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Foot Design for Lunar Walker

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By

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ME ~~4192~~ 4901 Special Problems Topic
for J.W. Brazell

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ABSTRACT

1.0

A ski pole-type foot is designed for the second generation SKITTER prototype. SKITTER is a three-legged walking work platform designed for use on the moon. The foot design is made up of three main sections: the tip, the annulus, and the connecting tethers. The resulting design is light weight, allows for low leg angles and will have good traction on both hard surfaces and loose, dry sand.

INTRODUCTION

2.0

The second generation SKITTER vehicle is now in the preparation stages. The purpose of this project is to design a new foot for the SKITTER vehicle. The first prototype SKITTER vehicle design was a proof-of-principle model only. The shortcomings of the simplistic foot design on that model were of no importance.

The next generation SKITTER prototype has more to prove. The foot design is of great importance to many things. The motion of SKITTER needs to be energy efficient; therefore, the foot should be light. The foot will be required to have good traction at severe angles on hard surfaces as well as in soft, dry sand. This project is specifically designated to provide a ski pole-type foot design. This means having a ring or annulus attached at the foot which is connected by one or more tethers.

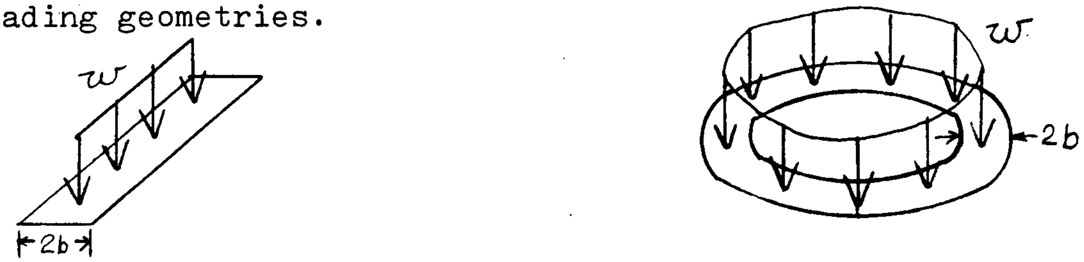
The work presented here is for the earth-bound scale model vehicle. The ideas can, however, easily be applied to a true scale vehicle.

The order of investigation begins with the calculation of the required annulus size. From this point, a program is utilized to design the tether lengths. Finally, the leg tip and the actual tether hardware is designed.

ANNULUS SIZING

3.1

The first and foremost problem in designing the foot is providing sufficient support capability. Following the design requirements, the shoes must be capable of supporting SKITTER on loose, dry sand. The size of the annulus part of the foot is critical in the design of a ski-pole type system. Research in classical soil mechanics revealed that soil bearing capabilities are calculated only for very simple bearing geometries. It was necessary to assume the annulus to be similar to one of these typical loading geometries.



Strip loading

Circular Strip loading

Figure 3-1

3.2

Methods of soil bearing capability calculations are typically done for circular, square, and long strip bearing shapes. Though it is tempting to use formulas for circular bearings, these were ruled out because they do not account for a ring-like structure. Rather, they account for only a flat circular bearing such as the end of a telephone pole. Instead, a formula for strip loading was chosen to approximate the case at hand. Because of the relative small size of the annulus member compared to it's diameter, the loading is similar to a strip turned back upon itself. (Fig. 3-1) The validity of this assumption is based in simple soil mechanics. Typical pressure distribution under a bearing are shown in Figure 3-2. It is obvious that at distances just a couple bearing lengths away the surface soil stress is not affected by the loading. Therefore, the bearing capability of a circular strip of sufficient radius should be equivilent to a strip loading of equal strip width. Furthermore, circular bearings can withstand greater loads per unit area than strip loading. Thus, if the above similitude is in error, then the error should be favorable.

