Design of a Parallel-Type Gripper with Force Control

Erica Tevere

University of Michigan – Ann Arbor

etevere@umich.edu

Prof. Dmitry Berenson

December 21, 2018

Design of a Parallel-Type Gripper with Force Control

Erica Tevere

***Abstract*—This report reviews the development of a custom parallel gripper for use in experimental testing. The issue with the previous solution is that the mechanism extends a large distance off the wrist of the robot and is very expensive. As a result, researchers in the Autonomous Robotic Manipulation Lab are limited by testing capabilities and opportunities. The entire engineering design cycle was completed to develop a custom parallel gripper that would meet the needs of the researchers. Focal points of the gripper were on modularity, manufacturability, distance extended off the wrist, and cost. After cycling through a large set of iterations of the mechanical hardware, electronics, and controller of the system, the design converged to the final gripper being presented in this paper. This resultant gripper is 35% lighter, has 57% less distance extended off of the robot wrist, and is over $15,000 cheaper than the previous gripper. With strong improvements in the categories needed, this custom parallel gripper will be able to be easily adjusted and used by researchers in the lab for their testing.**

I. Introduction

As a roboticist, there are already so many limitations in the technologies available that it can be frustrating when research and experimental testing is limited by physical capabilities of hardware. While most robots, especially collaborative robots like the KUKA LBR iiwa, are robust enough to adjust to certain levels of uncertainty in the environment [1], many end effectors and grippers are truly limited by their design. Examples of these limitations can be seen in many commercial grippers available on the market. The Robotiq 3 finger adaptive gripper is an incredible product offering a robust solution to grasping; however, in some cases it can be excessive in functionality while not actually delivering exactly the needs of the roboticists. In addition, it is an expensive piece of hardware to be testing high risk algorithms with. The Robotiq 3 finger adaptive gripper, and products like it tend to have price points around $18,000. This gripper is a great solution to robotics problems where a variety of objects are being grasped in many different configurations; however, as stated before this can be excessive in function if one is looking to work with a smaller range of objects or position configurations.

The problem with the current use of the Robotiq 3 finger gripper is that it is preventing members of the Autonomous Robotic Manipulation (ARM) lab from being able to test their work in all realistic environments and applications. The addition of a robust, modular, and more adaptable gripper would allow these researchers the ability to extend their research into realms they have been barricaded from as a result of the gripper design.

This paper will be broken into four additional sections delving into approach, results, discussion, and conclusion. The paper will look to fully define the problem, describe each step in the process for approaching the problem, evaluate the performance of the project, discuss the successes and failures of the project, and make recommendations for future work to compliment the current status of the project.

II. Approach

A standard engineering design cycle approach was used to find a solution to the stated problem. The engineering design cycle model followed can be broken down into seven sections- ask, research, imagine, plan, create, test, and improve- each which served a different purpose in developing the final product. The sections are broken down below to identify and discuss the approach of each step in further detail.

A. *Step 1: Ask- Identify the Need and Constraints*

The problem being addressed was a need to replace the current Robotiq 3 finger adaptive gripper being used on the KUKA LBR iiwa for testing as the gripper was preventing lab members from testing their work in all realistic environments and applications. The major issues with the current solution are listed and discussed below:

1) *Gripper Length*: The gripper protrudes off of the media flange at a maximum distance of

254 mm, limiting the maneuvers that can be made by the robot and the versatility of the test environment.

2) *Gripper Availability:* The current gripper costs $18,000 and has a lead time from the manufacturer. Although the gripper is very capable, a large portion of the gripper's capabilities are not needed or used in most testing being performed. The high cost and associated lead time of the gripper requires users to be limited in the scope of testing allowed based on the potential risk of damage to the system.

3) *Gripper Adjustability:* Because the gripper is purchased from a third party the modifications that could be made to the design and function are limited. With a custom modular gripper, components can be altered as needed to adjust the gripper's functionality for specific solutions. Limiting factors of the current gripper can be found in Table I. These limitations include the grip force of 30 to 70 N and gripper mass of 2.3 kg [2]. With a custom gripper, all of these specifications could be adjusted to meet the needs of the experiment.

