

Three Inflatable Spheres as a Theoretical Basis for a Soft Stewart Platform

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Abstract

A Stewart Platform[4] is a fundamental mechanism for varying the angle between two objects. A soft Stewart Platform can be made of two discs and three inflatable spheres. Stacking such devices might make a soft tentacle. Soft robots are meant to deform under force, but it is useful to have an analytic description of a plane in contact with three spheres before deforming force is applied. In 1881, the problem of computing the plane tangent to three spheres was set as an exercise in a textbook, em Practical Solid Geometry[2], but not solved. We have solved the problem of computing the plane in contact with three adjacent spheres from known radii via close-form expressions and in JavaScript, producing an interactive, browser-based web page that dynamically solves the problem[3]. More importantly, we have solved the inverse problem, of computing the sphere radii which orient a plane in contact with all three spheres, in both closed-form solutions and on the web page. This would allow a soft Stewart Platform or a tentacle to be positioned in basis by choosing the expansion of inflatable spheres. The closed-form expressions allow derivatives and Jacobians to be computed symbolically. All of the code is released under the GNU Public License.

1 Introduction

A parallel manipulator varies the angle between two planes. The best known parallel manipulator is a Stewart Platform[4] (https://en.wikipedia.org/w/index.php?title=Stewart_platform&oldid=898429010). Having a soft parallel manipulator analogous to a Stewart Platform would allow soft, gentle positioning[1], and might be particularly valuable *in vivo* or in some space applications. Varying angular displacement is a composable building block of more complicated systems, such as tentacles.

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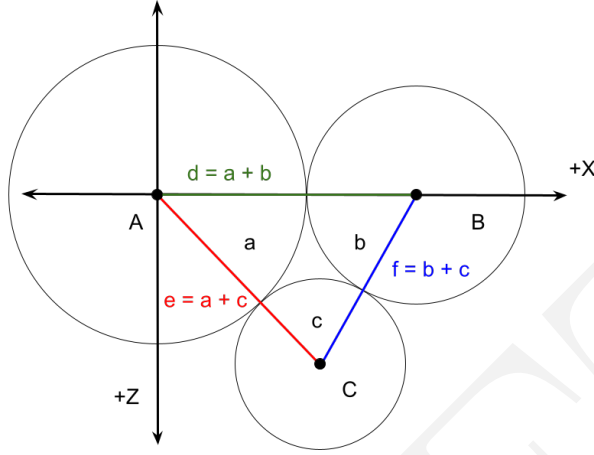


Figure 1: Three Touching Circles

One way to build such a manipulator is to have three inflatable spheres sandwiched between two planes and constrained to always be in contact with each other. As these spheres are inflated or deflated changing their size, the top plane changes its orientation relative to the bottom plane. This paper develops both the forward and inverse mathematics of this problem. The forward problem is given three radii, to determine the orientation of the top plane. The inverse problem is much harder: given a desired orientation and the radius of one sphere, find the radius of the other two spheres that achieves it.

This paper gives closed-form expressions of both the forward and inverse problem. Additionally, we have create an online, browser based realtime simulation that reifies the math in this paper in JavaScript, both verifying it and making it easy to reuse.

2 Prelude: Three Touching Circles

Our goal is to be able to determine the orientation of plane resting on top of three spheres of different radii which are touching each other. Because there is a plane through any three points and we have three spheres, we can construct the plane through the center of these points. The projection of the edges of the spheres onto this plane form three touching circles. Knowing the position of these circles is a valuable prelude to solving the three dimensional problem.

To solve this problem most conveniently, we place the first circle on the negative x -axis, and the second circle on the positive x -axis, with the circles intersecting at the origin. The third circle is place in the positive y direction.

It's center will not be on the y -axis itself unless the radii of the first two circles are equal.

We seek a formula for the coordinates of the third circle in terms of three input radii a, b, c .

