Miami University
School of Engineering & Applied Science
Department of Engineering Technology

ENT 498 Senior Design
Final Report

Universal Robot Gripper

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Supporting Companies:
Rimrock Corp

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Statement of Purpose (Executive Summary)

This project will consist of multiple goals and milestones to achieve the desired result of assessing the feasibility of a more universal type of gripper used for material handling in the Rimrock Corporation. A successful project will mean that there is a small-scale functional prototype robot modified with the new gripper that will be used to provide useful data back to Rimrock. There should be usable, measurable test results from a functional prototype. A successful project will not necessarily mean that the prototype demonstrated a performance improvement. This is a Research and Development type project. Meaning that the data and research throughout the project is more useful than the product itself. This project was created by Rimrock to be a learning tool for the future. The prototype will be designed and tested to determine the real-world practicality.

Goals:

1. Pick up spheres from 1”, 2”, 4” diameters
2. Pick up cylinders from 1”, 2”, 4” diameters
3. Pick up rectangle 1”, 2”, 4” width
   (Perform all tests dry and wet)
4. Pick up and place repeatability within 0.125” in all directions (*requires a gauge to be designed and built)
5. Pick a part or simulated part with a torque load of ½ the robot torque. Determine max robot load, perform movement test and measure the function
6. Research and test materials

Milestones:

1. Pick a design direction, finger style, flexible bag style, or other.
2. At the end of the third goal, the team will have gone through several revisions to have a functional gripper.
3. At the end of the 5th goal, the team should be able to demonstrate that the gripper is physically capable of picking up an off-loaded casting with some useful repeatability
4. A small-scale functioning model that can pick up hot parts up to 800°F without losing the performance established in the first milestones.

Full-scale design gripper (Probably not built or tested). Loading specs to the maximum of the ABB 6700 2.85M

If successful, this robot gripper design could be a marketable product for Rimrock as a cost savings gripper because one style gripper can handle various castings. The end goal is to have a gripper that can handle both finished and raw materials. There are many obstacles to overcome to achieve this result. Some of these obstacles are finding materials that can withstand extremely high temperatures, materials that can withstand sharp edges, and a gripper that can pick up wet materials. If not successful, the goal is to know what works, what doesn’t work, and if what doesn’t work can be solved. Future projects could include building and testing a full-scale model to be tested in a foundry industry.

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Scope and Methodology

Supporting Company:
Rimrock Corporation located in Columbus, Ohio is our supporting company. According to Rimrock's website:

> "Rimrock is a premier supplier of automation products and integration services. Founded in 1956 as a manufacturer of automatic lubrication systems, Rimrock has expanded to supply products including ladles, sprayers, extractors, finishing equipment, and turnkey robotic systems. We have expanded our integration capabilities to include the design, manufacture, and installation of ABB, Fanuc, Motoman, and Gudel robot-based systems." (Rimrock 2020)

Justification:
Currently, robots need prepped uniquely for various casting lots. This means downtime that could be anywhere from a couple of hours up to a day of man-hours and lost production opportunity. If there was a way that a robot could be more multi-purposed to handle a larger variety of casting lots, this initial cost would be quickly offset by higher production efficiency.

Rimrock Senior Project Group Decision Matrix

	Budget	Feasibility	Usability	Research	Complexity	Timeline	Rimrock Preference	Totals
Universal Robot Gripper	2	3	4	5	2	3	5	**24**
Body and arm design (longer arm)	5	4	1	2	5	3	4	**24**
Adjustable base	4	4	1	3	4	3	4	**23**
Nozzle test	4	3	3	4	4	2	3	**23**
Small Reciporator	3	2	3	3	3	2	3	**19**
Palletized Robot Assembly Design	1	1	3	4	2	1	1	**13**
Bottom Pour Ladle	3	2	2	1	2	2	2	**14**
Notes (scale 1 to 5):	High number = Lower cost	High number = High feasibility	Low number = Few applicable uses	Low number = Not much to research	Higher Number = Less Complex	Ability to complete within timeframe. High number is good.	High number = Rimrock preference	Larger number = better project selection
Selected Project: Universal Robot Gripper								

Figure 1. Rimrock Senior Design Project Selection Decision Matrix

Figure 1 shows the decision matrix created to select a project. There were several factors considered when selecting our senior design project. Rimrock Corporation is sponsoring our senior project; therefore, Rimrock's preference was a major influence on our project selection. Rimrock wanted to research the 'Universal Robot Gripper' for feasibility in their industrial environment. A universal gripper could be a marketable product for Rimrock if it is feasible for their industrial environment. Completing the project within the set timeframe for Miami University coursework, before the end of ENT 498 and prior to the project presentation, was another major consideration for our project selection. A project was needed that was complex enough to learn and have material to research, but not too complex or broad for the timeframe. Taking all these factors into consideration, 'the universal robot gripper,' and the ‘body and arm design’ were the top selections. We selected the universal robot gripper out of these two selections because meeting our sponsors needs is a high priority. Appendix A lists the project possibilities proposed by Rimrock. The universal gripper is being designed for use with the ABB robot shown in Figure 2 and Figure 3. A proposed gripper type is shown in Figure 4. Figures 5, 6, and 7 show a proposed robot gripper design for this project. This is a preliminary design that could change based upon research and testing as the project progresses.

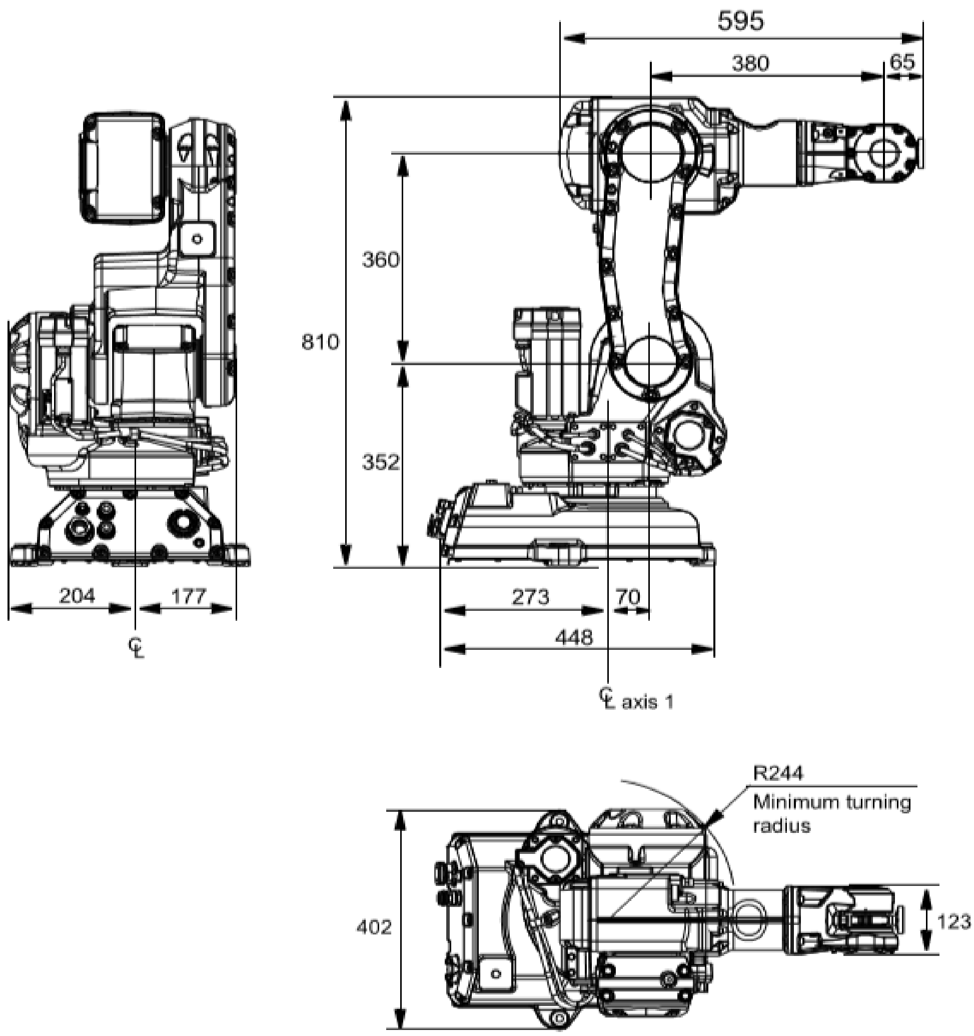


Figure 3 View of the manipulator from the back, side and above (dimensions in mm).

Figure 2. Robot Gripper will be designed for this ABB Robot (IRB 140 M2000)
("IRB 140 data - Industrial Robots (Robotics)”)

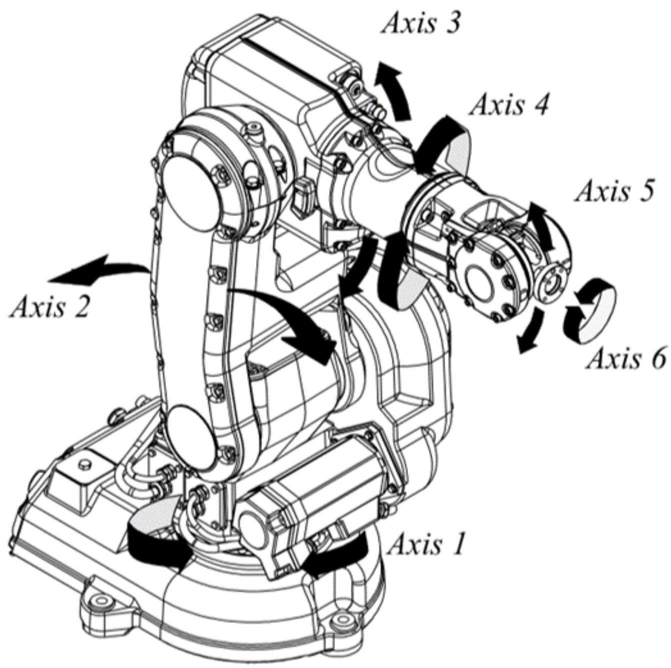


Figure 1 The IRB 140 manipulator has 6 axes.

Figure 3. Robot Gripper will be designed for this ABB Robot
("IRB 140 data - Industrial Robots (Robotics)")

Figure 4. Gripper Design – Item being held by gripper (Ju 2010)

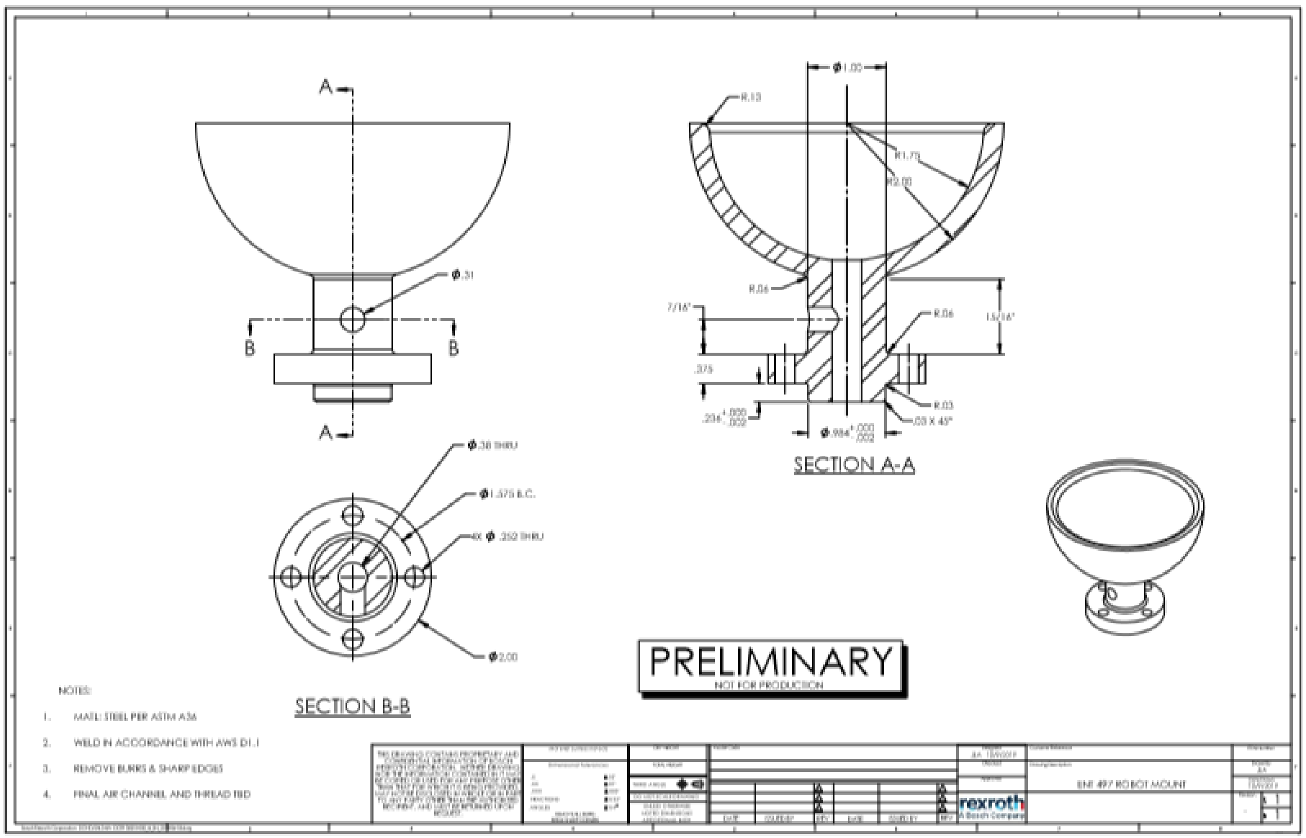


Figure 5. Robot Mount Preliminary Design

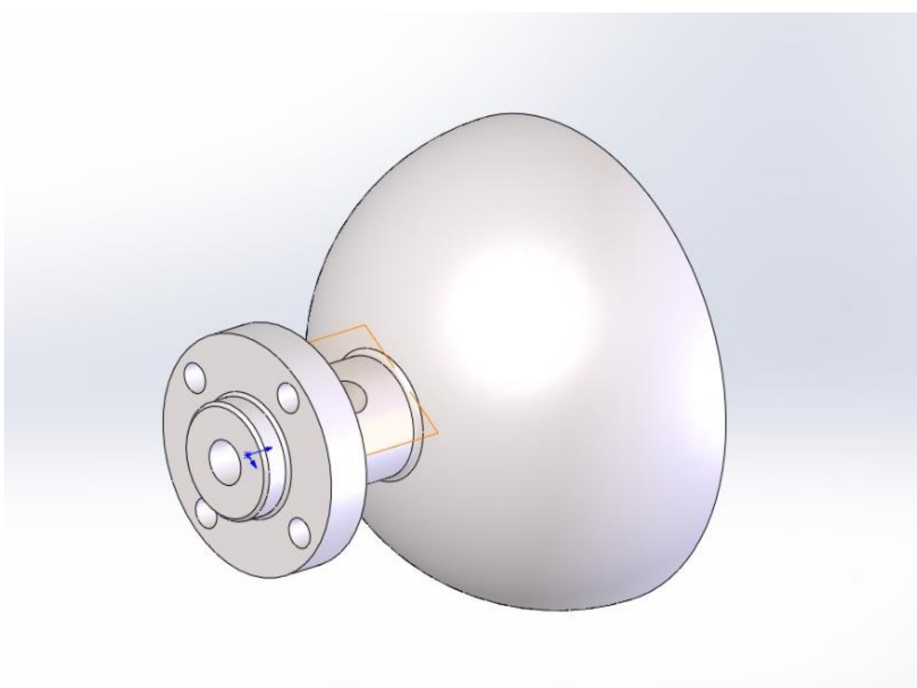


Figure 6. Robot Gripper Solid Model – View 1

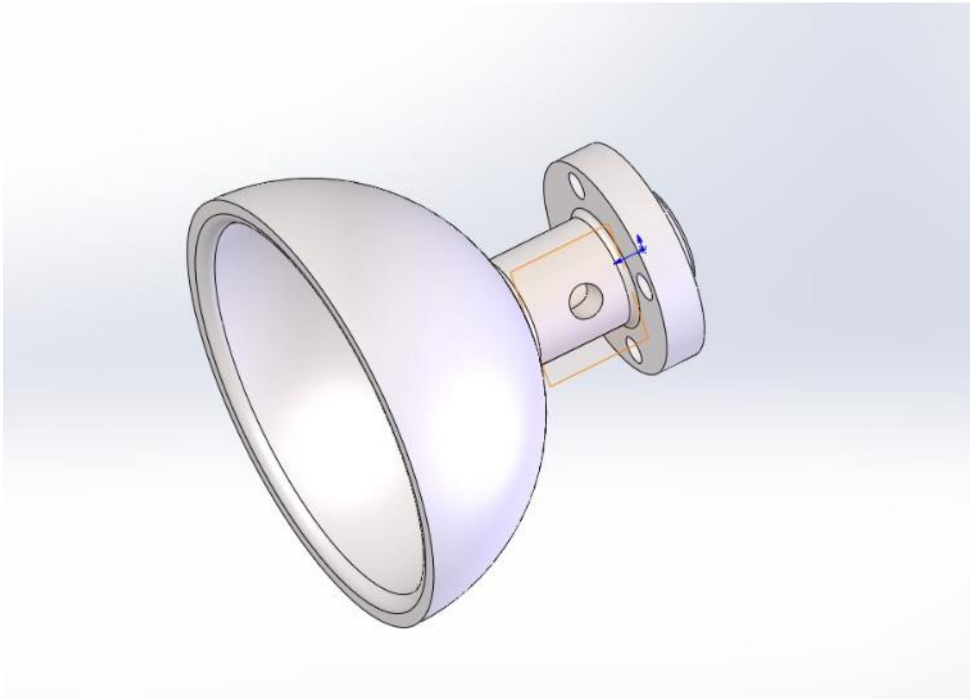


Figure 7. Robot Gripper Solid Model – View 2

Step-By-Step Plan:

1. Journal Entries – Team to record weekly progress during Senior Design project with weekly journals, and journal entries for any special meeting such as assembly, testing, or troubleshooting with the balloon gripper.
2. Identify Project – Project identification involved securing Rimrock as our sponsor, researching for back-up project ideas in the event Rimrock did not agree to sponsorship, getting a list of projects from Rimrock.
3. Matrix for Project Selection – A decision matrix was used to determine which project to select out of the list provided by Rimrock. Important characteristics to Rimrock, class requirements for Miami, and our abilities were factors considered with our decision matrix.
4. Defining Deliverables – We met with our contact points at Rimrock, which are two members of their Research and Development team. The universal gripper project was discussed, desired deliverables from Rimrock, and additional objectives to explore if time allowed.
5. Defining Budget – A budget was defined with Rimrock. Being our sponsor, it was important that we were on the same page for deliverables and cost. It was determined Rimrock has a robot for the design project team to use, and budget needs were discussed.
6. Project Proposal – The project proposal is a Miami required document which follows a process like an external project as well. Before funding, additional research, and so forth the project must first be proposed, evaluated for feasibility, and ensure a positive direction could occur.
7. Obtain information for robot – Rimrock provided the product specification manual for the robot the senior design group will be using for the universal gripper project.

8. Gripper Design Research – The team will research which design of universal gripper would be best for this project. Research regarding present styles such as balloon or finger gripper will be conducted. Rimrock's usability is a major factor in the consideration.
9. Matrix for gripper design selection – A decision matrix with appropriate considerations will be created to determine the gripper design the group will proceed to design.
10. Research Materials for gripper style, gripper materials, gripper fill (if needed) – Materials that can withstand extremely high temperatures, resist tear, appropriate friction to hold materials even when the materials are hot, wet, and rough within tolerances.
11. Matrix for Gripper Materials – Create a design matrix to determine appropriate material considerations and select best material for this application.
12. Design mounting for gripper to robot – Design the connection between the gripper to the ABB robot. This will likely be 3D printed.
13. Design gripper – Design the gripper style for the ABB robot end effector.
14. Create Bill of Materials – Create a bill of materials with cost of items. This will help ensure the project is on budget and be used for record if this gripper is to be built again.
15. Samples for smaller castings (raw and finished) – Obtain sample castings to use for testing of gripper design.
16. ENT 497 Oral Presentation (Due Dec 5) – Prepare and present oral presentation
17. ENT 497 Final Report (Due Dec 12) – Prepare and submit final report and supporting documentation
18. Torque Equations – Complete torque equations to determine range and limitations of robot gripper.
19. Obtain Material Samples for Gripper – Contact companies for samples of material based from research conducted.
20. Obtain misc. materials – Obtain any other materials needed for robot gripper
21. 3D print materials – 3D print gripper to robot mounting and any other items that require 3D printing.
22. Build working scale model – Build a working scale model for testing based upon research and design during this project.
23. Test scale model – Test the scale model by trying to pick up the smaller castings.
24. Troubleshooting – Figure out what worked well, what doesn't work well, and what can be done to improve gripper.
25. Additional research and redesign – Research the areas of improvement that needs explored.
26. Adjust design and rebuild working scale model – Again, based from the first test and troubleshooting results, considerations for improvement and rebuilding.
27. ENT 498 Final Report – Complete ENT 498 final report.
28. ENT 498 Final Presentation – Complete ENT 498 final presentation.

Gantt Chart:
Rimrock's design group has tasks planned to meet the project needs within the timeframe according the Gantt chart. See figure 8 for additional information. A larger version of figure 8 is in Appendix B. Data used to create the Gantt chart is in Appendix C. This Gantt chart has been modified for increased research, design, and material gathering timeframes. Updates will be made accordingly when building and testing occurs.

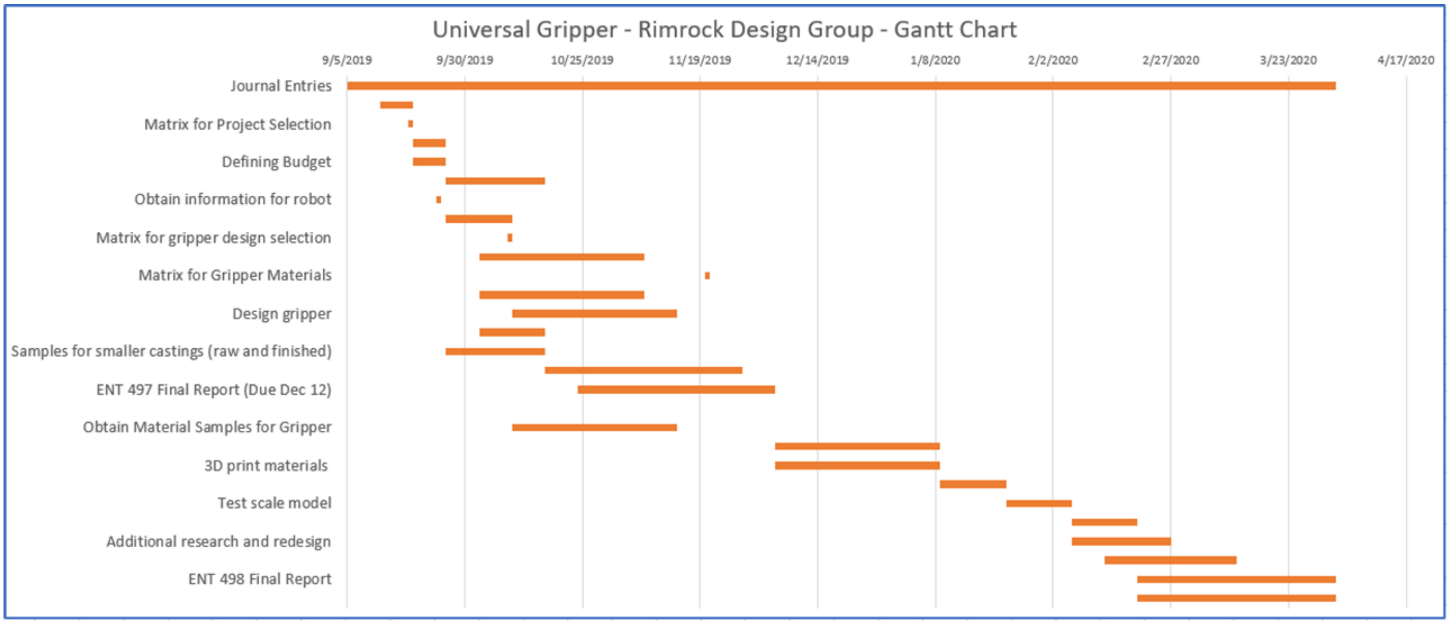


Figure 8. Gantt Chart

Cost:
The estimated cost for the robot gripper is shown in figure 9. These costs are subject to change as research is conducted and designs modified. Possible additional costs are gripper fill material and adhesive to join the fabric for the balloon to the piece that connects the gripper to the end of the ABB robot. Figure 10 shows an updated Bill of Material reflecting updated costs and costs of filler material and fabric.