TABLE I. SPECIFICATIONS OF ROBOTIQ 3 FINGER GRIPPER

Metric	***Value***
Stroke (programmable)	155 mm
Grip force (programmable)	30 to 70 N
Gripper mass	2.3 kg
Distance off media flange	254 mm
Cost	$18,000.00

Based on the major issues with the current gripper, the identified limitations in the design, and input from researchers who have had issues with the current gripper, user needs of a replacement gripper were outlined and can be seen in Table II below. Those user needs were then further specified in terms of performance metrics and translated into design requirements that outline the basic qualifications a replacement gripper would need to meet for success.

TABLE II. USER NEEDS AND DESIGN REQUIREMENTS

User Needs	***Design Requirements***
Better ability to position gripper with respect to the robot wrist	Less than 6 inches of length of gripper extended off of KUKA media flange
Ability to understand design and operation of gripper (including common repairs) with minimal previous knowledge of the gripper	Full computer-aided design (CAD) model, assembly instructions of gripper, and bill of materials provided with final gripper design
Ability to fix gripper quickly and easily	Failure point of the system located in easily accessible place, minimal disassembly of the gripper required
Ability to reproduce gripper easily	75% or more of parts should be purchased from manufacturer and require no machining operations or should be 3D printed
Gripper should be cost effective	Total cost of the gripper should be below $1,000.00
Simple gripper to make and operate	System must be a parallel gripper
System must be electrically powered	System will use a DC motor to actuate the fingers
Similar control of the system	Force control implemented
Gripper must not use the majority of the KUKA payload	Gripper can weigh no more than 2.3 kg

B. *Step 2: Research the Problem*

In performing research of the problem there were many solutions to consider. There is a huge variety of parallel grippers available for purchase on the market; however, a lot of these gripper designs were passed over in consideration as a result of their price, generally around $5,000.00, and their packaging. Many of these available parallel grippers had similar packaging to the Robotiq 3 finger adaptive gripper which would result in the same issue of limited position configuration of the gripper.

Another major area for inspiration for the gripper design was through hobbyist. There is a lot of content available from robotics hobbyists on designing and 3D printing custom parallel grippers. Although a lot of these grippers were ultimately not meant to be used in advanced environments, the hobbyists presented a variety of innovative ideas that helped form baselines for designs of the custom gripper.

C. *Step 3: Imagine – Develop Possible Solutions*

In order to adhere to the design requirements in designing the solution, different designs for a parallel gripper were investigated. In researching the problem, it was demonstrated that the major areas where deviation in design were seen were in the selection of the driveline system, the sliding system for the fingers, and the packaging of the entire system. Three designs were initially modeled and are identified by their driveline systems. Initial computer aided design (CAD) mockups of these designs are seen in Fig. 1, Fig. 2, and Fig. 3 below for visualization purposes.

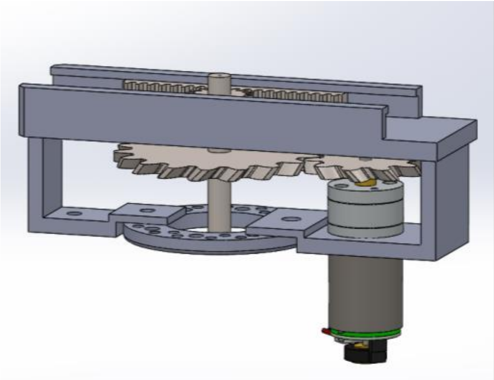

Fig. 1. CAD mockup of rack and pinion concept.

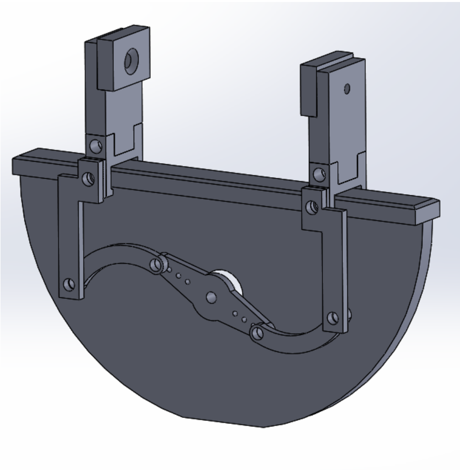

Fig. 2. CAD mockup of rotational linkage concept.