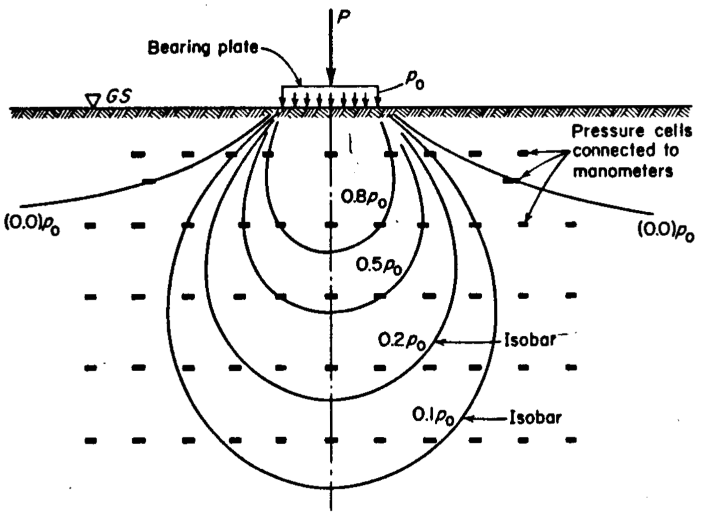


Figure 3-2

3.3

The chosen method for soil bearing capacity calculation is the Hogentogler-Terzaghi system for a strip loading. In this system, the ultimate bearing capacity is given by:

$$\sigma_u = \frac{\gamma}{2}\frac{b}{\tan^5(\pi/4-\phi/2)} + \frac{p}{\tan^4(\pi/4-\phi/2)} + \frac{\gamma}{2}\frac{b}{\tan(\pi/4-\phi/2)},$$

For loose sand, γ=82.37 lb/ft^3 and ϕ=33.55°

The second term dissapears because p=γz and z=0 in this case.

Finally, upon substitution the value of   is found to be:

= 3788 lb/ft^2 or = 26.3 lb/in^2

Assuming a worst case loading as the whole weight of SKITTER or 300 lb the required projected area of the annulus is:

$$A_a = \frac{300}{26.3}\ \text{in}^2 = 11.4\ \text{in}^2$$

For an annulus made of tubing, the equation

$$\pi(R^2-(R-0.75)^2) = 11.4$$

is used iteratively to calculate a suitable radius. A value of R = 3 gives an area of 12.4 in^2. If the margin of safety for support is low, then 3/4″ or 1″ tubing may be substituted. The annulus area is then 17.3 in^2 or 22.6 in^2 respectively, which are 40% or 80% increases in bearing capacity.

ANNULUS TETHER GEOMETRY

4.1

The length and number of the annulus tethers is of ultimate importance to the design of the foot. The design process for these parts is a study in the relative motion of the annulus allowed by the tether lengths. To perform a complete study, the possibility of different numbers of tethers was investigated.

4.2

The simplest design is, of course, one tether. This choice has two important drawbacks.

Figure 4-1

The first is that the annulus must be connected very high on the leg to prevent it from passing over the tip. The second is evident in Fig. 4-1b. When a force is placed on the leg, it will sink until a large enough surface area of the annulus is contacting the sand to support the loading - this is an inefficient configuration. Primarily, it will be difficult to lift the leg from its lower depth.

4.3

The investigation of a two-tether configuration showed better possibilities. The kinematics of the two-tether system were approached from two angles. One of these was looking at the motion in a plane passing through the tether connecting points and the other exactly perpendicular about the two axes as in Fig. 4-2.