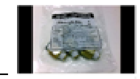
Part Number	Qty	Details	Site	Cost	Picture
9687283011	1	Vacuum Pump, DC 24V Mini Vacuum Pump Water Air Gas Vacuum Pump -85KPa Flow 40L/min Oil-Less Vacuum Pump, Mini Air Pump Motor	Amazon Prime	$ 42.39	
KQ2H12-02S - PACK OF 5	1	Smc Kq2h12-02S - Pack Of 5 - Pneumatic Fitting 12Mm Kq2h12-02S - Pack Of 5 -	Amazon Prime	$ 8.80	
D508759-TU 1208B	1	SMC TU 1208B 8MM ID 12MM OD 90FT Polyurethane TUBING D508759	Amazon Prime	$ 130.70	
CF0070	Per litter Yard	ARMATEX QF 70 402	Mid-Mountian Material	$ 138.75	
CF0079	Per litter Yard	ARMATEX SBQF 100 402	Mid-Mountian Material	$ 182.75	
CF0244	Per litter Yard	ARMATEX SBKG 21.5 502	Mid-Mountian Material	$ 139.75	
			Total	$ 643.14	

Figure 9. Robot Gripper Estimated Cost

Part Number	Qty	Details	Site	Cost	Picture
9687283011	1	Vacuum Pump, DC 24V Mini Vacuum Pump Water Air Gas Vacuum Pump -85KPa Flow 40L/min Oil-Less Vacuum Pump, Mini Air Pump Motor	Amazon Prime	$ 42.39	
KQ2H12-02S - PACK OF 5 -	1	Smc Kq2h12-02S - Pack Of 5 - Pneumatic Fitting 12Mm Kq2h12-02S - Pack Of 5 -	Amazon Prime	$ 8.80	
D508759-TU 1208B	1	SMC TU 1208B 8MM ID 12MM OD 90FT Polyurethane TUBING D508759	Amazon Prime	$130.70	
CF0070	Per litter Yard	ARMATEX QF 70 402	Mid-Mountian Materials	$138.75	
CF0079	Per litter Yard	ARMATEX SBQF 100 402	Mid-Mountian Materials	$182.75	
CF0244	Per litter Yard	ARMATEX SBKG 21.5 502	Mid-Mountian Materials	$139.75	
	1	coffee grounds	Amazon Prime	$ 7.98	
	1	sand	Amazon Prime	$ 22.99	
	1	bead pellets	Amazon Prime		
	1	borax powder	Amazon Prime	$ 26.50	
	1	silme	Amazon Prime	$ 15.47	
154403	1	silicone sand	lowes	$ 9.10	
	1	foam pellets	Amazon Prime	$ 18.98	
	1	wood shavings	Amazon Prime	$ 27.95	
	1	water	Walmart	$ 8.44	
	1	crumb rubber	Amazon Prime	$ 79.99	
	1	vegetable oil	Amazon Prime	$ 2.48	

Figure 10. Updated Bill of Material

Figure 10 shows costs of materials that were researched in figure 11 and figure 13. The gripper fill material was categorized by rating temperature resistance, ability to withstand pressure, formability of the material, moisture resistance of the material, and electrically non-conductive. The higher the total the better the material should be for this project. As it can be seen in figure 11, bead pellets ("Zirconia" 2019) or sand ("Sand" 2018) is the best material for the gripper filler material. These materials are pictured in figure 12. These filler materials will conform around the castings and will grip to the casting after a vacuum is applied. Figure 13 shows the categories considered for the fabric that will be best suited for the gripper. The material was categorized by flexibility, puncture resistance, temperature rating, formability, thickness, friction, and moisture resistance. All these factors were considered because fabric is needed that can withstand temperatures of at least 800-degree-Farenheit, that can grip onto objects, and that resistant tearing from burred castings. Again, the higher the total the better the material should be for this project. As it can be seen in Figure 13, McAllister MM2220-S Alumina Fabric ("High Temperature Resistant Fabrics" 2019) is the best option from those researched ("Fabrics" 2019). McAllister Alumina fabric is pictured in figure 14. Our team also preferred the Mid-Mountain SS 40 silicone coated silica because it seemed that this material could grip objects better than the other options. This material has the required temperature resistance. The Mid-Mountain coated silica fabric is pictured in figure 15.

Gripper Fill Material Decision Matrix

	Temperature Resistance	Pressure	Formability	Moisture	Electrically Non-conductive	**Totals**
Coffee Grounds	4	4	5	1	4	**18**
Sand	5	5	5	3	4	**22**
Bead pellets	4	4	4	5	5	**22**
Borax Powder	5	4	5	1	5	**20**
Slime	2	3	5	3	3	**16**
Silicon Sand	3	4	5	3	4	**19**
Foam pellets	2	4	5	3	3	**17**
Wood shavings	3	3	2	3	5	**16**
Water (Non-distilled)	1	5	4	5	2	**17**
Crumb Rubber	2	3	4	4	4	**17**
Vegetable Oil	2	3	4	3	3	**15**
Notes (scale 1 to 5):	High number = able to withstand 800 degree F or higher	Higher Number = Can withstand pressure	High number = material can be easily formed and reformed	Higher number = moisture will not damage material integerity	High number = material is non-conductive	Larger number = better material selection
Optimal Filler Material: Bead pellets or Sand						

Figure 11. Gripper Fill Material

Figure 12. Bead Pellets (Zirconia 2020) and Sand (Martin 2018)

Gripper Material Decision Matrix

	Flexibility	Puncture Resistance	Temperature Rating	Formability	Thickness	Friction	Moisture Resistance	Totals
McAllister Mills 1800F Cloth Reflective	2	2	5	3	2	3	3	**20**
DuPont Kevlar XP S300	1	5	1	1	3	1	1	**13**
DuPont Kevlar XP S103	1	5	1	1	3	1	1	**13**
Premlene GCP Commerical Grade Neoprene Rubber Sheet	2	2	2	2	4	4	3	**19**
GLT Products Refractory Silica Fabric	2	3	5	2	3	3	3	**21**
Mid-Mountain Materials Armatex SF 45 Silicone Coated Fiberglass	1	2	3	2	3	3	3	**17**
Mid-Mountain Materials Siltex 36-UH Amorphous Silica Cloth	3	2	5	3	4	4	4	**25**
Mid-Mountain Materials Siltex 70-UH Amorphous Silica Cloth	3	3	5	4	4	4	4	**27**
Mid-Mountain Materials Armatex SS 40 Silicone Coated Silica	4	2	4	4	3	5	4	**26**
McAllister Mills MM36-88-36 Silica Fabric	3	3	5	4	3	4	4	**26**
McAllister MM2220-S Alumina Fabric	5	4	5	4	4	4	4	**30**
McAllister MM3025 Alumina Fabric	5	4	5	4	4	4	3	**29**
McAllister Mills MM50MTS Maxsil-Tex Silica Fabric	4	4	5	3	4	2	2	**24**
Notes (scale 1 to 5):	High number = High flexibility	High number = high puncture resistance	High number = Able to withstand temp of 800 degree F	Higher Number = More likely to form easily with pressure	Too thick or too thin = low number	Higher number = more likely to hold/grip onto item	High number = Material can get wet and/or should not absorb water	Larger number = better material selection
Optimal Gripper Material: McAllister MM2220-S Alumina Fabric								

Figure 13. Gripper Material Decision Matrix

Figure 14. McAllister Alumina Fabric (Alumina Fabrics 2019)

Figure 15. Mid-Mountain Coated Silica Fabric (Fabrics 2019)

Code of Ethics:

It is of the utmost importance that the Engineering Code of Ethics are followed. Portions of the Engineering Code of Ethics that relate to the Universal Robot Gripper are 4a and 4b, which states the following:

> "4. Engineers shall not disclose, without consent, confidential information concerning the business affairs or technical processes of any present or former client or employer, or public body on which they serve.
>
> > a. Engineers shall not, without the consent of all interested parties, promote or arrange for new employment or practice in connection with a specific project for which the engineer has gained particular and specialized knowledge.
> >
> > b. Engineers shall not, without the consent of all interested parties, participate in or represent an adversary interest in connection with a specific project or proceeding in which the engineer has gained particular specialized knowledge on behalf of a former client or employer." ("Code of Ethics")

4a and 4b above relate to the Universal Robot Gripper project. It is important that all team members of the project do not disclose information or findings without having consent from the other team members and our sponsoring company, Rimrock. All team members should not give this project information to any Rimrock competitors.

Another portion of the code of ethics that pertains to this project is “hold paramount the safety, health, and welfare of the public” ("Ethics"). A primary material consideration was safety if the filler material was inadvertently released. It is important that the filler material does not cause harm to the material it picks up and most importantly to the operators, maintenance personnel, or any other people.

Design Progression:

The design progressed as research continued and during testing. Figure 16 is a SolidWorks 3D model of the gripper without the filled balloon mounted to the ABB robot. Figure 17 is the SolidWorks model of the gripper when the two sections are held together by bolts. Figure 18 is a SolidWorks model of the gripper cross section. In Figure 18, how the upper portion and lower portion of the gripper fit together can be seen. The upper and lower portion of the gripper are designed so that the flanges come together. The screws are 35mm in length. ¼” NPT threads are used to connect the compressor. A ring is used to hold the puncture resistant fabric. There are ribs on the outside of the cup to secure the puncture resistant fabric.

The design progression is seen in figures 19 through 22 compared to the preliminary design in figure 5 through figure 7. Some of the design components that remained the same was the bolt pattern to attach the gripper to the robot, and the vacuum pump connections. The final design of the gripper has an upper and lower portion of the gripper and a retaining ring. These modifications are from information gained during research and testing. The upper portion still contains the bolt pattern and vacuum pump connections. The vacuum pump connections now have threading in the design. The lower portion was redesigned to have a balloon will filler material connected over the circle. Next, the puncture resistant material wraps over the filled balloon and is held in place with the retaining ring. The design would be simplified to fewer pieces if this gripper is used for manufacturing purposes.