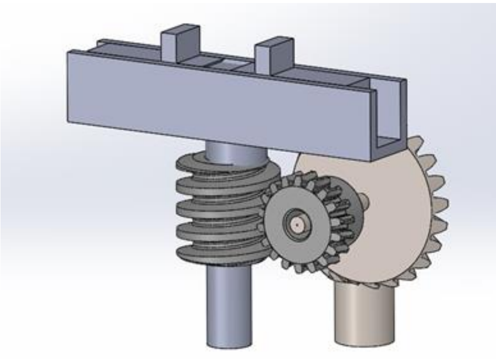

Fig. 3. CAD mockup of worm gear slider concept

D. *Step 4: Plan –Select a Promising Solution*

The designs that were investigated were evaluated using a Pugh Chart whose outcome is shown in Table III.

The criteria of evaluation that were selected were the distance from the mounting, manufacturability of the design, modularity of the design, ease of assembly of the design, and cost effectiveness of the design.

The weight scale had the distance from the mounting criteria ranked as the highest consideration. This was ranked so high because this was one of the major problems with the current design and ensuring this functionality was crucial to the success of the gripper. The second highest criteria was the manufacturability of the design as this is important so that the gripper can be made with ease and potential risk of downtime due to limited availability of parts can be reduced. The last three evaluation criteria – modularity, ease of assembly, and cost effectiveness - were all weighted the same as they are important features of the design, but are less important to the success of the gripper than the other two considered criteria.

For most evaluation criteria, the parallel gripper designs clearly out ranks the current Robotiq gripper. However, the parallel gripper designs were paled when compared to the current solution in the ease of assembly category. This is clearly a set-back of manufacturing a custom gripper verses purchasing a pre-assembled gripper, but ultimately this criteria had no major effect on the overall scores of the parallel gripper designs.

Based on the Pugh Chart evaluation, it was clear that the rack and pinion design had the most ability to exceed the performance of the current solution and other considered designs. This design was selected to further iterate and develop into a final solution.

TABLE III. PUGH CHART

Criteria	***Weight (1-10)***	***Baseline: Current Design***	***Design 1: Rack and Pinion***	***Design 2: Rotational Linkage***	***Design 3: Worm Gear Slider***
Distance from the mounting	10	0	5	3	1
Manufacturability	5	0	4	5	2
Modularity	3	0	3	4	3
Ease of assembly	3	0	-3	-2	-3
Cost effectiveness	3	0	4	5	3
Total Points		0	**82**	76	29

E. *Step 5: Create – Build a Prototype*

The final gripper solution consists of four different subsections: gripper CAD model, gripper hardware, gripper electronics, and force controller. Detail into the development of each portion of the gripper has been deconstructed to better understand the how the final design converged.

1) *Gripper CAD Model:* Before any components of the model were going to be produced, the first requirement was a full CAD model of the gripper. The design work began by piecing the driveline together. Once the driveline was fully assembled in the model and spaced correctly, support features could be designed. These features included the housing components whose deign looked to minimize print material needed while also protecting the internals of the gripper. Lastly, the smaller purchased components such as fasteners, plastic inserts, and alligator clips were placed in the model. The fulll model was evaluated on ease of assembly, manufacturability, and modularity, and adjustments were made to improve the design in those areass of interest. The model was also properly constrained to ensure that it could be used as a playground to design new features for the gripper. Additionally, once a full model of the gripper was created in CAD, design adjustments were made to better refine the model. This included the addition of additional supports in the form of bearings and frictionless sliders. Fig. 4 provides a screenshot of the CAD model of the final gripper design.

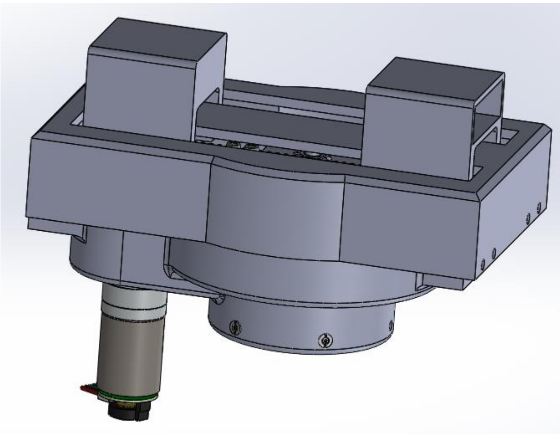

Fig. 4. CAD model of final gripper design

2) *Gripper Hardware:* Once the gripper was designed in CAD and checked for manufacturability, ease of assembly, and modularity, components were ready to be procured and printed. The majority of the gripper did end up being 3D printed using the Form 2 stereolithography (SLA) printer from Formlabs. All of the components in the gripper were either printed in the standard or grey pro resin options. Using the software PreForm, supports were generated and spacing was determined for components to be 3D printed. An example of a component being prepared using the software can be seen in Fig. 5. Hardware that was not 3D printed was procured through third parties such as Amazon or McMaster Carr that offer products with short lead times and competitive prices so that the gripper would not have to be down for an extended period of time if one of the purchased components went bad.

