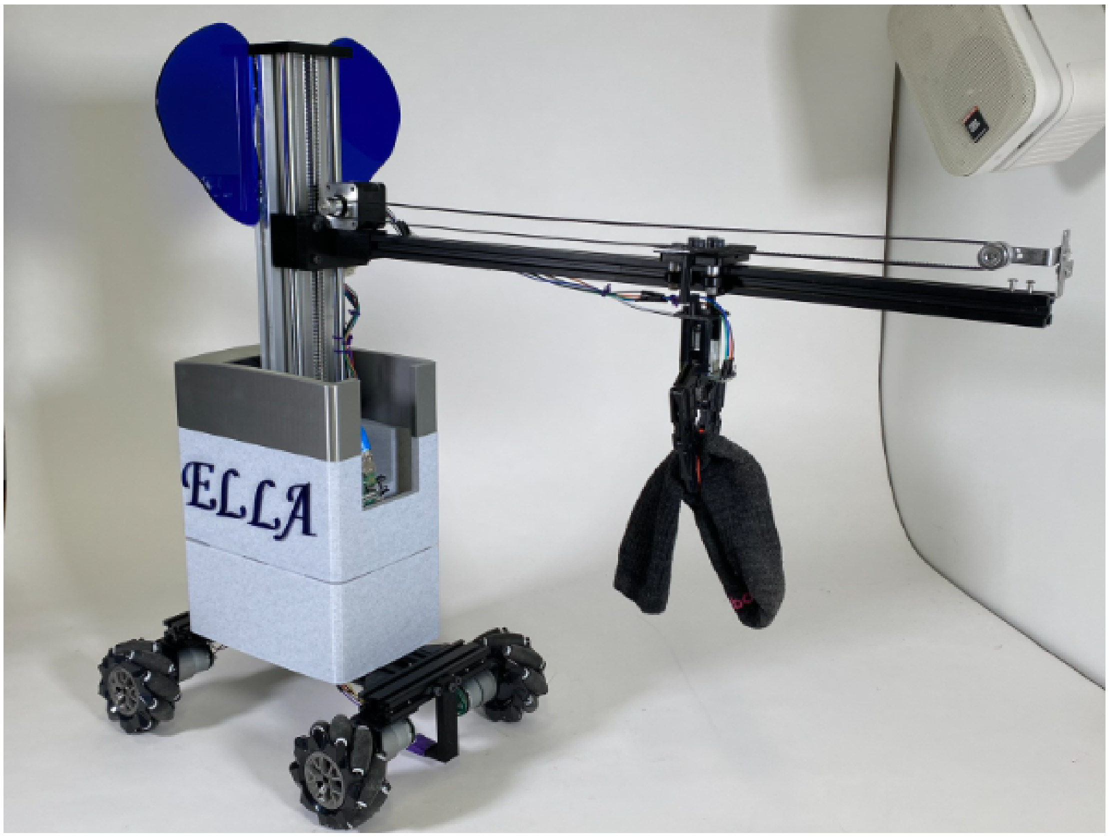
Electronic Laundry Loading Assistant

(ELLA)



Samsung Home Robot Exploration
ME74: Senior Design
Fall 2022

Olivia Goss, Julia Huckaby, Toki Nishikawa

Table of Contents

Executive Summary

This senior design project was completed in the fall of 2022 by Olivia Goss, Julia Huckaby, and Toki Nishikawa-- seniors at Tufts University in Medford, Massachusetts.

The goal of this project was to design a new robot for everyone's home. Project mentors at Samsung Research America requested a home robot that could become a mass-market product. Through careful deliberation and detailed brainstorming, we ultimately decided to create ELLA, the Electronic Laundry Loading Assistant. ELLA is a robot that automates the transfer of clothes from the washer to the dryer, simplifying the laundry chore.

