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SPHINXCAM: COMPUTER-AIDED MANUFACTURING FOR SPHERICAL MECHANISMS

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ABSTRACT

In this paper we present SPHINXCAM, a computer-aided manufacturing software for spherical four-bar mechanisms. 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, and ISIS. 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. SPHINXCAM, when used with the CAD tools mentioned above, facilitates the design, visualization, and manufacture of spherical four-bar mechanisms.

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. This complex motion is desirable since the mechanism can be designed to move a body through many positions while still being driven by one motor. Also, having only one degree of freedom greatly simplifies the control of the mechanism. It is often stated that spherical mechanisms are difficult 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, SPHINXPC and ISIS. SPHINXCAM facilitates the prototyping and manufacturing of spherical mechanisms. The challenges of manufacturing spherical four-bar mechanisms that SPHINXCAM address are:

Precise link arc length
Placement of link axes
Accurate orientation of axes
Compactness of the mechanism

SPHINXCAM enables accurate axes location for the links and draws the mechanism with compact circular arcs. Accurate axis placement is vital to the building 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.

SPHINXCAM is 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) mill machines 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).

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

SPHERICAL FOUR-BAR MECHANISMS

A spherical four-bar mechanism consists of four links connected by four revolute joints. A body undergoing spherical motion has three degrees of freedom; rotation about three mutually perpendicular axis passing through the center of a sphere. This constrains spherical motion to be purely rotational. The rotations may be about a fixed axis or an instantaneous axis. In either case the axis still must pass through the center of the sphere. Hence, the axes of the four revolute joints of spherical mechanisms must intersect in the sphere center (Chiang 1992).

An axis of rotation is defined by a unit vector whose origin is at the center of the sphere. The unit vector defines the direction of the line about which the link rotates. In spherical kinematics a link is characterized by the great circle arc subtended by it's two joints at the center of the sphere. A great circle is any circle lying on the surface of a sphere that has a radius equal to the sphere. Two great circles intersect at two points on the sphere and define a line in space. This line passes through the center of the concentric spheres. Unit vectors originating from the sphere center along the line in either direction define the axis of rotation. Fig. 1 (a) shows the intersection of four great circles and the resulting axes of rotation and Fig. 1 (b) shows the spherical four-bar linkage axes and link name notation.

Thus far, most studies of planar four-bar linkages have been made on the kinematics of the connecting rod (Chiang 1992). 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 the moving frame to the coupler link usually requires additional parts. SPHINXCAM lays out two parts to attach the moving frame 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. 2. The **coupler attachment** is normal to the coupler but still in the same layer. A layer is the surface of one of the concentric spheres. The coupler, coupler extension, and the coupler attachment all have the same radii and lie on the surface of the same sphere.

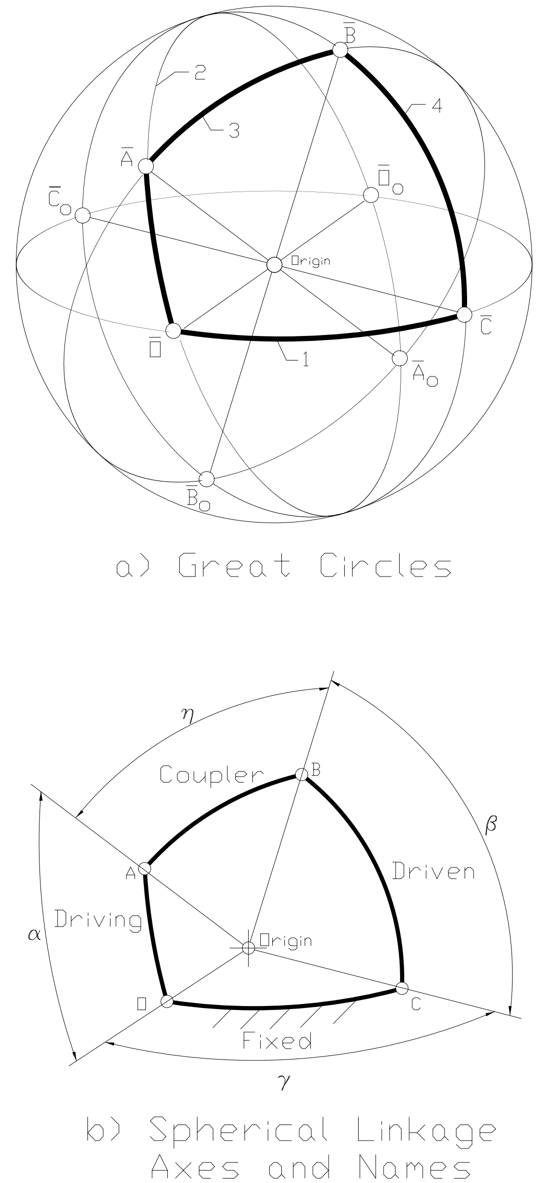

Figure 1. SPHERICAL MECHANISM DESIGN.