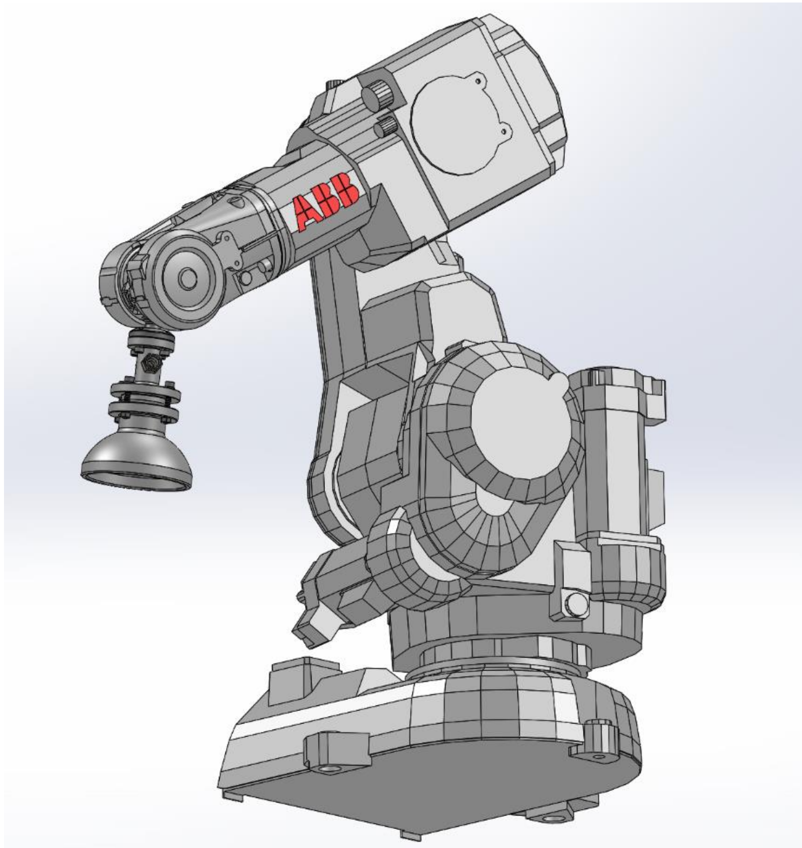


Figure 16. SolidWorks Model of Gripper Mounted to Robot

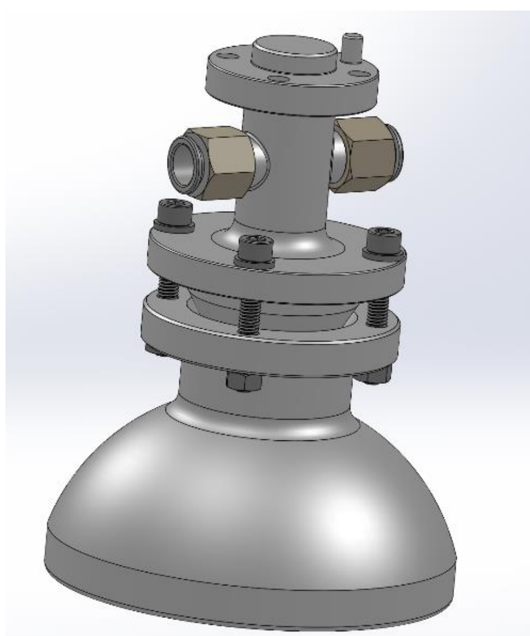


Figure 17. SolidWorks Model of Gripper

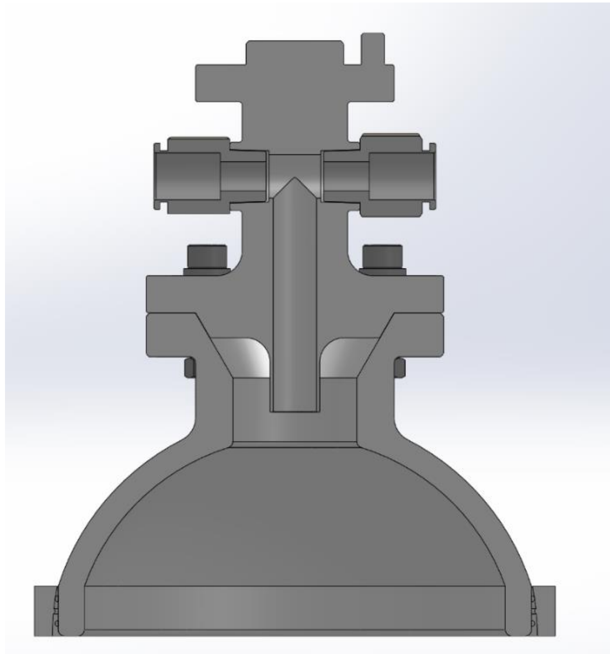


Figure 18. SolidWorks Model Cross Section View

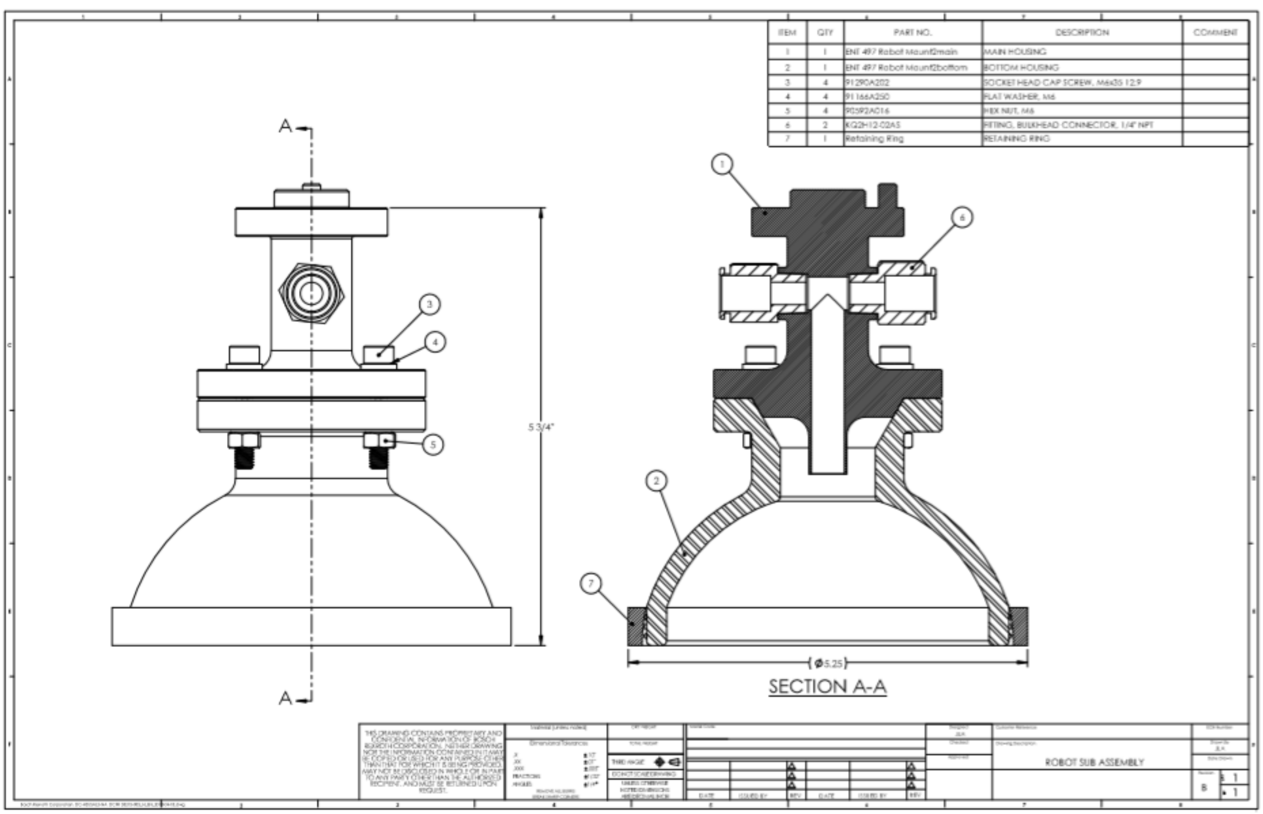


Figure 19. Universal Robot Gripper Sub Assembly

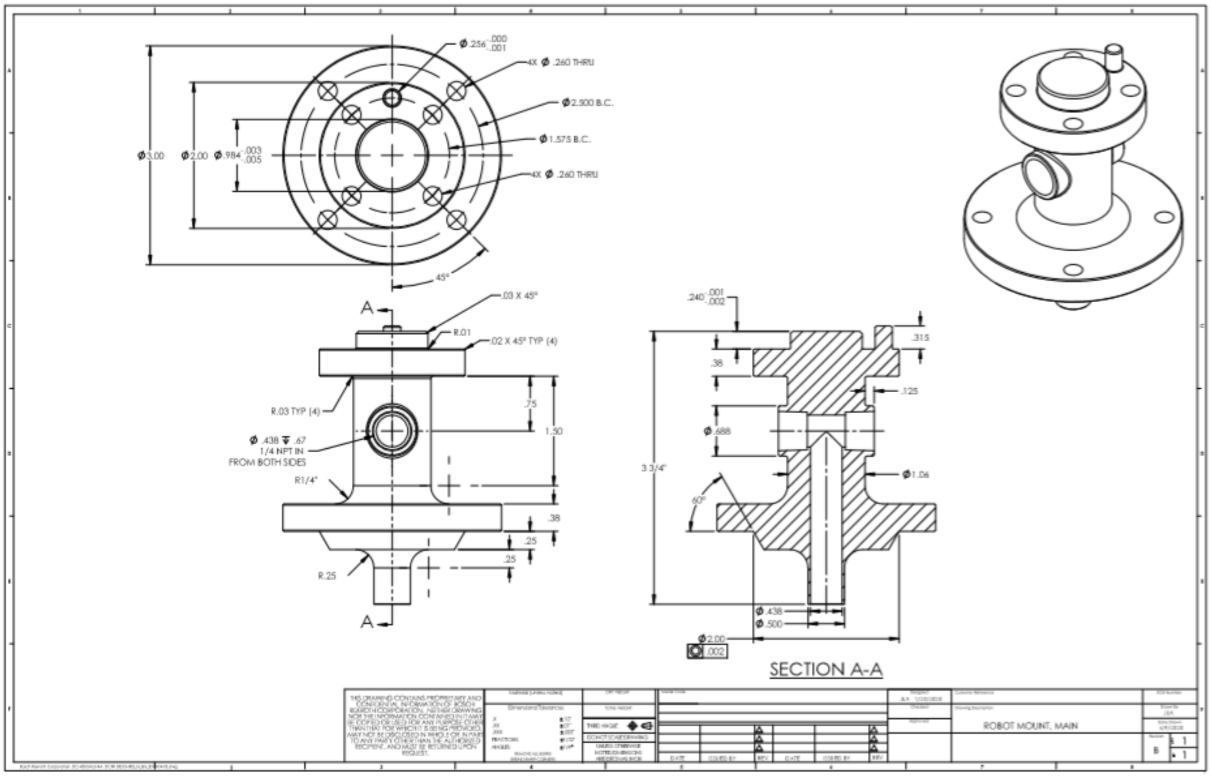


Figure 20. Universal Robot Gripper Upper Portion

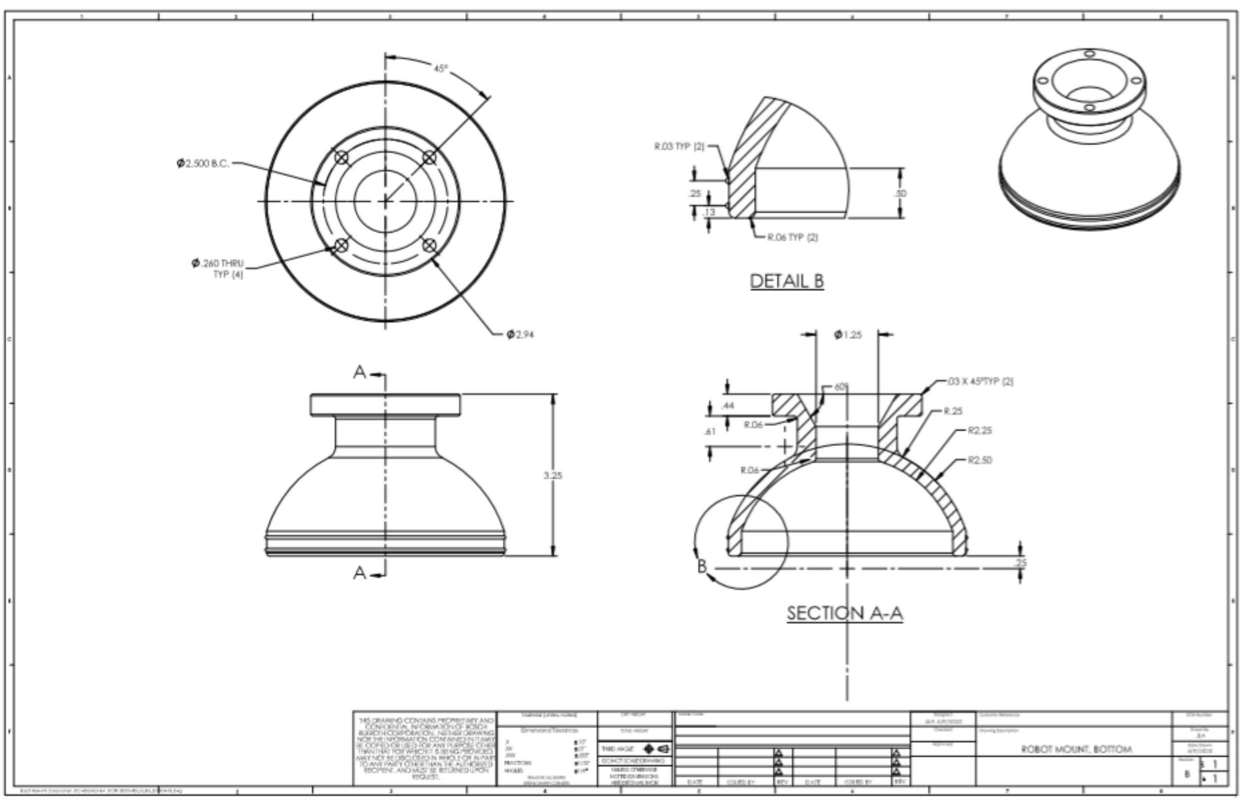


Figure 21. Universal Robot Gripper Lower Portion

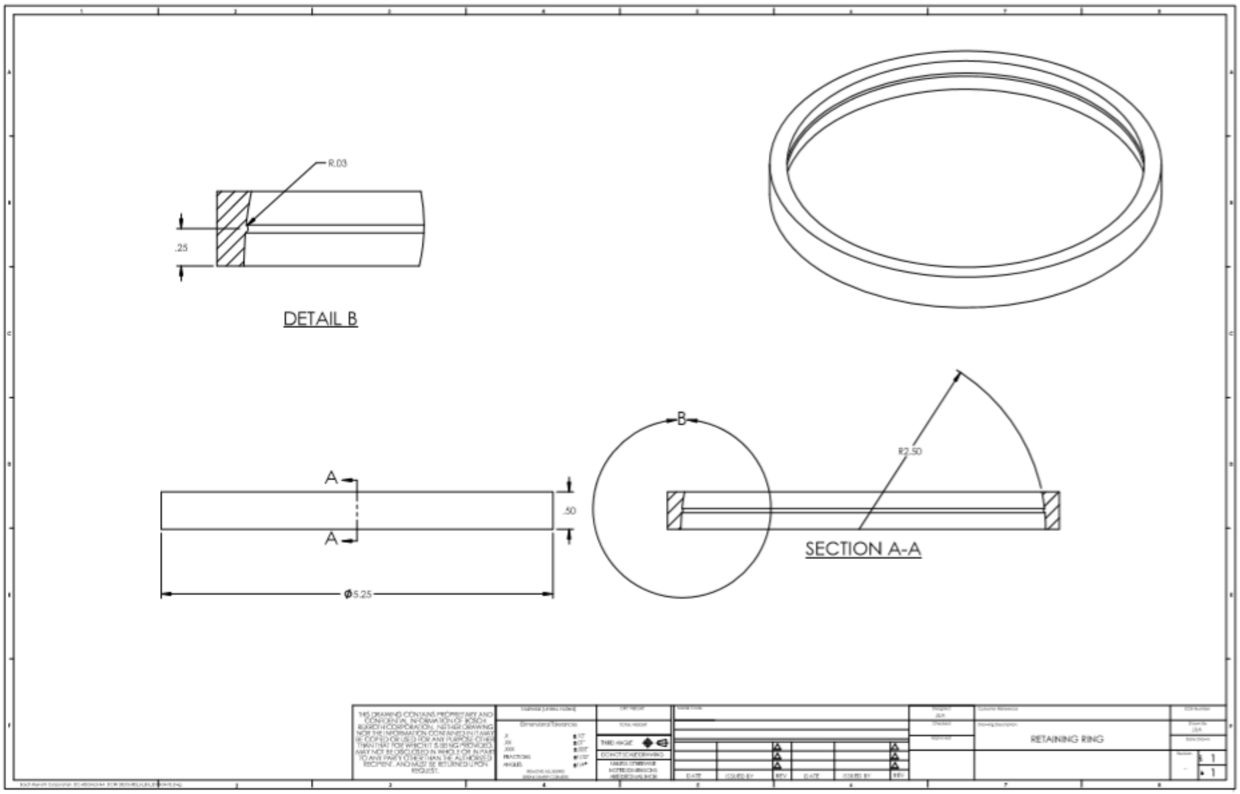


Figure 22. Universal Robot Gripper Retaining Ring

3D-Printed Portions of Gripper:

Figure 23 depicts the upper portion of the gripper after it was 3D-printed. There are bolt holes matching the bolt pattern to attach the gripper to the robot. The holes on the side are for the hoses to create a vacuum of the filler material. This vacuum is what will compress the material around the item to be gripped, which will allow the gripper to pick up the item. To release the item, the vacuum will be released, which will decompress the filler material releasing the grip on the object. Figure 24 shows the upper and lower portion of gripper after it was 3D-printed, and the bolts were added to the upper portion of the gripper. Figure 25 shows the upper and lower 3D-printed sections of the gripper put together. As seen in figure 26, the upper and lower portion of the 3D-printed sections are held together by bolts. Also seen in figure 26, is the 3D-printed ring holding the puncture resistant material over the filled balloon.

Figure 23. 3D-Printed Upper Portion of Gripper

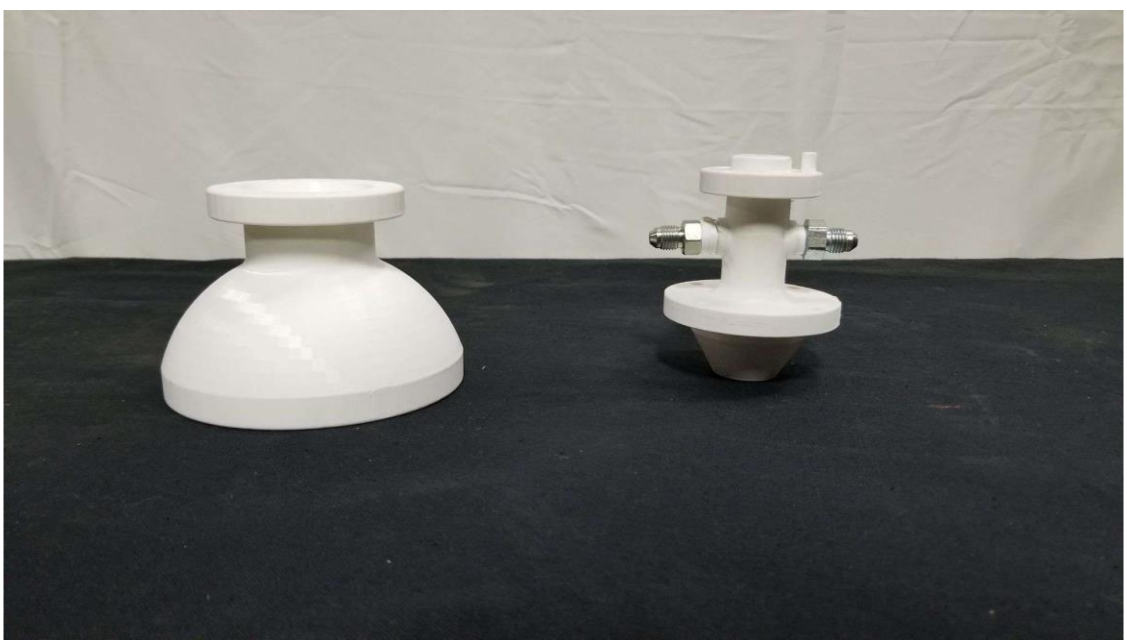


Figure 24. 3D-Printed Gripper in Sections

Figure 25. 3D-Printed Gripper Together

Testing:

It is important to mention that bench testing was used for this project. This is a result of the coronavirus impact. Rimrock was preparing for possible closure and social distancing policies. This limited the time and availability of the robot for testing.

Figure 26 shows the gripper with all items 3D-printed, the balloon filled with coffee grounds, and the puncture resistant material over the filled balloon. The vacuum is located behind the gripper and is shown in figure 29 by itself. Figure 27 shows the vacuum power supply used for bench testing. Figure 28 shows the vacuum gauge and control switch used for bench testing. Figure 30 through figure 32 show the rough castings used for testing of the universal gripper. Figure 33 and figure 34 show the universal robot gripper with the filled balloon and without the puncture resistant material. During bench testing, it was found two check valves are needed. One check valve for each side of the fitting. This allows air in the gripper so the balloon can fill with air so it can form around the part being picked up. The other fitting needs a vacuum, so the part stays in place once gripped. Adding the check valves stops the coffee grounds from filling up the vacuum. A stronger vacuum is suggested for further testing to allow for larger castings to be picked up.

If testing could have been performed directly on the ABB robot, these are the items that could have been tested: pick up spheres that are 1”, 2”, 4” diameters, pick up cylinders from 1”, 2”, 4” diameters, pick up rectangle 1”, 2”, 4” width. These are the fundamental shapes that form most castings. This would help determine if the gripper can function as needed. These tests would be performed with wet and dry castings. Next, testing would include picking up and placing repeatability within 0.125” in all directions. This would require a gauge to be designed and built. It is important that the gripper can pick up and place items with precision and accuracy.

Lastly, testing cloud have included picking a part or simulated part with a torque load of ½ the robot torque. This testing would determine maximum robot load and perform movement test and measure the function. Additional testing includes ensuring the materials can withstand extremely high temperatures of at least 800 degrees Fahrenheit. Sharpness testing would need performed to ensure the material is puncture resistance and that rough castings would not damage the gripper.

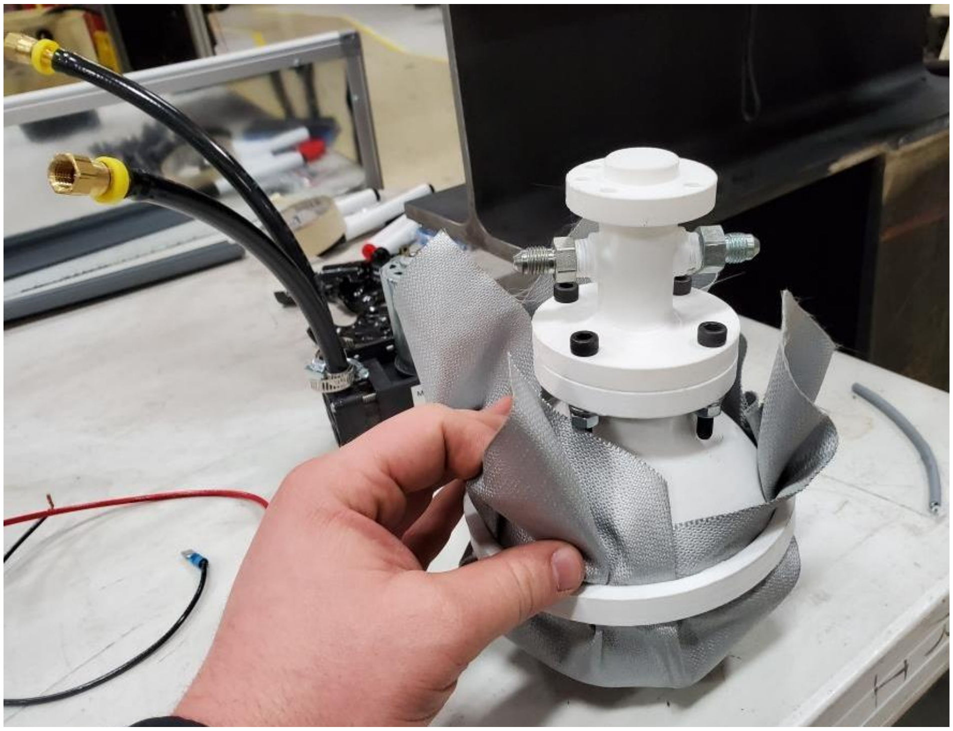


Figure 26. Gripper with Filled Balloon and Puncture Resistant Material – In Testing

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Figure 27. Vacuum Power Supply – For Testing

Figure 28. Vacuum Gauge and Control Switch

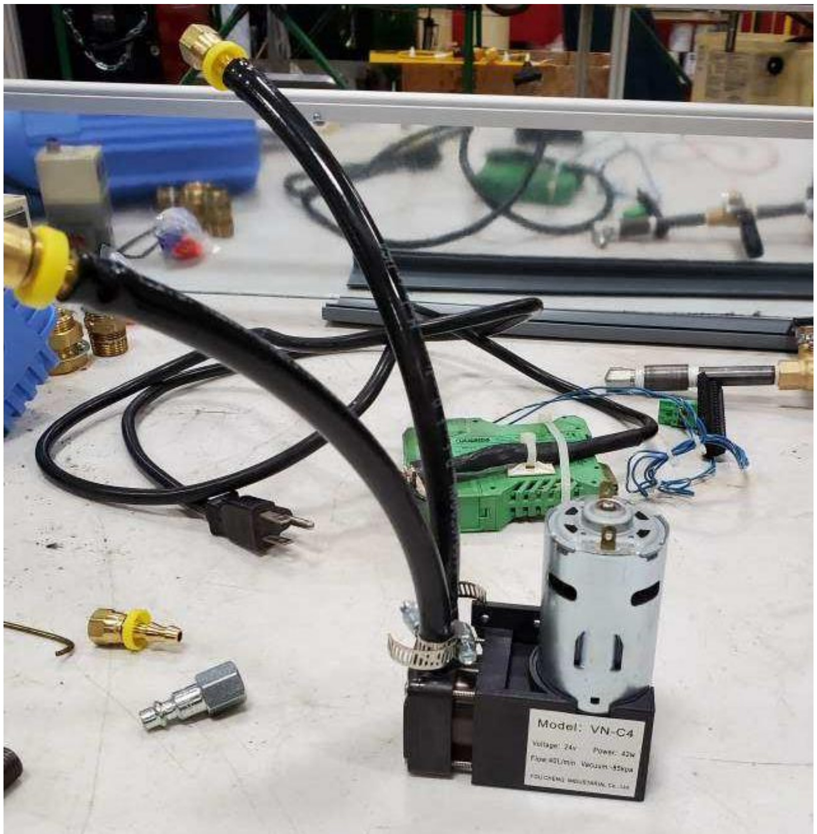

Figure 29. Vacuum Pump

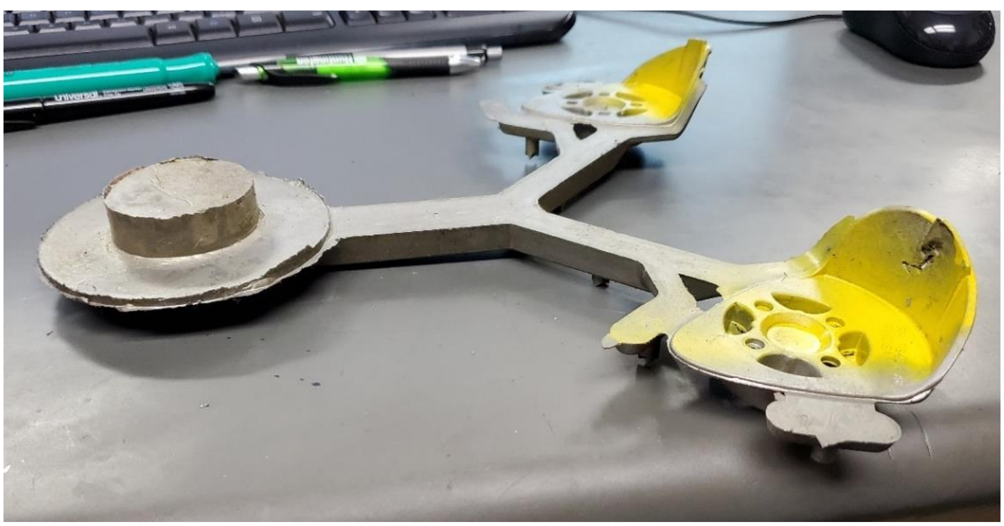

Figure 30. Rough Casting #1 for Testing – View 1

Figure 31. Rough Casting #1 for Testing – View 2


Figure 32. Rough Casting #2 for Testing – Views 1 and 2

Figure 33. Gripper with Filled Balloon View 1

Figure 34. Gripper with Filled Balloon View 2

Expected Findings

Rimrock and the group expects to have a universal robot gripper that can be tested. A material and setup that can withstand the extreme temperatures will likely be a significant hurdle. This is an important project because there are no other studies for this application in an industrial environment. It should be noted, however, that even if the gripper cannot withstand the ultimate test, it may still prove useful up to a certain point. The project will still provide useful data due to what is researched, discovered, and learned throughout the process. In this way, the project is expected to fulfill Rimrock's deliverable goal completely.

The repeatability of the gripper should be enough, assuming the material can withstand the tough environment in which it will operate. There are several variables involved, however. For example, if the material would break down, then it could lose its contents, or the vacuum function could be hindered.

All of this said the group has a high confidence level that this project will be a success and a solution can be achieved for every hurdle. There will be further experiments with materials or liners and certainly some minor revisions to the gripper along the way. Rimrock stated that they are pleased with the groups progress. This is the ultimate good news for our group given that Rimrock is our sponsor company.

Conclusion and Recommendations for Further Study

The advantages of the universal robot gripper are:

- saved equipment downtime to change specialized robotic grippers (end effectors) for each casting
- saved labor costs for changing the robotic ends
- increased efficiency due to reduced downtime and lead time from the manufacturer
- increased environmentally friendly due to less supplies needed for the robotic end

The expected results are to have a balloon style universal type robot gripper that can be used in a foundry environment with close tolerances and high repeatability.

This project could lead to a manufacturable product for Rimrock. The universal robot gripper could save time and money for industrial robotic applications. This savings could lead to resources being available for other aspects in the businesses and/or the savings could be passed to the customer.

For further study, a group can build and test a full-scale model of this universal robot gripper for an industrial foundry application. Further study could also include finishing tests the group was unable to perform due to the coronavirus shutdowns. If testing could have been performed directly on the ABB robot, these are the items that could have been tested: pick up spheres that are 1”, 2”, 4” diameters, pick up cylinders from 1”, 2”, 4” diameters, pick up rectangle 1”, 2”, 4” width. These are the fundamental shapes that form most castings. This would help determine if the gripper can function as needed. These tests would be performed with wet and dry castings. Next, testing would include picking up and placing repeatability within 0.125” in all directions. This would require a gauge to be designed and built. It is important that the gripper can pick up and place items with precision and accuracy. Lastly, testing cloud have included picking a part or simulated part with a torque load of ½ the robot torque. This testing would determine maximum robot load and perform movement test and measure the function. Additional testing includes ensuring the materials can withstand extremely high temperatures of at least 800 degrees Fahrenheit. Sharpness testing would need performed to ensure the material is puncture resistance and that rough castings would not damage the gripper.

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Appendix A: Meeting Journals

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_23_

Meeting Date:_____4/9/20______________ Meeting Time:_5 pm - 7 pm___
Advisor: ______Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung_____________________ Present: [X]

_Chandler Klass_____________________ Present: [X]

_Catherine Dyer_____________________ Present: [X]

Topics discussed:

- Wrap up any items left for this project and course

Action Items (what, who, when):

- Complete self-reflective essays
- Submit PDF copy of report
- Submit link to Presentation
- Submit PowerPoint Presentation

Next meeting (date/time/location): _____N/A – Congratulations Graduates!_____

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_22_

Meeting Date:____4/2/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert___________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass_____________________ Present: [ ]

_Catherine Dyer_____________________ Present: [X]

Topics discussed:

- PowerPoint for Senior Design day is in progress.
- Report changes are being reviewed by team.
- Additional project pictures were sent via e-mail
- We will record our presentation via google meets and post to a YouTube channel as a non-searchable but shareable link.

Action Items (what, who, when):

- Need to schedule a meeting time to do our presentation.

Next meeting (date/time/location): ____4/9/2020, 5 pm – 7 pm, WebEx______

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_21_

Meeting Date:_____3/19/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung______________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Senior Design day is happening! It will likely be a WebEx session. Our team will practice our speech prior so we can time our slider per team member and have smooth transitions between team members.
- Rimrock is busy trying to figure out what to do with shutdowns due to coronavirus; therefore, bench testing is going to happen since there is not time to test on the robot.
- PowerPoint for Senior Design day is in progress.
- Catherine stopped working on the poster for senior design day since the poster is likely to be a soft copy due to remote senior design day.

Action Items (what, who, when):

- Report is in progress. Adding additional information and team is reviewing.
- Next week is spring break.

Next meeting (date/time/location): _____4/2/2020, 5 pm – 7 pm, WebEx______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_20_

Meeting Date:____3/12/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:______Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass_____________________ Present: [ ]

_Catherine Dyer_____________________ Present: [X]

Topics discussed:

- A check valve is ordered and in shipment.
- Chandler is testing of strength of materials (resistance to tearing/punctures from castings) will begin this week.
- PowerPoint for Senior Design day is in progress.
- Poster for Senior Design Day is in progress
- Rimrock representatives are pleased with our progress on this project. Anything that we accomplish past this point they are considering extra. This is the best news for our team!

Action Items (what, who, when):

- Report is in progress. Pictures are added of testing and design so far. Adding additional information and then sending to writing center for review.

Next meeting (date/time/location): ____3/19/2020, 5 pm – 7 pm, WebEx______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_19_

Meeting Date:____3/5/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [ ]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Chandler is testing new design. A check valve is needed and a larger vacuum. Chandler sent pictures and update to the rest of the team.
- Catherine is adding progress information and pictures Chandler sent to the report.
- PowerPoint for our senior day presentation is in progress.

Action Items (what, who, when):

- Chandler is using a program called MiniTab to determine how many cycles the gripper needs to perform to be considered successful or failed. Otherwise, 500 runs will be used as a basis if the program does not meet our needs.
- Testing of redesigned gripper. Need a check valve to keep filler material out of vacuum.

Next meeting (date/time/location): ____3/12/2020, 5 pm – 7 pm, CSCC______

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_18_

Meeting Date:____2/27/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Chandler 3D printed design changes. Chandler put together gripper with filled balloons and materials.
- Catherine is gathering items for senior day poster.
- PowerPoint for our senior day presentation is in progress.