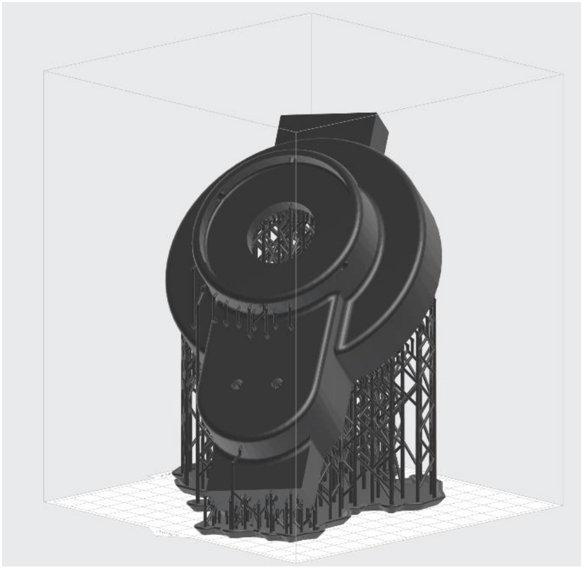

Fig. 5. Bottom gripper housing modeled in Preform

3) *Gripper Electronics:* To prepare the electronics for the gripper, original electronic prototyping was done using an Arduino Uno board, a L298N H-Bridge, and a Pololu 9.7:1 metal gearmotor with a 48 counts per revolution (CPR) encoder. A circuit was created and wired to power the motor and read back the motor position from the encoder. Although this electronic hardware was used for initial prototyping of the gripper, it could not be used when integrated with the KUKA LBR iiwa. For the electronics to be incorporated with the KUKA LBR iiwa, the microprocessor was switched to a the smaller and more compact Raspberry Pi Zero. The Raspberry Pi was coupled with the PiJack Ethernet Hat for Pi Zero as seen in Fig. 6 to allow an Ethernet cord to be plugged into the system. A TB6612 1.2A DC/Stepper motor driver breakout board was also added into the electronic system. Lastly, to move the system to the desired force control, two FlexiForce pressure sensors were also wired into the electronic system.

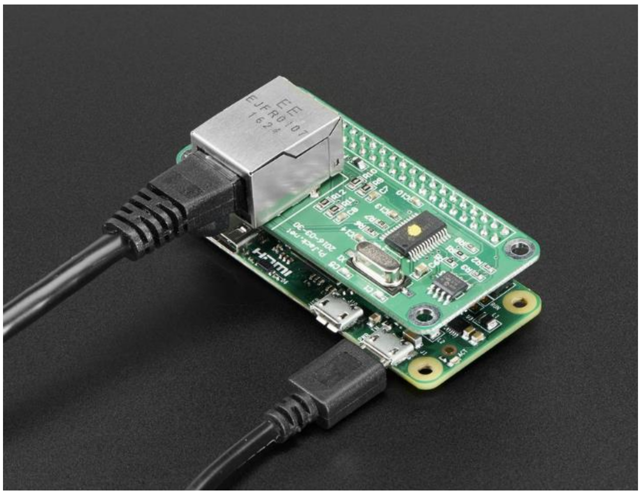

Fig. 6. Raspberry Pi Zero and PiJack Ethernet Hat coupled together [3]

4) *Force Controller:* To produce a custom force controller for the gripper quite a bit of work had to be done to fully characterize the system. First, both the electrical and mechanical systems that are pertinent to the controller were modeled as seen in Fig. 7 and 8 and the governing equations of the systems were derived. Equation 1 represents the governing equation for the electrical system of the motor while equation 2 represents the mechanical system of the rack and pinion.

$$V = L\frac{di}{dt} + iR_m + K_t \quad (1)$$

$$2rF = K_t i \quad (2)$$

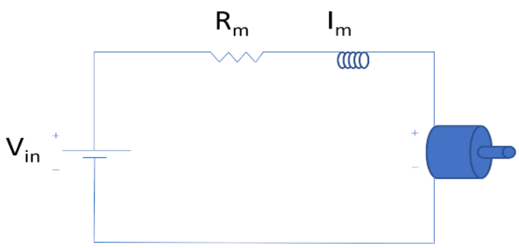

Fig. 7. Model of the electrical system of the motor.