Because of the open-ended nature of the project, it was important to come up with criteria that that robot must meet. First and foremost, the robot needed to be useful and simplify a household chore. Research quickly identified laundry as a time-consuming and burdensome task. The robot also needed to be useful in a variety of locations, and modular enough to work in homes of different layouts. ELLA works with most front-loading washers and dryers, and can function in any home/location with an available 10 cubic feet of space.

After many design iterations, reviews, and discussions, the final ELLA prototype was created. The key features include a linear actuator lead screw, a chassis with omnidirectional wheels, a gripper claw actuator, and color and current sensors. The linear actuator moves the arm up and down, the current sensor tells the claw when to open and close, the chassis with omnidirectional wheels allows the cart to move in any direction, and the color sensor detects colors of tape on the floor, which then instructs the wheels to move in a certain direction.

ELLA transfers laundry from the washer to the dryer by following a series of steps. Simply put, the arm moves down into the barrel of the washing machine. The claw then grabs a piece of clothing from the washer. The arm moves back up. Then, the cart moves backwards until the color sensor detects color-coded tape on the floor. ELLA then moves sideways and then forward to the dryer by following the tape. The claw then opens to deposit the article of clothing into the dryer. The process repeats until all of the clothing has been transferred.

The final prototype is a functional, automated robot that simplifies the laundry process. ELLA was designed with the intent of working in a variety of locations, making it a useful home robot. The modular design ensures its versatility, making it an excellent candidate for large-scale manufacturing and marketing.

Problem Background, Motivation and Competitive Benchmarking

In the United States, the average household washes around 2000 lbs of laundry a year [1]. Wet clothes left in the washing machine may need to be rewashed, wasting time, energy, and resources. We aimed to create a robot that would simplify the laundry process by automating the transfer of clothes from the washer to the dryer.

Motivation

The primary sources of motivation included accessibility, efficiency, and environmental concerns. Laundry is considered an Activity of Daily Living (ADL), which is a commonly used benchmark to determine if a person can live independently [2]. By automating some of the laundry process, a person may be able to live independently for a longer amount of time. The second motivation was efficiency. Washing and drying clothes takes approximately 170 minutes a week [1]. ELLA would expedite some of this process, shortening the overall length of the chore. The final motivation was rooted in environmental considerations. Washing clothes takes on average 19 gallons of water [3]. When clothes are left in the washing machine, an extra 19 gallons of water may need to be used to rewash the clothes.

Competitive Benchmarking

In considering how this product would compare with the existing market, different existing technologies were researched. The first competitor on the market is the two-in-one washer/dryer machine. This defeats the purpose of a laundry changing robot because there is no need to transfer the laundry. However, the machine itself is less efficient and much more expensive [5]. The two-in-one washer/dryer costs around $1400, which is considerably more expensive than ELLA. The second device on the market is a highly technical robot arm that has similar capabilities to ELLA. The robotic arm was invented by researchers at the University of Bologna in Italy [6]. However, this device is specifically for industrial testing of washing machines and not currently part of household markets. It is also much bulkier and we are assuming more expensive than ELLA.

Table 1: Competitive Benchmarking				
	Specification			
Competitor	Speed of Transfer (<10 mins)	Completion of Transfer (95%)	Space Occupied (10 cu ft)	Cost ($150)
2 in 1 Machine	✔	✔		
Industrial Arm	✔	✔		
ELLA	✔	✔	✔	✔

Design Recommendations

Problem Definition

To appropriately define the problem definition, it is important to also identify the key stakeholders and their needs. The primary stakeholders that have been identified are: Samsung, people who do laundry in the home, and commercial laundry businesses. Their needs and specifications are outlined below.