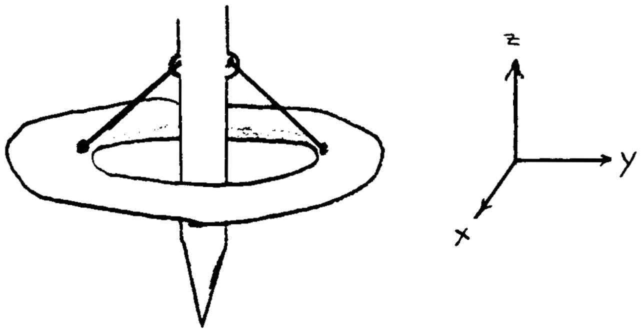


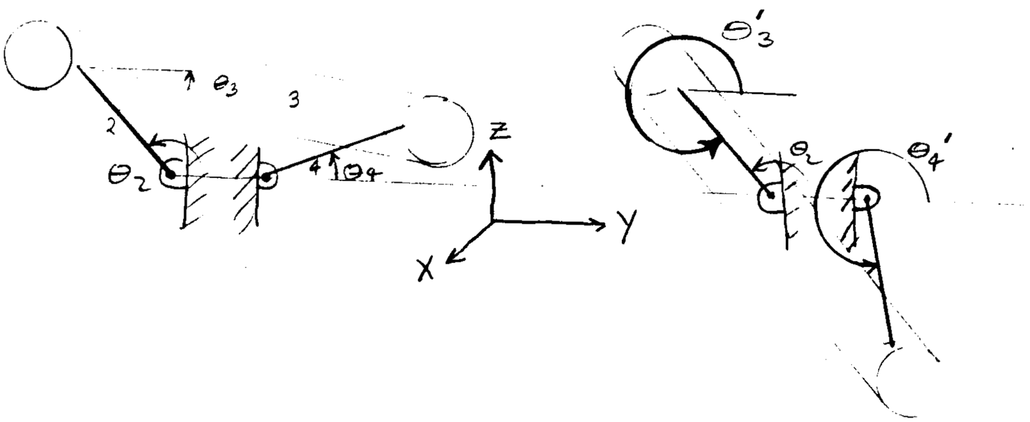
Figure 4-2

Rotation of the annulus about the y-axis is simple. The annulus is free to rotate 180° where the upper end of the annulus will contact the leg. It is also important to know that if the tether is much longer than the inside radius, then the ring can pass over the end of the ring. Again, we have a problem with the depth of the leg restricting motion in loose sand. For motion about the x-axis, the problem is more complicated, and is dealt with in the next section.

4.4

A calculator program was used to study the annulus motion about the x-axis for two-tether setups and in all planes for 3 or more tether configurations. This program is based upon the solution for a 4-bar analysis given by Shigly[4] on pgs. 56-57. The program is listed in the Appendix.

Figure 4-3



In this program, the leg itself is the first member of the four-bar linkage. See Fig. 4-3. The tethers are represented by bars 4 and 4. Although these bars represent flexible members, this approach is valuable because it calculates the extreme positions possible for the annulus.

One other factor is that this method of solution (a planer one) is only valid when the annulus motion is restricted to being around one axis. However, it can be selectively used to calculate the extreme motions by viewing the system from other planes, as in the case of the three-tether design.

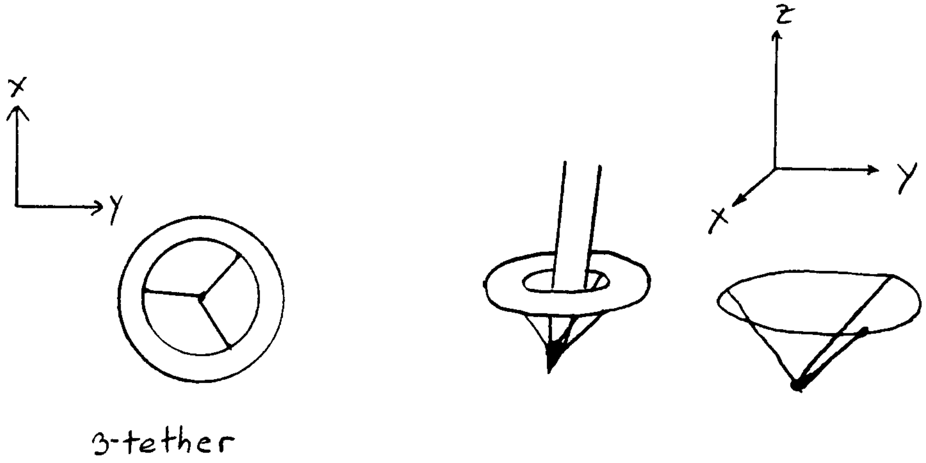


Figure 4-4

Viewed in the y-z plane in Fig. 4-4, the projected length of the two tethers on the right is a function of the tether length and the constant distance of the connection point on the annulus to the y-z plane.

Tables 1 and 2 show the possible positions of the foot system calculated by the projected tether lengths and connecting point distances. The favorable qualities begin with sufficient annulus motion in all planes of motion. At θ_2 of near 90°, the ring should not be able to slip off of the leg end. This gives a minimum tether length. The necessity for great angular range does, however, require a minimum length. The program changes θ_2 from 180° to 90°. At each iteration, it calculates the positive and negative closure angles for the system. The results of the program show that $2''$ tethers are good for rotations about the x or y axis. This length allows for the annulus to deflect upwards all the way to the leg for SKITTER's horizontal leg position. However, the annulus cannot slip over the leg.