Action Items (what, who, when):

- Chandler is using a program called MiniTab to determine how many cycles the gripper needs to perform to be considered successful or failed. Otherwise, 500 runs will be used as a basis if the program does not meet our needs.
- Testing of redesigned gripper

Next meeting (date/time/location): ____3/5/2020, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_17_

Meeting Date:____2/20/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass_____________________ Present: [X]

_Catherine Dyer_____________________ Present: [X]

Topics discussed:

- Jimmy finished redesigning gripper.
- Chandler 3D printed design changes. Chandler put together gripper with filled balloons and materials.
- Catherine modified report based on writing center comments, and added new information based on progress.
- Senior design project team met at Rimrock and took group pictures. We discussed our progress. Pictures were forwarded to Rob to use for senior day flyer.

Action Items (what, who, when):

- Chandler is using a program called MiniTab to determine how many cycles the gripper needs to perform to be considered successful or failed. Otherwise, 500 runs will be used as a basis if the program does not meet our needs.
- Catherine is gathering items for senior day poster.

Next meeting (date/time/location): ____2/27/2020, 5 pm – 7 pm, CSCC______

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_16_

Meeting Date:____2/13/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass_____________________ Present: [X]

_Catherine Dyer_____________________ Present: [X]

Topics discussed:

- Chandler began testing. There is vacuum, and the 3D printed gripper seems like it will function properly. A larger pump will be needed for a stronger vacuum. Chandler will purchase with Rimrock sponsored funds.
- Testing will continue with temporary connection
- Students will revise project presentation day flyer information and resubmit to Rob
- Senior design project team will meet at Rimrock on 2/14/20 at 12:30 pm


Action Items (what, who, when):

- Jimmy is designing a part to hold the balloon to the gripper
- Chandler will 3D print Jimmy's design
- Chandler is using a program called MiniTab to determine how many cycles the gripper needs to perform to be considered successful or failed. Otherwise, 500 runs will be used as a basis if the program does not meet our needs.
- Catherine is modifying report based on writing center comments and adding new materials/information to report.

Next meeting (date/time/location): ____2/20/2020, 5 pm – 7 pm, CSCC______

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_15_

Meeting Date:____2/6/20______________ Meeting Time:_5 pm - 7 pm___
Advisor:______Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung_____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Chandler finished 3D printing gripper holder, added fill materials to balloon. Top 5 fill materials were purchased and will be tested (coffee grounds, sands, beads, borax)
- Chandler is using a zip tie to temporarily hold balloon to mounting device.
- Jimmy is designing another component to mount balloon to mounting device.
- Chandler will continue putting together the gripper during available work hours.
- Next steps on the project and any possible troubleshooting. For example, Chandler has contacts to have gripper 3D printed with closer tolerances if needed.
- Catherine submitted ENT 497 repot to writing center for comments.

Action Items (what, who, when):

- Testing will begin after gripper is printed and items are put together

Next meeting (date/time/location): _____2/13/2020, 5 pm – 7 pm, CSCC______

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_14_

Meeting Date:____1/30/20_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer_____________________ Present: [X]

Topics discussed:

- Jimmy redesigned gripper and submitted files to Chandler.
- Chandler obtained materials needed to put together gripper. Items were donated or purchased through Rimrock.
- Chandler will begin putting together the gripper during available work hours.
- Next steps on the project and any possible troubleshooting. For example, Chandler has contacts to have gripper 3D printed with closer tolerances if needed.

Action Items (what, who, when):

- Catherine will submit report to writing center for review
- Chandler will continue to 3D print gripper
- Testing will begin after gripper is printed and items are put together

Next meeting (date/time/location): ____2/6/2020, 5 pm – 7 pm, CSCC_____

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_13_

Meeting Date:____12/12/19______________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [ ]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass_____________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Submitted final paper for ENT 497
- Discussed changes to gripper design proposed by Chandler and Rimrock representatives based on documentation found and located in report.
- Jimmy will redesign gripper and submit files to Chandler to 3D print at Rimrock.

Action Items (what, who, when):

- Jimmy will redesign gripper and submit files to Chandler to 3D print at Rimrock.
- Chandler will get materials to put together robotic gripper.

Next meeting (date/time/location): ____1/30/2020, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_12_

Meeting Date:____12/5/19_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [ ]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- The team will continue putting together the final paper for ENT 497.
- Chandler will work on the updated BOM, commenting on any differences, and will write this portion of the final paper.
- Jimmy will continue working on the detailed design and will write this portion or the final paper.
- Catherine is adding the matrices, journal entries, and updated Gannt chart to the final paper.

Action Items (what, who, when):

- Chandler will continue gathering materials for gripper project.
- Jimmy will continue working on the Solidworks gripper design, modifying the design as needed throughout the project process.
- Each team member is working on their portion of the final paper for this course. When completed, everyone will review and provide feedback.

Next meeting (date/time/location): ____12/12/19, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_11_

Meeting Date:____11/21/19_____________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung_____________________ Present: [ ]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Oral presentation for Robot Gripper project was given.
- Each team member present evaluated the other groups performance using the provided matrix in class.
- The team will continue putting together the final paper for ENT 497.

Action Items (what, who, when):

- Chandler will continue gathering materials for gripper project.
- Jimmy will continue working on the Solidworks gripper design, modifying the design as needed throughout the project process.
- Each team member is working on their portion of the final paper for this course. When completed, everyone will review and provide feedback.

Next meeting (date/time/location): ____12/5/19, 5 pm – 7 pm, CSCC_____

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_10_

Meeting Date:____11/14/19______________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Material and design specifications for the robot gripper are being discussed.
- Catherine selected ethics case and wrote paper with discussion and review from other team members.
- Each team member wrote their portions of Code of Ethics and how it relates to robot gripper project.
- Catherine wrote decision matrices for gripper materials and gripper fill materials.
- Catherine added to the PowerPoint presentation for oral presentation using what Jimmy created for the proposal presentation. Chandler and Jimmy reviewed and made changes where needed.
- Catherine modified the Gannt chart for the project to reflect changes.
- Chandler modified the Bill of Material for the project to reflect changes.

Action Items (what, who, when):

- Chandler will continue gathering materials for gripper project.
- Jimmy will continue working on the Solidworks gripper design, modifying the design as needed throughout the project process.
- The remaining pieces of the final paper were sectioned out to each team member. When completed, everyone will review and provide feedback.

Next meeting (date/time/location): ____11/21/19, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_9_

Meeting Date:_____11/7/19_______________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Material and design specifications for the robot gripper are being discussed.
- The team selected an ethics case for the team ethics assignment.
- The team will write and review a 1-2 page paper regarding the ethics case selected.
- Each team member will select a portion of the code of ethics that relates to our project. Then each team member will write about how this portion of the code of ethics relates to our project. This will be included in our ENT 497 and ENT 498 paper.

Action Items (what, who, when):

- Chandler will continue gathering materials for gripper project.
- Jimmy will continue working on the Solidworks gripper design, modifying the design as needed throughout the project process.
- Catherine will continue researching materials.

Next meeting (date/time/location): _____11/14/19, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_8_

Meeting Date:_____10/31/19________________ Meeting Time:_5 pm - 7 pm____
Advisor:_____Rob Speckert_____________ Present: [X]

Team Members:
_Jimmy Amelung_____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [ ]

Topics discussed:

- Jimmy put together slides for the proposal presentation. Catherine and Chandler provided feedback.
- Jimmy and Chandler presented the proposal presentation. (Catherine was not present for this class).
- Initial specifications for design will be discussed such as vacuum pressure, size of gripper, etc. This discussion will be an on-going discussion with multiple phases of research.
- The team will review the upcoming team ethics assignment.

Action Items (what, who, when):

- Chandler will continue gathering materials for gripper project.
- Jimmy will continue working on the Solidworks gripper design, modifying the design as needed throughout the project process.
- Catherine will continue researching materials.
- Begin reviewing team ethics assignment.

Next meeting (date/time/location): _____11/7/19, 5 pm – 7 pm, CSCC______

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_7_

Meeting Date:____10/17/19______________ Meeting Time:_5 pm - 7 pm___
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [ ]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Jimmy has a preliminary gripper design which required large quantities of time and considerations. Some of the considerations were drill holes, clearances, and so forth.
- Catherine added cost section and final comments section to the proposal document. Chandler provided the cost information diagram. Preliminary gripper design was added to the proposal document. As previously stated, Jimmy designed the gripper, and provided the gripper design files.
- Chandler shared the proposal document with Sam at Rimrock for comments. The comments were returned to the senior design team.
- All team members reviewed the project proposal, provided final revisions, and the proposal document was submitted via Canvas.
- Initial specifications for design will be discussed such as vacuum pressure, size of gripper, etc. This discussion will be an on-going discussion with multiple phases of research.
- The team will review the upcoming team ethics assignment.

Action Items (what, who, when):

- Chandler will continue gathering materials for gripper project.
- Jimmy will continue working on the Solidworks gripper design, modifying the design as needed throughout the project process.
- Catherine will continue researching materials.
- Begin reviewing team ethics assignment.
- Be ready to give a presentation on project proposal with 5 slides or so.

Next meeting (date/time/location): ____10/31/19, 5 pm – 7 pm, CSCC_____

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_6_

Meeting Date:_____10/10/19_______________ Meeting Time:_5 pm - 7 pm____
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung_____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Jimmy researched different styles of gripper designs.
- Jimmy began a proposed gripper design for this project.
- Catherine researched different gripper materials, and gripper fill material.
- Catherine completed the supporting company, added matrix and discussion of matrix to justification, proposed robot gripper design figure, step-by-step plan, Gantt chart, appendix A, and appendix B portions of the proposal paper.
- Initial specifications for design will be discussed such as vacuum pressure, size of gripper, etc. This discussion will be an on-going discussion with multiple phases of research.
- Chandler created a rough bill of materials.
- Chandler sent an e-mail to companies Catherine found for gripper materials. He used his Rimrock account to add accountability for the materials request.

Action Items (what, who, when):

- Chandler will share our proposal paper with Sam at Rimrock for comments prior to submission for class.
- Jimmy will continue working on the Solidworks gripper design.
- Catherine will continue researching materials for gripper fill material and adhesive.

Next meeting (date/time/location): _____10/17/19, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_5_

Meeting Date:____10/03/19______________ Meeting Time:_5 pm - 7 pm____
Advisor:_____Rob Speckert____________ Present: [X]

Team Members:
_Jimmy Amelung____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

- Catherine will research different styles of gripper designs. These designs will be compared, discussed, and a design style selected.
- Catherine is researching different gripper materials, and gripper fill material.
- All group members will provide input for gripper design, gripper material, and gripper fill material (if applicable) selection.
- Initial specifications for design will be discussed such as vacuum pressure, size of gripper, etc. This discussion will be an on-going discussion with multiple phases of research.
- Chandler has a rough bill of materials. He has researched approximately what materials we need and how much these costs.
- Chandler is working with partners of Rimrock to gather materials specifically materials for the gripper, and raw and finished materials to pick up with the gripper.
- Jimmy is using the robot product specification to use for considerations of mounting design.
- Jimmy is designing the mounting piece that will connect universal gripper to the robotic arm, and the mounting piece for the air compressor. He will design in SolidWorks and will have an assembly view.

Action Items (what, who, when):

- Chandler will continue working on Bill of Materials information.
- Catherine will continue working on Gantt chart using Excel.
- Jimmy is designing the mounting pieces in SolidWorks with an assembly view.

Next meeting (date/time/location): ____10/10/19, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_4_

Meeting Date:_____9/26/19_______________ Meeting Time:_____5 pm - 7 pm_______
Advisor: ______Rob Speckert_____________ Present: [X]

Team Members:
_Jimmy Amelung_______________________ Present: [X]

_Chandler Klass________________________ Present: [X]

_Catherine Dyer________________________ Present: [X]

Topics discussed:

- On Friday, September 20, 2019 the Senior design project team visited Rimrock. We discussed project deliverables and budget with Rimrock team. The senior design project team took a tour of Rimrock facilities, and saw the robot that will be used for this project.
    - Senior design project team is collaborating with two Research and Development members at Rimrock.
- Jimmy began the Proposal document starting objectives, goals, milestones, and justification sections.
- Chandler is coordinating with a Rimrock partner to gain material samples for gripper.
- Chandler forwarded robot manual provided by Rimrock.
- Jimmy and Catherine reshared contact information with Rimrock contacts.

Action Items (what, who, when):

- Chandler will work on Bill of Materials information.
- Catherine will work on Gantt chart.
- Jimmy will be working on design file when information is available.

Next meeting (date/time/location): ____10/03/19, 5 pm – 7 pm, CSCC______

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_3_

Meeting Date:_____9/19/19_______________ Meeting Time:_____5 pm - 7 pm_______
Advisor: ______Rob Speckert_____________ Present: [X]

Team Members:
_Jimmy Amelung______________________ Present: [X]

_Chandler Klass________________________ Present: [X]

_Catherine Dyer________________________ Present: [X]

Topics discussed:

- Visit to Rimrock for all team members, address, steel toe shoes, safety glass
- Store all team documents on Google drive then everyone has access and can modify the most recent copy (live document).
- Begin defining deliverables with Rimrock and team communication.
- Agreement between client and team with supporting documentation such as decision matrix.

Action Items (what, who, when):

- Jimmy created and shared share drive with group.
- Group to discuss and determine deliverables with Rimrock.
- Group to discuss and determine budget with Rimrock.

Next meeting (date/time/location): ____9/26/19, 5 pm – 7 pm, CSCC______

MIAMI UNIVERSITY

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_2_

Meeting Date: 9/12/19 Meeting Time: 5 pm - 7 pm
Advisor: Rob Speckert Present: [X]

Team Members:
Jimmy Amelung Present: [X]

Chandler Klass Present: [X]

Catherine Dyer Present: [X]

Topics discussed:

- Catherine provided back-up project ideas in case Rimrock did not proceed; however, these were not needed.
- Chandler provided project ideas from Rimrock
- The team: Jimmy, Chandler and Catherine, discussed the project ideas and decided to select "develop and model a universal robot gripper design for extract or material handling." A decision matrix was used to help make the selection.
- This project and its feasibility were discussed with Rob.
- The project proposal was discussed and will be discussed in more details in the upcoming weeks.

Action Items (what, who, when):

- Each team member will review the project proposal for further discussion.
- Catherine will complete a decision matrix for proposed projects. Project selection will be discussed again if needed.
- Jimmy requested a visit to Rimrock for all team members. Chandler will provide the team with possible dates. The team will discuss and select the best date.
    - A visit to Rimrock for all team members is scheduled for Friday, September 20, 2019.

Next meeting (date/time/location): 9/19/19, 5 pm – 7 pm, CSCC

Miami University
Department of Engineering Technology
ENT 497-498 Senior Design

Journal Entry #_1_

Meeting Date:_____9/5/19_______________ Meeting Time:_____5 pm - 7 pm_______
Advisor: ______Rob Speckert_____________ Present: [X]

Team Members:
_Jimmy Amelung_____________________ Present: [X]

_Chandler Klass______________________ Present: [X]

_Catherine Dyer______________________ Present: [X]

Topics discussed:

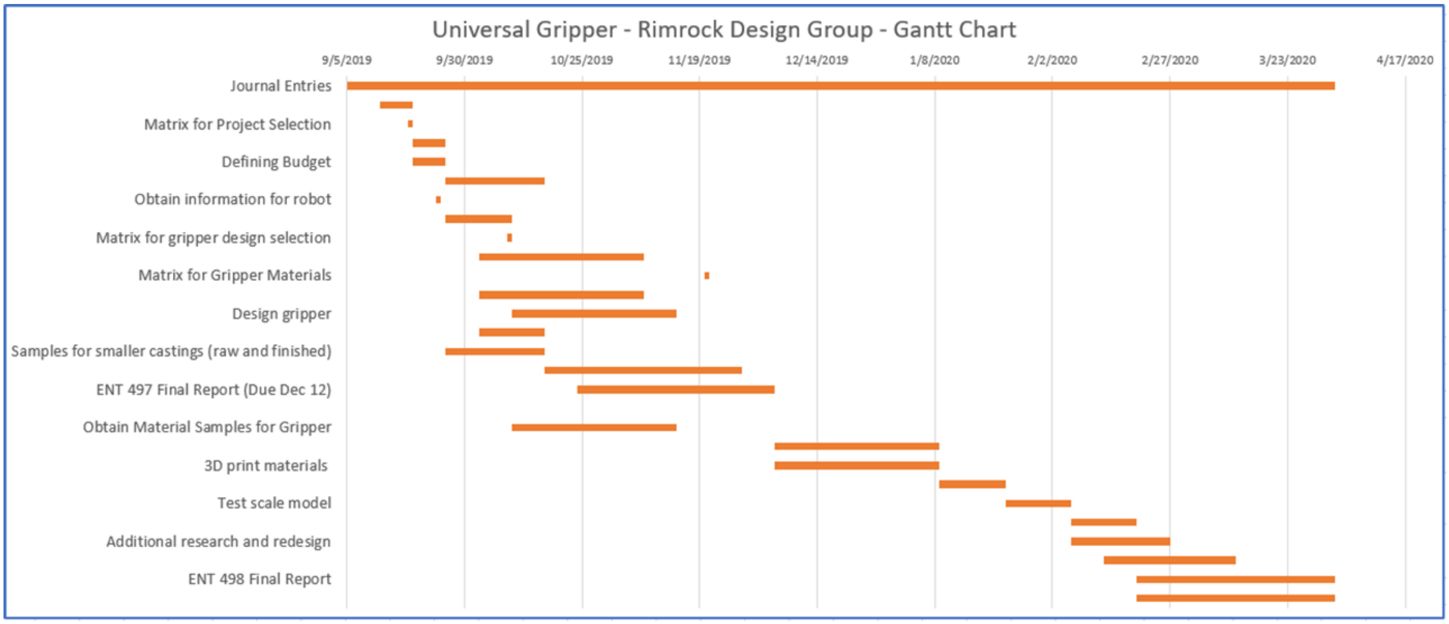
- Team formation; Jimmy, Chandler, Catherine
- Discussed strengths of each member
- Chandler's company, Rimrock, is willing to finance our Senior Design project
- Catherine presented an idea for senior project; however, during this meeting found out that this idea is already being pursued by another team.

Action Items (what, who, when):

- Chandler will discuss project ideas and funding with Rimrock
- Chandler will present project ideas and information to senior design team
- All team members will present/share any senior project ideas/suggestions
- Jimmy will put together the project proposal after the team decides on a project
- Catherine will put together the journal entries for the senior project

Next meeting (date/time/location): _____9/12/19, 5 pm – 7 pm, CSCC_________

Appendix B: Gantt Chart



Appendix C: Gantt Chart Data

Task	Start Date	Duration (Days)	Person Responsbile
Journal Entries	9/5/2019	210	Catherine
Identify Project	9/12/2019	7	Team with Rimrock Collaboration
Matrix for Project Selection	9/18/2019	1	Catherine
Defining Deliverables	9/19/2019	7	Team with Rimrock Collaboration
Defining Budget	9/19/2019	7	Team with Rimrock Collaboration
Project Proposal	9/26/2019	21	Team - Jimmy is lead
Obtain information for robot	9/24/2019	1	Chandler and Jimmy
Gripper Design Research	9/26/2019	14	Jimmy
Matrix for gripper design selection	10/9/2019	1	Catherine
Research Materials for gripper style, gripper, and fill material	10/3/2019	35	Catherine
Matrix for Gripper Materials	11/20/2019	1	Catherine
Design mounting for gripper to robot	10/3/2019	35	Jimmy
Design gripper	10/10/2019	35	Jimmy
Create Bill of Materials	10/3/2019	14	Chandler
Samples for smaller castings (raw and finished)	9/26/2019	21	Chandler
ENT 497 Oral Presentation (Due Dec 5)	10/17/2019	42	Team
ENT 497 Final Report (Due Dec 12)	10/24/2019	42	Team
Torque Equations	1/30/2019	14	Team
Obtain Material Samples for Gripper	10/10/2019	35	Team - Chanlder is lead
Obtain misc. materials	12/5/2019	35	Team
3D print materials	12/5/2019	35	Team
Build working scale model	1/9/2020	14	Team
Test scale model	1/23/2020	14	Team
Troubleshooting	2/6/2020	14	Team
Additional research and redesign	2/6/2020	21	Team
Adjust design and rebuild working scale model	2/13/2020	28	Team
ENT 498 Final Report	2/20/2020	42	Team
ENT 498 Final Presentation	2/20/2020	42	Team

Appendix D: Detailed Proposal

Robot Gripper
(Improved Method of Handling Parts)

Senior Design Project, sponsored by Rimrock Corporation

Team Members:
Chandler Klass
Jimmy Amelung
Catherine Dyer

Advisor:
Rob Speckert

Date:
10/15/19

Supporting Company:
Rimrock Corporation located in Columbus, Ohio is our supporting company. According to Rimrock's website, "Rimrock is a premier supplier of automation products and integration services. Founded in 1956 as a manufacturer of automatic lubrication systems, Rimrock has expanded to supply products including ladles, sprayers, extractors, finishing equipment, and turnkey robotic systems. We have expanded our integration capabilities to include the design, manufacture, and installation of ABB, Fanuc, Motoman, and Gudel robot-based systems."
Objective:
This project will consist of multiple goals and milestones to achieve the desired result of assessing the feasibility of a more universal type of gripper used for material handling in the Rimrock Corporation. A successful project will mean that there is a small-scale functional prototype robot modified with the new gripper that will be used to provide useful data back to Rimrock. There should be usable, measurable test results from a functional prototype. A successful project will not necessarily mean that the prototype demonstrated a performance improvement i.e. this is an R&D type project. This project was created by Rimrock to be a learning tool for future plans. The prototype will be designed and tested to determine the real-world practicality.
Goals:

7. Pick up spheres from 1", 2", 4" diameters
8. Pick up cylinders from 1", 2", 4" diameters
9. Pick up rectangle 1", 2", 4" width
   (Perform all tests dry and wet)
10. Pick up and place repeatability within 0.125" in all directions (*requires a gauge to be designed and built)
11. Pick a part or simulated part with a torque load of ½ the robot torque. Determine max robot load, perform movement test and measure the function
12. Research and test materials

Milestones:

5. Pick a design direction, finger style, flexible bag style, or other.
6. At the end of the third goal, the team will have gone through several revisions to have a functional gripper.
7. At the end of the 5^{th} goal, the team should be able to demonstrate that the gripper is physically capable of picking up an off-loaded casting with some useful repeatability
8. A small-scale functioning model that can pick up hot parts up to 800°F without losing the performance established in the first milestones.
9. Full-scale design gripper (Probably not built or tested). Loading specs to the maximum of the ABB 6700 2.85M

Justification:
Currently, robots need prepped uniquely for various casting lots. This means downtime that could be anywhere from a couple of hours up to a day of man-hours and lost production opportunity. If there was a way that a robot could be more multi-purposed to handle a larger variety of casting lots, this initial cost would be quickly offset by higher production efficiency from less lost time.