Table 2: Key Stakeholders, Needs, and Specifications		
Stakeholder	**Need**	**Specification**
Samsung	Innovative, versatile, and safe home robot	Speed of Transfer (<10 minutes), Completion of Transfer (95%)
People who do laundry in the home	Robot that simplifies laundry process by automating transfer of clothes from washer to dryer	Space Occupied (<10 cu ft), Weight (<50 lbs), Noise (<50dB)
Commercial Laundry Businesses	Automatic laundry transfer immediately following completion of washing cycle	Speed of transfer (<10 minutes), Cost ($150)

Discussion of Needs:

- Samsung requested the invention of a new home robot. The robot needed to be versatile, safe, and innovative.
- People who do laundry in the home needed a robot that would automate a portion of the laundry process. Laundry is commonly identified as one of the most burdensome home chores, so a robot that eases some of this burden would be of use to people who do laundry in the home.
- Commercial laundry businesses needed a robot that would simplify and speed up laundry, as the more laundry they can complete, the more efficient they are and the more money they can make. For this reason, they needed a reliable, safe, and speedy robot.

Discussion of Specifications:

- The specifications most relevant to Samsung are the speed of transfer and the completion of the transfer. The speed of the transfer should be no more than 10 minutes, and the completion of transfer should be at least 95%. Additionally, the cost to manufacture the robot should be low, ideally no more than $100.
- People who do laundry in the home request a robot that will not take a lot of space, a robot that is not too heavy, and a robot that does not make too much noise. The total space occupied by the robot should not be more than 10 cu ft, the weight should not be more than 50lbs, and the noise should be no more than 50dB.
- Commercial laundry businesses prioritize the speed of the transfer and the cost of the robot. The speed of the transfer should be no more than 10 minutes, and the cost no more than $150.

Description of Concept Generation

Because of the open-ended nature of the task described by Samsung, it took many design iterations and brainstorms to settle on the final design. Some of the early ideas included a robot that would sort clothes into lights and darks, a robot that would automatically change the roll of toilet paper, and a robot that would automatically prepare meals. Some initial laundry-related design sketches are included below.

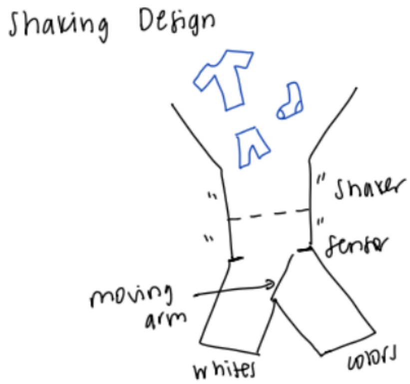


Figure 1: Laundry Sorter "Shaker"

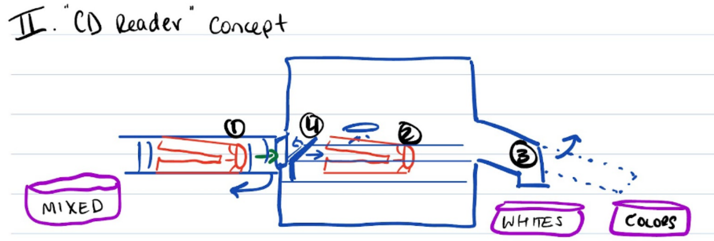


Figure 2: Laundry Sorter "CD Reader"

With each of the first ideas, several key problems/shortcomings were identified. The primary shortcomings included difficulty to implement, and not saving enough time/effort to be worth the money/hassle. It was then decided that a robot that moved laundry from the washer to the dryer would be both a doable project for the semester, as well as a robot that could be very versatile and have many functions in the household. Additionally, the ELLA design has potential applications outside of laundry. For example, with more time, more sensors could have been implemented, which would allow ELLA to grab other things, such as toys, to declutter the house.

After it was decided to focus on a laundry transferring robot, it was then important to decide what kind of claw mechanism would be best to use. Some designs that were considered were the simple pincher (which is what the final design used), a scooper, a hook, and an arcade game claw. The scooper was ruled out because of the lack of uniformity within the barrels of the machines. The hook, which would have picked up a bag of laundry from the washer, was ruled out because the bag full of laundry would have likely been too heavy for the little robot to hold up. Finally, the arcade game claw was ruled out because of its primary purpose of not picking up what is intended. Therefore, the gripper claw seemed like the best, most versatile option.