FOOT TIP DESIGN

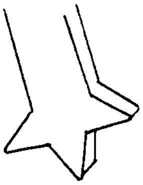
5.1

The leg tip will attach to the lowest section of the tibia leg member. This tip will support the vehicle on hard surfaces where the annulus cannot. The primary concerns for the design of the leg tip are traction, durability and leg attachment methods.

5.2

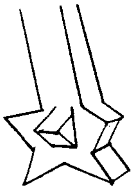
The SKITTER leg motion will produce a great variance in "toe" angle. The leg can bend underneath the vehicle and reach up to above horizontal angles. With this information, a simple pointed tip can be ruled out. At these extreme angles, there is little or no traction available for that design. Here are some of the originally proposed designs:

Simple point
flat geometry



3-Pronged
flat geometry

Simple point
round geometry



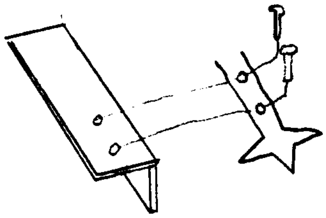
Multi-point

A version of the flat 3-Promged design was chosen. Due to the reasons stated above, the simple point geometries are unsatisfactory. The Multi-point tip does not gain that much in the way of traction and would be difficult to manufacture.

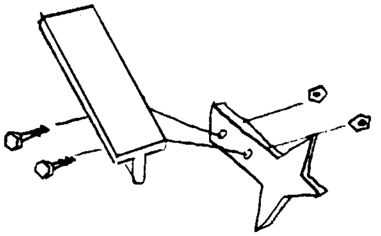
The material used in this tip must have great durability and strength. UNS41400 steel in 1/4" stock was calculated to be satisfactory material for the leg tip construction. tha tip may be cut from this material and machined to any degree of point sharpness.

5.3

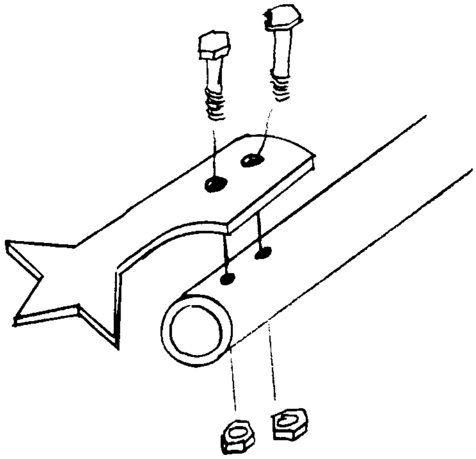
The method of leg connection is very important. Because the leg has not yet been designed, the connection scheme will have to be completed. Here are some possible schemes:



Bolt on Angle-section leg



Bolt on T-section leg



Bolt on Tubular leg

(probable)

TETHER MATERIAL

6.1

The maximum stresses on the tethers are calculated for worst case loading. For a tether at an angle of 85° from the leg, the tension is given by:

$$T = \frac{F_2}{\sin\theta}$$

where F is the entire loading from the leg for a loading of 400 lb. T is equal to 4,500 lb. Applying a factor of safety of 2 to this gives the required tensile strength of 9000 lb.

6.2

Amsted Industry's Pacific Preform Aircraft Cable has a 5/16" diameter, 7x7 flexible aircraft cable with tensile strength of 9000 lb. This rope is flexible, but also has good abrasion resistance. Standard fork swaged cable terminals can be used to attach the tethers with 100% of cable strength. These forks will attach to the three tether connection "teeth" on the annulus. See Fig. 7.1.

