn with dashed red lines. To offset the coupler extension axial line, since it also intersects the common center, SphinxCAM uses a different linetype that is blue. If there is a coupler attachment its axial lines are drawn with another linetype that is green.

5.2. Saving

When saving and exporting the drawings it is important to know the origin of the drawing. If there are four links (i.e. no attachment link) then the origin is located at the lower left corner of the leftmost link. If there is a coupler attachment then the origin is located at the intersection of the projections of the lines that run along the bottom of the four links and the line that runs vertically down the left side of the coupler attachment link, shown in Fig. 18.

Table 3
Infinity fan mechanism data

Link/Prompt	Angle/value
Sphinx data	
Largest radii link	88.284 (deg)
Second largest radii link	53.806 (deg)
Second smallest radii link	47.350 (deg)
Smallest radii link	87.894 (deg)
Link to extend	1
Link extension	−86.350 (deg)
Link attachment	−46.690 (deg)
Prompt	Value entered
Other data used	
System of units	1 (US customary)
Stock thickness	1 (in)
Cutting tool diameter	0.375 (in)
Off-set distance	0.125 (in)
Link width	0.500 (in)
Maximum radius	4.250 (in)
Sphinx CAM output	
Spacer sizes, two of each needed: 0.5 and 1.5 (in)	

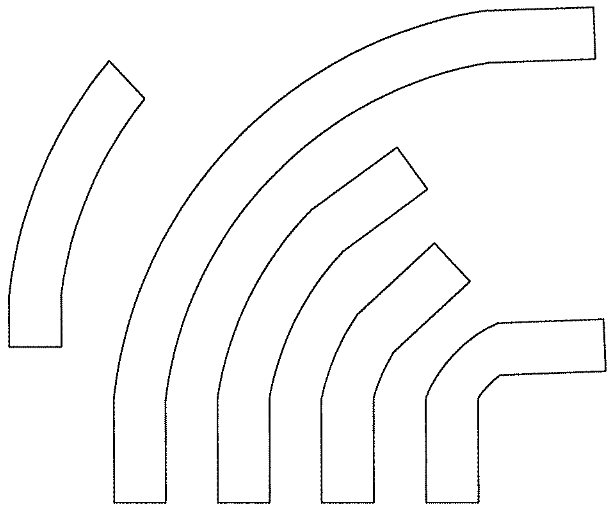

Fig. 19. SPHINXCAM infinity fan link layout.

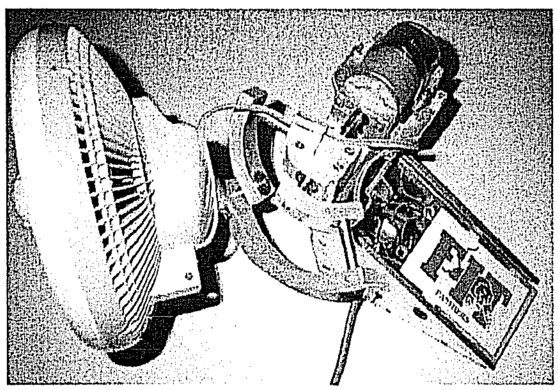

Fig. 20. Infinity fan-top view.

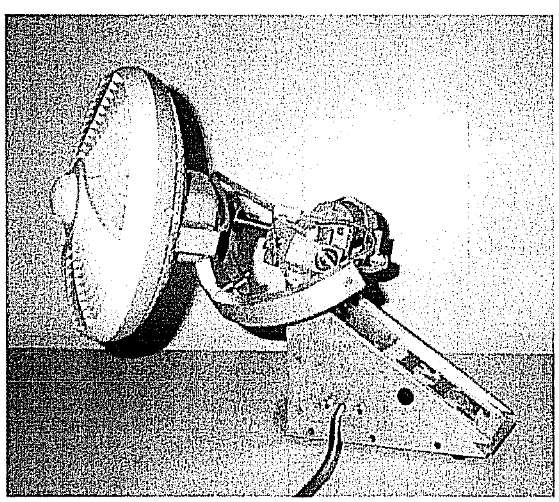

Fig. 21. Infinity fan-side view.

6. Test case

SphinxCAM has been used in conjunction with various CAD programs to design and build many mechanisms. SphinxCAM was used to layout the links for the Infinity Fan (Patent 6213715 B1). The data for constructing the fan's spherical mechanism was acquired from Sphinx (see Table 3) and combined with the desired stock thickness, link width, offset distance, and cutting tool diameter. SphinxCAM produced the AutoCAD drawings, see Fig. 19, that were then exported into a CAM package which generated the NC code to manufacture the links of the mechanism. Figs. 20 and 21 show the completed Infinity Fan.

7. Summary

The geometry and nomenclature for spherical four-bar mechanisms were reviewed. Next the link geometry and spacing necessary to facilitate the manufacture and assembly of the mechanisms was discussed. Then the design considerations including all the possible cases for the coupler extension and attachment were covered. This was followed by a brief look at the CAD/CAM software currently available for spherical four-bar mechanisms including SphinxCAM.

SphinxCAM uses computer-aided drafting and manufacturing to address many of the challenges encountered when building spherical mechanisms. SphinxCAM lays out the links of the mechanisms in AutoCAD. The links are designed to facilitate accurate axis placement which is critical to spherical mechanisms. Moreover, SphinxCAM creates compact links which reduces internal loading and conserves raw materials.

The source code for SphinxCAM and the SphinxCAM *User's Guide* are available at the Robotics and Spatial Systems Laboratory (RASSL) website: http://my.fit.edu/~pierrel/.

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