1. **Design a 3D kinematic coupling (for example that could be used for example as a tool or fixturing holder on your machine). (2 pts)**

   a. **You cannot just "print it": you have to make it!**

   For my kinematic coupling, I decided to build a system that could provide feedback (in the form of an LED) as to when it was properly coupled (or decoupled). To do this, I started by gluing (Krazy Glue) a piece of ~1/8" aluminum sheet to a piece of ~7/16" acrylic.
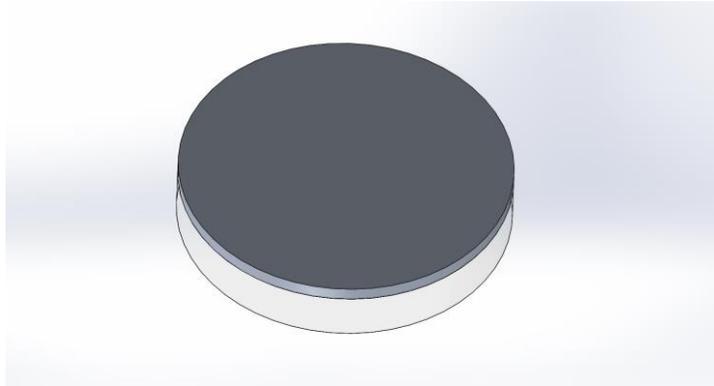

   I then proceeded to cut the 3 V-grooves (120° spacing) for the balls in this bilayer structure using a 90° chamfer end mill. I cut the grooves to a depth just greater than the thickness of the aluminum layer, thus electrically isolating the three "pie pieces" from one another.
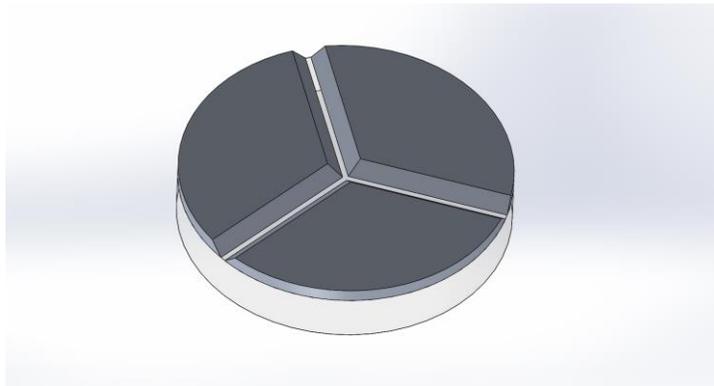

