IMPROV: Inexpensive Maker-Made Piston Respiratory Open-Source Ventilator

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IMPROV system version 2 with model low compliance lung.

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Objective:

With the current COVID-19 (Coronavirus) pandemic, the US and world face a realistic threat of overwhelming the medical system, and more specifically, running out of available ventilators. With SARS-CoV-2 viruses (to include the Coronavirus), the primary area of the body impacted is the pulmonary system. In certain individuals, Acute Respiratory Distress Syndrome (ARDS) develops and rapidly leads to a critical need for mechanical ventilation/breathing support. We are entering a time period, however, where "ventilators are like gold," and we anticipate a potential for a widespread lack of ventilators to support critical care requirements across the nation and the world. Due to the epidemiology of the disease, time is of the essence. In order to support a wide range of populations as soon as possible, there is the need for ventilator designs that can be implemented by anybody, anytime, anywhere at low cost. Izuta Design Engineering & Associates are proposing to develop an innovative easy to assemble ventilator design, which can be built for less than $300. It takes under an hour per unit to assemble and relies on no medical equipment from the supply chain. We believe that this is the solution to the current shortage of ventilators in the world.

Specifications:

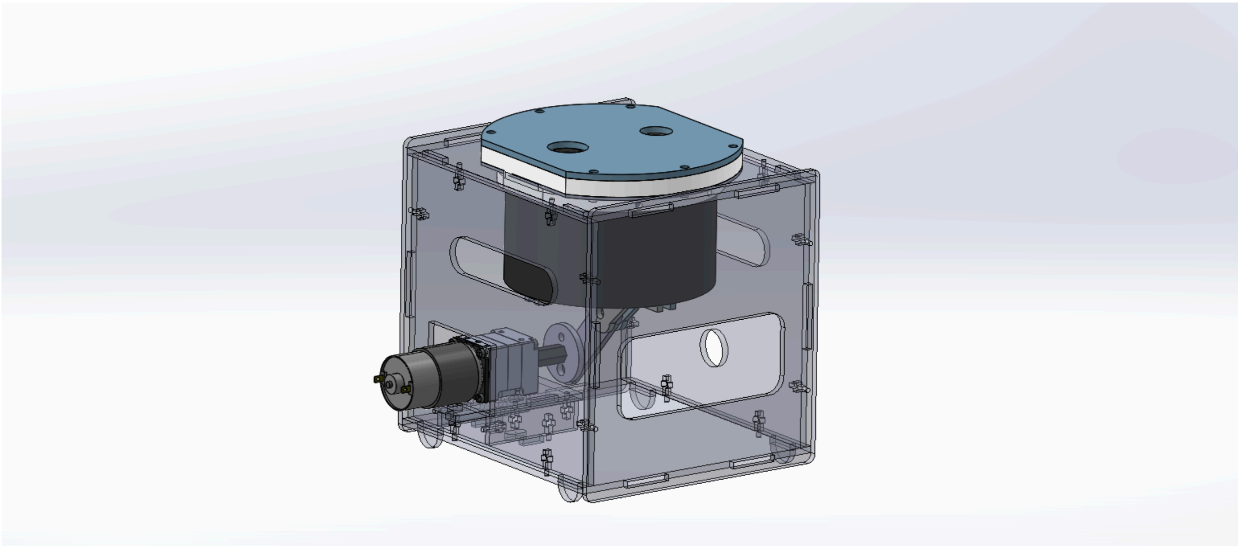
- Low Cost. Materials and components <$260
- Able to be assembled and operated by low-skill levels
- Assembled from readily available, consumer off-the-shelf parts and capabilities 3D printer or CNC router required.

- Fits with standard respiratory equipment connectors including air and oxygen supply from the hospital
- Capable of providing a Respiratory Rate of 12-40 breaths per minute
- Capable of Providing 5-24 cm H20 of PEEP (Positive End Expiratory Pressure)
- Capable of limiting the Peak Inspiratory Pressure to 18-40 cm H20
- Capable of tidal volumes between 100-1000 cc (must install alternate rod and crank disc)
- Variable breaths per minute with PWM controller
- Uses 12V DC power battery or 120V AC power with 12V DC power supply
- Inspiratory Time of 0.4 seconds at max respiration rate
- Ability to control Flow during inspiration by using adjustable restrictor
- Expired air scrubbing

Description of Solution:

IMPROV: Inexpensive Maker-Made Piston Respiratory Open-Source Ventilator is a piston type ventilator. There is an immediate need for an economical easy to assemble and modify non-FDA approved ventilator. The system specifically targets supplies and materials readily available throughout the U.S.A. The cylinder is made of 6" plastic water pipe. The cap and piston can be made on FDM 3D printers readily available at maker spaces, schools, and universities throughout the nation. Hardware including electronics is based on readily available COTS parts. The powertrain system uses Vex Robotics motors, gearboxes, shafts, bearings and couplers. Vex Robotics components are used throughout the nation by middle school and high school robotics programs. These components can be substituted for other COTS components but it is believed this system can be built by students and would promote a positive mindset in our youth during this difficult time. The inhalation/exhalation valves and mounting frame can be made via laser cutting, CNC routing, waterjet abrasive cutting, or by manual methods. Respiration volume and rate can be changed but require disassembly of the system to insert different size cams and gearboxes. With implementation of a motor controller respiration rate can be easily changed.

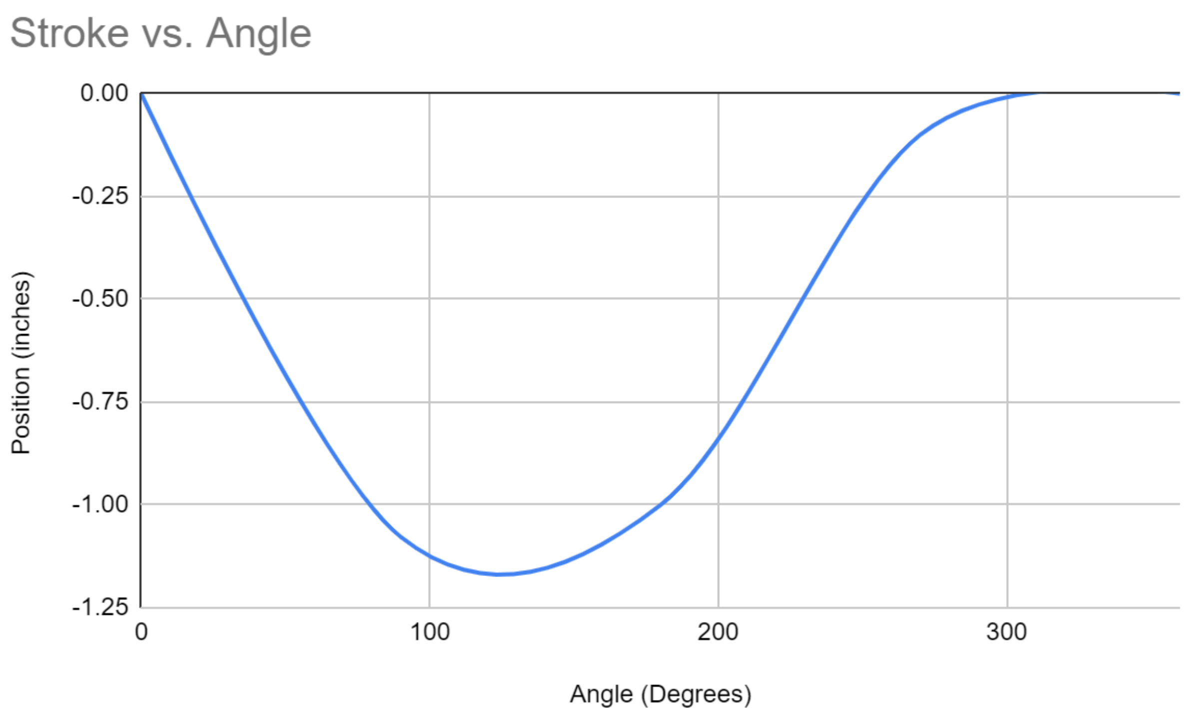
The system uses one 6" diameter ABS pipe section 4.5" long to create the cylinder bore. The crank, rod, piston, and couplers can all be 3D printed. Although there is potential for COTS substitutes to facilitate faster production. The current prototype uses three 10:1 planetary gearboxes to reduce motor speed to 18 rpm. A low pressure o-ring seal was designed to reduce the high frictional forces of a +200 psi system typical of o-ring design. Standard hardware and bearings were selected; the 608 size ball bearing is used for the wheels on skateboards and fidget spinners. The frame is water jet cut from 1/8" and 3/16" 6061 aluminum sheets and held together with 6-32 screws with hex nuts.