Because the distance between adjacent circles is the sum of their radii, define:¹

$$d = a + b \tag{1}$$

$$e = a + c \tag{2}$$

$$f = b + c \tag{3}$$

$$\tag{4}$$

Then we can use the cosine law to compute the angle $\angle ABC = \theta$:

$$\theta = \arccos \frac{a^2 + b^2 - c^2}{2ab} \tag{5}$$

$$\theta = \arccos \frac{(b + c)^2 + (a + c)^2 - (a + b)^2}{2(a + c)(a + b)} \tag{6}$$

$$\tag{7}$$

It is clear that once θ has been calculated:

$$C_z = a \sin \theta \tag{8}$$

Allowing us to form a right triangle $\triangle ACD$ and use the Pythagorean theorem:

$$b^2 = C_z^2 + C_x^2 \tag{9}$$

$$C_x = \sqrt{b^2 - C_z^2} \tag{10}$$

$$\tag{11}$$

3 Three Touching Spheres

Our fundamental goal now is to describe three touching spheres. As robotocists, our interest is in the slope of the plane of the tops of these spheres as if they were resting on a table. Then by inflating or deflating spheres, we would be able to control the direction of a plane or platform. Such a device is sometimes called a parallel manipulator, of which a Stewart Platform[4] (https://en.wikipedia.org/w/index.php?title=Stewart_platform&oldid=898429010) is the best-known example.

The fundamental action of a parallel manipulator is to tilt a plane or platform in a desired direction based on changes in the radii of the spheres.

¹This is a confusing use of the variables a , b , and c .

The problem finding the planes tangent to three touching spheres is given as an exercise in an advanced textbook on solid geometry from 1881[2]. It does not give a solution, but it gives a hint: to consider the cones enveloping three spheres taken two at a time.

Choosing the coordinate system of the XZ plane through the center of the spheres greatly simplifies the derivations, because the center of the spheres always form tangent circles in this plane. Call this plane the *center plane*. The position of A is fixed, B is constrained to the x -axis, and C is constrained to the xz -plane. The center of these circles in the xz plane can be calculated from the radii independent of the tilt they induce. In this coordinate system, the y -coordinate of the center of all spheres is 0. Furthermore, a cone tangent to two spheres has its axis and apex in the xz -plane. The projection of all three spheres into this plane produces three touching circles. We seek an expression for the normal of the plane of the tops of these spheres as a function purely of the three radii. Call this plane the *top plane*. We can imagine the spheres resting on a fixed surface called the *bottom plane*. The tilt of the top and bottom plane relative to the center of the spheres is always a mirror image of each other across the coordinate XZ -plane.

If the tilt of the top plane relative to the coordinate plane is given by a rotation about the z axis of θ and then a rotation about x axis of γ , the tilt of the top plane relative to the bottom plane is given by the zx extrinsic Euler angles $(2\theta, 2\gamma)$.²

3.1 Physical Embodiment

To embody this system precisely, the sphere A could be pinned to the origin of the bottom plane. The contact point of the sphere B with the bottom plane could be placed on a linear slider on the x -axis. The contact point C could be constrained to rest on the bottom plane by gravity or some elastic cables. Choose the convention that the C object is to the right hand (clockwise) side of the AB line. As the spheres change change, the origin of the center plane will experience minor translation relative to the bottom plane, but will not experience rotation about the y -axis. If needed the coordinates of the spheres in the bottom plane can be easily calculated from the radii and the computed extrinsic Euler angles θ and γ .

3.2 Variable definitions

We assume that the spheres centered at points A, B , and C of radii a, b , and c . We setup our coordinate system as a left-handed coordinate system with XZ plane containing the center of all spheres. The A sphere is placed at the origin, so that $O = A$, and the B sphere is placed on the positive X axis. Without loss of generality assume $a \geq b \geq c$. Following computer graphics convention, we think of the Y dimension as vertical.

²Is this really true?