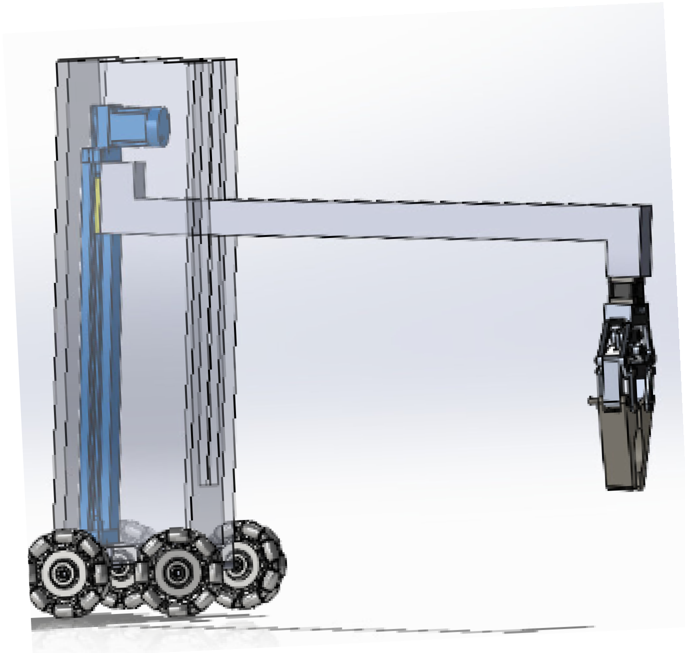


Figure 3: CAD Model v1

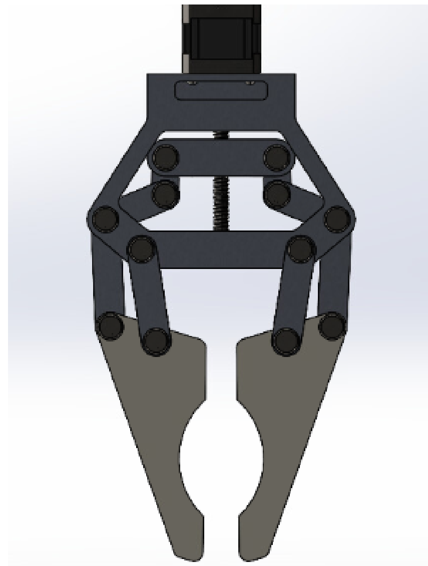


Figure 4: Claw CAD Design

After a thorough design review with classmates, professors, and mentors, we made several improvements to the first prototype. Version two of the prototype (Fig. 5), looked much more similar to the final physical robot made. We made the cart smaller and less tall, as we were concerned about the torque from the arm and heavy clothes.