CONCLUSIONS/RECOMMENDATIONS

7.0

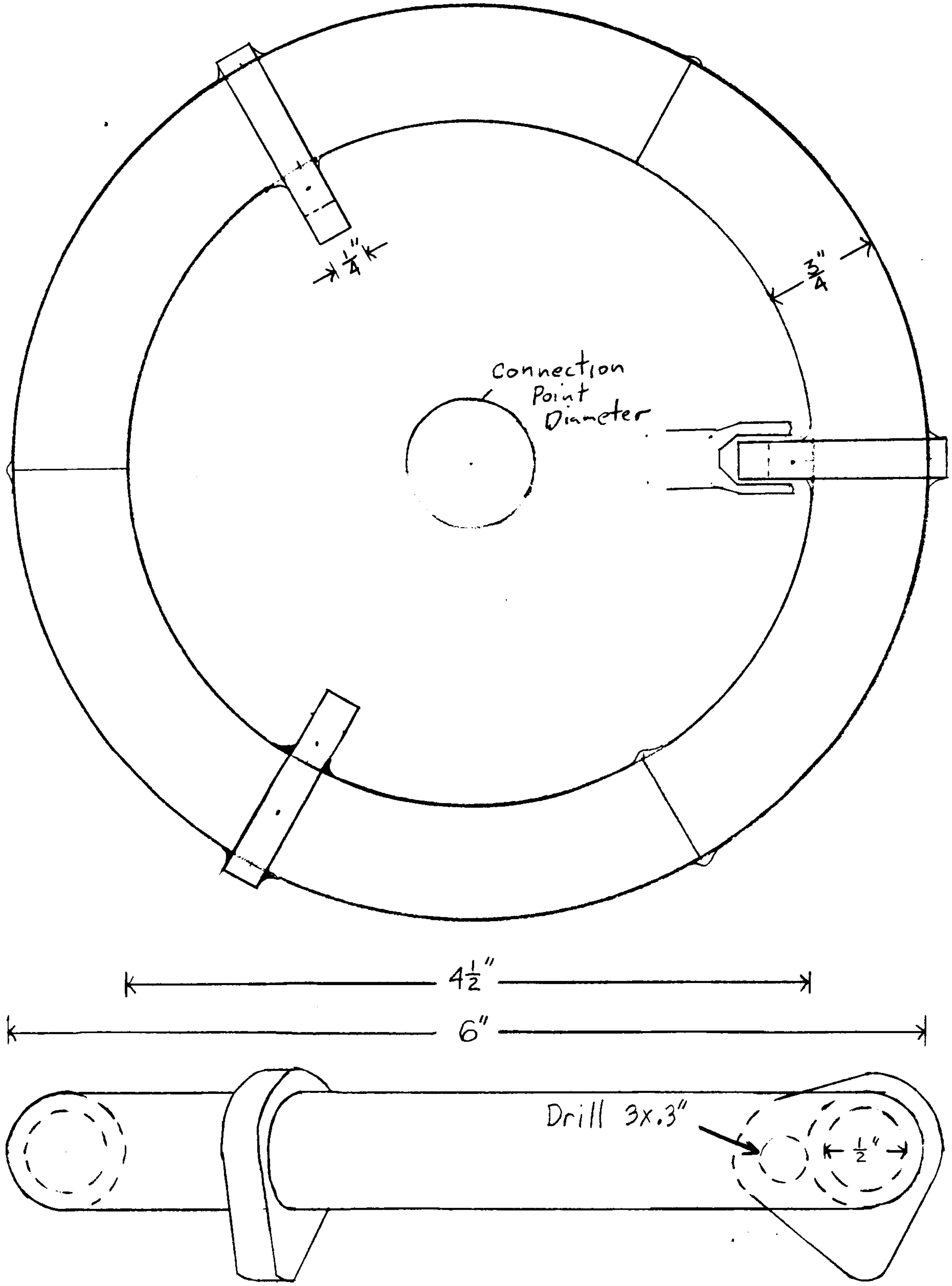
The size of the annulus itself is of utmost importance to the support of the vehicle. It is recommended that loading tests with a prototype ring be performed in sand to insure that it will work. If it should fail to support loading satisfactorily, then either a larger tubing can be used, or perhaps a thin, flat flange could be welded onto the annulus to increase its area. The latter method would be more weight efficient.

Though it has been neglected in this report, the method of connecting the tethers to the leg is also important. Probably the best way is to attach the annulus directly to the foot tip. The high strength of the steel is useful in this application because the connection is less bulky.