CAD/CAM FOR SPHERICAL FOUR-BAR MECHANISMS

SPHINX (Larochelle et al 1993), SPHINXPC (Ruth and McCarthy 1997), ISIS (Larochelle, Vance, and McCarthy 1998) (Furlong, Vance, and Larochelle 1998) 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.

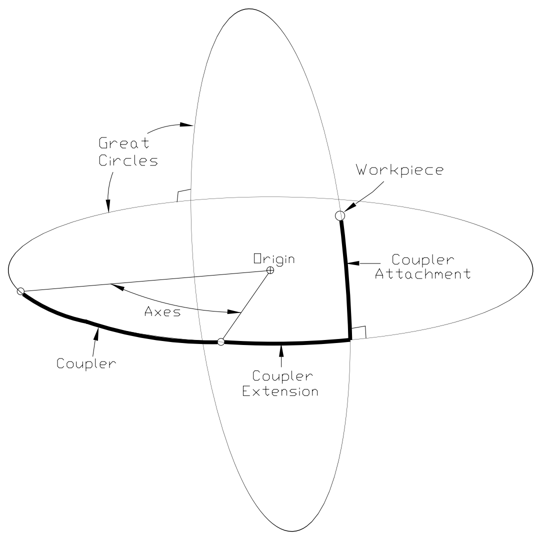

Figure 2. ATTACHING THE WORKPIECE TO THE COUPLER.

GEOMETRY OF *S*PHINXCAM

The *S*PHINXCAM program draws links that are circular arcs with rectangular ends called **feet**. This geometry solves the manufacturing problems of axis location while still keeping the mechanism compact. The program 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. The coupler attachment is drawn as the other links but the feet of the link are drawn differently. These differences will be further discussed below.

The general layout of the links, including the coupler attachment case, is shown in Fig. 3. *S*PHINXCAM 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, *S*PHINXCAM uses a different dashdot line that is blue. If there is a coupler attachment its axial lines are drawn with dotdashdot green lines. These colors and linetypes are shown in Fig. 3.

*S*PHINXCAM asks the user to enter geometric data about the mechanism to be drawn. The program asks for the stock thickness or foot length and link width to be entered. The stock thickness is the thickness of the material from which the links are to be machined. These data determine the dimensions of the feet, see Fig. 3. The stock thickness determines the foot's height and depth. The height and depth are made equal to each other so that the surface of the foot will be square. This facilitates the use of bearings that can be housed in the foot. The depth is important if there is a coupler attachment for the mechanism. The link width sets the thickness of the links to be drawn. The foot shape is also important for axis location. With purely circular links machining the holes for the axes was difficult. Proper placement of the axes in spherical four-bar mechanisms is vital. If the location of the axes is 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. Circular links may roll when machining the axes, which results in the axes having different centers than the other links. The feet eliminate the above problems. Axis location is facilitated by locating the geometric center of the rectangular foot. 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. The design addition of the feet on the links facilitates the accurate machining of spherical mechanisms.

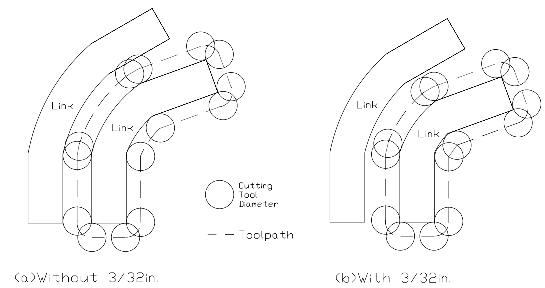

Figure 4. SPACING BETWEEN LINKS.

Link Layout and Spacing

The spacing between the drawn links is set at the cutting tool diameter plus $\frac{3}{32}$(in). 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. 4 (a) shows how the inner arc of the next link would be improperly machined and may result in poor axis placement. By using the spacing shown in Fig. 4 (b), the links have sufficient spacing to prevent machining problems 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 perpendicular to the feet. More than $\frac{3}{32}$(in) could be added but that would increase the radii of the other links and make the final mechanism larger and heavier. By adding the $\frac{3}{32}$(in) the links can be properly spaced so the feet are not clipped and the mechanism remains compact.