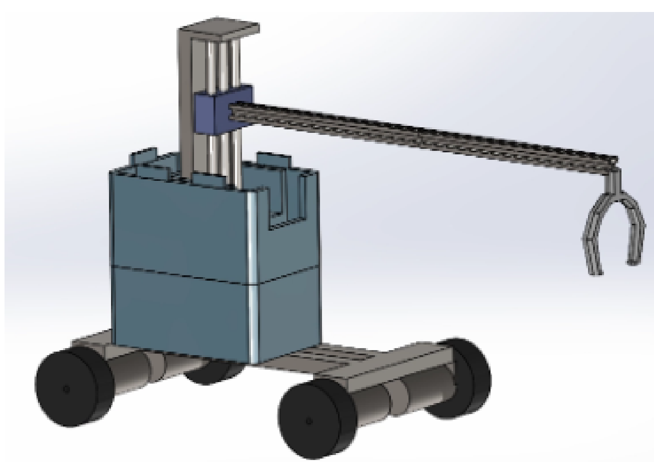


Figure 5: CAD Model v2

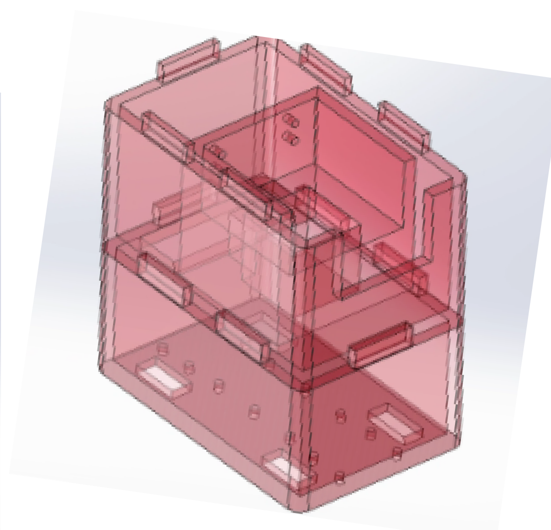


Figure 6: CAD Assembly of Cart Body

Decision Matrix

The process of narrowing down to a final design had two major phases. It was established early on that the subject of this home robot was going to be laundry, but the decision matrix illuminated the specifics of the project. Initially, the focus was on a robot that would sort one's dirty clothes into piles of whites and colors for ease of washing multiple loads. Several mechanisms were considered to solve this design challenge, but one in particular caused the project idea to shift. One of the brainstormed sorting designs was a portable robot arm that would sense the color and place the clothes in like-colored bins. We were excited by this idea, but felt it was highly over-complicated to create an entire robot arm to do such a small task, when its functions could be used in a multitude of other ways. Slowly, the idea morphed from one that could simply sort your clothes to one that would automate a more significant aspect of the laundry process. Once we shifted to a laundry switching robot, the new focus became the mechanism for retrieving the clothes from the washer, as that would be the most fundamental component of the robot. As the second phase of idea creation ultimately became the final design, this section will only include the relevant design matrix (see Appendix for more detailed decision matrix content).

Table 3: Robot Arm Actuator Decision Matrix (simplified)

Specifications			Target	Claw	Scoop	Washer Bag Hook	
Washer-dryer exchange (↑)	%	5	95	95	70	0	100
			3	3	1	1	5
Speed of exchange (↓)	min	4	10	10	15	7	
			3	3	2	4	
Cost (↓)	$	3	200	250	250	200	
			3	2	2	3	

Final Design Solution

The final design of this robot encompassed much of the iterative designs and the finished prototype accomplished all of our initial goals of autonomous laundry switching. Several considerations went into the overall design and footprint of the robot. We narrowed the scope of the project to design a robot specifically for any orientation of front loading, side by side washer/dryer units. Dimensions of a standard washer were used to finalize the height of the robot, length of the arm and the vertical distance range of the actuator. The robot was also designed with maximum versatility with the idea that it could be modified for other household functions. With future branding in mind, we integrated the elephant motif into the final design.