The overall ski pole scheme is a light and efficient load transferring mechanism. 7.1 is the final drawing of the proposed foot annulus. The manufacture of this part of the system should easily be accomplished in 3 stages. The first is bending 3-120° sections of tubing, the second is cutting the three tether connection teeth and welding to the mid section of each of the three tubes. Finally, welding the pipes will complete the construction. The tethers can then be attached to the leg top and annulus to complete assembly.

Fig 7-1

Material : Aluminum
Weight : 1.64 lb

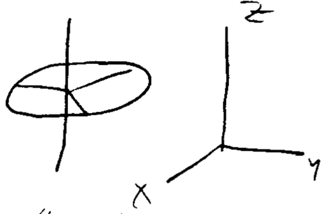


APPENDICES

TABLE 1

Run for 3 tether - Rotation about double tether

or about x axis



1.9" tether

θ_2	180	170	160	150	140	130	120	110	100	90
θ_3	21	13		-10			-28		-50	-64
θ_4	70	62		33			7		-26	-50
θ_2'	180	170	160	150	140	130	120	110	100	90
θ_3'	339	331		308			296		284	280
θ_4'	290	283		267			260		260	266
$\Delta\theta_4$	140	139		126			106		73	43

2.3"

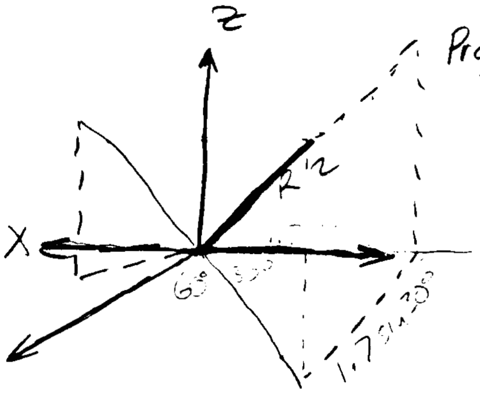
θ_2	180	170	160	150	140	130	120	110	100	90
θ_3	25	18.8	12.7	7	0	-6	-13	-20	-29.5	-38
θ_4	90	83	76	67	58	47	36	22	7	-12
θ_2'	180	170	160	150	140	130	120	110	100	90
θ_3'	335	329	323	317	311	305	299	294	290	286
θ_4'	270	265	260	256	253	251	250	251	253	260
$\Delta\theta_4$	180	178	176	171	165	156	144	130	113	88

2.1

θ_2	180	170	160	150	140	130	120	110	100	96
θ_3	28				-3			-28	-38	-42
θ_4	88				53			18	5	0
θ_2'	180	170	160	150	140	130	120	110	100	96
θ_3'	331				300			277	269	266
θ_4'	272				245			230	226	225
$\Delta\theta_4$	176				167			148	147	

Use no less than 2.1 tether

Now for roktion about y axis



Projected lengths of tethers are each

$$R_{4,2} = \sqrt{R_{4,2}^2 - (1.75 \times .30)^2}$$

$.85^2)$

TABLE 2

2 tether y axis rotation

Annulus ~~leg~~ is projected as (2)1.7 sin60 + .72 = 3.65
with r, (leg thickness is .72"

2" tether

θ_2	180	170	160	150	140	130	120	110	100	90
θ_3	27	20	12.4	4.5	-3	-12	-21	-30	-42	-55
θ_4	66	59	51	48	32	21	9	-5	-21	-40
θ_2'	180	170	160	150	140	130	120	110	100	90
θ_3'	333	326	319	312	305	299	293	287	282	278
θ_4'	293	287	280	275	270	266	263	267	261	264
$\Delta\theta_4$	133	132	130	126	122	115	106	94	78	

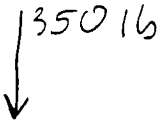
1.9"