The program asks for the maximum link radius. This value is the outer radius of the largest link, see Fig. 3. The inner radius of the largest link is set at the maximum radius minus the link width. *S*PHINXCAM calculates the minimum radius that the mech-

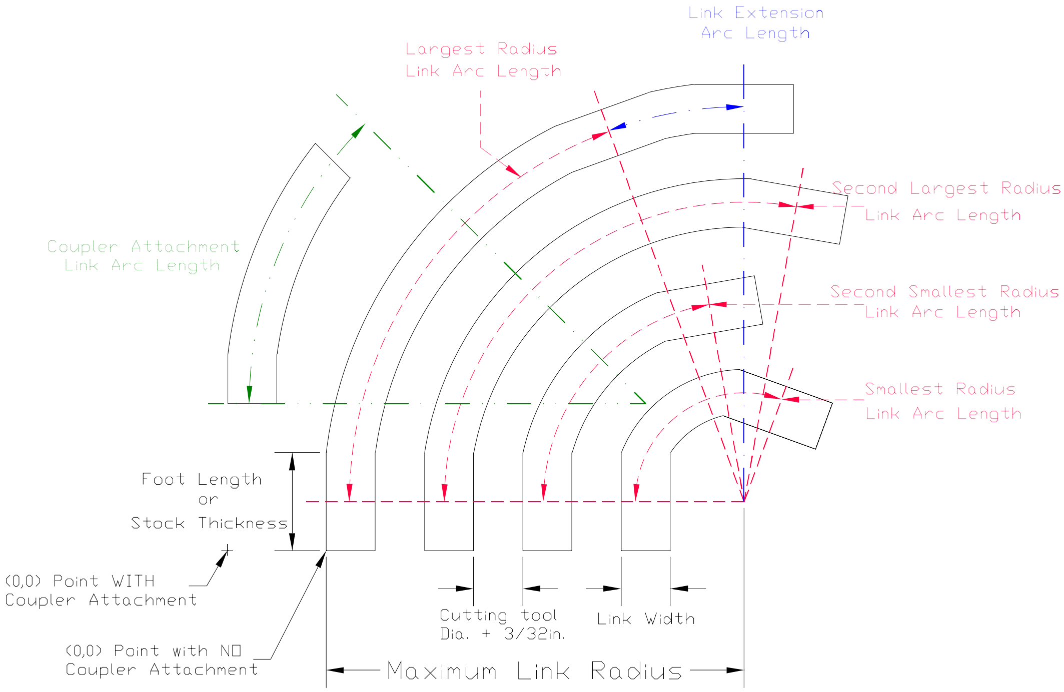

Figure 3. GENERAL LAY OUT OF LINKS.

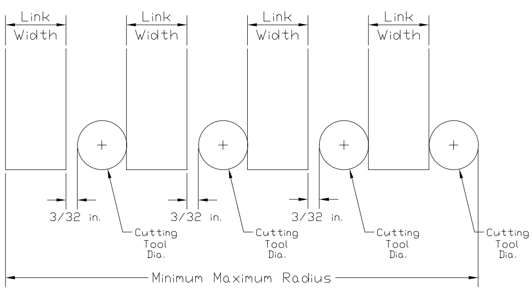

Figure 5. MINIMUM MAXIMUM RADIUS.

anism can have using an equation which takes into account the link width and the cutting tool diameter,

$$\begin{array}{c}\text{Minimum}\\ \text{Maximum}\\ \text{Radius}\end{array} = 4lw + 4ct + 3 * \frac{3}{32}\text{in}, \qquad (1)$$

where: lw is the link width and ct equals the cutting tool diameter. Fig. 5 shows the layout of the links with the required minimum spacing. If a value is entered that is not large enough for all the links to be drawn then the program uses Eq. 1 and determines the minimum acceptable value.

SphinxCAM also asks for the link arc lengths. The program draws the links from largest to smallest radius. Each link's arc length is checked by SphinxCAM, using rotation matrices, to make sure that it is large enough. The program uses Eq. 2 on the foot that is to be moved to determine its location.