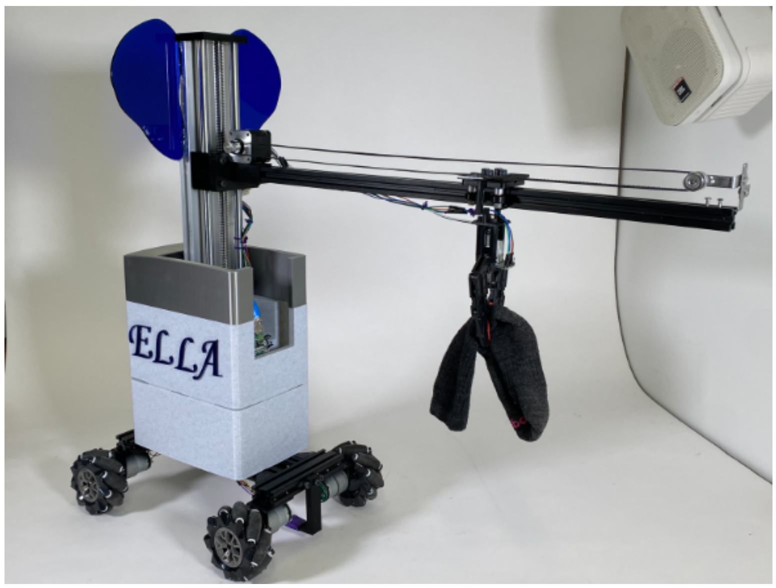


Figure 7: Final ELLA Prototype

Hardware

The first key feature of the final design was the wheeled chassis which provided the robot the ability to move to and from the washer and dryer. Omnidirectional motion was achieved through the use of mecanum wheels, which have angled treads that allow the chassis this freedom. For autonomous movement, a color sensor was integrated with the motors which read and responded differently to colored lines marked on the floor between washer and dryer. It was secured to the bottom of the robot with a 3D printed connector and programmed to stop at green lines, move sideways at blue lines and forwards at red lines. This feature modulates the robot as it could be integrated in any laundry room as the lines could be placed in any configuration and the robot would still know to respond properly without user input.

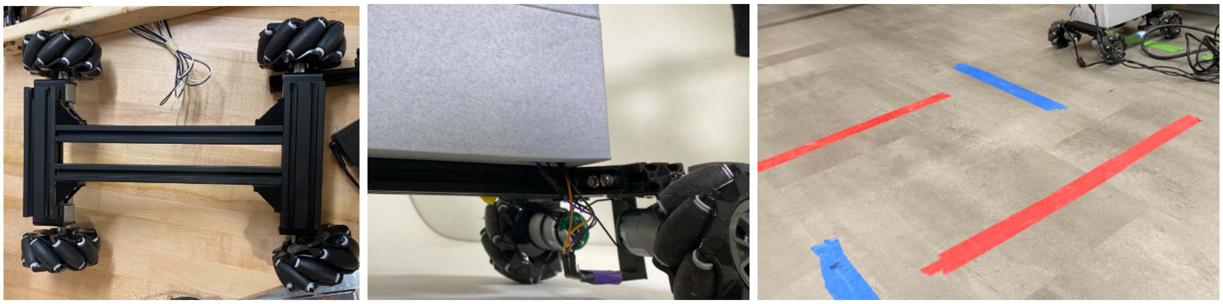


Figure 8-10: Assembled Chassis (1), Color Sensor + 3D Printed Connector (2), Model Path (3)

The next aspect of the design was the body of the robot, which included the electronics housing and the linear actuator/arm mechanism. The 3D printed body secured the linear actuator in place, while hiding and protecting the internal wiring. The linear actuator ran on a stepper motor that allowed for the precise vertical motion of an aluminum extrusion rod that was attached to the linear mover with a 3D printed adapter. A color sensor was integrated with this stepper motor and secured to the end of the claw to indicate when the arm had reached the pile of clothes and in turn signal for the actuator to stop descending.

Figure 11-13: 3D Printed Body Piece (1), Electronic Housing View (2), Arm Connector Piece (3)

The final major component of the design was the claw system. The specific claw was chosen for its ability to grab a localized part of the clothing with enough force to ensure safe transport. A current sensor was integrated with the claw motor to recognize when the claw had securely grabbed an article of clothing. The claw was then secured to a wheeled cart which slotted into the extrusion rods via 3D printed adapter. This cart was secured to a pulley system that operated to move the claw along the arm to bring the clothes out of the washer and move them closer to the center of mass of the robot.