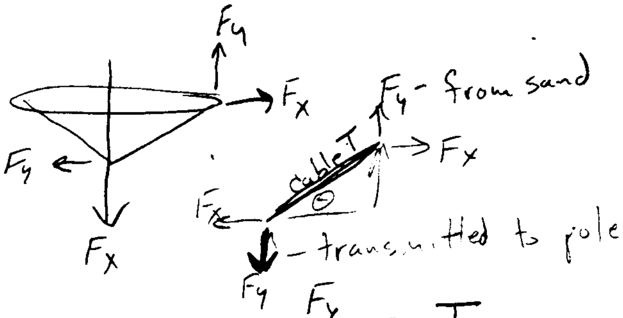
θ_2	180	170	160	150	140	130	120	110	100	99.8	90
θ_3	22.7	16	8	0	-8	-17	-27	-38	-56	-56	
θ_4	56	49	40	31	20	8	-5	-23	-52	-53	
θ_2'	180	170	160	150	140	130	120	110	100	99.8	
θ_3'	337	330	324	317	311	305	300	297	298	298	
θ_4'	304	297	291	287	283	280	279	281	294	295	
$\Delta\theta_4$	112	111	109	104	97	88	75	56	13.7	11.22	

Impossible Geometry

Results

After investigating the two extreme methods of rotation in the 3 tether design, Making the total length of connectors 2" seems good





$$\frac{F_y}{\sin\theta} = T$$

Where is T a max.
where sinθ is Min

Input / Output for Program

Input				
	R 1	....	r_1	length in inches ... leg thickne
	R 2		r_2	" " " } Tether length
	R 3		r_3	" " "
	R 4		r_4	" " " annulus I.D.
	R.2	input/output	θ_2	in degrees
Output	R.3		θ_3'	" "
	R.4		θ_4'	" "
	R.6		θ_3	" "
	R.7		θ_4	" "
	R.8			difference between θ_4' and θ_4

Program Listing

HP Routine
Hewlett Packard 15C

	$\boxed{f}\boxed{LBL}$ A	Program A
	180 $\boxed{STO}$ .2	Initialize θ_2
	$\boxed{f}\boxed{LBL}$ C	Label for loop control
	1 $\boxed{STO}$ 0	Set to calculate pos. closure
	$\boxed{GSB}$ B	Call subroutine B (calculates all angles)
	$\boxed{RCL}$ .4 $\boxed{STO}$ .7	Saves value of θ_4 in register $\boxed{.7}$
	$\boxed{RCL}$ .3 $\boxed{STO}$ .6	" " " θ_3 " " $\boxed{.6}$
	1 $\boxed{CHS}$ $\boxed{STO}$ 0	−1 in 0 for negative loop clo[illegible]
	$\boxed{GSB}$ B	Call subroutine B (calculates angles for [illegible])
	$\boxed{RCL}$ .7, $\boxed{RCL}$ .4, 360 $\boxed{-}$ $\boxed{-}$	$\theta_4 - (\theta_4' - 360)$ difference in angles
	$\boxed{g}\boxed{ABS}$	|difference|
	$\boxed{PSE}$	display |difference|
	$\boxed{STO}$ .8	STORE The |diff.| in .8
	$\boxed{R/S}$	
1.27	5 $\boxed{\rightleftarrows}$	Enter 5, exchange w/ |diff.|
	g $\boxed{x \leq y}$	test if |diff.| less than 5°
	$\boxed{GTO}$ E	Go to label E if true.
47 new	# $\boxed{STO}\boxed{-}$ .2	Subtract # from θ_2 register
L.35	$\boxed{GTO}$ C	Iterate
	$\boxed{f}\boxed{LBL}$ E	Label
	$\boxed{RCL}$ .2	Bring θ_2 to X register
	$\boxed{RTN}$	END