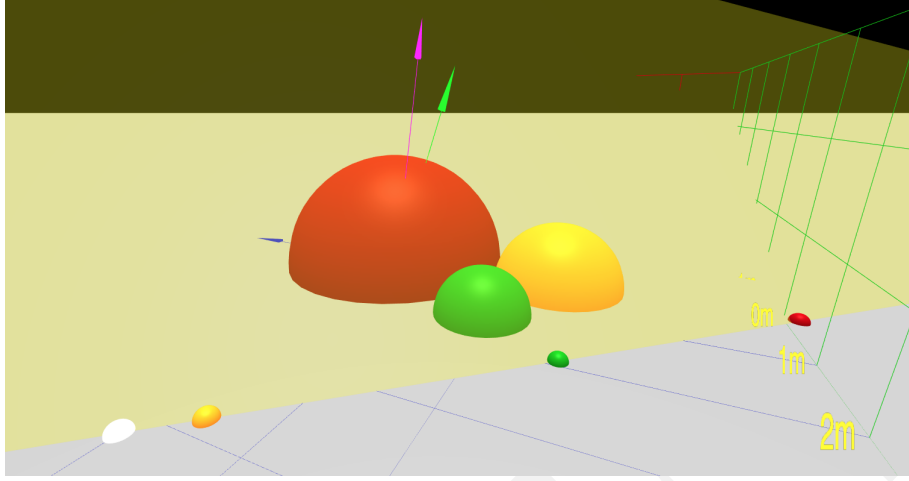


Figure 2: Three Touching Spheres

Taking any two spheres defines a cone whose apex is in the XZ plane. Call the apex of the AB cone U , the AC cone V , and the BC cone W .

It is a beautiful fact that the three apices U, V and W are colinear on a line we call the *apex line*, depicted in both Figure 2 or Figure 3. Further, by your choice of coordinates, this line is in the XZ plane. Finally, the top and bottom planes intersect at this line, because those planes are tangent to the three cones.

We assert that these three points form a line, which we call the *apex line*, in the XZ plane and that this line is the intersection of the *tangent plane* touching all three spheres at a single point with the XZ plane. We will use points U and V in our calculation.

3.3 Axis Angle of Cone Enveloping Two Spheres

In order to compute the apex line, it is helpful to note that the apex angle ψ of a cone which envelopes (by being tangent to) two tangent spheres of radii r, s , is:

$$\psi = \arcsin \frac{s - r}{s + r} \quad (12)$$

$$(13)$$

where $r < s$ without loss of generality. Note that when $r = s$ there is a special case, the cone tangent to both is degenerate (that is, a cylinder, or a cone of $\psi = 0$ apex angle.)



We seek to compute the normal of the tangent plane. Observe that this plane is tangent to all three cones. Observe that the AB cone intersects the A sphere in a circle on the surface of the A perpendicular to and centered on the X axis.

A vector of length a that is always rotated about the origin is always a point on the sphere. The first operation is move this vector perpendicular to the AB cone. A vector N in the Y direction and rotated counterclockwise about the Z -axis by θ_{ab} is perpendicular to the AB cone.

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to rotate the plane by so that it intersects with the Z -axis at a point, referred to as I_z . By basic geometry of similar triangles, this is computed from the right triangle of the origin with h and I_z . Having computed θ_{ab} and γ , these two degrees of rotation give us the plane tangent to all three spheres, and its corresponding tilt for our desired soft Stewart Platform.

Note: Do we really need to define vectors here instead of points?

Vectors \vec{U} , \vec{V} , and \vec{W} represent the vectors from the center of the spheres A , B , and C to the apices of the cones tangent to A and B , B and C , and C and A respectively.

$$\vec{U} = \vec{A} + \vec{AB} \frac{a}{\sin \theta_{ab}} \quad (16)$$

$$\vec{V} = \vec{B} + \vec{BC} \frac{b}{\sin \theta_{bc}} \quad (17)$$

The point H is the intersection of the AB cone with the y axis. This is right triangle of the origin with the points U and H . (The hypotenuse of this triangle is \vec{HU} , and side adjacent to θ_{AB} is \vec{OH} .) It is computed by projecting the contact point of the top plane in the xy -plane onto the xz -plane. This allows γ to be computed as a pure rotation about the x -axis.

$$H_y = U_x \tan \theta_{ab} \quad (18)$$

$$Z' = \frac{H_y}{\sin \gamma} \quad (19)$$

$$\gamma = \arcsin \frac{Z'}{H_y} \quad (20)$$

Equations 14 and 20 give the Euler angles θ_{ab} and γ for the tilt of the tangent plane as a function of the three radii a, b, c .