Rimrock Senior Project Group Decision Matrix								
	Budget	Feasibility	Usability	Research	Complexity	Timeline	Rimrock Preference	**Totals**
Universal Robot Gripper	2	3	4	5	2	3	5	**24**
Body and arm design (longer arm)	5	4	1	2	5	3	4	**24**
Adjustable base	4	4	1	3	4	3	4	**23**
Nozzle test	4	3	3	4	4	2	3	**23**
Small Reciporator	3	2	3	3	3	2	3	**19**
Palletized Robot Assembly Design	1	1	3	4	2	1	1	**13**
Bottom Pour Ladle	3	2	2	1	2	2	2	**14**
Notes (scale 1 to 5):	High number = Lower cost	High number = High feasibility	Low number = Few applicable uses	Low number = Not much to research	Higher Number = Less Complex	Ability to complete within timeframe. High number is good.	High number = Rimrock preference	Larger number = better project selection
Selected Project: Universal Robot Gripper								

Figure 1. Rimrock Senior Design Project Selection Decision Matrix

There were several factors considered when selecting our senior design project. Rimrock Corporation is sponsoring our senior project; therefore, Rimrock's preference was a major influence on our project selection. Feedback from Rimrock determined their preference was the 'Universal Robot Gripper' because this is something they want to research for feasibility in their industrial environment. A universal gripper could be a marketable product for Rimrock if it is feasible for their industrial environment. Completing the project within the set timeframe for Miami University coursework, before the end of ENT 498 and prior to the project presentation, was another major consideration for our project selection. A project that was complex enough to learn and have material to research, and not too complex or broad. Taking all these factors into consideration, the universal robot gripper, and body and arm design were the top selections. We selected the universal robot gripper out of these two selections due to Rimrock's preference being a high priority. Meeting our sponsors needs is a high priority. Appendix A lists the project possibilities proposed by Rimrock. The universal gripper is being designed for use with the ABB robot shown in Figure 2 and Figure 3. A proposed gripper type is shown in Figure 4. Figures 5, 6, and 7 show a proposed robot gripper design for this project. This is a preliminary design that could change based upon research and testing as the project progresses.

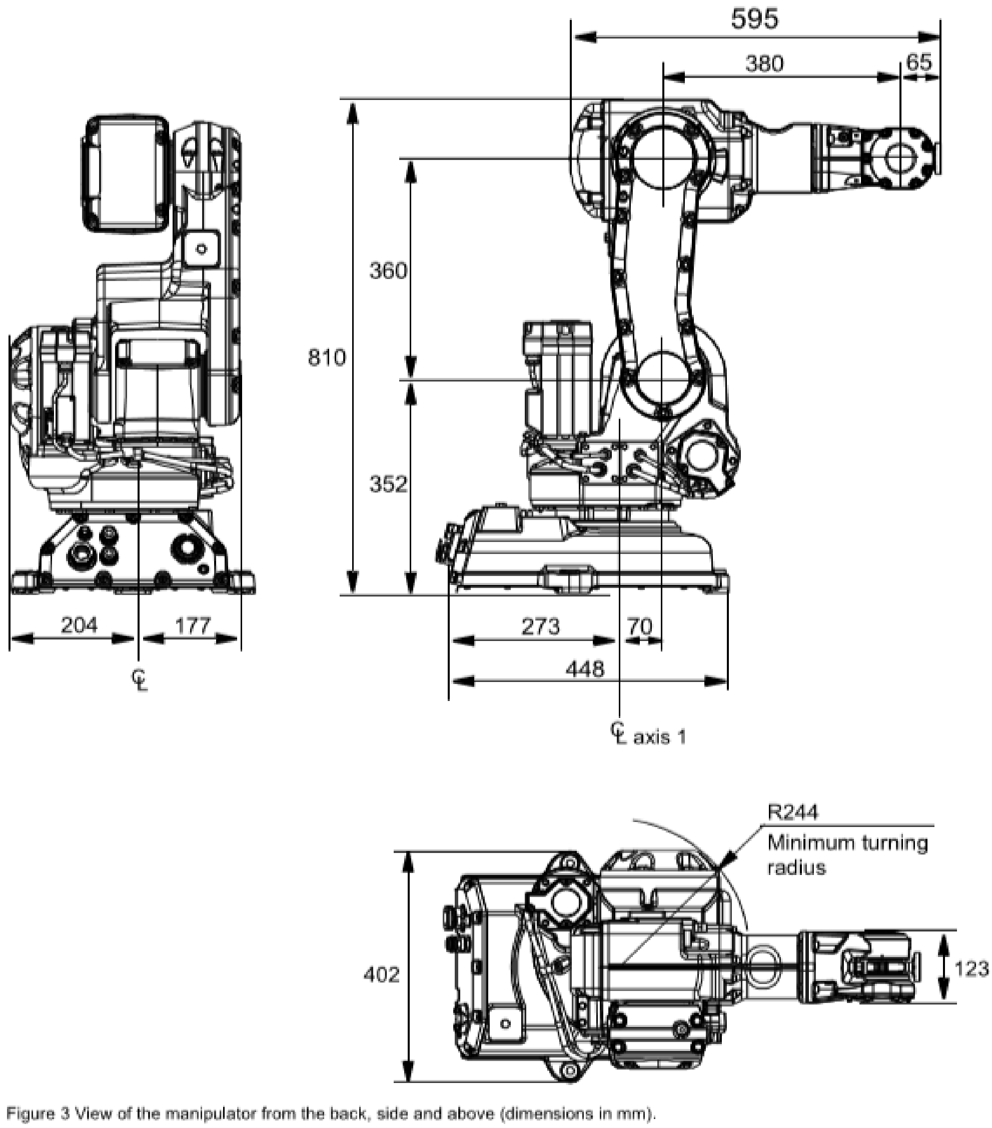


Figure 2. Robot Gripper will be designed for this ABB Robot (IRB 140 M2000)
Image from ABB Manual

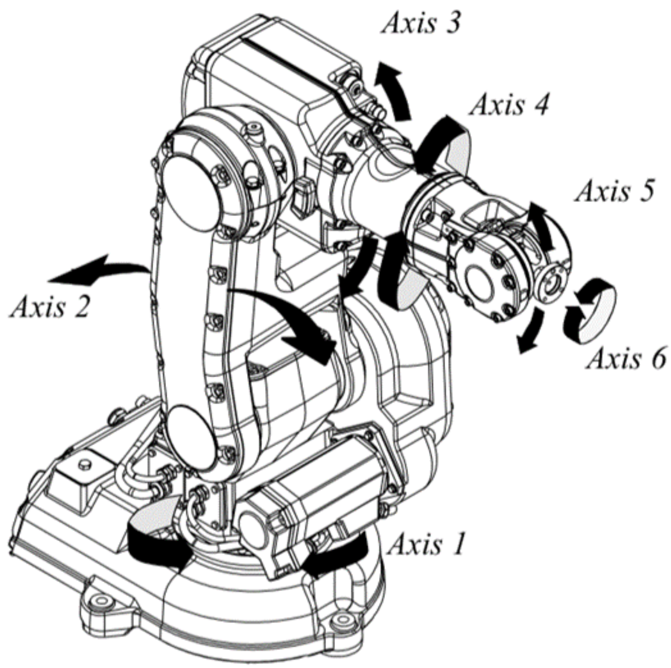


Figure 1 The IRB 140 manipulator has 6 axes.

Figure 3. Robot Gripper will be designed for this ABB Robot
Image from ABB Manual

Figure 4. Proposed Robot Gripper Design – Item being held by gripper
Image from
http://www.modernapplicationsnews.com/cms/man/opens/enews/20140910MAN/UniversalRobotsVersaball

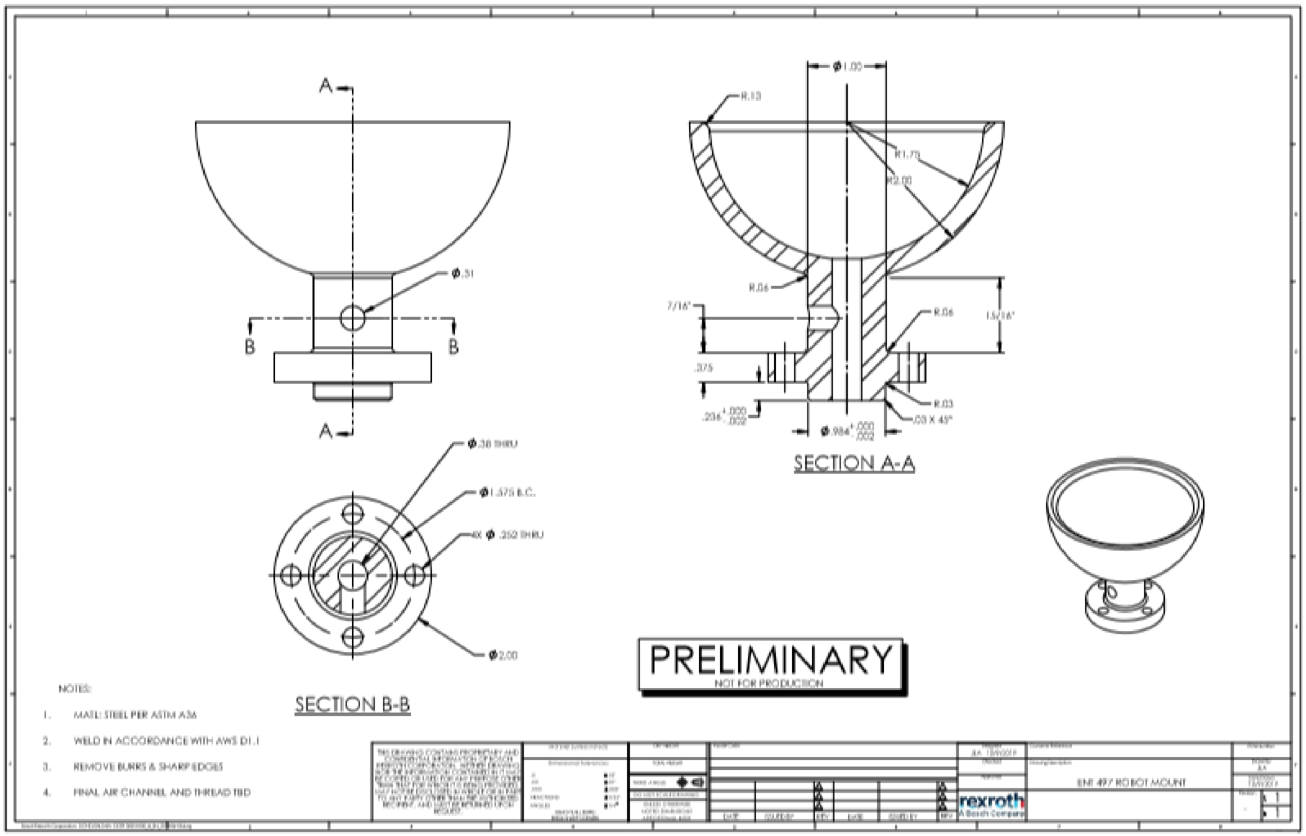


Figure 5. Robot Mount Preliminary Design

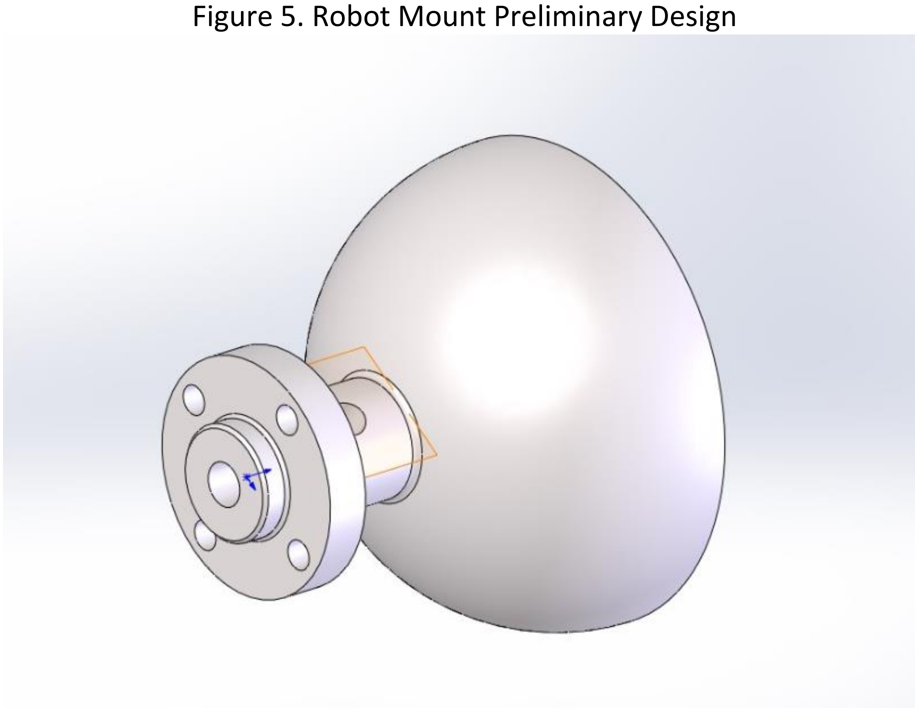


Figure 6. Robot Gripper Solid Model – View 1

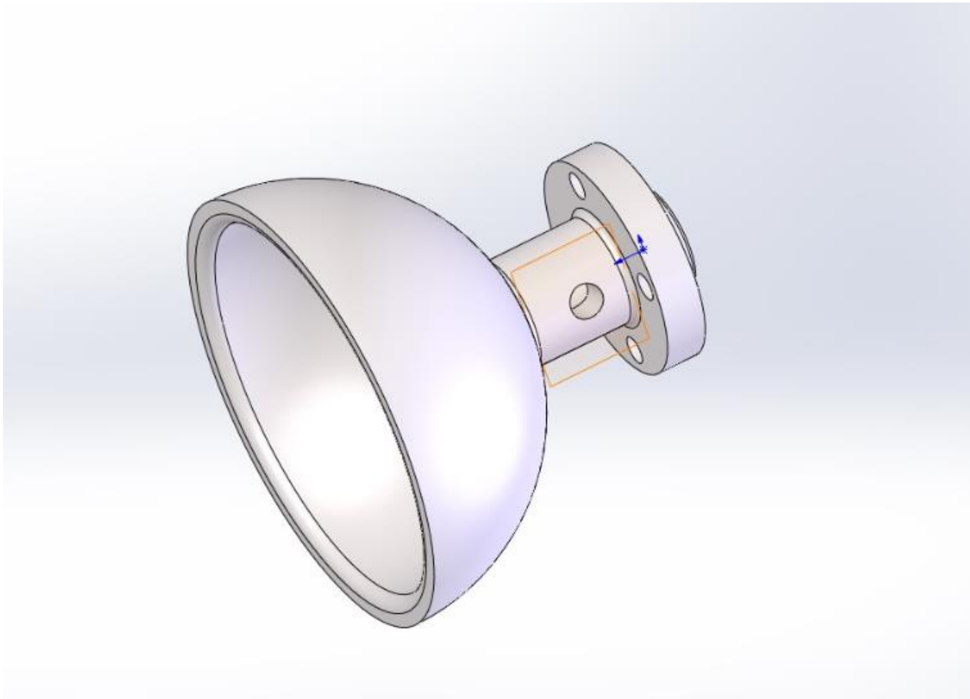


Figure 7. Robot Gripper Solid Model – View 2

Step-By-Step Plan:

1. Journal Entries – Team to record weekly progress during Senior Design project with weekly journals, and journal entries for any special meeting such as assembly, testing, or troubleshooting with the balloon gripper.
2. Identify Project – Project identification involved securing Rimrock as our sponsor, researching for back-up project ideas in the event Rimrock did not agree to sponsorship, getting a list of projects from Rimrock.
3. Matrix for Project Selection – A decision matrix was used to determine which project to select out of the list provided by Rimrock. Important characteristics to Rimrock, class requirements for Miami, and our abilities were factors considered with our decision matrix.
4. Defining Deliverables – We met with our contact points at Rimrock, which are two members of their Research and Development team. The universal gripper project was discussed, desired deliverables from Rimrock, and additional objectives to explore if time allowed.
5. Defining Budget – A budget was defined with Rimrock. Being our sponsor, it was important that we were on the same page for deliverables and cost. It was determined Rimrock has a robot for the design project team to use, and budget needs were discussed.
6. Project Proposal – The project proposal is a Miami required document which follows a process like an external project as well. Before funding, additional research, and so forth the project must first be proposed, evaluated for feasibility, and ensure a positive direction could occur.
7. Obtain information for robot – Rimrock provided the product specification manual for the robot the senior design group will be using for the universal gripper project.

8. Gripper Design Research – The team will research which design of universal gripper would be best for this project. Research regarding present styles such as balloon or finger gripper will be conducted. Rimrock's usability is a major factor in the consideration.
9. Matrix for gripper design selection – A decision matrix with appropriate considerations will be created to determine the gripper design the group will proceed to design.
10. Research Materials for gripper style, gripper materials, gripper fill (if needed) – Materials that can withstand extremely high temperatures, resist tear, appropriate friction to hold materials even when the materials are hot, wet, and rough within tolerances.
11. Matrix for Gripper Materials – Create a design matrix to determine appropriate material considerations and select best material for this application.
12. Design mounting for gripper to robot – Design the connection between the gripper to the ABB robot. This will likely be 3D printed.
13. Design gripper – Design the gripper style for the ABB robot end effector.
14. Create Bill of Materials – Create a bill of materials with cost of items. This will help ensure the project is on budget and be used for record if this gripper is to be built again.
15. Samples for smaller castings (raw and finished) – Obtain sample castings to use for testing of gripper design.
16. ENT 497 Oral Presentation (Due Dec 5) – Prepare and present oral presentation
17. ENT 497 Final Report (Due Dec 12) – Prepare and submit final report and supporting documentation
18. Torque Equations – Complete torque equations to determine range and limitations of robot gripper.
19. Obtain Material Samples for Gripper – Contact companies for samples of material based from research conducted.
20. Obtain misc. materials – Obtain any other materials needed for robot gripper
21. 3D print materials – 3D print gripper to robot mounting and any other items that require 3D printing.
22. Build working scale model – Build a working scale model for testing based upon research and design during this project.
23. Test scale model – Test the scale model by trying to pick up the smaller castings.
24. Troubleshooting – Figure out what worked well, what doesn't work well, and what can be done to improve gripper.
25. Additional research and redesign – Research the areas of improvement that needs explored.
26. Adjust design and rebuild working scale model – Again, based from the first test and troubleshooting results, considerations for improvement and rebuilding.
27. ENT 498 Final Report – Complete ENT 498 final report.
28. ENT 498 Final Presentation – Complete ENT 498 final presentation.

Gantt Chart:
Rimrock's design group has tasks planned to meet the project needs within the timeframe according the Gantt chart. See figure 8 for additional information. Data used to create the Gantt chart is in Appendix B.

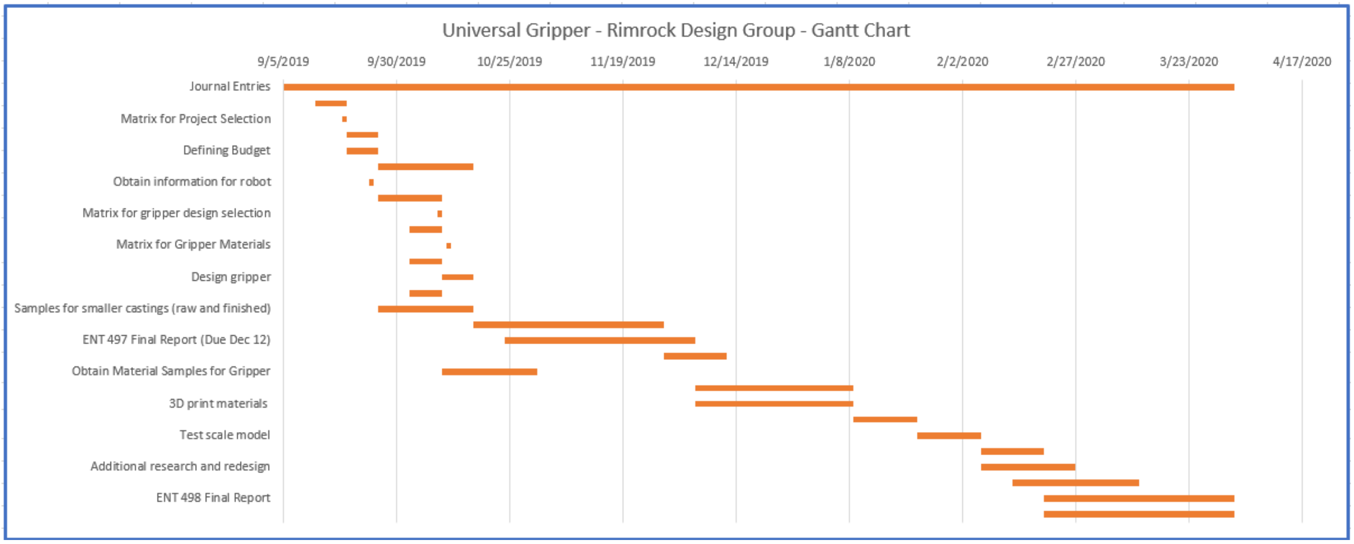


Figure 8. Rimrock Design Group Gantt Chart

Cost:
The estimated cost for the robot gripper is shown in figure 9. These costs are subject to change as research is conducted and designs modified. Possible additional costs are gripper fill material and adhesive.

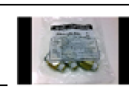
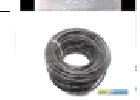
Part Number	Qty	Details	Site	Cost	Picture
9687283011	1	Vacuum Pump, DC 24V Mini Vacuum Pump Water Air Gas Vacuum Pump -85KPa Flow 40L/min Oil-Less Vacuum Pump, Mini Air Pump Motor	Amazon Prime	$ 42.39	
KQ2H12-02S - PACK OF 5	1	Smc Kq2h12-02S - Pack Of 5 - Pneumatic Fitting 12Mm Kq2h12-02S - Pack Of 5 -	Amazon Prime	$ 8.80	
D508759-TU 1208B	1	SMC TU 1208B 8MM ID 12MM OD 90FT Polyurethane TUBING D508759	Amazon Prime	$ 130.70	
CF0070	Per litter Yard	ARMATEX QF 70 402	Mid-Mountian Material	$ 138.75	
CF0079	Per litter Yard	ARMATEX SBQF 100 402	Mid-Mountian Material	$ 182.75	
CF0244	Per litter Yard	ARMATEX SBKG 21.5 502	Mid-Mountian Material	$ 139.75	
			Total	$ 643.14	

Figure 9. Robot Gripper Estimated Cost

Summary and Final Comments:

If successful, this robot gripper design could be a marketable product for Rimrock as a cost savings gripper. The cost savings is a result of having one style of gripper that can handle various castings. The end goal is to have a gripper that can handle both finished and raw materials. There are many obstacles to overcome to achieve this result. Some of these obstacles are finding materials that can withstand extremely high temperatures, example 1300 degrees Fahrenheit, materials that can withstand sharp edges, and a gripper that can pick up wet materials. The materials could be wet from using water to cool down the parts after casting. If not successful, the goal is to know what works, what doesn't work, and if what doesn't work can be solved.