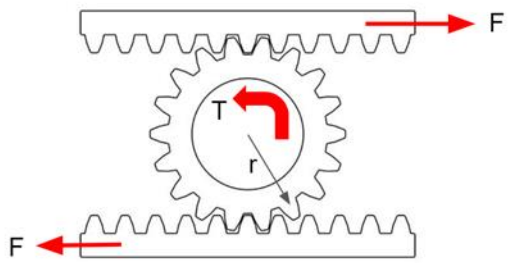

Fig. 8. Model of the mechanical system of the gripper.

The governing equations of the system were combined to then get the transfer function of the overall plant dynamics listed in equation 3.

$$\frac{F(s)}{V(s)} = \frac{K_t}{2r(Ls+R)} \quad (3)$$

Following the characterization of the plant dynamics, the sensor dynamics of the force sensors also had to be identified. The sensor was modeled as a first order system as seen in equation 4.

$$H(s) = \frac{K}{\tau s+1} \quad (4)$$

After both the plant and sensor dynamics were determined, the known constants of the system were found. Constants for the motor were found in the technical data sheet provided by Pololu [4]. Constants for the pinion size were found in the technical data sheet provided by Boston Gear [5]. Constants for the pressure sensors were found in the technical data sheet provided by SparkFun Electronics [6]. Unknown constants are identified in Table IV, and known constants and their values are identified in Table V.

TABLE IV. UNKNOWN CONSTANTS OF THE SYSTEM

Unknown Constant
V, voltage of the motor [V]
i , current of the motor circuit [A]
F , output force on the pinion [N]

TABLE V. KNOWN CONSTANTS OF THE SYSTEM

Known Constant	***Value***
K_t , motor torque constant [NmA]	0.0424
L , impedence of the motor [mH]	20
R_m , resistance of the motor [Ω]	2.14
r , radius of the pinion [m]	0.00740
K, sensor gain [V/N]	0.050
τ, sensor gain [sec]	0.00005

The next step in creating the force controller was choosing the type of controller. A proportional-integral (PI) controller was chosen as a result of the simplicity of the plant and sensor dynamics.

The last step in designing the controller was modeling the controller in Simulink and then tuning the controller using the Ziegler-Nichols method [7]. The full Simulink model can be seen in Fig. 9. The PI controller was tuned and values for proportional gain and integral gain are listed in Table VI. These values for the controller gains allowed the system to have a reasonable settling and rise time while minimizing overshoot and steady-state error. This can be observed from the step response to the system pictured in Fig. 10. In designing this controller, overshoot and steady state error were the most important criteria as if not well constrained by the controller, overshoot and steady-state error could cause the system to potentially damage the object being grasped or not provide enough force to grip the object properly.