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

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

This location is compared to the fixed foot of the link. SphinxCAM uses this rotation to see if, when moved, the link's feet will overlap. This is done by simply comparing the X-value of the right side of the fixed foot to the rotated value of the link's left side of the rotated foot. If the X-value of the fixed foot is larger than the X-value of the rotated foot, then the feet of the link will overlap. If overlapping occurs, SphinxCAM 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.

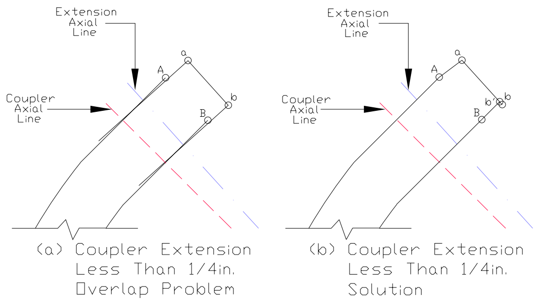

Figure 6. CASE 1: SMALL EXTENSION OF COUPLER LINK(<1/4in.).

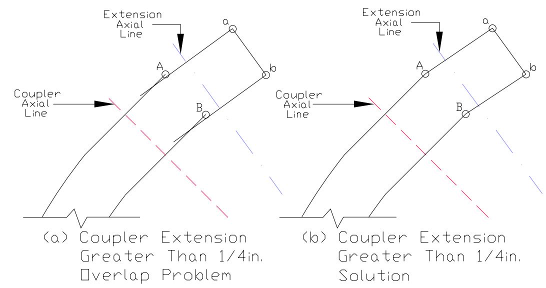

Figure 7. CASE 2: SMALL EXTENSION OF COUPLER LINK(>1/4in.).

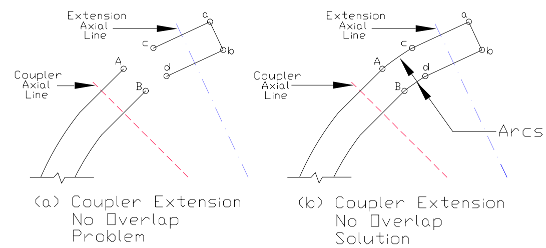

Figure 8. CASE 3: LARGE EXTENSION OF COUPLER LINK.

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.

Coupler Extension-Special Design Cases

The coupler extension can cause some special design cases which will now be discussed:

CASE 1: If the extension angle is small and the extension itself extends just beyond the link's foot, then the program draws the link as usual but the link has an addition. This case occurs when less than one-quarter of an inch will project beyond the link's foot as shown in Fig. 6 (a). For this case the link extension is laid out by drawing the end of the extension, $\overline{ab}$, 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 in $\overline{Aa}$ in Fig. 6 (b). The bottom of the extension is connected to the coupler differently. The bottom line of the foot of the coupler link is extended to intersect the extension end, $\overline{Bb'}$, and the bottom of the extension end is trimmed, see $\overline{bb'}$ in Fig. 6 (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.

CASE 2: The next case occurs when the extension is slightly larger, but the extension foot still overlaps the coupler link's foot. If the overlap is greater than one-quarter of an inch, then the case in Fig. 7 (a) occurs. The coupler's extension end, $\overline{ab}$, 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, $\overline{Aa}$, and the same is done for the bottom of the extension and coupler link, $\overline{Bb}$, as shown in Fig. 7 (b).

CASE 3: The final case, seen in Fig. 8 (a), occurs when the coupler extension does not overlap the coupler link's foot. The extension's foot is drawn as specified. The foot is connected to the coupler link's foot with arcs drawn from A to c and B to d, seen in Fig. 8 (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 were 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 damaging other links when machining the coupler extension link.

Coupler Attachment

The coupler attachment is drawn to the left of the other links, see Fig. 3. It has the same radius as the coupler link and its 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 width, cutting tool diameter, and the link number that has the extension. Eq. 3, where *st* is the stock thickness, *lw* is the link width and *ct* is the cutting tool diameter, shows the vertical offset distance used to locate the attachment link.

$$\begin{array}{c}\text{Vertical}\\ \text{Offset}\\ \text{Distance}\end{array} = 1.5st + \frac{n}{2}\left(lw + ct + \frac{3}{32}\right) \qquad (3)$$

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

If the coupler attachment link arc length is less than 30(deg) the vertical offset distance is set to zero. This prevents a small radius attachment link from being drawn high up, which would waste material. There are three different cases that are encountered when drawing the coupler attachment link:

CASE 1: 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, see point A in Fig. 9, is compared to the local zero line. If the value is less than or equal to zero then the attachment lies within the coupler link's foot and no attachment is drawn. Fig. 9 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 perpendicular to the coupler link.