The system uses a series of one way valves to control the flow of air. The following diagram depicts the flow of air depending on the motion of the stroke. Not shown is additional one way valve at the junction of the two hoses near the patient's respirator. This one way valve is on the fresh air supply side to prevent exhaled air from back flowing in the system.

Performance Characteristics:

A piston based system was chosen due to the ability to easily calculate tidal volumes, pressures, forces, and the widespread use of pistons in other industries. O-ring seals and cam follower systems have well-defined equations for design and their performance can be easily tailored to specific applications. The system performance for the offset rod and crank are detailed below



The system has a 1:2 inspiration to expiration ratio. At this stroke length 493cc of air are available.

Testing:

- Tested only at 18 RPM
- 375cc tidal volume at 20 cm of H2O with exhalation valve open at all times set to 10 cm of H2O

Bill of Materials:

Item	Quantity	Cost each	Total cost	Vendor	Vendor Minimum Quantity	Vendor price
VersaPlanetary Gearbox set	1	$89.95	$89.95	Vex Robotics	1	$89.95
Vex 775pro motor	1	$19.95	$19.95	Vex Robotics	1	$19.95
6082Z 8 x 22 x 7 mm Bearing	8	$0.60	$5.99	Amazon	10	$5.99
1/4-20 x 1.5" SHCS	6	$0.24	$1.41	McMaster-Carr	50	$11.78

1/4 washer	6	$0.03	$0.21	McMaster-Carr	100	$3.47
1/4 lock washer	6	$0.03	$0.15	McMaster-Carr	100	$2.56
1/4-20 nylock nut	6	$0.04	$0.26	McMaster-Carr	100	$4.39
6-32 x 0.75" SHCS	28	$0.05	$1.51	McMaster-Carr	100	$5.38
6-32 x 0.375" SHCS	4	$0.04	$0.17	McMaster-Carr	100	$4.24
8-32 x 3.0" SHCS	2	$0.77	$1.54	McMaster-Carr	10	$7.70
6-32 nylock nut	28	$0.03	$0.76	McMaster-Carr	100	$2.72
6 washer	32	$0.01	$0.38	McMaster-Carr	100	$1.20
6 lock washer	28	$0.01	$0.20	McMaster-Carr	100	$0.71
10-32 x 0.5" SHCS	4	$0.08	$0.32	McMaster-Carr	100	$8.10
10 washer	4	$0.02	$0.10	McMaster-Carr	100	$2.40
10 lock washer	4	$0.01	$0.05	McMaster-Carr	100	$1.24
5/16"-18 x 1.125" BHCS	8	$0.38	$3.04	McMaster-Carr	25	$9.50
5/16"-18 Nylock nut	8	$0.06	$0.51	McMaster-Carr	100	$6.43
O-ring-357	1	$1.25	$1.25	McMaster-Carr	5	$6.25
Silicone Rubber Sheet, for valves 0.020" Thick, 20A Durometer	4	$0.39	$1.58	McMaster-Carr	6" x 6"	$14.20
Spool of Plastic Filament ABS or PLA	1	$30.00	$30.00	Amazon	1	$30.00
1/8" aluminum	18"x32"	$33.00	$33.00	Royal metals	32 sq ft	330

360W Switching DC Power Supply with Cooling Fan, Vin=120VAC, Vout=12V@30A +/-15%, UL Listed. Meanwell, #3251-12V or Equivalent	1	44.99	$44.99	Amazon	1	$44.99
#14 AWG, Stranded, Annealed, Tinned, CU,Type MTW/TEW, Red, 105-Deg C, 300V. Powerwerx, #WIRE-ST-02 or Equivalent	2	0.31	$0.62	Powerwerx	Per/Ft	$0.62
#14 AWG, Stranded, Annealed, Tinned, CU, Type MTW/TEW, Black, 105-Deg C, 300V. Powerwerx, #WIRE-ST-02 or Equivalent	2	0.31	$0.62	Powerwerx	Per/Ft	$0.62
PP30, Red Colored Housing. Powerwerx, #1327 or Equivalent	1	0.37	$0.37	Powerwerx	1	$0.37
PP30, Black Colored Housing. Powerwerx, #1327-G6 or Equivalent	1	0.37	$0.37	Powerwerx	1	$0.37