4 The Inverse Problem

To build a useful robotic platform in by controlling the radii of the spheres by inflating and deflating them, we wish to solve the inverse problem. That is, given input θ_{ab} and γ as desired Euler angles, we want to compute a, b, c which achieve these angles.

Since these are smooth functions, the problem could be solved easily by a Newton-Raphson style solver based on 14 and 20. However, a closed-form solution is always superior, and allows derivatives, and hence Jacobians, to be expressed symbolically as closed-form solutions.

The radius b can be computed directly from θ_{ab} because of our choice of coordinates. By considering to proportionality of the similar triangles formed by the contacts points of sphere A and B and their centers with U_x in the XY

plane, we obtain:

$$U_x = \frac{a}{\sin \theta_{ab}} \quad (21)$$

$$b = \frac{(U_x - a) \sin \theta_{ab}}{\sin \theta_{ab} + 1} \quad (22)$$

Given the plane defined by a known radius a , θ_{ab} and γ , the point C is constrained by asserting that the perpendicular distance to this plane of C is c . Additionally, in the central plane we have two other constraints, that C is placed so that it touches the circle centered on A and the circle centered on B .

Then we know that the point C but have distance $a + c$ from the point A (the origin) and distance $b + c$ from the known point B . These two constraints can be generated from the Pythagorean Theorem and can be expressed:

$$a + c = \sqrt{C_x^2 + C_z^2} \quad (23)$$

$$b + c = \sqrt{(a + b - C_x)^2 + C_z^2} \quad (24)$$

If we were to plot the point C as c increases, we would find a gentle curve moving away from the intersection of the circle A and B . An additional constraint will allow us to select a point on this curve.

This gives us three equations, which should be more than enough to solve for the point C .

Let $H = [0, H_y, 0]$.

Let N be the normal to the plane (pointing up in our diagram when $a \geq b \geq c$.)

$$\vec{N} = \vec{Z'} - \vec{U} \times \vec{Z'} - \vec{H} \quad (25)$$

Since we have the normal of the plane three points (U, Z, H_y) in the plane, computing the distance from the point C to the plane has a simple formula. We'll use the point $H = [0, H_y, 0]$ as our main point. The equation of our plane (the condition for when a point \vec{P} is in the plane) is $\vec{N} \cdot \vec{P} = k$. In our situation, because the sphere A is at the origin, $k = a$.

$$a = \frac{N \cdot U}{N_y} \quad (26)$$

$$c = \frac{|N \cdot P - a|}{|N|} \quad (27)$$

$$c = \frac{|C_x N_x + C_z N_z - a|}{1} \quad (28)$$

By substituting 28 into equations 23 and 24, we obtain:

$$a + |C_x N_x + C_z N_z - a| = \sqrt{C_x^2 + C_z^2} \quad (29)$$

$$b + |C_x N_x + C_z N_z - a| = \sqrt{(a + b - C_x)^2 + C_z^2} \quad (30)$$

If the interior expression $C_x N_x + C_z N_z - a$ is positive, then upon solving the system we find only imaginary solutions.

So assuming it is negative, we obtain:

$$2a + -C_x N_x + -C_z N_z = \sqrt{C_x^2 + C_z^2} \quad (31)$$

$$2b + -C_x N_x + -C_z N_z = \sqrt{(a + b - C_x)^2 + C_z^2} \quad (32)$$

This is a system of two nonlinear equations with unknowns C_x and C_z . Solving this system is beyond the capacities of the authors, but not Mathematica, although the answer that Mathematica produces in its raw form is half a page long. Furthermore, there are actually two solutions, corresponding to the two sides of the AB line which the circle C could be on and satisfy these constraints. We have selected the solution that place C in the positive Z direction conformant to our problem set-up.