TABLE VI. SELECTED CONTROLLER GAINS

Proportional Gain	***Integral Gain***
$K_p = 25$	$K_i = 30$

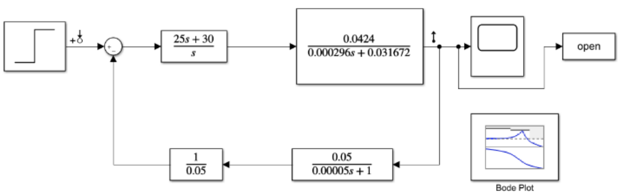

Fig. 9. Simulink model of the force control

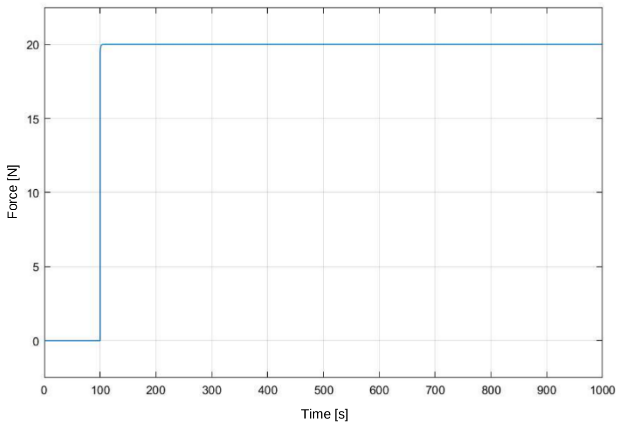

Fig. 10. Step response of the controller to a step of 20 N

F. Step 6: Test and Evaluate Prototype

While and after the gripper was being assembled, testing was performed to identify the best fits for the system, determine the lifecycle and failure mode of the system, quantify the difference in performance of components of different materials, and validate and further tune the hardware and controller.

1) *Manufacturing Testing:* As a large portion of the components did end up being 3D printed, some preliminary testing was required to find correct fits and manufacturing methods for the SLA printing.

a) *Bearing Press:* One of the components that had to be tested was the bearing press fit. Multiple samples of the mating feature in the gripper housing were printed all at different diameters to allow for different interference fits. The bearings were then pressed into these samples, and the fit and function of the bearing was evaluated. The sample that produced the best fit while not deforming the mating piece too extensively was chosen as the diameter for the mating features in the housing.

b) *Insert Installation:* For the selection of thread inserts to be installed into the housing of the gripper a variety of types were ordered and installed into a test piece. The inserts tested were the screw-to-expand style, the pull-out resistant screw-to-expand style, and the barbed insert style. Each style of insert was installed into a test piece and then a screw was repeatedly installed and removed from the test piece. The screw-to-expand inserts proved to be the easiest to install and functioned the longest and best, so that style of insert was chosen for the final gripper design.

2) *Durability Testing:* An important function of the gripper is that it is reliable and issues can be easily fixed. To determine the gripper's reliability and system failure point, the gripper was tested off the KUKA to isolate issues in functionality. Durability testing the prototype gripper also helped identify issues with the design and areas of improvement. Many of the design changes were results of problems seen during durability testing. The final gripper was tested to a desired lifecycle count of 10,000 cycles to validate the design and prove the reliability of the product.

Durability testing also provided an opportunity to locate the failure point of the gripper. The consistent failure point of the system proved to be the racks coming off track with the pinion. This was largely due to bending in the racks after extended lifecycle testing. This failure mode is ideal for the system for a couple of reasons listed below.

- It does not cause additional damage to the hardware. When the racks come off track, the pinion will spin freely one direction and generally engage the racks when spinning the opposite way. This does sometime cause the pinion to rub the rack, but as observed in testing this rubbing has little to no effect on the physical state of the rack or pinion.
- It is easy to replace. Because the final gripper uses a 3D printed rack, it is easy to replace when the component has failed. All that needs to be done is to have a rack printed, which takes less than one hour to complete. In addition, the rack is located in the top layer of the gripper, so when it needs to be replaced, only the rack cover and fingers need to be removed to access the component.

3) *Rack Material Testing:* Some initial durability testing demonstrated that one component of concern in the system was the racks in the rack and pinion portion of the system. Although initial durability testing identified concerns of using one rack material over another, there was no concrete data to support the choice of using a certain material for the rack. As a result of the lack of data to support a design decision, a design of experiment (DoE) was created and performed to test racks made of four different materials and compare their functional performance over extended lifecycles. This DoE is outlined in Table VII below.

TABLE VII. RACK MATERIAL DOE

Rack Material	***Cycle Checkpoints***
Standard clear resin, Formlabs	1000
Grey pro resin, Formlabs	3000
Durable resin, Formlabs	5000
Metal rack with plstic adapter, McMaster Carr	7000
	10000

Although Formlabs provides data about material properties of their resins [8], it seemed that testing the racks in actual application was necessary to determine their true performance. Conclusions from this DoE suggested that although the metal rack with the plastic adapter proved to perform the best in terms of wear resistance and long-term functionality, the grey pro resin rack had comparable performance to the metal rack and managed to complete an acceptable number of lifecycles on the gripper. Considering the additional factor of manufacturability of the racks, the grey pro resin rack outranked the metal rack by a notable amount. In the end, it was concluded that the grey pro resin rack would allow the gripper to function as needed, but would also allow for easy reproduction and replacement if the component did fail on the gripper.