Appendix A (Of Proposal). Rimrock Senior Project Selections Descriptions

- Develop and model a universal robot gripper design for extract or material handling - Balloon style gripper. Needs to handle heat and very sharp part. Different material (aluminum, zinc, plastic, etc.). Weights of the object.
  Example Videos:
  https://www.youtube.com/watch?v=0d4f8fEysf8
  https://robotiq.com/products/3-finger-adaptive-robot-gripper
- 410 body and arm design - This machine has different arm lengths, in order to change the arms out you must pull the arm all the way out.
- 305 adjustable base - Change the shot heights, angles and path with setup to different dies.
- Develop and assemble a nozzle test cell - develop a test station that will allow a piece of steel to be heated and then sprayed with various nozzles and configurations. Log spray usage, temperature changes, use various steel structures (cone, walls, thin walls, cylinders, etc.).
- Develop and model a small reciprocator - develop a small reciprocator for high pressure die casting machines
- Palletized robot assembly design - established a process and necessary hardware to build robot cells on a pallet system, saving assembly and install time
- Bottom pour ladle - develop an improved bottom pour ladle

Appendix B (Of Proposal). Gantt Chart Data

Task	Start Date	Duration (Days)	Person Responsbile
Journal Entries	9/5/2019	210	Catherine
Identify Project	9/12/2019	7	Team with Rimrock Collaboration
Matrix for Project Selection	9/18/2019	1	Catherine
Defining Deliverables	9/19/2019	7	Team with Rimrock Collaboration
Defining Budget	9/19/2019	7	Team with Rimrock Collaboration
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Obtain information for robot	9/24/2019	1	Chandler and Jimmy
Gripper Design Research	9/26/2019	14	Jimmy
Matrix for gripper design selection	10/9/2019	1	Catherine
Research Materials for gripper style, gripper materials, gripper fill (if needed)	10/3/2019	7	Catherine
Matrix for Gripper Materials	10/11/2019	1	Catherine
Design mounting for gripper to robot	10/3/2019	7	Jimmy
Design gripper	10/10/2019	7	Jimmy
Create Bill of Materials	10/3/2019	7	Chandler
Samples for smaller castings (raw and finished)	9/26/2019	21	Chandler
ENT 497 Oral Presentation (Due Dec 5)	10/17/2019	42	Team
ENT 497 Final Report (Due Dec 12)	10/24/2019	42	Team
Torque Equations	11/28/2019	14	Team
Obtain Material Samples for Gripper	10/10/2019	21	Team - Chanlder is lead
Obtain misc. materials	12/5/2019	35	Team
3D print materials	12/5/2019	35	Team
Build working scale model	1/9/2020	14	Team
Test scale model	1/23/2020	14	Team
Troubleshooting	2/6/2020	14	Team
Additional research and redesign	2/6/2020	21	Team
Adjust design and rebuild working scale model	2/13/2020	28	Team
ENT 498 Final Report	2/20/2020	42	Team
ENT 498 Final Presentation	2/20/2020	42	Team

Appendix E: Decision Matrices

Project Decision Matrix

Rimrock Senior Project Group Decision Matrix

	Budget	Feasibility	Usability	Research	Complexity	Timeline	Rimrock Preference	Totals
Universal Robot Gripper	2	3	4	5	2	3	5	**24**
Body and arm design (longer arm)	5	4	1	2	5	3	4	**24**
Adjustable base	4	4	1	3	4	3	4	**23**
Nozzle test	4	3	3	4	4	2	3	**23**
Small Reciporator	3	2	3	3	3	2	3	**19**
Palletized Robot Assembly Design	1	1	3	4	2	1	1	**13**
Bottom Pour Ladle	3	2	2	1	2	2	2	**14**
Notes (scale 1 to 5):	High number = Lower cost	High number = High feasibility	Low number = Few applicable uses	Low number = Not much to research	Higher Number = Less Complex	Ability to complete within timeframe. High number is good.	High number = Rimrock preference	Larger number = better project selection

Selected Project: Universal Robot Gripper

Gripper Fill Material Matrix

Gripper Fill Material Decision Matrix

	Temperature Resistance	Pressure	Formability	Moisture	Electrically Non-conductive	Totals
Coffee Grounds	4	4	5	1	4	**18**
Sand	5	5	5	3	4	**22**
Bead pellets	4	4	4	5	5	**22**
Borax Powder	5	4	5	1	5	**20**
Slime	2	3	5	3	3	**16**
Silicon Sand	3	4	5	3	4	**19**
Foam pellets	2	4	5	3	3	**17**
Wood shavings	3	3	2	3	5	**16**
Water (Non-distilled)	1	5	4	5	2	**17**
Crumb Rubber	2	3	4	4	4	**17**
Vegetable Oil	2	3	4	3	3	**15**
Notes (scale 1 to 5):	High number = able to withstand 800 degree F or higher	Higher Number = Can withstand pressure	High number = material can be easily formed and reformed	Higher number = moisture will not damage material integerity	High number = material is non-conductive	Larger number = better material selection

Optimal Filler Material: Bead pellets or Sand

Gripper Material Matrix

Gripper Material Decision Matrix								
	Flexibility	Puncture Resistance	Temperature Rating	Formability	Thickness	Friction	Moisture Resistance	**Totals**
McAllister Mills 1800F Cloth Reflective	2	2	5	3	2	3	3	**20**
DuPont Kevlar XP S300	1	5	1	1	3	1	1	**13**
DuPont Kevlar XP S103	1	5	1	1	3	1	1	**13**
Premlene GCP Commerical Grade Neoprene Rubber Sheet	2	2	2	2	4	4	3	**19**
GLT Products Refractory Silica Fabric	2	3	5	2	3	3	3	**21**
Mid-Mountain Materials Armatex SF 45 Silicone Coated Fiberglass	1	2	3	2	3	3	3	**17**
Mid-Mountain Materials Siltex 36-UH Amorphous Silica Cloth	3	2	5	3	4	4	4	**25**
Mid-Mountain Materials Siltex 70-UH Amorphous Silica Cloth	3	3	5	4	4	4	4	**27**
Mid-Mountain Materials Armatex SS 40 Silicone Coated Silica	4	2	4	4	3	5	4	**26**
McAllister Mills MM36-88-36 Silica Fabric	3	3	5	4	3	4	4	**26**
McAllister MM2220-S Alumina Fabric	5	4	5	4	4	4	4	**30**
McAllister MM3025 Alumina Fabric	5	4	5	4	4	4	3	**29**
McAllister Mills MM50MTS Maxsil-Tex Silica Fabric	4	4	5	3	4	2	2	**24**
Notes (scale 1 to 5):	High number = High flexibility	High number = high puncture resistance	High number = Able to withstand temp of 800 degree F	Higher Number = More likely to form easily with pressure	Too thick or too thin = low number	Higher number = more likely to hold/grip onto item	High number = Material can get wet and/or should not absorb water	Larger number = better material selection

Optimal Gripper Material:
McAllister MM2220-S Alumina Fabric

Appendix F: A Positive Pressure Universal Gripper Based on the Jamming of Granular Material

A Positive Pressure Universal Gripper Based on the Jamming of Granular Material

John R. Amend, Jr., *Student Member, IEEE*, Eric Brown, Nicholas Rodenberg, Heinrich M. Jaeger, and Hod Lipson, *Member, IEEE*

***Abstract*—We describe a simple passive universal gripper, consisting of a mass of granular material encased in an elastic membrane. Using a combination of positive and negative pressure, the gripper can rapidly grip and release a wide range of objects that are typically challenging for universal grippers, such as flat objects, soft objects, or objects with complex geometries. The gripper passively conforms to the shape of a target object, then vacuum-hardens to grip it rigidly, later utilizing positive pressure to reverse this transition—releasing the object and returning to a deformable state. We describe the mechanical design and implementation of this gripper and quantify its performance in real-world testing situations. By using both positive and negative pressure, we demonstrate performance increases of up to 85% in reliability, 25% in error tolerance, and the added capability to shoot objects by fast ejection. In addition, multiple objects are gripped and placed at once while maintaining their relative distance and orientation. We conclude by comparing the performance of the proposed gripper with others in the field.**

***Index Terms*—End effectors, grain size, jamming, manipulators, pressure control.**

I. Introduction

UNIVERSAL robot grippers are robotic end effectors that can grip a wide variety of arbitrarily shaped objects. Proposed universal grippers have ranged from vacuum-based suction grippers to multifingered hands, and these can be divided along a spectrum from active universal grippers to passive universal grippers [1].

Fig. 1. A universal jamming gripper is able to grip a wide variety of objects without grasp planning or sensory feedback. Multiple objects can be gripped at once, as demonstrated here with salt and pepper shakers.

Most active universal grippers typically have an anthropomorphic multifingered design with many independently actuated joints. Many such grippers have been developed, and multifingered grasping is an active area of research [2]. The active universal grippers that have been proposed are capable of both grasping and manipulation but also engender extensive physical and computational complexity, which is evident in grasp algorithm research [3]–[5]. The complexities of active universal grippers, coupled with their correspondingly high costs, have limited their adoption among commercial robotics industries.

Passive universal grippers [6]–[8] require minimal grasp planning. They often have ten or more degrees of freedom (DOF) per actuator and include components that passively conform to unique object geometries, giving them the ability to grip widely varying objects without readjustment. For example, Scott [6] presented a gripper design in which many independent telescoping pins could each passively slide in or out to conform to the shape of a target object, before pinching from the side to grip the object.

Passive universal grippers are generally simpler to use and require minimal visual preprocessing of their environment, but they too have had limited success gaining widespread adoption.

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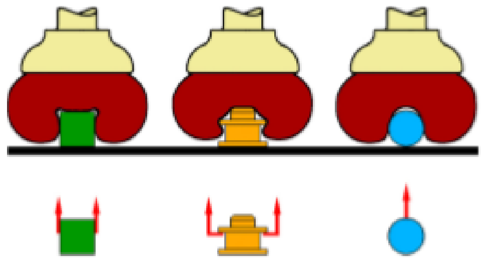

Fig. 2. A universal jamming gripper can achieve three separate gripping modes. (Left) Static friction from surface contact. (Center) Geometric constraints from interlocking. (Right) Vacuum suction from an airtight seal. Normally, it would be unlikely that the interlocking or vacuum modes would be achieved without some additional contribution from friction.

Often, their many passive components are easy to damage and difficult to replace. Passive universal grippers can be very expensive as well, and their ability to grip many different objects often renders them inferior at gripping any one object in particular (a mechanical ***no free lunch*** [9]).

The term ***underactuated*** [10] describes universal grippers falling somewhere between the active and passive distinctions. There are no clear dividing lines on this spectrum, but underactuated grippers [11]–[18] are in many ways comparable with passive universal grippers, especially when they possess many more DOF than actuators.

Lower thresholds of universal gripping can be achieved by adding deformable materials to the gripping faces of a traditional 1-DOF jawed gripper in order to increase the compliance of the surfaces [19]–[21]. This technique is straightforward and can be sufficient for some applications. Simpson [22] was likely the first to suggest adding pockets of granular materials to gripping surfaces for this purpose, and later Schmidt [23] and Perovskii [24] proposed designs that allowed vacuum hardening of similar grain filled pockets to produce a custom gripper jaw shape. Reinmueller and Weissmantel [25], while describing a similar idea, went so far as to speculate that a single membrane filled with granular material might be able to grip an object on its own and function as a passive universal gripper. However, this idea was not demonstrated in practice or rigorously explored until the universal jamming gripper that we have recently presented [26].

The approach that we propose in this paper is to use both positive and negative pressure to modulate the jamming transition in a universal jamming gripper. We design, manufacture, and test a prototype gripper that attaches to a commercial robot arm. Consisting of a single mass of granular material encased in an elastic membrane, the gripper can passively conform to the shape of the target object, then vacuum-harden to grip it rigidly, later using positive pressure to reverse this transition—releasing the object and returning to a deformable state. An example of this gripper can be seen in Fig. 1.

This universal jamming gripper is an example of a passive universal gripper that exploits the temperature-independent fluid-like to solid-like phase transition of granular materials known as ***jamming*** [27]–[32]. This gripper leverages three possible gripping modes for operation: 1) static friction from surface contact; 2) geometric constraints from capture of the object by interlocking; and 3) vacuum suction when an airtight seal is achieved on some portion of the object's surface [26]. These three gripping modes are illustrated in Fig. 2. The friction force results from the slight ($<0.5\%$) volume contraction of the membrane that occurs during evacuation, which, in turn, causes a pinch force to develop, normal to the point of contact. Analytical calculations for these values have been previously presented [26].

By achieving one or more of the three gripping modes, the jamming gripper can grip many different objects with widely varying shape, weight, and fragility, including objects that are traditionally challenging for other universal grippers. For example, we have successfully been able to grip a coin, a tetrahedron, a hemisphere, a raw egg, a jack toy, and a foam earplug. When mounted to the robot arm, the gripper functions entirely in open loop—without grasp planning, vision, or sensory feedback.

Optimal performance of a universal jamming gripper is maintained by resetting the gripper to a neutral state between gripping tasks. Prior to the work presented here, this was accomplished by shaking the gripper, by kneading or massaging the gripper, or by pushing the gripper against some resetting apparatus that was mounted in the workspace, for example. We call this process ***manually resetting the gripper***, and without it, the ability to grip subsequent objects degrades rapidly. We have found that positive pressure can be used to replace this procedure with a short burst of air that quickly unjams and resets the gripper. We also find that incorporating positive pressure improves the gripper's speed, reliability, error tolerance, and placement accuracy. In addition, the fast ejection that positive pressure can provide enables the gripper to launch objects a significant distance—a capability that we call ***shooting***, which may serve as a new method for robots to extend their workspace and perform tasks like sorting objects into bins in a factory or throwing away trash in a home.

In this paper, we develop a new universal jamming gripper that incorporates positive pressure. We quantify the gripper's ability to grip objects of different shapes and sizes, as well as its ability to tolerate errors in the location of the target object; we test the gripper's maximum speed and placement precision; we test the gripper's ability to grip multiple objects at once and to shoot objects of varying weight and shape. Our testing reveals the capabilities and limitations of the gripper, and we compare these with a manual reset gripper in order to isolate the performance contribution from positive pressure. We demonstrate that dramatic improvements in performance are possible through the addition of positive pressure, and we compare the performance of a positive pressure jamming gripper with related grippers in the field. We conclude that this gripper has potential applications in a variety of settings.

II. Design and Manufacture

In its simplest form, a jamming gripper needs only to include some granular material that is contained in a flexible membrane in order to achieve its gripping behavior (the combination of ground coffee and a latex balloon has been found to work well [26]). No motors, cables, or linkages are required (just an off-board pump to evacuate the air from the gripper). Here, we

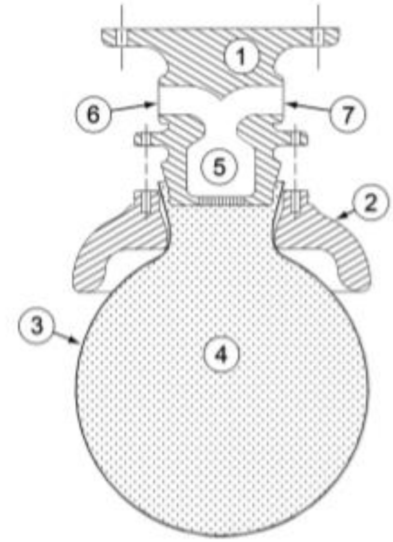

Fig. 3. Assembly drawing of the positive pressure jamming gripper, including components: 1) base, 2) external collar, 3) balloon membrane, 4) coffee grains, 5) air filter, 6) vacuum line port, and 7) high pressure port. The balloon is pinched between the base and the collar producing an airtight seal.

have developed a slightly more complex jamming gripper that interfaces with a commercial robot arm and includes a rigid collar surrounding the membrane, as well as a positive pressure port and an air filter. An assembly drawing of the design is shown in Fig. 3.

One of the primary benefits of this design is its mechanical simplicity. The gripper is composed of just 12 components (the seven shown in Fig. 3 plus five machine screws). This contributes to its low cost and easy manufacturability. The collar is an important element of the design because it helps guide the gripper as it conforms to an object, increasing the surface contact on vertical faces of the object and maximizing the potential for the interlocking gripping mode. In this prototype, the collar and the base are both manufactured from 3-D printed plastic, which permits the intricate internal structures of the base.

The latex balloon membrane is pinched between the base and the collar producing an airtight seal. The balloon membrane thickness is 0.33 mm, and it is filled with ground coffee beans to a volume of 350 cm^3. At this volume, the gripper is full but the membrane is not significantly stretched; therefore, the gripper can be easily deformed in the unjammed state. The gripper is approximately spherical, with a radius of 43 mm. The relatively low density of ground coffee is advantageous because it can be used in larger quantities without weighing down the gripper or straining the membrane in the way that a heavier material like sand would, for example.

III. Performance

The jamming gripper was mounted on a commercial robot arm for testing. Positive pressure was provided at 620 kPa and a flow rate of 2.16 L/s. Vacuum was achieved with an off-board vacuum pump. A maximum vacuum flow rate of 0.25 L/s was achieved with a pump rated for a maximum vacuum of 25 microns. For gripping, the jamming transition was considered complete when the pressure in the gripper dropped to −85 kPa, which took 1.1 s. The pressure in the gripper could also be neutralized with the atmosphere, and this state was used whenever the gripper was pressed onto an object. Solenoid valves that are controlled by serial communication through the robot arm were used to modulate the pressure in the gripper. All tests were performed at 100% joint angle speed for the robot arm, which corresponds to approximately 240 mm/s linear speed of the gripper. When the manual reset gripper was tested, a 2 s massage was given between each gripping task to return it to a uniform neutral state. This setup was used throughout the following subsections, except where otherwise noted.

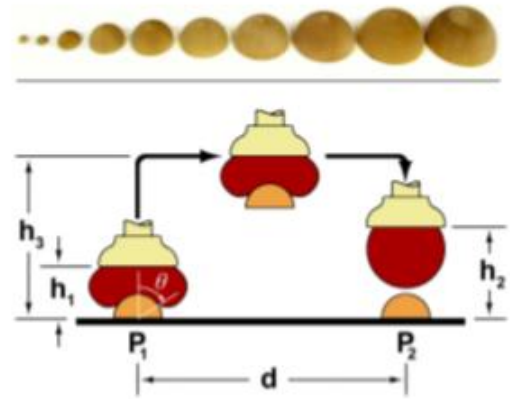

Fig. 4. Hemispheres used in this test ranging from 5-mm radius to 38-mm radius (left to right at top). Experimental setup showing key dimensions (bottom). The gripper picks the object at the pick location (P_1) and then moves to place the object at the place location (P_2). The contact angle between the gripper and the object is indicated by θ.

A. Size and Reliability

The positive pressure jamming gripper was first evaluated for its reliability in gripping objects of varying size. All objects were located at a position on a table that was hard-coded into the robot's software (the pick position). The robot was instructed to move to the pick position and press the jamming gripper onto an object and to then actuate the gripper to induce the rigid state. Next, the robot was instructed to move to a place position, release the vacuum, and apply a 0.1 s burst of positive pressure to eject the object. All tests were performed in open loop.

Spheres have been used as test objects for jamming grippers [26], but here, we have chosen to use hemispheres (oriented flat side down) so that the surface geometry of a sphere test would be preserved, but the height of the test objects would be reduced. Wooden hemispheres ranging from 5 mm radius to 38 mm radius were chosen, with a surface texture that was not smooth enough to permit an airtight seal between the gripper and the hemisphere, therefore, not inducing the vacuum mode of gripping. Since the objects are hemispheres, it is also impossible to achieve the interlocking gripping mode in this test. Each hemisphere was located in line with the central axis of the

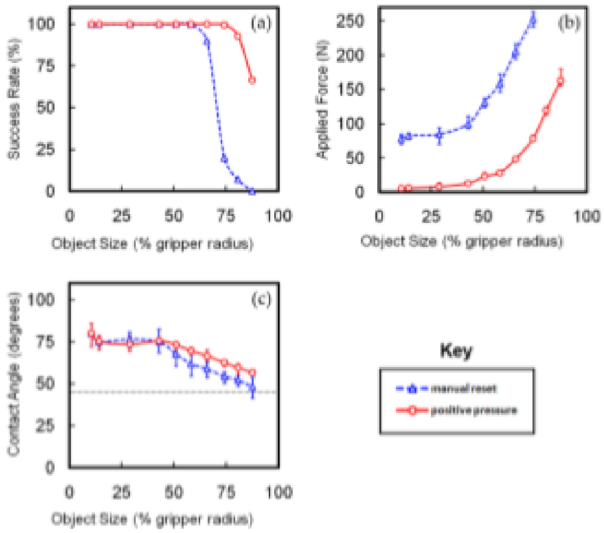

Fig. 5. Results of gripping tests on hemispheres of varying radius using a manually reset gripper and a gripper reset with positive pressure. (a) Success rate for gripping objects of varying size. (b) Force that the gripper applies to an object while deforming around it. (c) Contact angle that the gripper achieves. The horizontal dotted line in (c) indicates the critical 45° contact angle.

gripper so that the contact angle θ would be as consistent as possible around the hemisphere. The test setup and the hemispheres that are used for this test can be seen in Fig. 4. The dimensions associated with Fig. 4 were as follows: $h_1 = 48$ mm, $h_2 = 115$ mm, $h_3 = 130$ mm, and $d = 200$ mm.

Test results are shown in Fig. 5. The ordinate of each plot is presented as a percentage of the gripper size in order to account for the scalability of the gripper [26]. Fig. 5 shows the performance of the new positive pressure gripper compared with a manually reset gripper. Plots of success rate, applied force, and contact angle are shown. Success rate was determined over 30 trials for each hemisphere and represents how reliably the grippers could grip hemispheres of varying size. Applied force is the maximum force that a gripper applies to an object as it is deformed around it. This force is measured with a scale that is located beneath the test object. Contact angle is the maximum angle at which the gripper membrane and the object touch (as indicated by θ in Fig. 4). Contact angle was measured with the gripper pressed against the hemisphere and evacuated but before the hemisphere was lifted. For the applied force and contact angle tests, ten trials were performed on each hemisphere. For all three plots, the data points represent the average of the trials, and the error bars indicate the maximum and minimum measurements that are recorded during the test. Hemispheres were tested in random order for all tests.

It can be seen that for a gripper without positive pressure, the gripper's success rate falls off sharply as the object radius reaches about 65% of the gripper radius and falls to 0% for contact angles near 45° (i.e., the critical angle for gripping to occur [26]). No minimum object radius was observed in this test, although no hemispheres under 5 mm radius were tested because of their lack of availability in wood. We also see that the applied force increases with increasing object size, as more grains inside the gripper need to be displaced around larger objects. Adding positive pressure dramatically increases the success rate of the gripper by as much as 85% for some hemispheres by increasing contact angle. Positive pressure also decreases the force that is applied to the object by as much as 90%. These performance increases are most likely because of increased fluidization of the granular material, which allows it to flow more easily around the target object.

B. Error Tolerance

In this second test, the jamming gripper was evaluated for tolerance to errors in the location of the target object. The same test setup from Fig. 4 was used, with hemispheres that are again employed as test objects. In this test, however, the target object was located between 0 and 45 mm away from the pick location P_1, thus, causing the hemisphere to be unaligned with the gripper's central axis. Results from this test are shown in Fig. 6. In Fig. 6(a), only results for the 25 mm radius hemisphere are shown, and 30 trials were performed for each data point. We can observe an increased error tolerance of up to 25% from the addition of positive pressure. Fig. 6(b) illustrates a more general relationship between target object size, location error, and gripping success rate, and ten trials were performed for each data point shown, with errors ranging from 0 to 45 mm and hemispheres ranging from 5 to 38 mm radius.

Fig. 6(a) could be redrawn for any of the hemispheres that we tested, and a similar improvement for the positive pressure gripper would be shown. However, we find that the expression $\sqrt{e^2 + r^2}/R$ allows us to observe the error tolerance and reliability of the gripper more generally. This expression can be understood as the Euclidean distance from the apex of the target object to the point where the gripper touches the table along its central axis, compared with the radius of the gripper. It is a simple approximation of the total surface area the gripper will contact (table plus target object), as it attempts to wrap around the object to the critical contact angle, compared with the available surface area of the gripper. An analytical calculation of these two surface areas would likely produce a more accurate quantity, but such a calculation is prohibitively difficult because of the deformation and stretching of the gripper membrane that occurs during the gripping process. We see in Fig. 6(b) that our approximation is sufficiently simple and accurate to collapse the data and allow for quick estimations of gripping success rate. In addition, the close similarity between Figs. 5(a) and 6(b) should be noted. This result is expected because $\sqrt{e^2 + r^2}/R$ reduces to r/R for $e = 0$.