PP30, 30A Powerpole Contact. Powerwerx, #1331 or Equivalent	2	0.18	$0.36	Powerwerx	1	$0.36
#14 AWG, Fork/Spade Crimp Connector. Gardner Bender, #15-114 or Equivalent	2	2.6	$0.18	Home Depot	15 Pack	$2.60
#14 AWG, Insulated Female Crimp Connector. Utilitech, #15-151P-UT or Equivalent	4	4.58	$1.53	Lowes	12 Pack	$4.58
Panel Mount Fuse Holder, Type AGC/MDA, 15A Rated. Bussmann, #BP/HKP-HH or Equivalent	1	5.6	$5.60	City Mill	1	$5.60
10A, Type MDA, 250VAC@IR200A, 125VAC@IR10kA, Ceramic, Slow Blow Time Delay Fuse. Bussmann, #MDA-10 or Equivalent	1	5.9	$5.90	City Mill	1	$5.90
Single Pole Panel Mount Switch, 15A Rated. Rev Robotics, #REV-31-1387 or Equivalent	1	6	$6.00	Rev Robotics	1	$6.00

1/4" Split Plastic Wire Loom. Standard Ignition, #CL4S or Equivalent	1	0.49	$0.49	O'Reilly Autoparts	Per/Ft	$0.49
Zip Tie, Plastic, 4". Utilitech, #SGY-CT2 or Equivalent	6	4.98	$0.30	Lowes	100 Pack	$4.98
		Total cost per unit	$259.67		Cost at minimum purchase quantities	$645.64

Robert G.M. Izuta, Principal Investigator Biography:

Mr. Izuta is currently pursuing a Master's of Science in Integrated Design, Business and Technology at the Iovine and Young Academy at the University of Southern California. He received his B.S. in Mechanical Engineering from California Polytechnic State University-San Luis Obispo (Cal Poly SLO). He serves as a Design Technology Advisor for Punahou School in Honolulu, Hawaii. He manages the school's advanced manufacturing and design lab, develops STEAM curriculum, lectures, and mentors FIRST Robotics teams. Prior to Punahou Mr. Izuta worked as a mechanical engineer at Oceanit Laboratories where he served as a team member on numerous rapid development R&D efforts. Projects include SBIR or similar type efforts. Mr. Izuta continues to work on SBIR works as a contractor via his consulting business Izuta Design Engineering & Associates for businesses in Hawaii. Mr. Izuta's skills and expertise are in the areas of CAD, finite-element analysis, rapid-prototyping, CNC manufacturing, experimental analysis, design thinking, and teaching/training.

Ivan H. Uemoto, Electrical Designer Biography:

Over twenty years of Electrical, Electronic and Network System Engineering, Design, Installation, Construction, and Inspection. Mr. Uemoto is a graduate of DeVry Institute of Technology and is a Licensed Journeyman Electrician in the State of Hawaii. Mr. Uemoto has held key engineering and design roles with the following companies:

Silicon Graphics, Inc., Mountain View, CA – Member of Technical Staff
Intel Corporation, Hillsboro, OR – Hardware Design Engineer
Nvidia Corporation, Beaverton, OR – Hardware Design Engineer
Intersil Corporation, Hillsboro, OR – Field Applications Engineer
MK Engineers, Ltd., Honolulu, HI – Electrical Designer
Verizon Federal Networks, Mililani, HI – Network Design Engineer III
City and County of Honolulu, Dept. of ENV – Electrician, Electronics Technician, and Inspector

Appendix:

Comparison of Standard Pipe Sizes for Stroke Length Versus Tidal Volume:

3 inch ABS Pipe		**4 inch ABS Pipe**		**6 inch ABS Pipe**	
Stroke Length (inches)	**Volume (cc)**	**Stroke Length (inches)**	**Volume (cc)**	**Stroke Length (inches)**	**Volume (cc)**
1	115.83	1	205.93	1	463.33
2	231.66	2	411.86	2	926.66
3	347.49	3	617.79	3	1389.99
4	463.32	4	823.72	4	1853.32
5	579.15	5	1029.65	5	2316.65
6	694.98	6	1235.58	6	2779.98
7	810.81	7	1441.51	7	3243.31
8	926.64	8	1647.44	8	3706.64
9	1042.47	9	1853.37	9	4169.97
10	1158.3	10	2059.3	10	4633.3
11	1274.13	11	2265.23	11	5096.63
12	1389.96	12	2471.16	12	5559.96
13	1505.79	13	2677.09	13	6023.29
14	1621.62	14	2883.02	14	6486.62

Yellow highlighted values fall within target specified tidal volumes. Orange highlighted values are just outside the target range of the specifications but may be of interest in certain operating scenarios.