4) *Controller Simulation*: To initially test the force controller electronics before installing onto the gripper, the system was tested on an oscilloscope. Random but realistic inputs were fed to the system and the response was analyzed. In all cases the system responded as expected. This testing allowed validation of the electronics and force controller design. Furthermore, the testing allowed initial issues to be sorted out off of the hardware to protect the hardware from potential damage.

5) *Controller Testing on Gripper:* After initially testing the force control system with an oscilloscope to verify its performance was as expected, the force controller was tested on the gripper using a variety of test objects. These test object included a towel [Fig. 11], a pair of tweezers, a mustard bottle, and a soap bottle. The system was tuned on the gripper which allowed controller gains to be adjusted with respect to the controller's performance when fully integrated with the system.

Fig. 11. Testing controller with common objects such as a towel

G. *Step 7: Improve –Redesign as Needed*

As mentioned previously, durability testing the gripper after each new alteration was made allowed weak components of the system to be easily identified and redesigned to meet desired performance. Some of the notable redesigns are listed below.

- *Pinion size:* After determining that the desired speed of the gripper was higher than the current design, the gripper was redesigned to include a pinion of a smaller diameter.
- *Pinion shaft:* After multiple failures in a 3D printed shaft due to high torque loads and stress risers in the part, the shaft was switched to a solid steel shaft that was machined down to provide more reliable performance.
- *Addition of sliders:* After the identification of built-up friction in the custom designed racks and guide rail system, racks were mounted to a rail and carriage block system to greatly reduce friction in the translation motion.

III. Results

The final results of the gripper met all of the functional design requirements outlined in Table II. The performance was comparable or improved on the majority of performance metrics when directly compared to the Robotiq 3 finger adaptive gripper [Table 1]; however, one performance metric did decrease in value which was the stroke of the gripper. Major improvements of the design include gripper mass, distance off media flange, and cost. The gripper mass decreased by 35%. The distance off the media flange decreased by 57%. The cost of the gripper decreased by well over $15,000.

TABLE VIII. Custom Gripper Specifications

Metric	***Value***
Stroke	70 mm
Grip force (programmable)	110 N
Gripper mass	1.5 kg
Distance off media flange	108 mm
Cost	$615.00
Percent of components that are 3D printed or require no machining operations after being received [%]	81.3%

IV. Discussion

Based on the results of the gripper design, the final product was successful. In the areas where change was emphasized - distance off media flange, modularity, manufacturability – the final project did deliver. However, in the design process compromises definitely had to be made to meet all the criteria.

One example of this is using the grey pro rack over the metal rack. Although the metal rack is clearly superior in wear resistance to the grey pro resin rack, at the end of testing it was the grey pro rack that was chosen. This is a great example of design compromises that had to be made. By performing the testing of the four different material racks, the results informed the design by validating that the gripper could run an acceptable number of lifecycles with the grey pro resin. Because the grey pro rack met the standard and was significantly easier to reproduce and replace than the metal rack, the final design incorporated the grey pro rack.

Another compromise that was made was the decrease in the stroke. The stroke decreased by over 50% as a result of finding out that the fingers needed to be dual supported to prevent high stresses in the resin parts connecting them to the carriage blocks. Although the stroke was significantly decreased, it does not represent a difficult issue to fix. The stroke of the gripper could easily be increased by extending the top housing component and the guiderails along the grasping direction for the carriage blocks.

Overall the modularity and adjustability of the system opens it up to a lot of applications. After one week of work, someone could reproduce the entire gripper and have it ready to run on the KUKA. This means that making modifications to the design, especially in the realm of finger design, motor selection, and sensor selection, could result in varied gripper performance. This suggests that the custom gripper should have the ability to perform the desired task successfully in a larger set of environments than the Robotiq gripper.

V. Conclusions

A. *Critique*

The work performed to produce this gripper definitely had high and low points.

One area that was well performed was durability testing. After continuing to reiterate on the design after every failed part, when the failure point converged to the rack it was a relief. After identifying the rack as the failure point of the system from on and off testing, it was clear that comparable data was needed. A design of experiment (DoE) was created to test four different materials all against the same load case. The goal of the testing was to identify when the gripper would reach its maximum number of lifecycles with each different rack material. However, the rack that provided the greatest number of lifecycles did not balance out the other criteria of the gripper and ultimately choosing to incorporate the grey pro rack into the final design was a comparison of the "cost" of using one rack over the other. For the rack that ran for a longer lifetime, the machining operations needed on the rack were not worth the extra lifecycle gained from using that rack.