The error tolerance that we observe for the jamming gripper is very large considering its open-loop function. In Fig. 6(a), for example, we see that with the use of positive pressure, our 43 mm radius gripper can successfully pick up a 25 mm radius hemisphere 100% of the time, even when the hemisphere is 25 mm away from its target location. Furthermore, the ability of jamming grippers to resist torques and off-axis forces has been previously shown [26]. It is likely that this large error tolerance would prove very useful for gripping tasks in unstructured

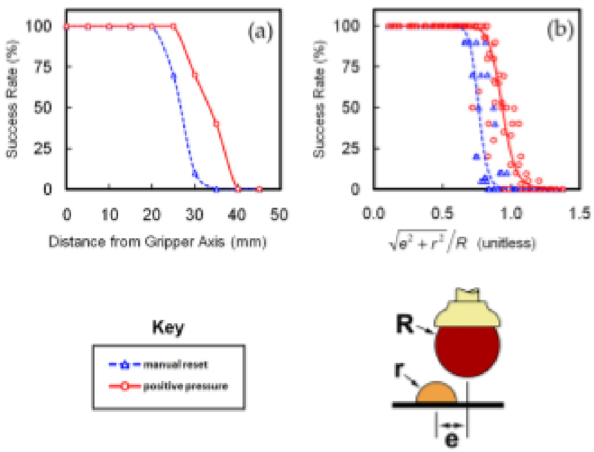

Fig. 6. Results from testing the gripper against errors in the location of the target object. (a) Error tolerance of about 30 mm as well as an increase in error tolerance of up to 25% for the positive pressure gripper can be seen for a hemisphere of 25 mm radius. (b) Error tolerance and reliability can be seen more generally for errors ranging from 0 to 45 mm and hemispheres ranging from 5 to 38 mm radius using the unitless value $\sqrt{e^2 + r^2}/R$.

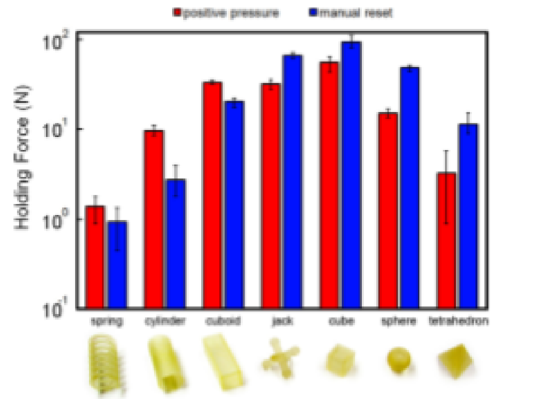

Fig. 7. Holding force for 3-D printed plastic shapes: helical spring, cylinder, cuboid, jack toy, cube, sphere, and regular tetrahedron. The sphere is 2.6 cm in diameter.

environments, where precise control over neither the situation nor the robot is possible.

C. Shapes and Strength

In our third test, the jamming gripper was evaluated for the range of shapes that it could grip and the forces with which it could retain those shapes. Seven shapes with similar mass, volume, and size were 3-D printed for the test. The mass of each shape was 15.5 ± 0.8 g. The minimum cross section of each shape was approximately 26 mm—a size chosen to be well within the 100% success rate from the previous tests. The 3-D printed material is not smooth enough for an airtight seal to be achieved. The shapes printed were helical spring, cylinder, cuboid, jack toy, cube, sphere, and regular tetrahedron. A photograph of the shapes is shown on the ordinate of Fig. 7. To test the strength with which each object was retained, we measured the force that is required to remove a held object from the gripper. The results of this test are shown in Fig. 7. Ten tests were performed for each shape, and the error bars indicate the maximum and minimum measurements that are recorded during the tests.

It can be seen that resetting the gripper with positive pressure improves the holding force for objects that displace a larger volume of grains in the gripper but decreases the holding force for smaller objects. This may be understood as a tradeoff between contact angle and applied force in the experimental setup. The enhanced flowability of the positive pressure gripper allows for a larger contact angle, as seen in Fig. 5(c) and, thus, an enhanced holding force for the larger objects that displace a larger volume of grains. However, a problem occurs for the smaller objects because no significant increase in contact angle occurs. Instead, the enhanced flowability may allow more grains to fall to the side of the object, possibly leaving a gap between the grains and the gripper base. This is supported by the low values of applied force in Fig. 5(b) for the positive pressure gripper, which are comparable with the weight of the grains for small objects. In this situation, when the membrane is evacuated, the grains may partially contract toward the open space near the gripper base rather than toward the target object, resulting in less holding force. This is not an inherent problem with the positive pressure modification, as it could be fixed by applying more force to the target object, either by adjusting the pick height h_1 to the target object size or by using a robot arm with force feedback.

D. Speed

The actuation speed of a positive pressure jamming gripper depends on the vacuum and positive pressure flow rates. These set the time required to complete the jamming transition when evacuating the gripper and the time required to reset the gripper with positive pressure. Here, we have achieved minimum actuation times of 1.1 s to evacuate the gripper and 0.1 s to reset the gripper. The 0.1 s reset time is probably near the lower limit of what is practical, as it was achieved with a standard 650 kPa compressed air line in a workshop. There is significant room for improvement, however, in the evacuation time. Faster evacuation times could be achieved by incorporating an evacuated reservoir between the pump and the valve leading to the gripper, for example, and we believe that evacuation times of the order of 0.1 s are also possible.

All of the tests in this paper were conducted at 100% joint angle speed of the robot, which was measured at 240 mm/s. We can, therefore, calculate that for the test setup shown in Fig. 4, a gripping rate of 16.2 picks/min can be achieved with the positive pressure gripper. Much higher gripping rates would be possible with a faster robot arm, for example, a delta robot.

E. Placement Precision

Typically, placement precision is recognized as a sacrifice that must be made when developing a passive universal gripper in order to maximize the range of objects that may be gripped [1]. However, placement precision is also a key performance measure for grippers that are used in manufacturing settings. Here, the jamming gripper is evaluated for the precision and

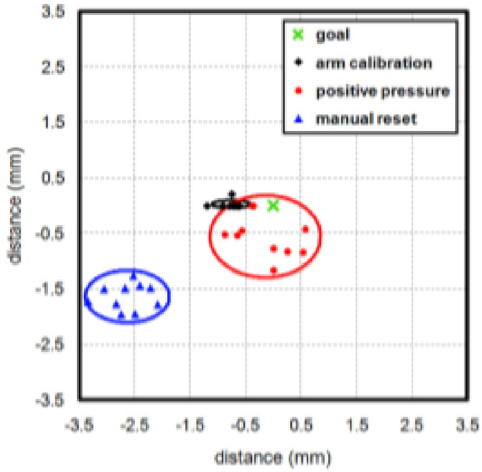

Fig. 8. Placement test results for the calibration of the robot arm, test of the positive pressure gripper, and test of the manually reset gripper. Ellipses represent 95% confidence regions.

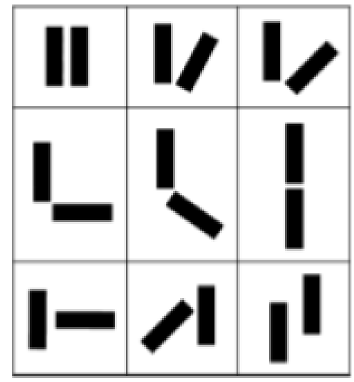

Fig. 9. Nine starting configurations that are used to test the jamming gripper's ability to grip multiple objects at once, shown from a top view.

accuracy with which it can place objects, again using the same test setup from Fig. 4 with slight modifications.

We first performed a calibration procedure to determine the precision and accuracy of the robot arm itself. A pen was firmly mounted to the wrist of the robot, extending to approximately the same point at which a fully reset gripper would make contact with the table. A similar test procedure to Fig. 4 was then executed, with the pen marking a fixed piece of paper at the pick and place positions P_1 and P_2. With this setup, we were able to determine the precision of the arm to be ± 0.35 mm in the worst case for 95% confidence, with an average offset of 0.76 mm from the goal. This result is seven times larger than the manufacturers reported repeatability of ± 0.05 mm, which is likely due to the dynamic effects that are caused by moving the robot arm at full speed.

Next, the pen was removed from the robot arm, and the gripper was reattached. The robot arm was programmed to execute a pick and place routine with the hemisphere, again using the test setup from Fig. 4. Following placement of the hemisphere, we were able to measure its deviation from its intended position in the plane of the table. In this test, only the 18 mm radius hemisphere was used. This hemisphere is similar to the part sizes that are used in the shape test and is well within the 100% success rate range in the reliability test. The dimensions of Fig. 4 were slightly modified for this test: When testing the positive pressure gripper, h_2 was set at 88 mm, and When testing the manually reset gripper, h_2 was set at 71 mm. The results are shown in Fig. 8.

We see from Fig. 8 that the positive pressure gripper places the hemisphere more accurately than the manually reset gripper, while the manually reset gripper is slightly more precise. Specifically, the average deviation of the positive pressure gripper is 0.98 mm from the arm's calibration center, with a precision of ± 1.00 mm in the worst case for 95% confidence, while the average deviation for the manually reset gripper is 2.63 mm from the arm's calibration center, with a precision of ± 0.76 mm in the worst case for 95% confidence.

The precision and accuracy in angular placement is comparable between the two grippers. Here, however, the manually reset gripper slightly was more accurate, while the positive pressure gripper was slightly more precise. The manually reset gripper rotated the hemisphere by 5.4° on average, $\pm 3.4°$ for 95% confidence. The positive pressure gripper rotated the hemisphere by 7.5° on average, $\pm 1.8°$ for 95% confidence.

The placement accuracy improvement that we observe for the positive pressure jamming gripper enables repeatable shooting behavior presented later in Section III-G. It should be noted that it is not strictly necessary to apply the positive pressure exactly at the moment of object release and that releasing the object and resetting the gripper can be separated into distinct operations. If the improved placement precision of the manual reset gripper is preferred, one could calibrate for the constant offset in placement accuracy and then simply release the vacuum to drop the object and pressurize the gripper later to reset it.

F. Multiple Objects

A unique feature of jamming grippers is their ability to grip multiple closely spaced objects simultaneously while maintaining their relative position and orientation. An example of this was shown in Fig. 1. To quantify this capability, we used two cuboids as test parts—each 13 × 13 × 45 mm. The gripper was evaluated to pick these objects at the nine starting configurations that are shown in Fig. 9. We again implemented the test procedure from Fig. 4 with the same modifications that are specified in the placement precision test. For each test, the centroid of the combined shape was located on the central axis of the gripper. The relative distance and angle between the two objects was recorded before and after the gripping operation.

We found that for relative distance, the manually reset gripper tended to increase the separation between the objects by 0.8 mm on average, ± 8.6 mm for 95% confidence, while the positive pressure gripper tended to increase the separation between the objects by 7.7 mm on average, ± 10.7 mm for 95% confidence. In terms of relative angle, the manually reset gripper changed the angle between the objects by 6.7° on average, ±20.5° for 95% confidence, while the positive pressure gripper changed the angle between the objects by 5.2° on average, ±22.2° for 95% confidence.

This test shows a significant decrease in accuracy from the previous test, where only one object was used. The increase in error is likely the result of grips that occur away from the central axis of the gripper, where off-axis forces that tend to rotate or translate the gripped objects are more likely to occur. The performance of the positive pressure gripper is slightly inferior to the manually reset gripper in this test, presumably because the rapid expansion of the membrane during the ejection of the object magnifies these off-axis forces, producing increased rotations and translations of the gripped objects. This test reveals the importance of centering objects on the gripper's central axis in order to maximize placement accuracy.

The performance of both the positive pressure gripper and the manually reset gripper in this test indicates that they can be used to grip multiple objects at once but that their ability to maintain the relative distance and angle between the objects is only suitable for tasks where a lower degree of accuracy is required. For example, this capability may be useful for transferring multiple aligned parts prior to a more accurate assembly operation.

G. Shooting

The fast ejection of objects by positively pressurizing the gripper enables the gripper to launch or shoot objects a significant distance. Other grippers are typically unable to throw or shoot objects on their own, instead relying on the robot arm to provide the momentum for throwing. To study the shooting capability of the positive pressure jamming gripper, we developed the test that is shown in Fig. 10. The gripper picks up the object at a known location and then moves to the shooting location ($h_4 = 290$ mm, $\phi = 45°$). A 0.1 s burst of pressurized air (2.16 L/s at 620 kPa) is then applied, and the shooting distance L is measured. Seven 38 mm diameter spheres weighing between 5 and 45 g were tested, along with the six additional shapes that were used in the holding force test. Results are shown in Fig. 10.

It can be seen that mass does not to have a significant influence on the travel distance of ejected spheres. We can then infer that the jamming gripper acts as a velocity source rather than a force source. This is useful because it means the angle ϕ is the relevant control parameter for shooting. It can also be seen that other objects tend not to travel as far as spheres. This can be explained by the increased likelihood that the ejection velocity vector is not aligned with the center of these objects and is instead partially lost in rotating the object. In addition, these nonspherical objects will likely experience increased atmospheric drag. Furthermore, the four objects that travel the shortest distance have the sharpest corners. This could indicate that a sharply bent membrane cannot relax as quickly and, thus, gives the object a lower initial velocity.

In general, for angle $\phi = 45°$ and $h_4 = 290$ mm, objects of varying size and weight can be ejected 602 mm ± 127 mm with 95% confidence, which can be improved if the shape of the object is known. Precision in the perpendicular direction is

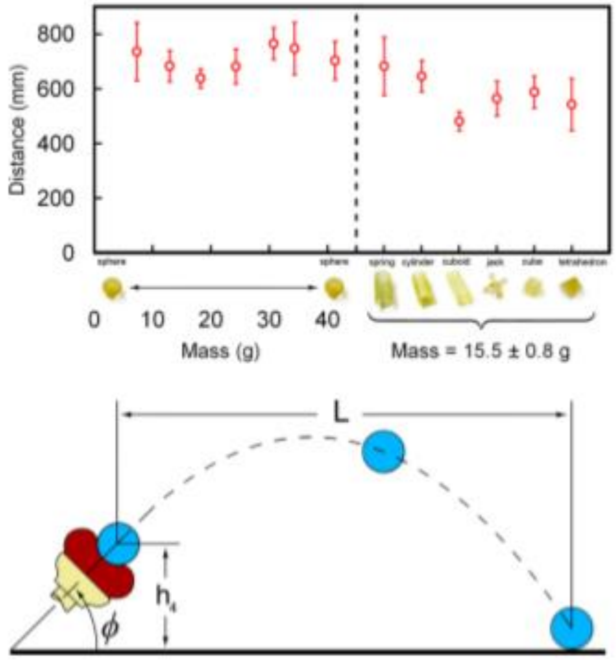

Fig. 10. Shooting test (top) results and (bottom) setup. The gripper shoots the object from angle ϕ and height h_4 so that distance L can be measured. Results show the shooting distance for seven spheres of varying mass and six other objects with the same mass and varying shape.

±60 mm for 95% confidence. This is certainly too coarse for high-precision manufacturing tasks but could be useful for tasks like sorting objects into bins in a factory or throwing away trash in a home.

IV. Related Grippers

To compare passive- and underactuated-type universal grippers with one another is a surprisingly difficult task. Grippers in this group often derive their utility from a unique gripping approach, and this, in turn, necessitates an equally unique set of tests to demonstrate the gripper's capabilities. No standard set of benchmark tests is followed in the literature. Further, many of the references in this field focus primarily on the design, manufacturing, and control strategies that are implemented in their particular gripper and, thus, provide minimal quantitative performance data. Some of the seemingly critical performance parameters that we have presented here (especially placement precision) are mostly absent from the related literature. Finally, most all of these grippers are singular prototypes that are produced for research purposes and, therefore, cannot be obtained for further testing.

In this paper, we too have devised a customized set of tests that we believe objectively and quantitatively reveal both the capabilities and limitations of our proposed gripper. We are able to compare the positive pressure jamming gripper with other passive- and underactuated-type universal grippers, as shown in Table I. Here, the ***DOF at Joints*** column indicates the number of DOF at traditional joints, such as revolute or ball and

TABLE I
COMPARISON OF PASSIVE- AND UNDERACTUATED-TYPE UNIVERSAL GRIPPERS

Gripper Name	DOF at Joints (number)	Additional Compliance (Y/N)	No. of Actuators	Object Size Range (% of size)*	Error Tolerance (% of size)†	Grip/Pinch Force (N)	Holding Force (N)	Placement Precision (mm)	Actuation Time (s)
Positive Pressure Jamming Gripper	NA	Y	1	<10 - 85	≈72	∼0.1 - 10	∼1 - 100	±1.00	0.1 - 1.1
100G [34][35]	4	N	1	unknown	unknown	unknown	unknown	unknown	0.025
CAVG [7][36]	80	N	2	?- >100	unknown	0	unknown	unknown	unknown
Keio Underactuated [37]	15	Y	1	∼human	NA	25-65	10-50	NA	0.8
Laval Underactuated [38]	15	N	1	∼human	unknown	2.5	40	unknown	unknown
Omnigripper [6]	255	N	1	≈1-90	<50	unknown	19.6	unknown	unknown
RTR II [39][40]	9	N	2	unknown	NA	4-20	≈1-5	NA	unknown
SARAH [16][17][18]	10	N	2	?-120	unknown	67-222	>267	unknown	3.5
SDM Hand [13][14][15]	8	Y	1	?-125	≈47	30	unknown	unknown	unknown
Soft Gripper [11][12]	18	N	2	unknown	unknown	0.2 N/cm	unknown	unknown	unknown
SPRING hand [41]	8	N	1	∼human	NA	5-10	≈1	NA	unknown
Starfish gripper [8]	NA	Y	1	≈17-83	unknown	unknown	≈0.5-3	unknown	unknown
TBM Hand [42]	6	N	1	∼human	NA	14	unknown	NA	4-5
TUAT/Karlsruhe [43]	20	N	1	∼human	unknown	unknown	unknown	unknown	unknown

*r/R; †e/R for $r/R \approx 0.5$ (r, R, and e are defined in Fig. 6).

socket joints. Flexural joints or members that can bend, stretch, or twist in multiple directions are included in the *Additional Compliance* column. The *Object Size Range* column specifies the range of objects that the gripper can pick up. This is normalized to the gripper size by dividing approximate object radius by approximate gripper radius (*r*/*R*). If the gripper is a five-fingered hand based closely on the dimensions of a human hand, then we replace otherwise unreported size ranges with ∼human. The *Error Tolerance* column is also normalized to the gripper size using an object with approximately half the radius of the gripper. With this constant object size, error tolerance is the maximum tolerable error in object location divided by gripper radius (*e*/*R*). For grippers that are intended specifically for prosthetic uses, we replace unreported values in the *Error Tolerance* and *Placement Precision* columns with NA, as these are typically the responsibility of the prosthesis operator rather than the hand itself. Any values that are not specifically reported in the literature but that could be closely estimated were added to the table.

We have limited our survey to grippers that have two actuators or less and at least three times as many DOF as actuators. We believe this is the appropriate bound for comparison because at the cutoff, it includes multifingered hands such as SARAH [16]–[18], which have some meaningful similarities in the area of shape adaptation, but it excludes others like the Barrett Hand [33], which are more highly actuated and with which a comparison would have little utility. This survey is not exhaustive (particularly, in the area of prosthetics and five-fingered hands) but serves to illustrate the trend of underreported and unknown performance metrics in the related literature. We hope that the performance-centric approach of this paper will provide some new benchmarks for future work in the field.

From Table I, we can see that the positive pressure jamming gripper is the top performer in both error tolerance and placement precision, and its performance on the remaining tests is also very good. There is no column in which the positive pressure jamming gripper is an obvious underperformer. These results further support the potential adoption of universal jamming grippers for tasks where low complexity but high versatility are required.

V. CONCLUSION

In this paper, we have presented a passive universal jamming gripper that incorporates both positive and negative pressure. The design and manufacture of a prototype gripper were described, and this prototype was evaluated against five metrics that revealed its capabilities for real-world applications. The positive pressure gripper proved capable at gripping objects of different size and shape, and when compared with a version without positive pressure, it showed an increase in reliability of up to 85% and an increase in error tolerance of up to 25%. The positive pressure gripper also applied up to 90% less force on target objects, demonstrated an increase in placement accuracy, and was able to extend its workspace up to 600 mm by shooting objects. This ability to manipulate objects by shooting may be useful for tasks like sorting objects into bins in a factory or throwing away trash in a home.

With this jamming gripper, objects of very different shape, weight, and fragility can be gripped, and multiple objects can be gripped at once while maintaining their relative distance and orientation. This diversity of abilities may make the gripper well suited for use in unstructured domains ranging from military environments to the home and, perhaps, for variable industrial tasks, such as food handling. The gripper's airtight construction also provides the potential for use in wet or volatile environments and permits easy cleaning. Its thermal limits are determined only by the latex rubber membrane, because of the temperature independence of the jamming phase transition; therefore, use in high- or low-temperature environments may also be possible with a modified design. Furthermore, the soft malleable state that the gripper assumes between gripping tasks could provide an improvement in safety when deployed in close proximity with humans, as in the home, for example.

The durability of a single latex membrane could be a concern, and we believe that future work in this area will lead to improved membrane materials. It should be noted, however, that throughout our several hundreds of tests conducted for this paper, the latex membrane never failed and showed no visible signs of wear.

We have demonstrated a jamming-based gripper with a number of unique capabilities and adept performance. However, the gripper that is presented here is still a fairly early prototype. We believe that significant performance gains are possible and that further research will serve to optimize the gripper membrane, jamming material, and overall design to produce a gripper that far surpasses the capabilities and performance that are demonstrated here.

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In 2007 and 2008, he was involved in research activities with the Automation Robotics and Mechatronics Laboratory, and the Design of Open Engineering Systems Laboratory, both at SUNY Buffalo. His current research interests include using controlled granular jamming for physically adaptive robots.

Mr. Amend is a Student Member of the American Society of Mechanical Engineers and the American Society for Engineering Education, as well as a National Science Foundation Graduate Research Fellowship recipient.

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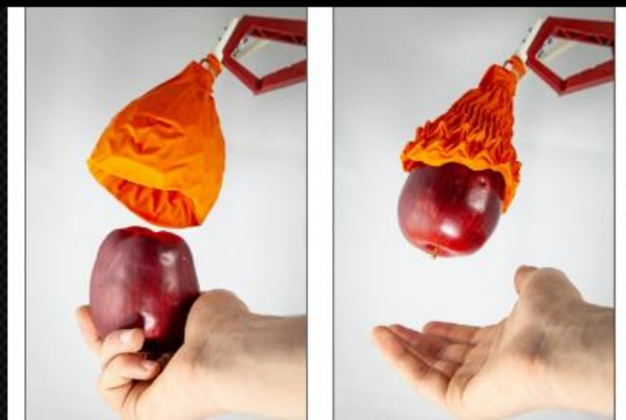
Appendix G: Robot Hand is Soft and Strong

MIT News



The origami gripper can lift a wide range of objects, from apples and soup cans to wine glasses and drones.

Image: Jason Dorfman/MIT CSAIL

Robot hand is soft and strong

Gripper device inspired by “origami magic ball” can grasp wide array of delicate and heavy objects.