θ_4 in .7 error in .8
θ_4' in .4

Subroutine B

Calculating position of
4 bar linkage
Taken From Shigley and Uicki

L 40)	$\boxed{\text{F}}\,\boxed{\text{LBL}}$ B	Program STO
90 enter	$\boxed{\text{RCL}}$ .2	Get stored value of θ_2
g x≤y	~~$\boxed{\text{RCL}}$ .2~~	
GTO 15	$\boxed{\text{COS}}$	$\cos\theta_2$
	$\boxed{\text{RCL}}$ 2 $\boxed{\times}$	get $r_2 \times \cos\theta_2$
L 50	$\boxed{\text{RCL}}$ 1 $\boxed{\times}$	$r_1 \cdot r_2 \times \cos\theta_2$
	2 $\boxed{\text{CHS}}\,\boxed{\times}$	$-2 \cdot r_1 \cdot r_2 \times \cos\theta_2$
	$\boxed{\text{RCL}}$ 2 $\boxed{g}\,\boxed{x^2}\,\boxed{+}$	$r_2^2 - 2 r_1 r_2 \cos\theta_2$
L.60	$\boxed{\text{RCL}}$ 1 $\boxed{g}\,\boxed{x^2}\,\boxed{+}$	$r_1^2 + r_2^2 - 2 r_1 r_2 \cdot \cos\theta_2$
	$\sqrt{x}$	$s = \sqrt{\text{above}}$
	STO 6	sto s in Register 6
	$\boxed{g}\,\boxed{x^2}\,\boxed{\text{CHS}}$	$-s^2$
	$\boxed{\text{RCL}}$ 4, g $\boxed{x^2}\,\boxed{+}$	
L.70	$\boxed{\text{RCL}}$ 3, g $\boxed{x^2}\,\boxed{+}$	$\dfrac{r_3^2 + r_4^2 - s^2}{2 r_3 r_4} = \cos\gamma$
	2 $\boxed{\div}$, $\boxed{\text{RCL}}$ 3 $\boxed{\div}$, $\boxed{\text{RCL}}$ 4 ÷	
	$\boxed{g}\,\boxed{\cos^{-1}}\,\boxed{\text{RCL}}$ 0 $\boxed{\times}$	If $\boxed{R}$0 is $\oplus$ we calculate postive closure. $\ominus$ vice ve.
L.80	$\boxed{\text{STO}}$ 7	γ = R7
	$\boxed{\text{RCL}}$ 1, 2 $\boxed{\times}$	get $r_1 \times 2$
	$\boxed{\text{RCL}}$ 6 $\boxed{\times}\,\boxed{1/x}$	$\dfrac{1}{2 r_1 s}$
	$\boxed{\text{RCL}}$ 1, g $\boxed{x^2}$	
	$\boxed{\text{RCL}}$ 6, g $\boxed{x^2}\,\boxed{+}$	$\dfrac{r_1^2 + s^2 - r_2^2}{2 r_1 s}$
	$\boxed{\text{RCL}}$ 2, g $\boxed{x^2}\,\boxed{-}$ ×	

521-4949

	B continued	Comments
96	$\boxed{g}$ $\boxed{\cos^{-1}}$ $\boxed{STO}$ 8	store ϕ in R.8
100	$\boxed{RCL}$ 4, 2 $\boxed{\times}$	
	$\boxed{RCL}$ 6 $\boxed{\times}$ $\boxed{1/x}$	$\frac{1}{2\cdot r_4\cdot s}$
	$\boxed{RCL}$ 3, $\boxed{g}$ $\boxed{x^2}$ CHS	$-r_3^2$
	$\boxed{RCL}$ 6 $\boxed{g}$ $\boxed{x^2}$ $\boxed{+}$	$s^2-r_3^2$
110	$\boxed{RCL}$ 4 $\boxed{g}$ $\boxed{x^2}$ $\boxed{+}$ $\boxed{\times}$	$\frac{r_4^2+s^2-r_3^2}{2\cdot r_4\cdot s}$
	$\boxed{g}$ $\boxed{\cos^{-1}}$ $\boxed{STO}$ 9	ψ stored in R9
120	$\boxed{RCL}$ 8, $\boxed{RCL}$ 9 $\boxed{RCL}$ 0 $\boxed{\times}$, $\boxed{+}$ $\boxed{CHS}$	$\phi + \underset{R0}{\boxed{\pm}}\ \psi$
	180, $\boxed{+}$	$180-\phi\pm\psi = \theta_4$ or θ_4'
	$\boxed{STO}$ .4	$\theta_4 = \boxed{rcL}\ .4$
	$\boxed{RCL}$ 7 CHS $\boxed{+}$	$\theta_4-\gamma$
130	$\boxed{STO}$ .3	$\theta_3 = r\ .3$
	$\boxed{RCL}$ .2, $\boxed{f}$ $\boxed{PSE}$	recall θ_2 and display
	$\boxed{RCL}$ .3, $\boxed{f}$ $\boxed{PSE}$	" θ_3 " "
	$\boxed{RCL}$ .4, $\boxed{f}$ $\boxed{PSE}$	" θ_4 " "
137	$\boxed{g}$ $\boxed{RTN}$	END

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