CASE 2: If the attachment angle is small, causing the attachment foot to intersect with the coupler link's foot as seen in Fig. 10 (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.

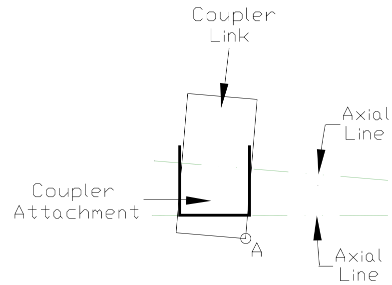

Figure 9. CASE 1: OVERLAP OF EXTENSION LINK.

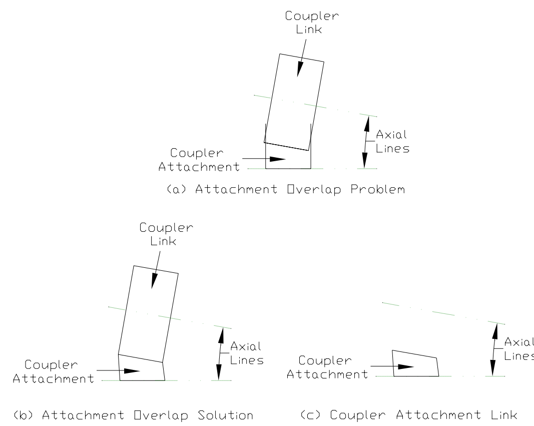

Figure 10. CASE 2: SMALL OVERLAP OF EXTENSION LINK.

Instead the attachment end is connected to the coupler foot with straight lines. Fig. 10 (b) and Fig. 10 (c) show the solution to the small overlap problem and the resulting coupler attachment link respectively. When this case occurs the vertical offset distance is set equal to zero.

CASE 3: The final case 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. When this happens the link is drawn similarly to the other links. Fig. 11 shows the geometry of the attachment link when there is no overlapping of the link ends.

The coupler attachment link has a slightly different geometry than the other links. The bottom foot is only half the stock thickness. This makes the point that the workpiece is to be attached to at the end and center of the half foot. The other foot is not drawn at all. This is because it is attached to the side of the coupler link and the thickness of the coupler link acts as the foot of the attachment link.

When saving and exporting the drawings it is important to

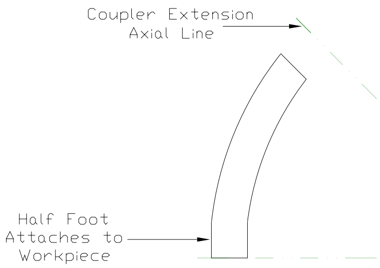

Figure 11. CASE 3: GEOMETRY WITH NO OVERLAP OF EXTENSION LINK.

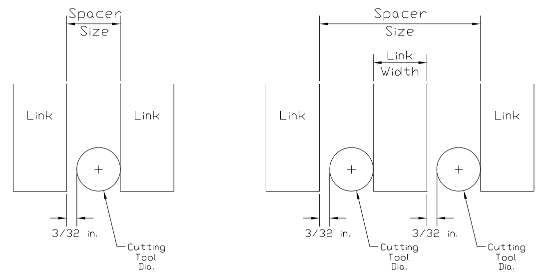

Figure 12. SPACER SIZES.

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. 3.

Spacer Sizes

The last information given by SphinxCAM is the spacer sizes needed to construct the mechanism. The spacer sizes, shown in Fig. 12, correspond to the distance that is required between the links to ensure that when rotated the links are moving on concentric spheres. Four spacers, of two different sizes, are needed to construct a mechanism: Size_1 for links that are consecutive, and Size_2 for the links that are not consecutive. Eq. 4 and Eq. 5 are used to calculate the two spacer sizes,

$$\begin{matrix}\text{Spacer}\\ \text{Size}_1\end{matrix} = ct + \frac{3}{32}\text{in.} \begin{pmatrix}\text{Consecutive}\\ \text{Links}\end{pmatrix} \tag{4}$$

$$\begin{matrix}\text{Spacer}\\ \text{Size}_2\end{matrix} = 2ct + lw + 2 * \frac{3}{32}\text{in.} \begin{pmatrix}\text{Nonconsecutive}\\ \text{Links}\end{pmatrix} \tag{5}$$

where ct is the cutting tool diameter and lw is the link width.