   After machining the grooves, I then bisected each of the "pie pieces" with a 3/32" end mill. This left 6 electrically isolated "pie pieces".
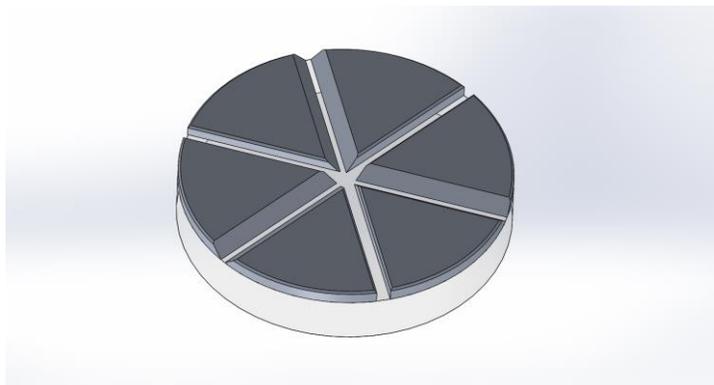
To finish the part, I machined a clearance circle at the middle of the part through the aluminum layer and then a smaller recess hole (0.249" diameter, 0.04" deep into the acrylic layer) for a 1/4" disc magnet (press fit).
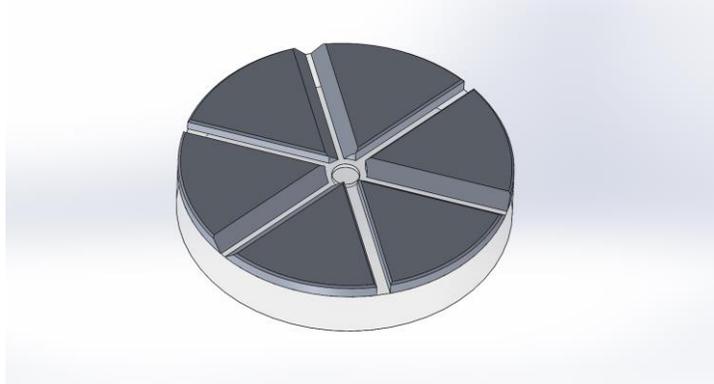
For the top piece of the coupling (with the balls), I started with a piece of ~7/16" acrylic and machined three ball retaining holes at a coupling diameter of 2". The balls I used were precision ground to a 1/4" diameter, so I machined the retaining holes to a diameter of 0.249" and a depth of 0.13" to allow for a press fit.
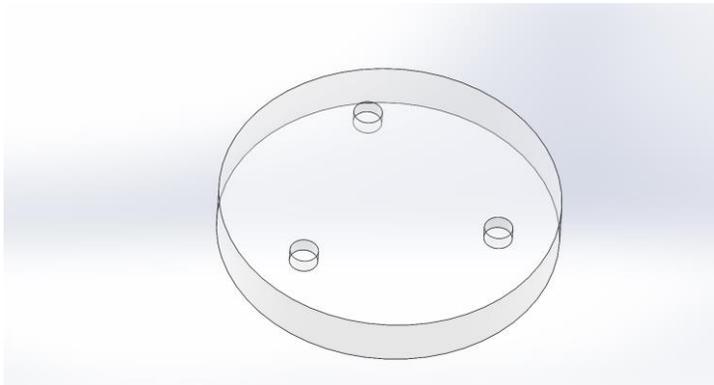
I also machined a matching magnet recess hole (0.249" diameter, 0.04" deep) at the center of this piece.
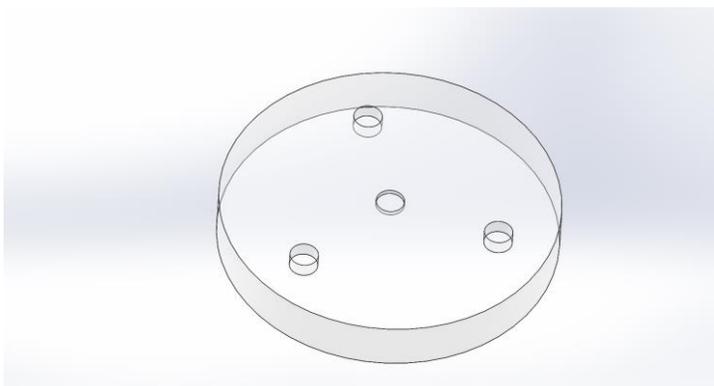
I carefully press fit the balls into retaining holes using a precision dowel pin mounted in a collet in the mill (to precisely and equally control the ball depth).
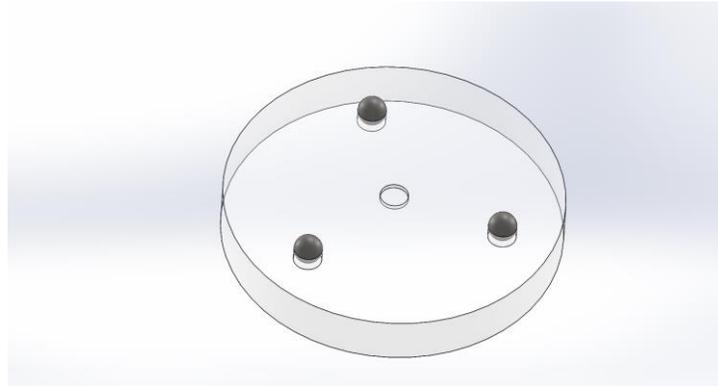
Next, to integrate the electrical feedback system, I taped an LED, a resistor, and a pair of wire leads to the adjacent pie pieces created by the 3/32" end mill cuts in the bilayer piece. (This certainly could have been done in a more sophisticated and aesthetically pleasing fashion, but I was primarily concerned with proving that the circuit would actually work).

With these electrical components added, the kinematic coupling essentially formed a simple LED lighting circuit, with the three balls acting as three "push-button switches" to connect the electrical components together. Here is a circuit diagram.
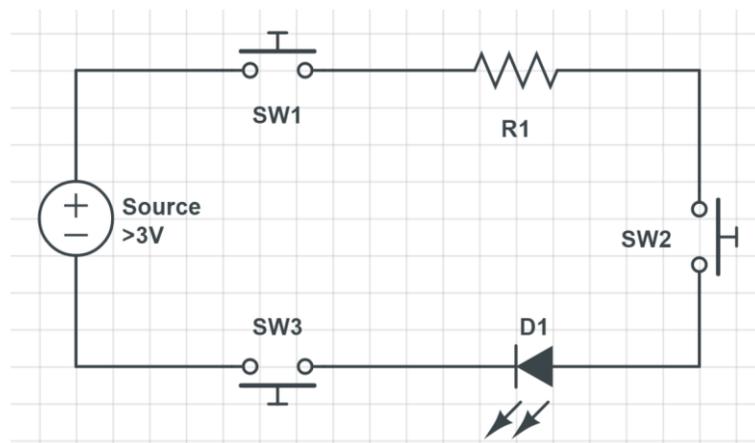
So basically, unless all 6 Hertzian contacts are being made (closing all three of the "switches"), the LED will not light up. It was pretty cool to see it actually work, and to fiddle with adding forces to different parts of the structure to break one or more of the contact points. Below are a few pictures of the setup in action (a video is also posted on my website and the link is here).
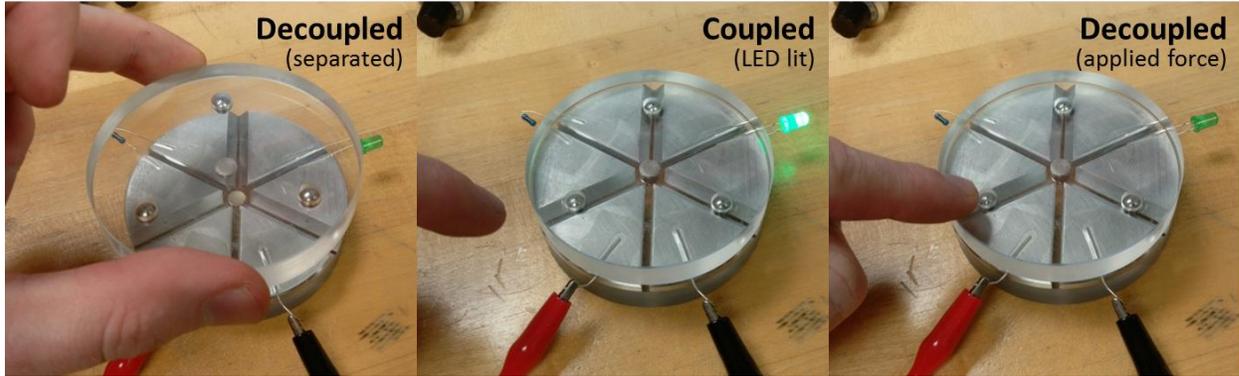
2. **Build and test it: (6 pts)**

See above for details of the build.

a. **Stiffness**

The stiffness of my coupling was inherently limited by my choice of a relatively soft/malleable metal (aluminum) for the groove material. However, aluminum was readily available, and I wanted to give my circuit a better shot of working, so I chose the extra electrical conductivity of aluminum over the extra strength of a steel alloy.

My preload stress was minimal (I measured the weight of my top piece (with the balls) to be just 0.58N, and my calculated my magnetic attraction force as 0.31N (I used grade N42 magnets with a 1/4" diameter and a 1/16" thickness, and when coupled, they are ~0.17" (4.2mm) apart).

To further test my kinematic coupling's stiffness, I positioned dial indicators at the edge of my coupling while I added weight to the middle (using a wide-mouth step collet to try and make sure the weight was distributed over the balls and not just deflecting the inner plastic). A picture of the setup is included below. I was able to measure just under 0.001" of deflection with ~132 N of force applied, which gives a stiffness of 5.2×10^6N/m, which is just about an order of magnitude less than the spreadsheet predicted, but it does not take into account that acrylic (with its appreciably smaller yield stress and Young's modulus) was used as a mounting material for the balls and a base material for the aluminum grooves.

(For background, those are lead door stops precariously balanced on top of a piece of scrap steel, which itself is balanced on top of the step collet).

b. **Repeatability**

For repeatability testing, my rough test was to repeatedly separate and recombine the coupling and see if the LED still illuminated (indicating all 6 contacts were being made). A video of this test is posted on my website and the link is here. For each of the 51 (50+1, in case I miscounted) coupling actions, the LED illuminated.

For more accurate testing, I again used a dial indicator, this time mounting it in the spindle of a mill and using it to find the center of the top piece of my kinematic coupling after each recoupling. I used a ~1N weight to counteract the force applied by the dial indicator. A picture of the setup is below. I was pleased to find that removing and then recombining the coupling did not change the dial indicator's reading of the part center in any appreciable fashion (i.e. the center changed <0.0005" between couplings).

c. **Accuracy**

The accuracy of a kinematic coupling is really based on how well you can hold the tolerances of your design. To test this in my part, I first took my top piece (with the balls) and measured the distance between the apex of each ball to the top surface to the opposite surface (giving the maximum "thickness" of the part) using Mitutoyo calipers. These thicknesses were consistent with each other to 0.0005". I then coupled my two pieces together and measured the distance from the bottom to the top of the kinematic coupling over each of the three balls. The thicknesses were again consistent to 0.0005". I chose this way of measuring to help minimize any inaccuracies to non-planarity in the stock material used. However, real life does not accept non-planarity as an excuse, so I also tested my full kinematic coupling on a surface with a dial indicator. I found that the maximum difference was 0.001", which is not perfect, but I think it is acceptable given the tools used and the somewhat limited amount of time expended in the fabrication process.

3. **Compare tests to predictions (close design loop). (2 pts).**

a. **How would you change the design and update the spreadsheet?**

Comparing my results to the results predicted by the spreadsheet, it is clear that choosing acrylic as a backing material was a poor decision from a stiffness point of view. To a lesser extent, aluminum was also

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a sub-par choice, but this is something I acknowledged beforehand and decided to ignore so that I could pursue the circuit idea. If I were to require a much stiffer coupling, using steel or some sort of silicon carbide or silicon nitride would be more appropriate. However, given my material choices, I was happy with the performance of my kinematic coupling, particularly its repeatability and accuracy.