However, by introducing new variables to represent repeated portions of this long expression, the expressions be made tractable and easily programmed.

$$M = (a + b + aN_x - bN_z)^2 - 4abN_z^2 \quad (33)$$

$$L = a(a + b + aN_x - bN_z) - b(a + b)N_z^2 \quad (34)$$

$$G = -a^2(a - b)^2bN_z^2 \quad (35)$$

$$H = 2a(-1 + N_x) - b((-1 + N_x)^2 + N_z^2) \quad (36)$$

$$F = \sqrt{GH} \quad (37)$$

$$K = 4a^2b^2N_z^2 + 2a^3b(-3 + N_x)N_z^2 \quad (38)$$

$$J = b^3(-1 + N_x)N_z^2 \quad (39)$$

$$C_{x0} = \frac{2(F + aL)}{M} \quad (40)$$

$$C_{z0} = \frac{K + 2bF(-1 + N_x) - 2a(F(1 + N_x) + b^3(-1 + N_x)N_z^2)}{(a - b)MN_z} \quad (41)$$

$$C_{x1} = \frac{-2F + 2aL}{M} \quad (42)$$

$$C_{z1} = \frac{K - 2bF(-1 + N_x) + 2a(F(1 + N_x) - b^3(-1 + N_x)N_z^2)}{(a - b)MN_z} \quad (43)$$

One solution $((C_{x0}, C_{z0})$ or $(C_{x1}, C_{z1}))$ will be on the positive side of the X axis, but which one is highly dependent on the input variables, so both are computed and the positive z value selected.

The variable c can be compute from a , C_x and C_z form Eq. 23.

This math can be found in the JavaScript which is licensed under the GPL[GPL] at our website[3].

4.1 Special case when $\gamma = 0$

In the above math when γ is 0, then N_z is zero, creating a division by zero. In this case we can use the proportionality of similar triangles to assert:

$$a = c + \frac{aC_x}{U_x} \quad (44)$$

Combined with our previous equations Eqn. 23 and Eqn. 24 in the plane relating C_x and C_z to c , we obtain the following equation:

$$c = \frac{a(a+b)(a-U_x)}{a^2 - ab + aU_x + bU_x} \quad (45)$$

4.2 Special case when $\theta = 0$

When $\theta = 0$, the point U is at infinity or cannot be found. In this case $b = a$. In this case the sphere C is symmetrically positioned in contact with A and B because they have the same radius; therefore $x = a$ and:

$$(a+c)^2 = a^2 + z^2 \quad (46)$$

In this case,

$$Z' = \frac{a}{\sin \gamma} \quad (47)$$

Projecting out the X dimension and forming similar triangles in the YZ plane, we find that

$$\frac{a}{Z'} = \frac{c}{Z' - z} \quad (48)$$

$$c = \frac{a(Z' - z)}{Z'} \quad (49)$$

Asking Mathematica to solve these two non-linear equations, we obtain, after again discarding the solution producing negative z values:

$$z = \frac{2a^2 Z' - \sqrt{a^4 (Z')^2 + 3a^2 (Z')^4}}{a^2 - (Z')^2}, \quad (50)$$

which allows us to obtain c from 49.

When both $\theta = 0$ and $\gamma = 0$, then $c = b = a$.

5 Usage

These equations can be used to compute the radii b and c from a given radius a and either a desired normal or euler angles. When implemented as a soft robot, it must be understood that the center plane is conceptual. The roboticists probably want to think of moving the top plane relative to the bottom plane,

which can be implemented as a simple rigid disc. The angles and normals between the top and bottom and will be twice the angles³ measured against the center plane.

Furthermore, an implementation based on soft inflatable spheres will not be really achieve perfect spheres at any pressure. Nonetheless, because these equations are trivial to implement in a micro-controller, they make a good basis for a control algorithm because it allows the Jacobian to be expressed as a closed form solution. A Stewart platform implemented in this would be expected to be have “softly” in response to pressure, and yet have a predictable shape in the absence of external forces.

A series of such Stewart platforms stacked together would make a soft tentacle.

Note: These closed-form expressions make it possible to compute the Jacobian of the system (the change in in the position of the plane relative to a change in the radius of any or all spheres.)

References

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³Megan, is this really true? Can we simply double the angles? I think so, but that might not be true.