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 the remaining ends of the second largest link and the smallest link together. The parts of a spherical mechanism are shown in Fig. 13 and the assembled mechanism is shown if Fig. 14.

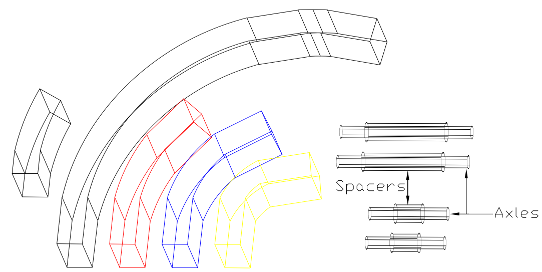

Figure 13. THE SAMPLE MECHANISM-PART LAYOUT.

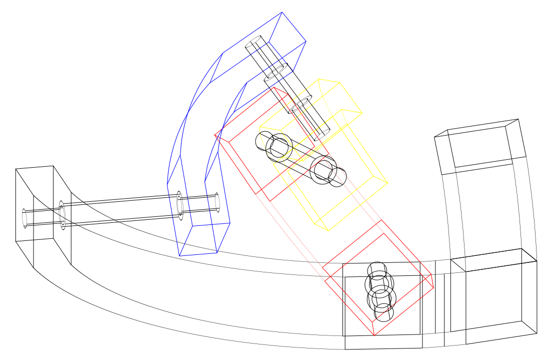

Figure 14. THE ASSEMBLED SAMPLE MECHANISM.

TEST CASE

SphinxCAM has been used in conjunction with Sphinx and SphinxPC to design and build several mechanisms. It was used in a design project for the graduate spatial mechanism design

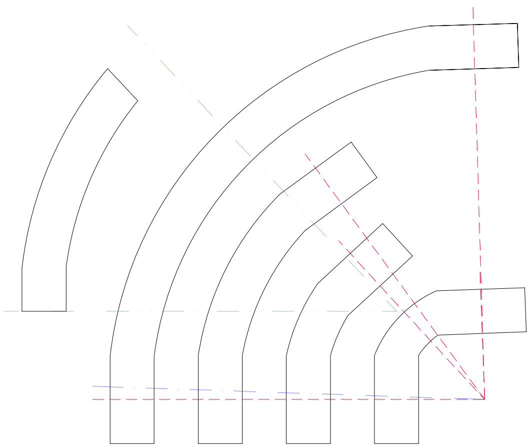

Figure 15. SphinxCAM INFINITY FAN LINK LAYOUT.

Figure 16. INFINITY FAN-TOP VIEW.

class, MAE5670, at Florida Tech. SphinxCAM was also used to layout the links for the Infinity Fan (Patent Pending). Fig. 16 and Fig. 17 show the completed Infinity Fan. The data for constructing the fan's spherical mechanism was acquired from Sphinx and combined with the desired stock thickness, link width, and cutting tool diameter. SphinxCAM produced the AutoCAD drawings, see Fig. 15, that were then exported into a CAM package which generated the NC code to manufacture the links of the mechanism.

SUMMARY

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

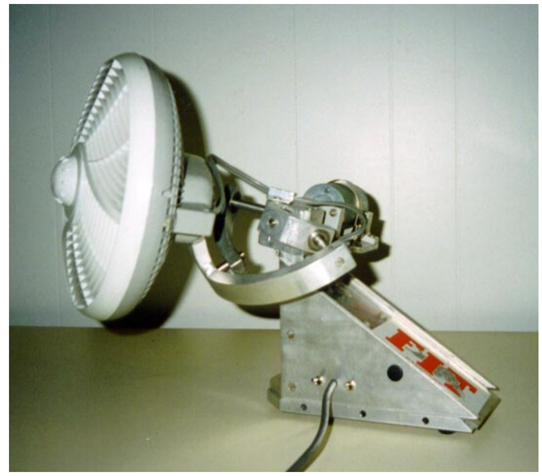

Figure 17. INFINITY FAN-SIDE VIEW.

loading and conserves raw materials.

Currently, SphinxCAM is in use at Iowa State and Florida Tech and has been utilized to prototype and build several spherical four-bar mechanisms. The source code for SphinxCAM and the SphinxCAM *User's Guide* are available at the Robotics And Spatial Systems Laboratory(RASSL) website: `http://www.fit.edu/~pierrel/rassl/`.

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