Watch Video

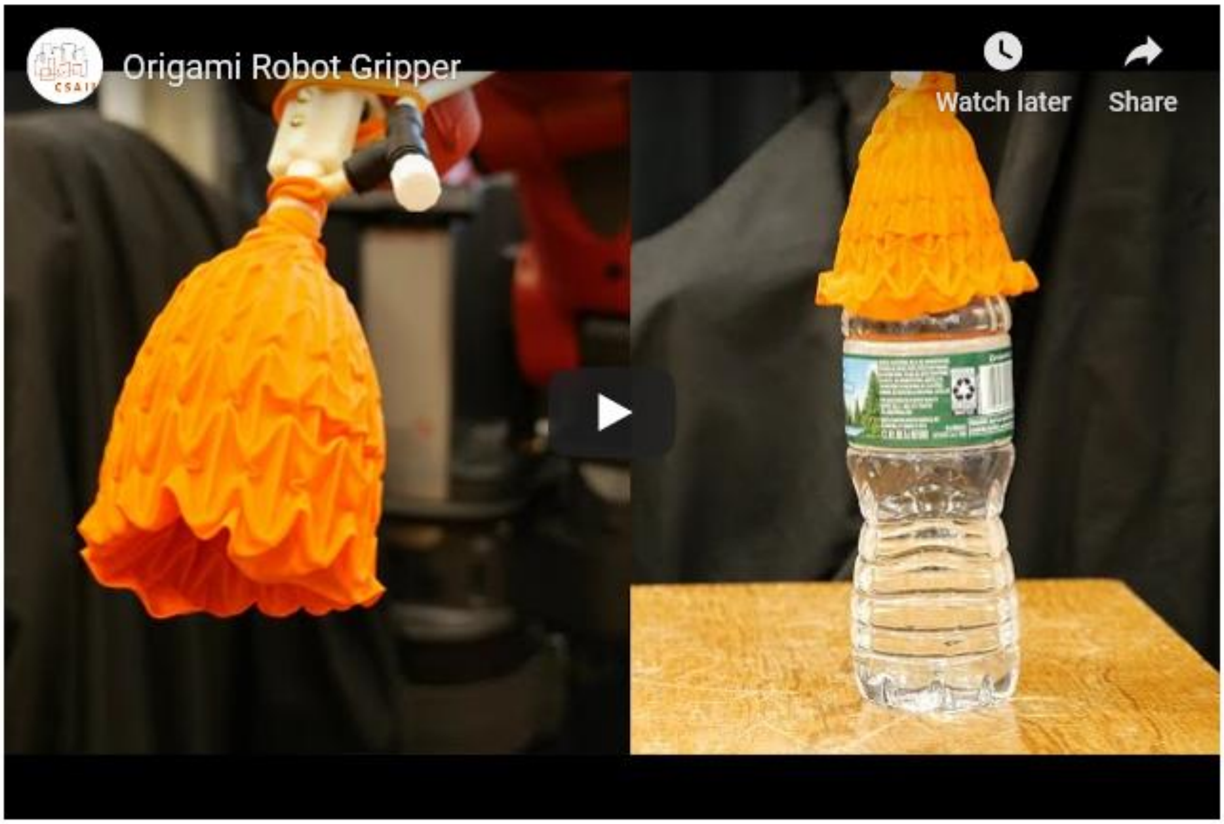
Rachel Gordon | MIT CSAIL
March 15, 2019

Fifty years ago, the first industrial robot arm (called Unimate) assembled a simple breakfast of toast, coffee, and champagne. While it might have looked like a seamless feat, every movement and placement was coded with careful consideration.

Even with today’s more intelligent and adaptive robots, this task remains difficult for machines with rigid hands. They tend to work only in structured environments with predefined shapes and locations, and typically can't cope with uncertainties in placement or form.

In recent years, though, roboticists have come to grips with this problem by making fingers out of soft, flexible materials like rubber. This pliability lets these soft robots pick up anything from grapes to boxes and empty water bottles, but they’re still unable to handle large or heavy items.

To give these soft robots a bit of a hand, researchers from MIT and Harvard University have developed a new gripper that’s both soft and strong: a cone-shaped origami structure that collapses in on objects, much like a Venus' flytrap, to pick up items that are as much as 100 times its weight. This motion lets the gripper grasp a much wider range of objects — such as soup cans, hammers, wine glasses, drones, and even a single broccoli floret.



“One of my moonshots is to create a robot that can automatically pack groceries for you,” says MIT Professor Daniela Rus, director of MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) and one of the senior authors of a new paper about the project.

“Previous approaches to the packing problem could only handle very limited classes of objects — objects that are very light, or objects that conform to shapes such as boxes and cylinders — but with the Magic Ball gripper system we've shown that we can do pick-and-place tasks for a large variety of items ranging from wine bottles to broccoli, grapes and eggs,” says Rus. “In other words, objects that are heavy and objects that are light. Objects that are delicate, or sturdy, or that have regular or free-form shapes.”

The project is one of several in recent years that has researchers thinking outside the box with robot design. Ball-shaped grippers, for example, can handle a wider range of objects than fingers, but still have the issue of limited angles. Softer robotic fingers typically use compressed air, but aren't strong enough to pick up heavier objects.

The structure of this new gripper, meanwhile, takes an entirely different form. Cone-shaped, hollow, and vacuum-powered, the device was inspired by the “origami magic ball” and can envelope an entire object and successfully pick it up.

The gripper has three parts: the origami-based skeleton structure, the airtight skin to encase the structure, and the connector. The team created it using a mechanical rubber mold and a special heat-shrinking plastic that self-folds at high temperatures.

The magic ball's skeleton is covered by either a rubber balloon or a thin fabric sheet, not unlike the team's previous research on fluid-driven origami-inspired artificial muscles, which consisted of an airtight skin surrounding a foldable skeleton and fluid.

The team used the gripper with a standard robot to test its strength on different objects. The gripper could grasp and lift objects 70 percent of its diameter, which allowed it to pick up and hold a variety of soft foods without causing damage. It could also pick up bottles weighing over four pounds.

"Companies like Amazon and JD want to be able to pick up a wider array of delicate or irregular-shaped objects, but can't with finger-based and suction-cup grippers," says Shuguang Li, a joint postdoc at CSAIL and Harvard's John A. Paulson School of Engineering and Applied Sciences. "Suction cups can't pick up anything with holes — and they'd need something much stronger than a soft-finger-based gripper."

The robot currently works best with cylindrical objects like bottles or cans, which could someday make it an asset for production lines in factories. Not surprisingly, the shape of the gripper makes it more difficult for it to grasp something flat, like a sandwich or a book.

"One of the key features of this approach to manipulator construction is its simplicity," says Robert Wood, co-author and professor at Harvard's School of Engineering and Wyss Institute for Biologically Inspired Engineering. "The materials and fabrication strategies used allow us to rapidly prototype new grippers, customized to object or environment as needed."

In the future, the team hopes to try to solve the problem of angle and orientation by adding computer vision that would let the gripper "see", and make it possible to grasp specific parts of objects.

"This is a very clever device that uses the power of 3-D printing, a vacuum, and soft robotics to approach the problem of grasping in a whole new way," says Michael Wehner, an assistant professor of robotics at the University of California at Santa Cruz, who was not involved in the project. "In the coming years, I could imagine seeing soft robots gentle and dexterous enough to pick a rose, yet strong enough to safely lift a hospital patient."

Other co-authors of the paper include MIT undergraduates John Stampfli, Helen Xu, Elian Malkin, and Harvard Research Experiences for Undergraduates student Evelin Villegas Diaz from St. Mary's University. The team will present their paper at the International Conference on Robotics and Automation in Montreal, Canada, this May.

This project was supported in part by the Defense Advanced Research Projects Agency, the National Science Foundation, and Harvard's Wyss Institute.

Appendix H: Balloon Filled with Ground Coffee Makes Ideal Robotic Gripper

Cornell University

CORNELL CHRONICLE

Balloon filled with ground coffee makes ideal robotic gripper

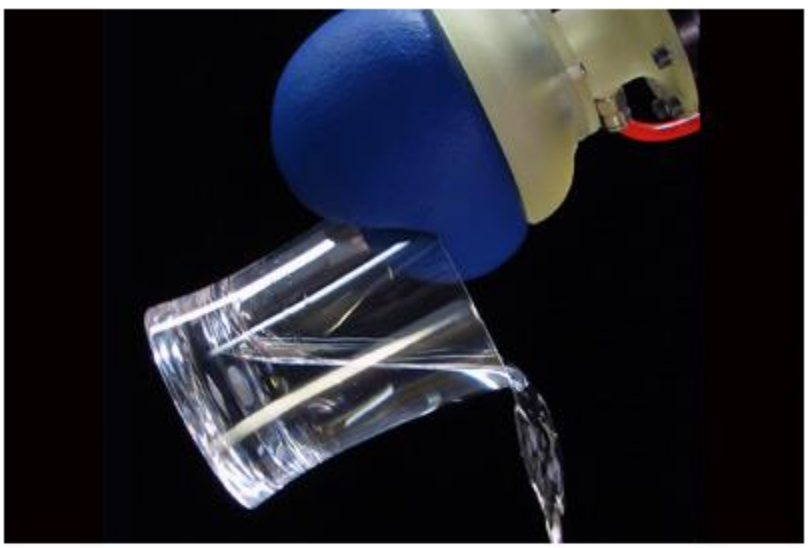
By Anne Ju | October 25, 2010

Robert Barker/University Photography

Graduate student John Amend, left, and associate professor Hod Lipson with the universal robotic gripper. Watch the gripper in action.

The human hand is an amazing machine that can pick up, move and place objects easily, but for a robot, this "gripping" mechanism is a vexing challenge. Opting for simple elegance, researchers from Cornell, the University of Chicago and iRobot Corp. have created a versatile gripper using everyday ground coffee and a latex party balloon, bypassing traditional designs based on the human hand and fingers.

They call it a universal gripper, as it conforms to the object it's grabbing, rather than being designed for particular objects, said Hod Lipson, Cornell associate professor of mechanical engineering and computer science. The research is a collaboration between the groups of Lipson, Heinrich Jaeger at the University of Chicago, and Chris Jones at iRobot. It is published online Oct. 25 in Proceedings of the National Academy of Sciences.



John Amend

The robotic gripper conforms to the shape of the item it is lifting.

"This is one of the closest things we've ever done that could be on the market tomorrow," Lipson said. He noted that the universality of the gripper makes future applications seemingly limitless, from the military using it to dismantle explosive devises or to move potentially dangerous objects, robotic arms in factories, on the feet of a robot that could walk on walls, or on prosthetic limbs.

Here's how it works: An everyday party balloon filled with ground coffee -- any variety will do -- is attached to a robotic arm. The coffee-filled balloon presses down and deforms around the desired object, and then a vacuum sucks the air out of the balloon, solidifying its grip. When the vacuum is released, the balloon becomes soft again, and the gripper lets go.

Coffee, Jaeger said, is an example of a particulate material, which is characterized by large aggregates of individually solid particles. Particulate materials have a so-called "jamming transition," which turns their behavior from fluidlike to solidlike when the particles can no longer slide past each other.

This phenomenon is familiar to coffee drinkers who have ever bought vacuum-packed coffee -- hard as a brick until the package is unsealed.

"The ground coffee grains are like lots of small gears," Lipson said. "When they are not pressed together they can roll over each other and flow. When they are pressed together just a little bit, the teeth interlock, and they become solid."

Jaeger explained that the concept of a jamming transition provides a unified framework for understanding and predicting behavior in a wide range of disordered, amorphous materials. All of these materials can be driven into a "glassy" state where they respond like a solid yet structurally resemble a liquid, and this includes many liquids, colloids, emulsions or foams, as well as particulate matter consisting of macroscopic grains.

"What is particularly neat with the gripper is that here we have a case where a new concept in basic science provided a fresh perspective in a very different area -- robotics -- and then opened the door to applications none of us had originally thought about," Jaeger said.

Eric Brown, a postdoctoral researcher, and Nick Rodenberg, a physics undergraduate, worked with Jaeger on characterizing the basic mechanisms that enable the gripping action. Prototypes of the gripper were built and tested by Lipson and Cornell graduate student John Amend, as well as at iRobot.

As for the right particulate material, anything that can jam will do in principle, and early prototypes involved rice, couscous and even ground-up tires, Amend said. They settled on coffee because it's light but also jams well, Sand did better on jamming but was prohibitively heavy. What sets the jamming-based gripper apart is its good performance with almost any object, including a raw egg or a coin -- both notoriously difficult for traditional robotic grippers.

The project was supported by the Defense Advanced Research Projects Agency.

Computing & Information Sciences | Physical Sciences & Engineering

Appendix I: McAllister MM2220-S Datasheet

Product Data Sheet
Style MM2220-S Alumina Fabric
McAllister Mills, Inc.
Revised: September 6, 2011

WEIGHT:	19.76 oz/yd2
THICKNESS:	.038"
BREAKING STRENGTH:	403 lbs/inch
FIBER:	Alumina
WEAVE:	Satin
WIDTH:	40"
ROLL LENGTH:	33 yards
SERVICE TEMPERATURE:	2300 F°

Style MM2220-S is a tough and durable woven fabric made from high strength continuous alumina fibers. Boron free, this material performs with superior flexibility at service temperature. Typical applications in the petrochemical, steel and semiconductor industries.

www.mcallistermills.com 276-773-3114

Appendix J: McAllister Silica Datasheet

Product Data Sheet
Style MM36-88-36 Silica Fabric
McAllister Mills, Inc.
Revised: September 6, 2011

WEIGHT:	36 oz/sq.yd
THICKNESS:	.054"
WEAVE:	12-H Satin
SILICA CONTENT:	95% Min.
BREAKING STRENGTH: METHOD: FED STD 191/5102	Warp: 480 Fill: 330
COLOR:	Tan
WIDTH:	36"
TEMPERATURE RESISTANCE:	1800 F. Continuous 3000 F. Melt Temperature
ROLL LENGTH:	50 YARDS APPROX
FINISH:	Vermiculite coated

MEETS U.S. COAST GUARD SPECIFICATION 164.009 FOR INCOMBUSTIBLE MATERIAL.
MEETS ASTM-E-84 FOR INCOMBUSTIBLE MATERIAL

www.mcallistermills.com 276-773-3114

Appendix K: Bead Pellets MSDS

ZIRCONIA CERAMIC BEADS (all grades)

Material Safety Data Sheet

COMPANY: Graystar* LLC
ADDRESS: 9 Simmonsville Road
Bluffton, SC 29910
PHONE: 843-815-5600

1. Identification of the substance:

Trade Name: Zirconia Ceramic Beads (ZCB), also named as Zirconia Silicate Beads (ZSB), or Peening Media / Ceramic Shot.

2. Composition and information about ingredients:

Zirconia ceramic beads are white inorganic pellets, which are produced by using a fusion process. The beads are mainly composed of Zirconium dioxide, silicate and other trace elements.

Substance and formula	%
Zirconium oxide ZrO_2	68
Silicon oxide SiO_2	31
Other inorganic matters	Less than 1

3. Hazards Identification:

The product is not classified as hazardous and/or harmful under environmental control. It contains no substances classified as hazardous or harmful to health.

4. First Aid Measures:

Generally: No hazards requiring special first aid measures.

Inhalation:	Move to fresh atmosphere. Give symptomatic treatment if necessary.
Skin contract:	Wash with water and soap
Eye contact:	Wash with water or neutral eyewash solution
Ingestion:	Do not induce vomiting; Give up to 200 ml water. Material is non-toxic and not retained in intestinal tract.

In case of persistent symptoms consult a doctor.

5. Fire-fighting Measures:

The product itself and the packing materials are not flammable, explosive and give no reason to be a fire risk. No special preventive action and protection matters/techniques for fire-

6. Accidental Release Measures:

This product is inert. No special personal or environmental precautions are required. Use any feasible mechanical means for cleaning (e.g. shovel, vacuum sweeping) but avoid dusting. Prevent contamination of sewerage and ditches leading to natural waterways.

7. Handing and Storage:

The product is typically packed in stainless iron drums. No special handling technique is required, but handing system should be designed and operated to minimize dust escape and/or cracking. No special storage conditions are demanded.

8. Exposure Controls / Personal Protection:

Respiratory protection	The use of exhaust ventilation at machinery and places where dust can be generated is recommended. An approved dust respirator must be used if the dust concentration is likely to exceed the occupational exposure limit or when dustiness is over 10 mg/m3.
Skin protection	The product is not an irritant. Prolonged exposure should be avoided by wearing suitable protective gloves and clothing.
Eye protection	The use of approved tightly fitting safety goggles is recommended if dust concentrations are likely to exceed the occupational exposure limit of 10 mg/m3.
Hygiene measures	No special requirements except keeping basic rules of hygiene.

9. Physical and Chemical Properties:

Physical State	Fine spherical pellets or beads
Color	White, partly grayish
Color	Odorless
Bulk specific weight	2.35
Real specific weight	3.86
Beads size range (mm)	0.2-0.4, 0.4-0.6, 0.6-1.0, 0.8-1.25, 1.0-1.6, 1.6-2.0, 2.0-2.5
Solubility	Insoluble in fats, water, alkalis, diluted acids and organic solvents. Dissolves slowly in hydrofluoric acid or hot concentrated sulphuric acid.

10. Stability and Reactivity:

Material is stable under normal conditions (up to 2300C) and inert to most chemical reagents.

11. Toxicological Information:

The product is not toxic and/or genotoxic. No acute or chronic effects have been reported.

12. Ecological Information:

The product is inert, not biologically active and non-biodegradable. The mobility of solid particles in environment is limited. Prevent contamination of sewerage surface and subterranean waters.

13. Disposal Considerations:

Spilled material can be disposed as non-toxic waste in accordance with local and national regulations.

14. Transport Information:

Material is not labeled as dangerous. There are no special requirements under national or international regulations for the transportation by road, rail, sea or air.

15. Further Information:

The product described in this document is only designed for industrial or related use, such as research and development, by qualified persons.

16. Disclaimer:

Although reasonable care has been taken in the preparation of the information contained herein, the originator and **Graystar*LLC** extends no warranties, makes no representation and assumes no responsibility as to the accuracy of suitability of such information for application to the purchaser's intended purposes or for consequences of its use.

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Appendix L: Sand SDS

SAFETY DATA SHEET (SDS): ALL PURPOSE SAND

SECTION I –IDENTIFICATION		
PRODUCT IDENTIFIER All Purpose Sand	TRADE NAME Sand	OTHER SYNONYMS Play Sand, Silica Sand, Quartz Sand, Concrete Sand, Blended Sand, Mason Sand, Asphalt Sand, Filter Media, Foundry Sand, Golf Course Sand, Golf Sand
RECOMMENDED USE AND RESTRICTION ON USE Used for construction purposes This product is not intended or designed for and should not be used as an abrasive blasting medium.		
MANUFACTURER/SUPPLIER INFORMATION Martin Marietta Materials 2710 Wycliff Road Raleigh, North Carolina 27607 Phone: 919-781-4550 For additional health, safety or regulatory information and other emergency situations, call 919-781-4550		

SECTION II – HAZARD(S) IDENTIFICATION

HAZARD CLASSIFICATION:
Category 1A Carcinogen
Category 1 Specific Target Organ Toxicity (STOT) following repeated exposures
Category 2A Eye Irritant
Category 2 Skin Irritant

SIGNAL WORD: DANGER

HAZARD STATEMENTS:
May cause cancer by inhalation.
Causes damage to lungs, kidneys and autoimmune system through prolonged or repeated exposure by inhalation.
Causes skin irritation and serious eye irritation.

PRECAUTIONARY STATEMENTS
Do not handle until the safety information presented in this SDS has been read and understood.
Do not breathe dusts or mists. Do not eat, drink or smoke while manually handling this product. Wash skin thoroughly after manually handling.
If swallowed: If gastrointestinal discomfort occurs and if person is conscious, give a large quantity of water and induce vomiting; however, never attempt to make an unconscious person drink or vomit.
If on skin (or hair): Rinse skin after manually handling and wash contaminated clothing if there is potential for direct skin contact before reuse.
If inhaled excessively: Remove person to fresh air and keep comfortable for breathing.
If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do, and continue rinsing.
If exposed, concerned, unwell or irritation of the eyes, skin, mouth or throat/nasal passage persist: Get medical attention.
Wear eye protection and respiratory protection following this SDS, NIOSH guidelines and other applicable regulations. Use protective gloves if manually handling the product.

Avoid creating dust when handling, using or storing. Use with adequate ventilation to keep exposure below recommended exposure limits.

Dispose of product in accordance with local, regional, national or international regulations.

Please refer to Section XI for details of specific health effects of the components.

SECTION III – COMPOSITION/INFORMATION ON INGREDIENTS		
COMPONENT(S) CHEMICAL NAME	CAS REGISTRY NO	% by weight (approx)
Silicon Dioxide (SiO_2)(1) Calcium Carbonate ($CaCO_3$)	7631-86-9 471-34-1	50-100 0-50

(1): The composition of SiO_2 may be up to 100% crystalline silica, content of this material varies naturally

SECTION IV – FIRST-AID MEASURES

INHALATION: If excessive inhalation occurs, remove to fresh air. Dust in throat and nasal passages should clear spontaneously. Contact a physician if irritation persists or develops later.

EYES: Immediately flush eye(s) with plenty of clean water for at least 15 minutes, while holding the eyelid(s) open. Occasionally lift the eyelid(s) to ensure thorough rinsing. Remove contact lenses, if present and easy to do, and continue rinsing. Beyond flushing, do not attempt to remove material from the eye(s). Contact a physician if irritation persists or develops later.

SKIN: Rinse skin with soap and water after manually handling and wash contaminated clothing if there is potential for direct skin contact. Contact a physician if irritation persists or develops later.

INGESTION: If gastrointestinal discomfort occurs and if person is conscious, give a large quantity of water and induce vomiting; however, never attempt to make an unconscious person drink or vomit. Get medical attention.

SIGNS AND SYMPTOMS OF EXPOSURE: There are generally no signs or symptoms of exposure to respirable crystalline silica. Often, chronic silicosis has no symptoms. The symptoms of chronic silicosis, if present, are shortness of breath, wheezing, cough and sputum production. The symptoms of acute silicosis which can occur with exposures to very high concentrations of respirable crystalline silica over a very short time period, sometimes as short as 6 months, are the same as those associated with chronic silicosis; additionally, weight loss and fever may also occur. The symptoms of scleroderma, an autoimmune disease, include thickening and stiffness of the skin, particularly in the fingers, shortness of breath, difficulty swallowing and joint problems.

Direct skin and eye contact with dust may cause irritation by mechanical abrasion. Some components of the product are also known to cause irritant effects to skin, eyes and mucous membranes. Ingestion of large amounts may cause gastrointestinal irritation and blockage. Inhalation of dust may irritate nose, throat, mucous membranes and respiratory tract by mechanical abrasion. Coughing, sneezing, chest pain, shortness of breath, inflammation of mucous membrane, and flu-like fever may occur following exposures in excess of appropriate exposure limits. Repeated excessive exposure may cause pneumoconiosis, such as silicosis and other respiratory effects.

SECTION V – FIRE-FIGHTING MEASURES

EXTINGUISHING AGENT
Not flammable; use extinguishing media compatible with surrounding fire.

UNUSUAL FIRE AND EXPLOSION HAZARD
Contact with powerful oxidizing agents may cause fire and/or explosions (see Section X of this SDS).

SPECIAL FIRE FIGHTING PROCEDURES	HAZARDOUS COMBUSTION PRODUCTS
None known	None known