Volume Data Table for Two Inch Cam Displacement with 6 Inch Diameter Piston:

Time (s)	**Angle**	**Displacement**	**Volume (cc)**
0	0	0	0.00
0.1667	15	0.0972	45.04
0.3334	30	0.3333	154.43
0.5001	45	0.6667	308.91
0.6668	60	1	463.33
0.8335	75	1.3333	617.76
1.0002	90	1.6667	772.24
1.1669	105	2	926.67
1.3336	120	1.8667	864.91
1.5003	135	1.7333	803.10
1.667	150	1.6	741.33
1.8337	165	1.4667	679.57
2.0004	180	1.3333	617.76
2.1671	195	1.2	556.00
2.3338	210	1.0667	494.24
2.5005	225	0.9333	432.43
2.6672	240	0.8	370.67
2.8339	255	0.6667	308.91
3.0006	270	0.5333	247.10
3.1673	285	0.4	185.33
3.334	300	0.2667	123.57
3.5007	315	0.1333	61.76
3.6674	330	0.0355	16.45
3.8341	345	0	0.00
4.0008	360	0	0.00

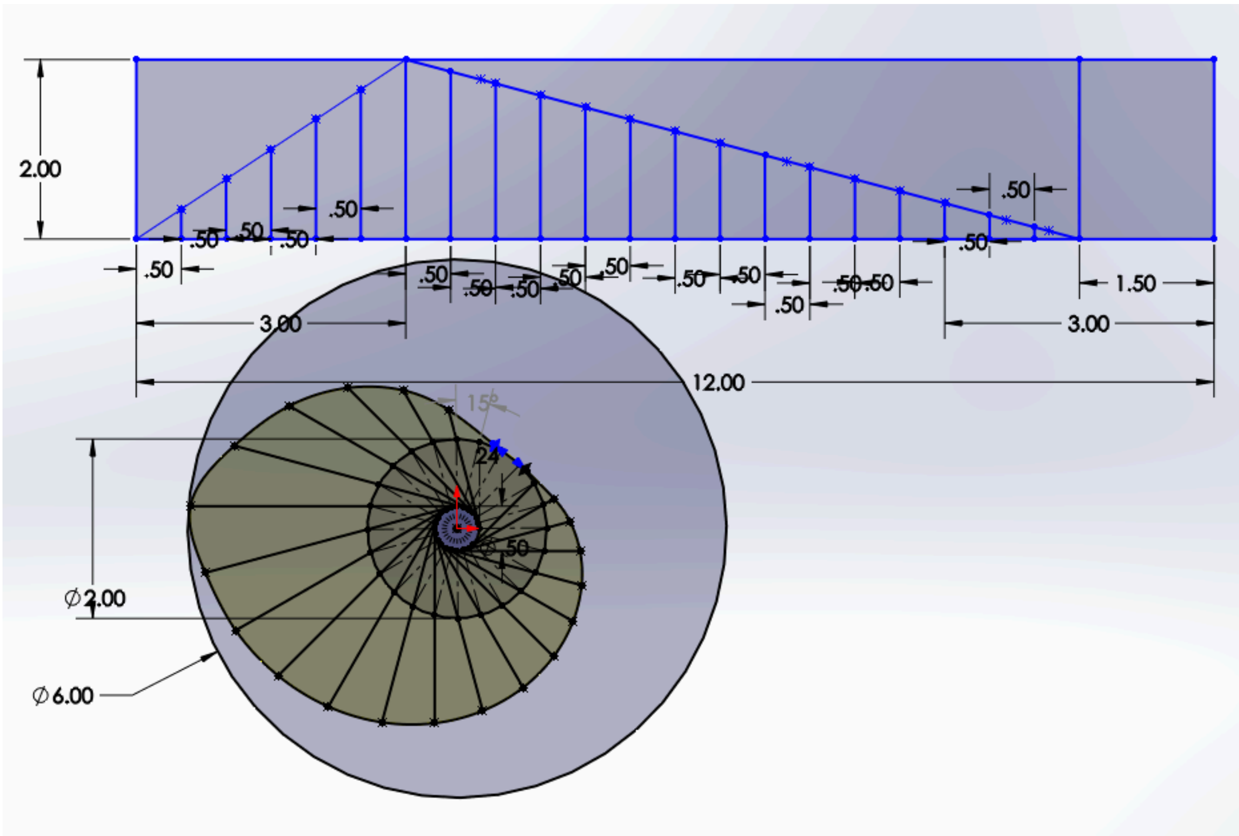
Data Table for Cam Follower Velocity and Acceleration Versus Displacement:

Time (s)	**Angle (Degrees)**	**Displacement (in)**	**Velocity (in/s)**	**Acceleration (in/sec^2)**
0	0	0	0.29	3.317872718
0.1667	15	0.0972	1.00	-0.8044941702
0.3334	30	0.3333	1.71	2.99940012
0.5001	45	0.6667	2.00	0.8735505448
0.6668	60	1	2.00	0
0.8335	75	1.3333	2.00	0.000899640108
1.0002	90	1.6667	2.00	-4.198620384
1.1669	105	2	0.60	-8.397240768
1.3336	120	1.8667	-0.80	-4.198620384
1.5003	135	1.7333	-0.80	0.000899640108
1.667	150	1.6	-0.80	0
1.8337	165	1.4667	-0.80	-0.000899640108
2.0004	180	1.3333	-0.80	0.000899640108
2.1671	195	1.2	-0.80	0
2.3338	210	1.0667	-0.80	-0.000899640108
2.5005	225	0.9333	-0.80	0.000899640108
2.6672	240	0.8	-0.80	0
2.8339	255	0.6667	-0.80	-0.000899640108
3.0006	270	0.5333	-0.80	0.000899640108
3.1673	285	0.4	-0.80	0
3.334	300	0.2667	-0.80	0.3184725982
3.5007	315	0.1333	-0.69	1.200119904
3.6674	330	0.0355	-0.40	1.760595691
3.8341	345	0	-0.11	2.073670449
4.0008	360	0	0.29	3.317872718

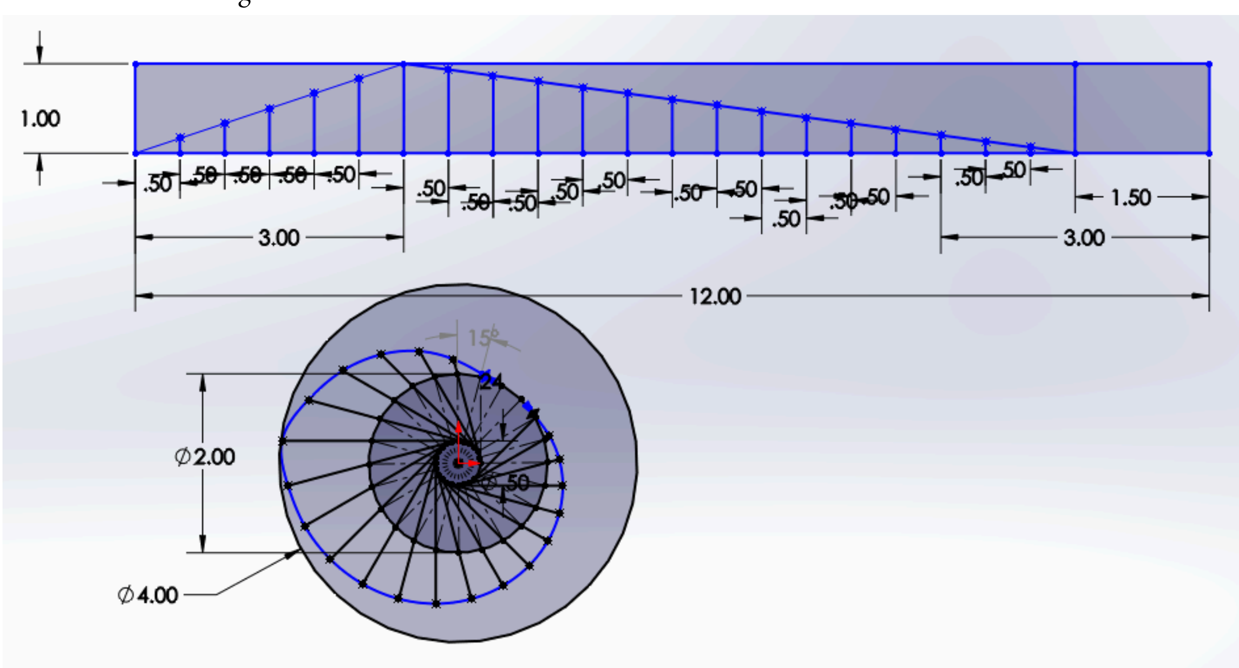
From angle and displacement values determined in CAD, utilized a finite difference method to calculate the average slope at the point of interest for the velocities and accelerations.

Cam Profiles:

2-inch offset cam design:



1-inch offset cam design:



O-ring Design for Dynamic Seal: