Separation Connector Improvement for Orbital Sciences Corporation

By
Koll Christianson, Luis Herrera,
and Zheng Lian
Team 19

Ball Bearing Detent Design Proposal

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design – Fall 2012

Department of Mechanical Engineering
Northern Arizona University
Flagstaff, AZ 86011

Table of Contents

Abstract

Orbital Sciences Corporation is an engineering design company that contracts in space vehicles and missile defense systems. Within each space vehicle or missile, there is a separation connector that allows the communication wires, located between each stage of the vehicle, to be safely disconnected. The current design of the separation connector uses many small pieces and requires an excessive pulling force to de-mate. Our team has designed the 'Ball Bearing Detent' separation connector to solve these problems. Based on the customer's requirements and constraints, we developed a reliable connector that: leaves the male end of the connector unchanged, separates with a reasonable amount of force, is easy to manufacture, withstands military specification testing, and can de-mate under static and dynamic conditions. The Ball Bearing Detent design also reduced the number of internal components; thus, reducing the manufacturing process. The new design can statically de-mate with a pulling force less than 30 lbs. and sustain dynamic shock loads up to 200 lbf. Lastly, the new design can achieve higher pull angles, which increases the chance of separation; thus, making it more reliable than its predecessor.

1. Problem Statement

The goal of this project is to design and prototype a relatively easy to manufacture, inexpensive, and reliable separation connector.

1.1 Introduction

Orbital Sciences Corporation is an engineering design company that contracts in space vehicles and missile defense systems. Our sponsor from Orbital Sciences Corporation is Mary Rogers. She is the current electronics packaging and actuator manager. She has requested, on behalf of Orbital Sciences Corporation, that our capstone group aid in redesigning their current separation connector. The separation connector is the device that allows the launch vehicle to safely separate from the device being deployed. It is a mechanical device that detaches the communication wires of the launch vehicle and the deployed device. Ideally, this new separation connector will be easy to manufacture, lightweight, and more reliable than its predecessor.

Figure 1: Current Separator Connector

1.2 Background Research

Mary Rogers supplied a series of resources for us including the Glenair and Amphenol catalogs, several news articles about failures due to separation connectors, as well as a sample of a separation connector. The Glenair and Amphenol catalogs have a collection of different separation connectors. This allowed us to use some of the different ideas combined with the constraints given to us by our client to design a unique separation connector for our project. The news articles provided an insight on how important the separation connector is during the stage separation and launching of a rocket. Lastly, the sample of the separation connector allowed us to gather important dimensions about the original device that will be used throughout the designing of our new separation connector.

1.3 Needs Identification

Mary Rogers approached us with this project in hopes of improving the current separation connector. She had some specific requests on what her company was looking for. Some of her requests included:

- The device being able to withstand military specification testing
    - Including but not limited to thermal, shock, and vacuum tests
- The device should not de-mate prematurely
- The device should separate with a reasonable amount of force
    - For static separation, reasonable is defined as a force of 10-30 lbs.
- The device must withstand a shock load force of 200 lbs. during a dynamic de-mate
- The leash must be able to withstand a pulling force of 300 lbs.
- The device must be reliable enough to mate and de-mate a minimum of 50 times without failure, fatigue, or damage
- The male end of the connector is to remain unchanged
- Must be able to be easy to manufacture

From these needs, we concluded that the customer needs a separation connecter that is easy to manufacture, reliable, and can statically de-mate under smaller loads than are currently available.

1.4 Project Goal

It is essential that the new separation connector mates and de-mates at least 50 times with no signs of damage or failure. Thus, the goal of the project is to design an improved separation connector that will separate cleanly 100% of the time. Static de-mate, for this new separation connector, will be achieved when a force of 10-30 lbs. is applied to it and it will be able to withstand a shock load force of 200lbs. during dynamic de-mate. Lastly, the entire design will be easy to manufacture so that it can be machined in-house at Orbital Sciences' machine shop.

1.5 Objectives

Our objectives are to create an inexpensive, more reliable, separation connector that is easy to manufacture. We want the price to be less than $400, which is the average price of a single separator connector. For reliability, we want the new separator connector to meet the client's requirement of passing 50 tests without failure or damage. Our team would also like to increase the pull angle at which the device can separate. If the pull angle can be increased the reliability will also increase. Furthermore, the total size of the new separation connector cannot increase more than 25% greater than the original connector. Lastly, the new design needs to be easier to manufacture. Our client currently purchases all of their separator connectors from other companies. However, they would like to manufacture them in their own machine shop. See below for the table of objectives.

Table 1: Table of Objectives

Objectives	**Basis**	**Units**
Inexpensive	Material Cost	US Dollars ($)
Ease of manufacturing	Time to Manufacture	US Dollars per Hour ($/hr.)
Reliability	Percent of Failure	Percent (%)
Robust design	Pull Angle	Degrees (°)
Size no greater than 125% of original	Total Size	Inches (in.)

1.6 Constraints

This section includes the specifications to which our design must abide by. These constraints were given by our client to ensure the separation connector meets Orbital Sciences Corporation's rigorous standards. Below is a list of the required specifications:

- Bayonet grooves must match military specifications
  - This can be achieved by leaving the male end of the original separation connector unchanged
- Must de-mate statically with a force ranging from 10-30 lbs.
- Must be able to withstand a shock load force of 200 lbs. during dynamic de-mate
- Leash must be able to withstand a minimum pulling force of 300lbs.
- Must be able to statically mate/de-mate a minimum of 50 times without failure
- Must not out-gas when subjected to a vacuum
  - This can be achieved by choosing the correct material
- Must withstand a temperature gradient of -34°C – 71°C with no damage to the material
  - This can be achieved by choosing the correct material
- Must withstand a static acceleration of 15 G-Force
- Must not fail during a drop test
  - From a height of 3 feet dropped onto a concrete floor
- Must pass a "rattle test"
  - The object is shaken by hand, or in a vibration machine, and must not rattle or de-mate
- Must not exceed an increase in size of 25 % greater than the original (~1.43" inner diameter for male end)
- Must not exceed an increase in size of 25 % greater than the original (~1.42" outer diameter for female end)

2. Problems with Original Design

The original separation connector is a complex design that requires it to flower open in order for the wires to be disconnected. This can be seen below in the fully assembled view of the original separation connector (figure 2). The original connector also requires in excess of ten individual pieces in order to function properly. The fact that it requires a lot of small moving parts decreases its reliability and increases the time and cost required to manufacture the connector. See figure 3 below for the exploded view of the original separation connector.

Figure 2: Original Separation Connector - Fully Assembled

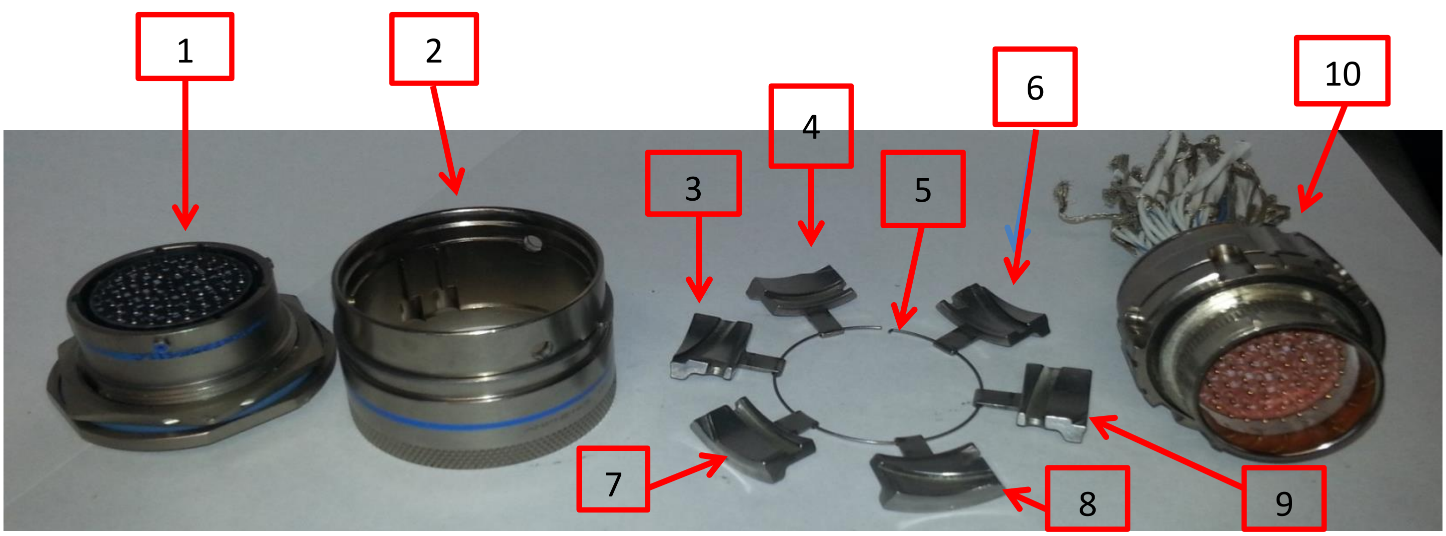

Figure 3: Original Separation Connector – Exploded View

3. Design Proposal

We started our concept generation phase by brainstorming design ideas that we thought had the potential to solve the problem. Throughout the brainstorming sessions, we generated one hundred different ideas that could solve the problem. Although some of the ideas were not feasible, it allowed us to become more creative in the ways we approached the problem. Our team was able to eliminate the impractical ideas and narrow it down to four feasible concepts that we believe best solved the problem presented by our client. Then, through use of a decision matrix and other design comparison tables, one design was chosen as the best solution to pursue.

3.1 Preliminary Ball Bearing Detent Design

This design utilizes six evenly spaced bearings on the female end of the connector. The bearings are implanted into the female piece with springs directly behind them. The springs allow the bearings to retract so that the male end of the connector may mate/de-mate with the female end of the connector easily. There is also a coupling piece in the middle that mates the female to the male end. On one side, there is a helical track cut on the inside that allows the male end to screw in one-third of a turn, per request of the customer. On the opposite end, there is a groove cut into it to allow the ball bearings to expand and hold onto the coupling. The groove will be big enough to allow the ball bearings to slide into it, but small enough to allow them to be pulled out. Figure 4 below shows a CAD drawing of the conceptual “Ball Bearing Detent” design. A modified version of this design became our final design choice.

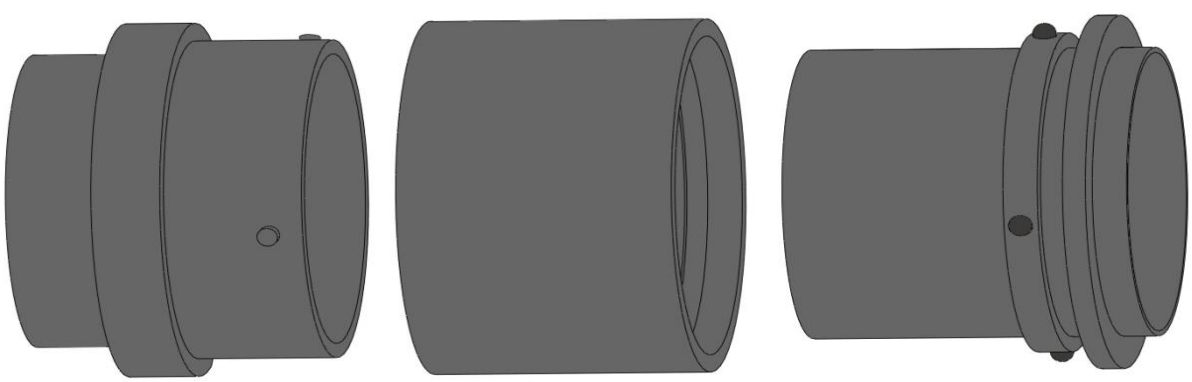

Figure 4: Ball Bearing Detent Design Concept

3.2 Prototyping

Before making the first prototype of our ball bearing detent design, we had to imagine how this design would be assembled. We wanted our design to be as simple as possible to assemble while reducing the amount of pieces being used; thus, we redesigned our preliminary design. Our first prototype of this new design was created using fused deposition modeling (FDM), shown below in figure 5.

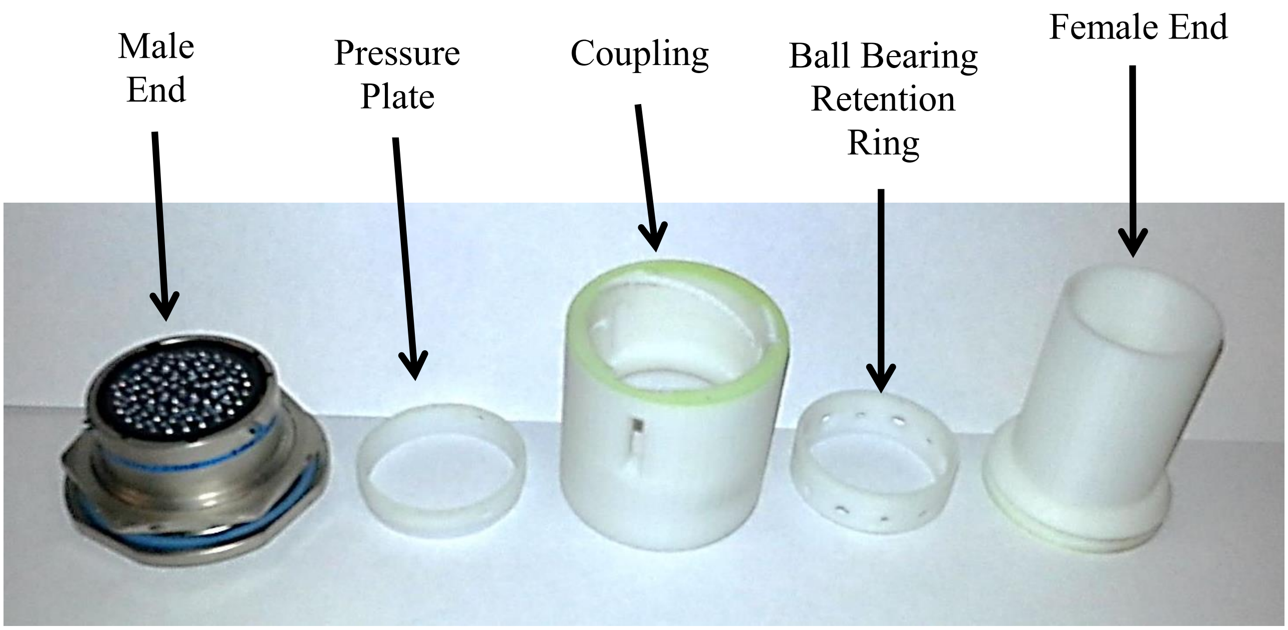

Figure 5: First FDM Prototype

This new design keeps the male end of the connector unchanged. In fact, the male end in the picture is the original male end given to us by the client. Starting the assembly from the female end, the ball bearing retention ring would be slid onto the female end with the springs and ball bearings behind it. The ball bearing retention ring would bet set in place at the bottom of the female end with set screws. Next, this entire piece (female end with ball bearings in place) would be pushed into the bottom end of the coupling. The ball bearings would retract into the female end and expand once it reached a groove that was cut into the inside of the coupling. Then, a wide spring would be placed into the top of the coupling and the pressure plate would be placed on top of it.

The pressure plate would be set in place by three pins which prevent it from twisting and only allow it to travel straight up and down the inside of the coupling. Lastly, the male end of the connector would be twisted into the coupling following the helical grooves that are cut on the inside of the coupling. When the male end reaches the end of the helical groove, it will be forced up into a notch by the pressure plate locking it in place. This completes the assembly and mating of the ball bearing detent separation connector. See below for the fully assembled FDM prototype.

Figure 6: Fully Assembled FDM Prototype

4. Engineering Analysis

This section will elaborate on the assumptions made during our calculations and the material analysis of our final design that we plan to prototype. The analysis was performed on the newest modification of the ball bearing design that we named the "Ball Bearing Detent" design. The final design is explained in-depth below in section 6.

4.1 Assumptions in Analysis

We have not finalized the dimensions for our designs; therefore, the calculated values for our analysis are all approximates. Additional assumptions for the analysis of the designs include:

1. Material used is Aluminum 6061- T6
2. Horizontal de-mate (no pull angle)
3. No friction while de-mate occurs
4. Perfect reliability
5. Dimensions of the device are correct

4.2 Material Analysis

The materials we chose for the final metal prototype were the aluminum 6061 T6, steel ball bearings, and high-carbon steel springs (music wire). Although the properties of 7075 aluminum are better than 6061 aluminum, we chose aluminum 6061 T6 for the male end, female end, and the coupling because it is the most workable of all our choices and met all of our requirements. Both the steel ball bearings and high-carbon steel springs were chosen from catalogs online because they met the calculated values needed.

Using the data from tables 6 and 7 below, we determined that Aluminum 6061-T6 is the best material for our prototype. Aluminum 6061 has ultimate tensile strength of at least 40,000 psi and yield strength of at least 35,000psi. Its thickness can vary from of 0.250 inches or less and has elongation of 8% or more. The fatigue limit of aluminum 6061 T6 under cyclic load is 14,000 psi for 500,000,000 completely reversed cycles using a standard RR Moore test machine. Based on this data and material properties, aluminum 6061 T6 is the best material for our separation connector.

Table 2: Material Analysis

Length (L=1 in.)	Aluminum alloys				Stainless steel	
Force (F = 300 lbs.)	6061-T6		7075-T6		AISI Type 304	
Area (in^2)	σ (psi)	ε	σ (psi)	ε	σ (psi)	ε
0.1	3.00E+03	2.88E-04	3.00E+03	3.00E-04	3.00E+03	1.07E-04
0.2	1.50E+03	1.44E-04	1.50E+03	1.50E-04	1.50E+03	5.36E-05
0.3	1.00E+03	9.62E-05	1.00E+03	1.00E-04	1.00E+03	3.57E-05
0.4	7.50E+02	7.21E-05	7.50E+02	7.50E-05	7.50E+02	2.68E-05
0.5	6.00E+02	5.77E-05	6.00E+02	6.00E-05	6.00E+02	2.14E-05
0.6	5.00E+02	4.81E-05	5.00E+02	5.00E-05	5.00E+02	1.79E-05
0.7	4.29E+02	4.12E-05	4.29E+02	4.29E-05	4.29E+02	1.53E-05
0.8	3.75E+02	3.61E-05	3.75E+02	3.75E-05	3.75E+02	1.34E-05
0.9	3.33E+02	3.21E-05	3.33E+02	3.33E-05	3.33E+02	1.19E-05
1	3.00E+02	2.88E-05	3.00E+02	3.00E-05	3.00E+02	1.07E-05
1.1	2.73E+02	2.62E-05	2.73E+02	2.73E-05	2.73E+02	9.74E-06
1.2	2.50E+02	2.40E-05	2.50E+02	2.50E-05	2.50E+02	8.93E-06
1.3	2.31E+02	2.22E-05	2.31E+02	2.31E-05	2.31E+02	8.24E-06
1.4	2.14E+02	2.06E-05	2.14E+02	2.14E-05	2.14E+02	7.65E-06
1.5	2.00E+02	1.92E-05	2.00E+02	2.00E-05	2.00E+02	7.14E-06
1.6	1.88E+02	1.80E-05	1.88E+02	1.88E-05	1.88E+02	6.70E-06
1.7	1.76E+02	1.70E-05	1.76E+02	1.76E-05	1.76E+02	6.30E-06
1.8	1.67E+02	1.60E-05	1.67E+02	1.67E-05	1.67E+02	5.95E-06
1.9	1.58E+02	1.52E-05	1.58E+02	1.58E-05	1.58E+02	5.64E-06
2	1.50E+02	1.44E-05	1.50E+02	1.50E-05	1.50E+02	5.36E-06

Table 3: Material Properties

	Stainless steel	Aluminum 6061	Aluminum 7075	Abs Plastic
Tensile Yield Strength (ksi)	31.2	40	73	61
Fatigue Strength (ksi)	35	14	23	11
Brinell Hardness	123	95	150	X
Modulus of Elasticity(ksi)	28000	10000	10400	310

5. Modifications to FDM Design

After choosing a material and doing analysis on how our design fit together, we decided to simplify our design again. The previous FDM prototype proved difficult to assemble. We found that sliding the ball bearing ring down the female end with springs in tension and ball bearings in place was nearly impossible to accomplish. So, we made the following modifications to make our device easier to assemble:

- Combined the female end with the ball bearing retention ring
    - This makes one solid piece that allowed us to drill holes straight through the piece where the ball bearing retention ring used to be. Then we would chamfer the hole from the inside and insert the ball bearings and springs from the inside. To hold them in place we added in inner spring retention ring which is explained below. Lastly, we added keys to the female end to guarantee the wires in the female end exactly matched up with the wires in the male end.
- Added the spring retention ring
    - This piece would make assembling the ball bearing portion of the female end significantly easier. It allows for the ball bearings and springs to be placed first then the spring retention ring would be placed into the female which would compress the springs. It would then be set in place by set screws to ensure that it does not rotate or fall out.
- Added a wave spring
    - By adding this simple spring, we were able to completely remove the pressure plate, the stabilizing pins, and the wide spring underneath the pressure plate. The wave spring would be inserted into a groove cut right below the end of the helical groove. It provides the upward force needed to hold the male end in place without the need for any extra pieces.

- Changed the Coupling
    - The coupling originally had slots cut into it to guide the pressure plate. However, we found the pressure plate to be unnecessary. So, the slots were removed which increases the overall strength of the part. Also, holes were added at the end of the helical grooves to simply the manufacturing of the notch at the end of the groove.
- Removed the pressure plate, stabilizing pins, and wide spring
    - These pieces became excessive when we found that the same job could be down with a simple wave spring.
- Removed the ball bearing retention ring
    - This piece was combined with the female end.

6. Final Design – Ball Bearing Detent

The "Ball Bearing Detent" design has undergone extensive modifications in order to meet the requirements and constraints given by the client. The new design consists of five major pieces: a male end, a female end, a coupling connector, the spring retention ring, and the leash ring. The minor pieces include: a leash, six ball bearings, and six smaller springs that rest behind the ball bearings, and a wave spring.

This design will de-mate statically when a pulling force of approximately 30lbs. is applied to the connector. This condition is also true for dynamic de-mating as the separation connector will be located inside of a rocket and will not experience too many forces. However, the device has potential to experience higher pull forces during flight as opposed to being on the ground. These higher forces are the forces experienced when, for example, a rocket has separating stages. When the stages separate, one end will continue its flight causing a high pull force on all of the internal components. To account for these high pull forces, we have designed our separation connector to be able to withstand forces of up to 200 lbs. This ensures the parts used in separation connector will not shear or catastrophically fail due to instant "shock" forces that may happen during flight.

6.1 Final Design Description

This design utilizes the original male end and a modified female end. Both ends connect to each other by being inserted into a third piece, the coupling. The male end inserts into the coupling by twisting it clockwise one-third of a turn, which allows the bayonet pins to follow a track on the inside of the coupling. When it reaches the end of the track, the wave spring inside of the coupling applies an opposing force that forces the bayonet pins into a notch and mates the male end to the coupling. To mate the female end, simply push the female end into the coupling and twist until the keys line up. Once the keys line up, push the female end into the male end to finish the mate. When the female end is pushed into the coupling, the ball bearings will retract allowing it to enter the coupling. When the ball bearings reach the inner groove cut into the coupling, the ball bearings will expand and mate the female end to the coupling.

In order to de-mate the device there must be a pulling force on both ends of the connecter. The ball bearings on the female end will retract when a force of approximately 30lbs. is applied to them. This allows the female end to detach both statically and dynamically. For static de-mate of the male end, the male end must be simultaneously pushed down and twisted counter-clockwise one-third of a turn. The male end will not de-mate during dynamic conditions. Instead, the female end will be removed and the coupling will stay with the male end.

6.2 Major Pieces

- Male end
  - Due to the customer's constraint, we were unable to change this part. Therefore, this part remained the same as the original design.
- Female End
  - This piece is a simplistic shell that holds all of the communication wires. It has an extrusion on the bottom half with holes tapped in it to hold the springs that apply force to the ball bearings. It will contain the springs and ball bearings when the spring retention ring is set screwed in place.
- Coupling
  - This piece is a coupling that has grooves cut into both ends to accept both the male and the female ends. The end that accepts the male end has a helical groove that allows the male end to rotate one-third of a turn (as per military specifications). The end that accepts the female end has a circular (360°) groove cut into it to accept the ball bearings. When the ball bearings are pushed into the coupling, they compress. The ball bearings will expand when they hit this groove causing it to mate with the coupling and male end.
- Spring Retention Ring
  - This piece is a simple cylinder that is used to simplify the assembly of the ball bearings. It allows the manufacturer to drill holes in the female end and insert the ball bearings and springs through the inside. Once all the pieces are in place, the spring retention ring is slid in the back of the female end which compresses the springs. It is set screwed in place to ensure that it does not twist or fall out.
- Leash Ring
  - This part will be machined using a CNC mill. It will be pressure fit onto the bottom of the female end. It allows the leash to be attached to the female end. It also allows the leash to rotate freely apart from the entire connector.

6.3 Minor Pieces

- Wave Spring
    - This piece will be purchased from a catalog. It is located inside of the coupling at the bottom of the helical grooves. It applies the upward force required to keep the male end in place when it is inserted into the coupling.
- Leash
    - The leash is a cable wire that is rated at 300 lbf. It will be looped through the holes on the leash ring and crimped on both sides. The leash ensures that the female end will safely pull apart from the male end without pulling on the communication wires themselves.
- Ball Bearings
    - There are six steel ball bearings. Each ball bearing will have a diameter of 3/16”. They will be purchased from a catalog. The ball bearing will be held to the female end with help from the spring retention ring. Behind each ball bearing, there will be a small spring to allow the ball bearing to retract into the female end when a 5 lb. force is applied to it. The ball bearings expand when the force is no longer being applied. For example, in our design the ball bearing retracts when the female end is forced into the coupling and expands when it reaches the inner groove of the coupling; causing them to be mated.
- Small Springs
    - There are six small springs. These springs sit behind the ball bearings on the female end. They allow the ball bearings to expand and contract when forces are applied and removed from them. They are 3/16”in diameter and 1/5” long. Each spring will be able to support approximately 5 lbs. of force. These springs will be purchased from a catalog.

6.4 Detailed CAD Drawings

This section contains the three-dimensional computer aided design (CAD) drawings of our final design. Figure 7, below, is the cross-sectional view of our Ball Bearing Detent design. The male end and leash ring are in light gray, the female end is in blue/gray, and the spring retention ring is in black. See Appendix B for dimensions of individual pieces.

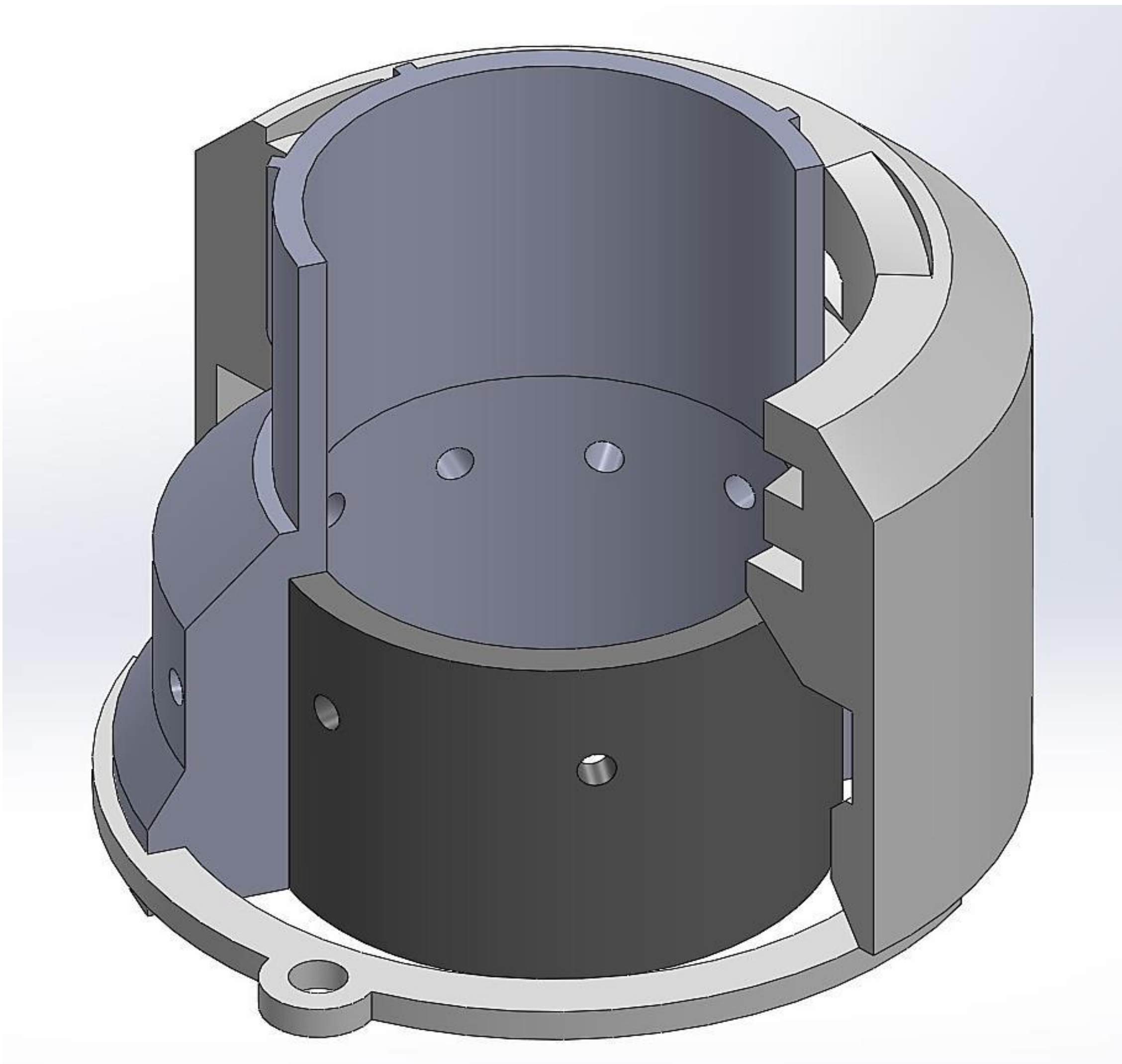

Figure 7: Ball Bearing Detent: Cross-Sectional View

Figure 8, below, is the exploded view of our assembly. This view shows each individual part in the order they are assembled. From left to right we have: the male end, coupling, female end, leash ring, and the spring retention ring.

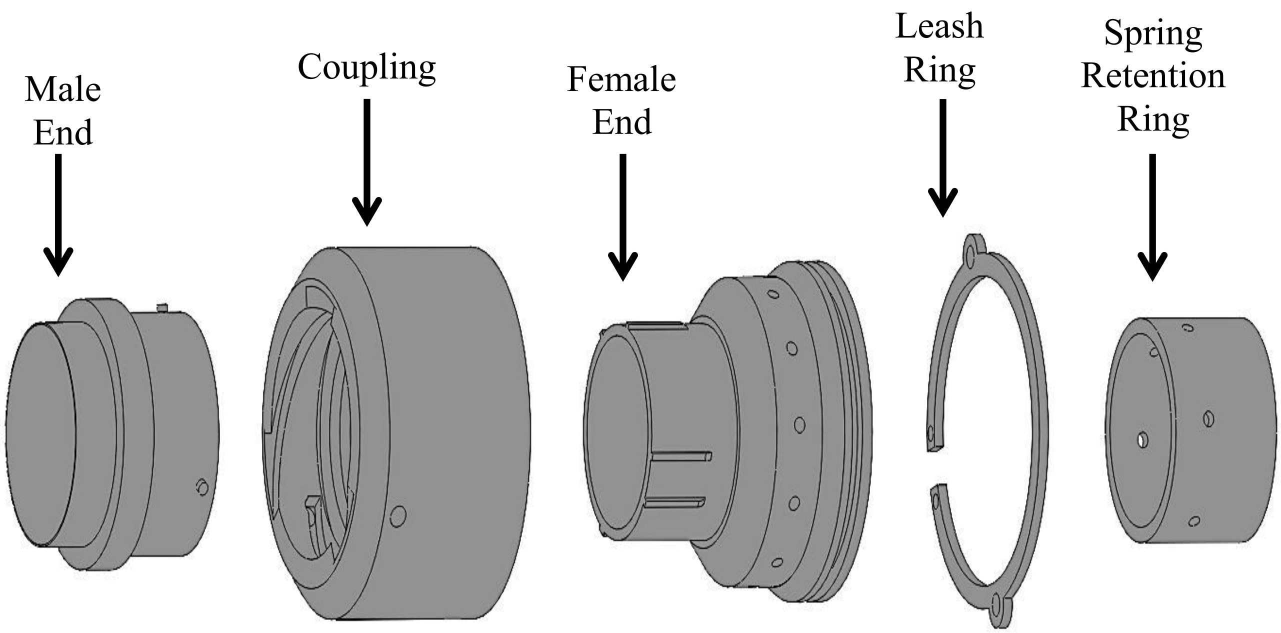

Figure 8: Ball Bearing Detent: Exploded View

6.5 Deflection Analysis

This section contains the deflection analysis of the female end and the coupling. In the following deflection analysis screenshots, blue areas have the least deflection and red has the most deflection. Each of the defection analysis screenshots below was done using a simulator in SolidWorks. Each of the simulations was calculated using Aluminum 6061-T6 and a force of 300 lbs.

Female End Deflection Analysis:

- The green arrows are fixtures and are placed where the ball bearings and springs would be. This tells the simulator that this piece would deflect with the entire female end and should not be treated as empty holes.
- The red ring on the bottom represents the stress concentrator do the sharp corner this can be reduced with the use of a fillet however the deflection at the concentrator is only 2.27 µm (89.37 µin.), which is negligible.
- Aluminum 6061 T6 is an acceptable material to be used in this part.

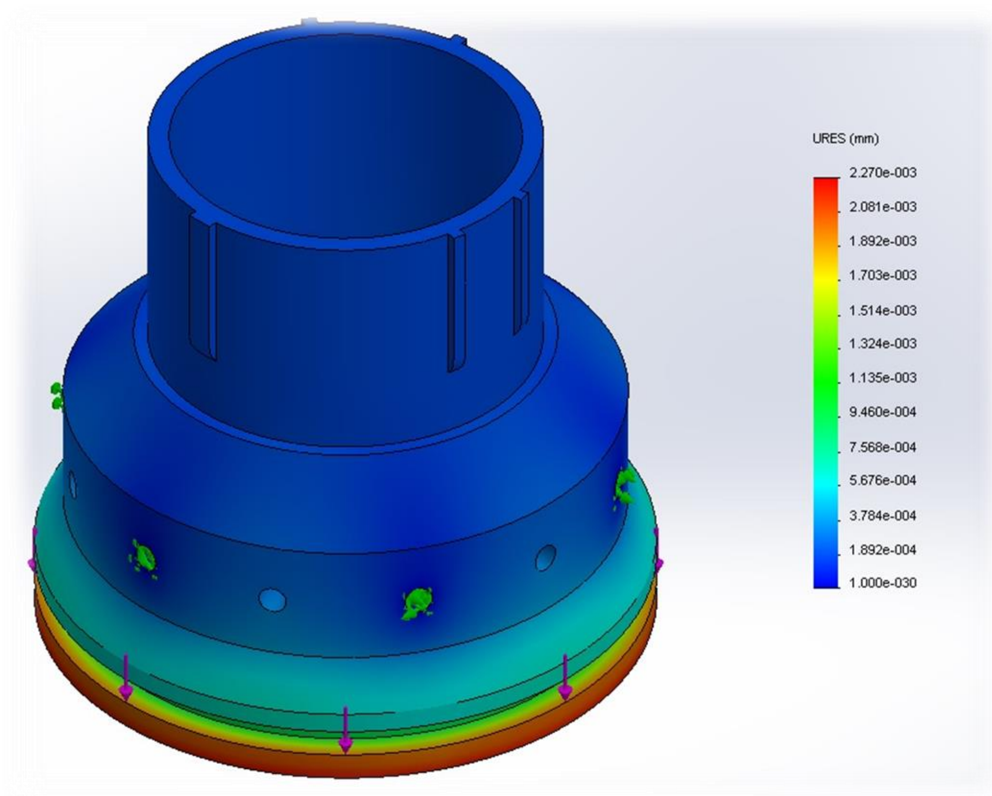

Figure 9: Female End Stress Analysis

Coupling Stress Analysis:

- The fixtures are placed where the male end bayonet pins will be in place during the deflection.
- The force is acting down on the inside of the grove where the ball bearings will sit.
- There is no significant deflection going on in this piece. The maximum deflection is at the bottom where the ball bearings will be sliding off. This concentrator is due to the fact that the force is being applied to a groove on the inside of the coupling. The maximum deflection is a negligible 2.32 μm (91.34 μin.)
- Aluminum 6061 T6 is an acceptable material for this piece

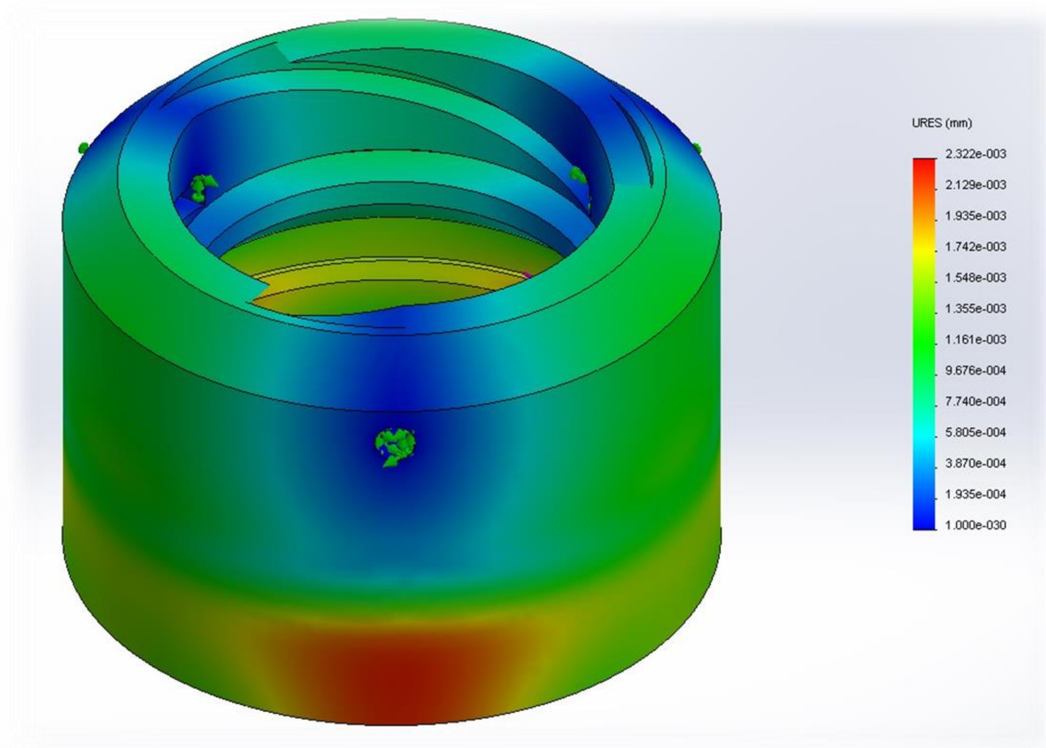

Figure 10: Coupling Stress Analysis

7. Metal Prototype

This sections contains our actual Aluminum 6061-T6 prototype of the ball bearing detent separation connector. This entire prototype was machined in Northern Arizona University's machine shop. The pictures of the final prototype below, shown as an exploded view in figure 11 and fully assembled in figure 12, has four major pieces and three minor pieces. The amount of parts was reduced because of simplifications that were found and implemented during the manufacturing process. These modifications are explained below in detail.

Figure 11: Ball Bearing Detent Metal Prototype – Exploded View

Figure 12: Ball Bearing Detent Metal Prototype – Assembled View

7.1 Modifications to Design

Due to the limitations of the Northern Arizona university machine shop, we had to make a few modifications during the machining of this prototype. We had to simplify the design in order to make it easier to machine. The modifications we made were as follows:

- Coupling
  - Changed the helical grooves to straight slots
  - Did not cut holes/notches for the bayonet pins because we did not have the correct wave spring
- Female end
  - Created a crimp tool that crimped the ball bearings in place. This allowed for the removal of the spring retention ring.
  - Only added the biggest key (the master key). The original had 5 keys; however, we did not have the specifications for the keys.
- Spring retention ring
  - Removed this piece because we developed a crimping tool.

7.2 Manufacturing Process

All of our machining was done in the Northern Arizona university machine shop. Both the coupling and the female end were made on a lathe and the leash ring was made using a CNC mill. To install the ball bearings and springs into the female end, we first drilled six evenly spaced holes around the female end that were 1/5’ deep. We then inserted one spring and one ball bearing into the hole. Next, we used a crimping tool, that our team created in the machine shop, to push the ball bearing into the hole and compress the spring. Lastly, we used the hydraulic press to push down on the crimping tool and crimp the metal around the ball bearing. A picture of our crimping tool is shown below in figure 13.

Figure 13: Crimping Tool

8. Cost Analysis

Throughout the project our goal was to keep the price of the new separation less than $400, which was the average price of separation connector currently on the market. We were allowed a budget of $100 of which we spent $80. The breakdown of our costs is shown below in table 4. It should be noted that we did not take into account the cost of machining because we machined the prototype by ourselves in our university's machine shop.

Table 4: Cost breakdown

Material	Cost
Aluminum Stock	~ $60
Leash	~ $10
Ball Bearings	~ $5
Springs	~ $5

9. Conclusion

The goal of this project was to design and prototype a relatively easy to manufacture, inexpensive, and reliable separation connector. The ball bearing detent design machined with 6061 T6 aluminum is the best solution to this problem. During unofficial testing of our design our design met and exceeded the customers' requirements. Our design:

- Does not show any sign of fatigue or failure after 50 consecutive mates and de-mates.
- De-mates when a force of approximately 27 lbs. is applied to it.
- Leaves the original male end of the connector unchanged.
- Is approximately 10% larger than the original

Thus, the Ball Bearing Detent separation connector that our team has developed is easy to manufacture, inexpensive in comparison to the original connector, will be more reliable than its predecessor, and meets all of the customer's requirements.

.

10. References

"A World of Interconnect Solutions." *Glenair*. Glenair, 2012. Web. 4 Oct 2012. <http://www.glenair.com/interconnects/mildtl38999/>.

Acxess Spring. (2012). *Spring Calculator.* Available: <http://www.acxesspring.com/spring-calculator.html>. Last accessed 5 Dec 2012.

"Amphenol Tri-Start Subminiature Cylindrical Connectors." *Powell Electronics*. Powell Electronics, n.d. Web. 4 Oct 2012. <http://www.powell.com/Amphenol/D38999/D38999catalog.pdf>.

Bedford and Fowler (2008). *Engineering Mechanics: Dynamics*. 5th ed. Upper Saddle River, NJ: Pearson Prentice Hall.

Planet Spring. (2012). *Extension Spring Calculator.* Available: <http://www.planetspring.com/pages/extension-spring-calculator-extension-spring-calculation.php>. Last accessed 5 Dec 2012.

R. C. Hibbeler (2010). *Engineering Mechanics: Statics*. Upper Saddle River, NJ: Pearson Prentice Hall.

Richard G Budynas and J. Keinth Nisbett (2011). *Shigley's Mechanical Engineering Design*. 9th Ed. New York: McGraw-Hill.

Timothy A. Philpot (2011). *Mechanics of Materials*. 2nd ed. Missouri: John Wiley & Sons, Inc.

Appendix A

Appendix B

This appendix contains the drawings made from our SolidWorks CAD models.

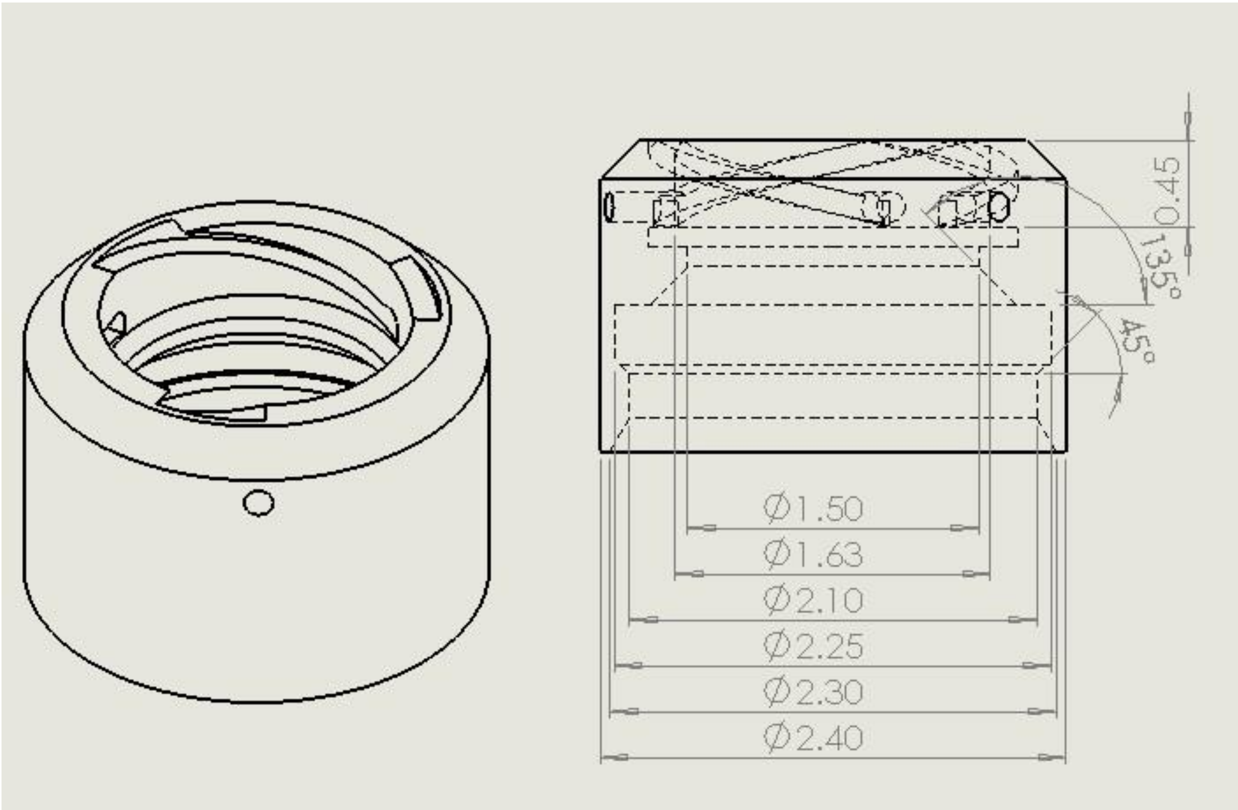

Figure 14: Coupling Dimensions

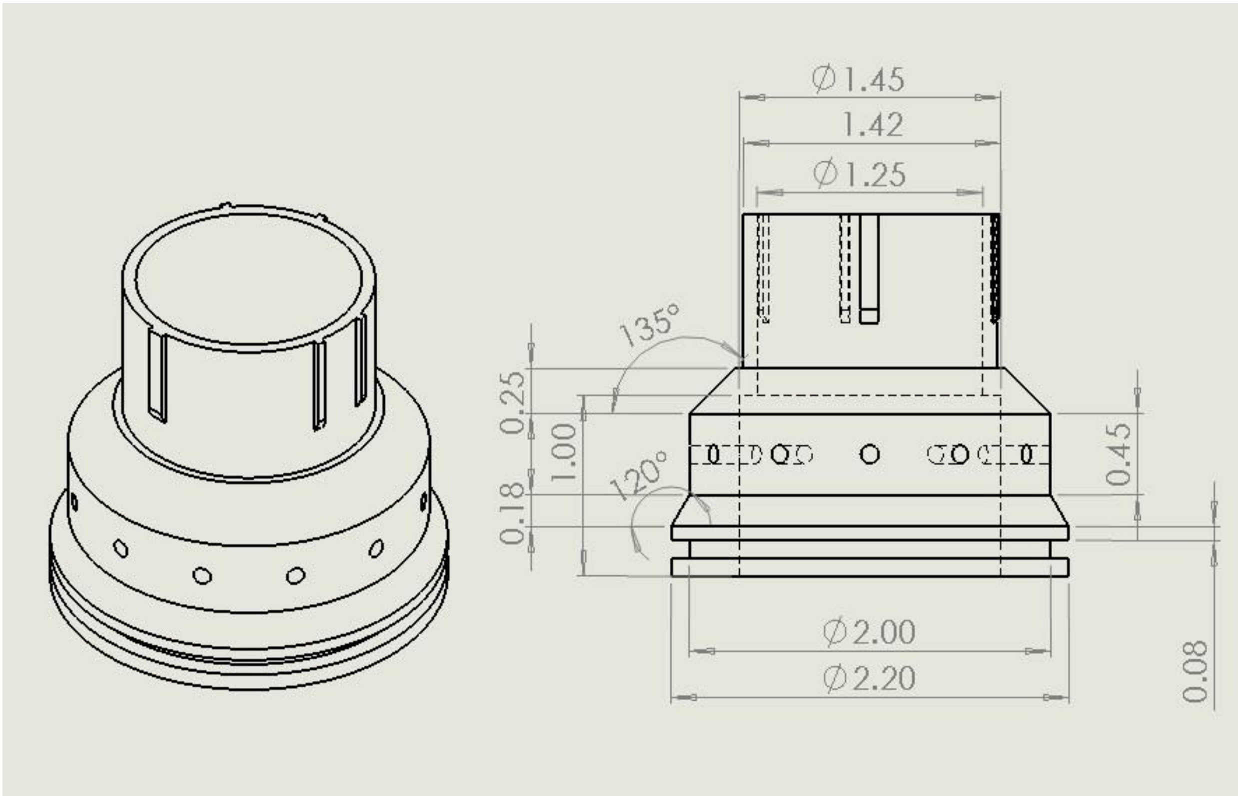

Figure 15: Female End Dimensions

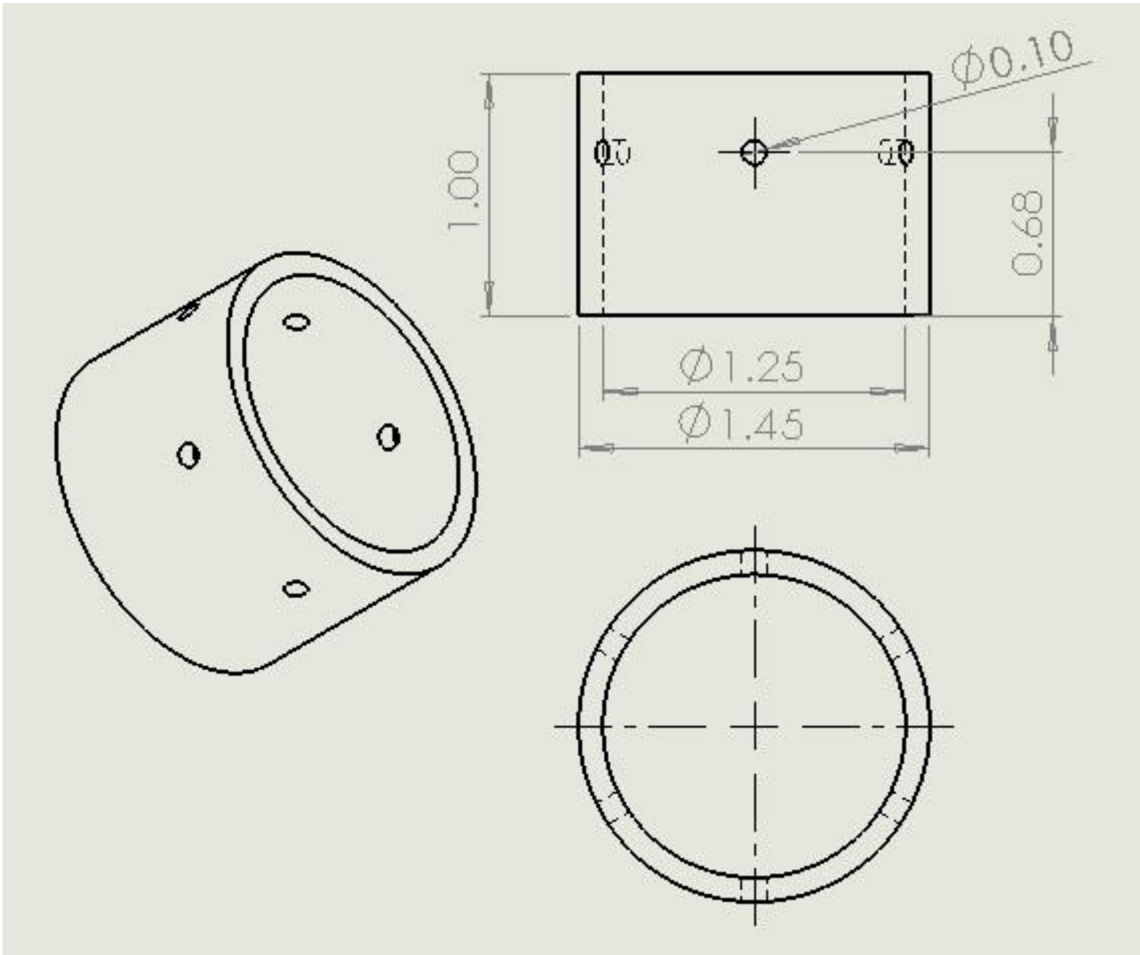

Figure 16: Spring Retention Ring Dimensions

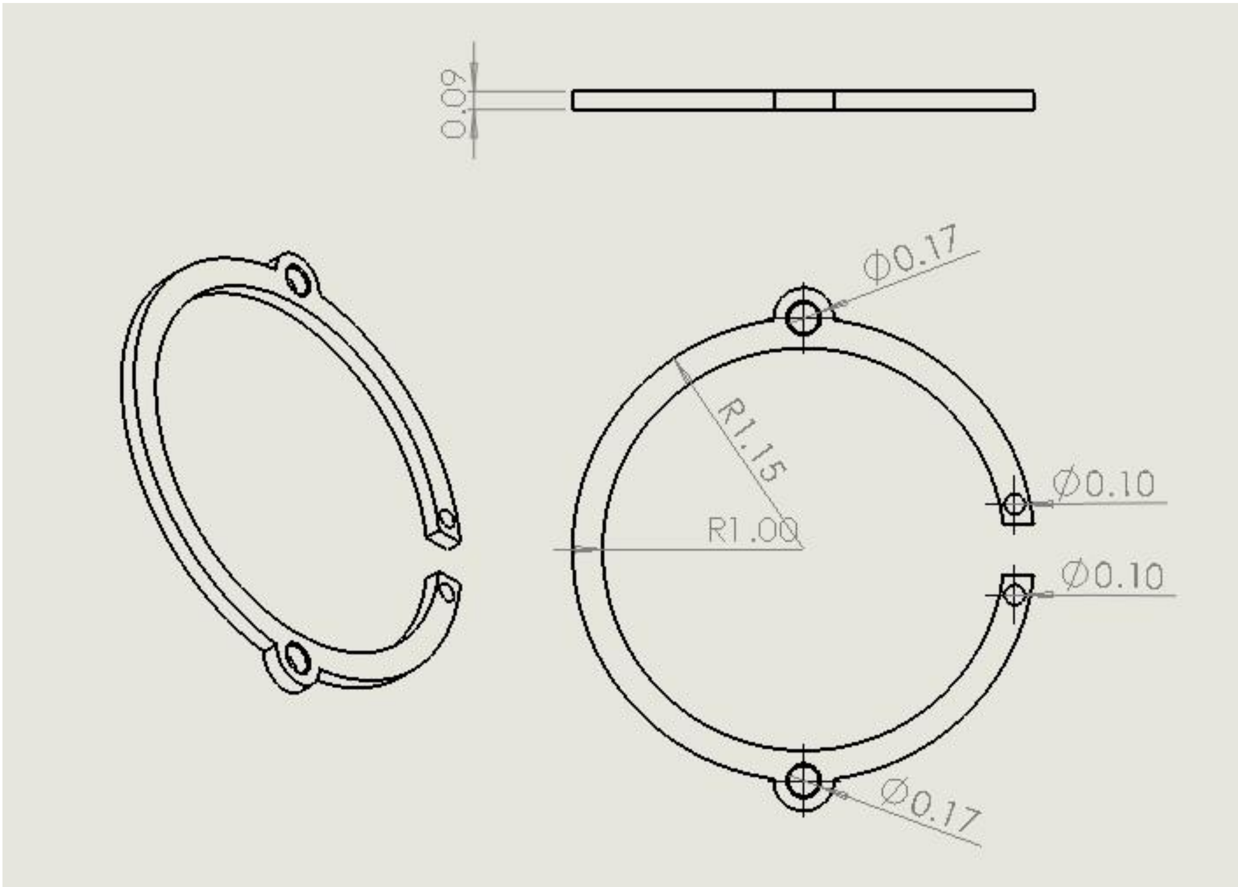

Figure 17: Leash Ring Dimensions