One area that could have improved performance was identifying and picking force sensors. Having less experience with sensors it was difficult to look at the technical data sheets of sensors ranging from pressure sensors, strain gages, load cells, capacitive force sensors, and piezoelectric force sensors and compare the performance of the sensors. Ultimately the sensor that was chosen was one that could be incorporate well with the pre-existing mechanical and electrical systems.

Another area that could have improved was testing on the KUKA. Although the infrastructure for the communication was set-up and durability of the system was proven off of the KUKA, the only testing done on the KUKA was checking that the gripper could be installed easily enough. Actually recreating testing scenarios that drove the need for the custom gripper would be interesting to observe to see if and how well the new gripper improves the testing capabilities of the robot.

B. *Future Work*

In terms of future work, there are plenty of extensions of this project that can be implemented. Before further extension occur, the software for communicating with the KUKA robot needs refining. Additionally, portions of the electronic system, especially the force sensors and motor, can be evaluated and replaced by better more effective performing components if desired. An additional gripper will need to be made eventually to have a set of two grippers to use on the robot together.

C. *Implications*

The implication of this project is to provide a platform for robotics researchers in the ARM lab to extend their experimental testing. With a significantly improved gripper in terms of adjustability and replicability, researchers will now have a higher tolerance for risk in testing scenarios. Additionally, with a 60% reduction in distance extended off of the media flange, this gripper should fix issues in position configuration that have been faced with the previous gripper.

ACKNOWLEDGMENT

The author would like to thank Professor Dmitry Berenson of the University of Michigan for creating a space in his lab for the author to pursue her interest in robotics, apply her skill set to a unique design project, and acquire new information. The author would also like to thank Brad Saund from the University of Michigan for the invaluable mentorship and advising of the project he provided. In addition, the author would like to acknowledge the contributions of all the lab members of the Autonomous Robotic Manipulation (ARM) lab for providing feedback and advice throughout the project.

REFERENCES

[1] "LBR iiwa," *KUKA AG*. [Online]. Available: https://www.kuka.com/en-us/products/robotics-systems/industrial-robots/lbr-iiwa. [Accessed: 16-Dec-2018].

[2] "3-FINGER ADAPTIVE ROBOT GRIPPER," *Robotiq*, Aug-2018. [Online]. Available: https://blog.robotiq.com/hubfs/Product-sheets/Product-sheet-3F-EN.pdf?_ga=2.26212798.2036091980.1545406083-1045534472.1545406083. [Accessed: 16-Dec-2018].

[3] Industries, A. (2018). *PiJack Ethernet HAT for Pi Zero*. [online] Adafruit.com. Available at: https://www.adafruit.com/product/3374 [Accessed 16 Dec. 2018].

[4] "Pololu - 9.7:1 Metal Gearmotor 25Dx48L mm HP 12V with 48 CPR Encoder," *Pololu Robotics & Electronics*. [Online]. Available: https://www.pololu.com/product/3214. [Accessed: 09-Nov-2018].

[5] "Boston Gear H2412 Spur Gear, 14.5 Pressure Angle, Steel, Inch, 24 Pitch, 0.250' Bore, 0.583' OD, 0.250' Face Width, 12 Teeth," *Amazon*. [Online]. Available: https://www.amazon.com/Boston-Gear-H2412-Pressure-Angle/dp/B000LDIYE0/ref=cm_cr_arp_d_product_top?ie=UTF8. [Accessed: 16-Dec-2018].

[6] "FlexiForce Standard Force & Load Sensors Model #A401," *Sparkfun*. [Online]. Available: https://cdn.sparkfun.com/datasheets/Sensors/Pressure/A401-force-sensor.pdf. [Accessed: 16-Dec-2018].

[7] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback control of dynamic systems*, 7th ed. NY, NY: Pearson, 2019.

[8] "Materials Data Sheet Photopolymer Resin for Form 1+ and Form 2," *Formlabs*, 18-Sep-2018. [Online]. Available: https://formlabs.com/media/upload/XL-DataSheet.pdf. [Accessed: 16-Dec-2018].