Figure 14-16: Claw/Connector + Color Sensor (1), Pulley System (2-3)

Software

The main control of the robot was placed on the Raspberry Pi, fed with information from several arduinos. One arduino contained the logic for the claw, its current sensor and the color sensor for the linear actuator. A second arduino controlled the chassis wheels, the linear actuator stepper motor and the pulley motor and a third arduino controlled the color sensor for path detection. There are three power supplies associated with the robot; a 12V 10A to supply the linear actuator, a 12V 5A supply to power the chassis wheels and a portable battery to power the Raspberry Pi. Future interactions would not require external supply but instead have two more portable batteries integrated into the robot.

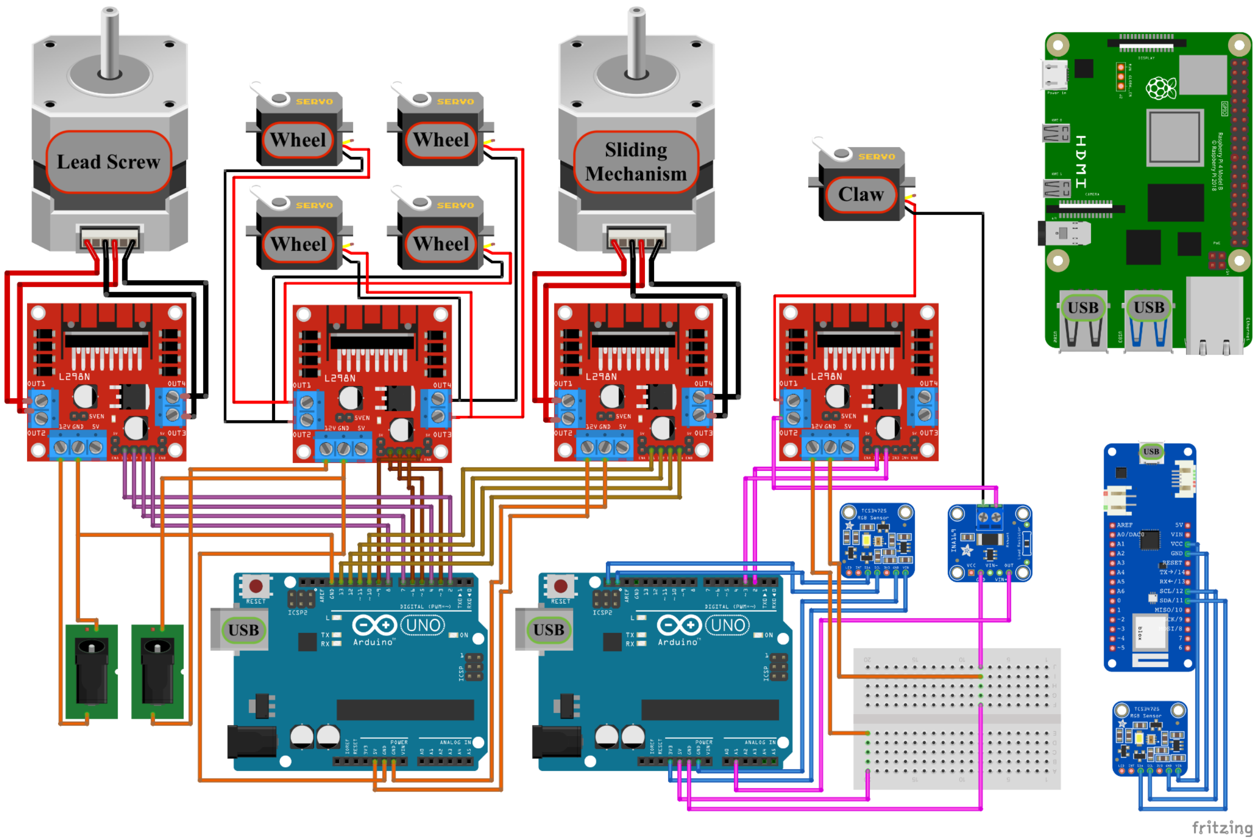


Figure 17: Overall Wiring Schematic of the Robot Electronics

Validation of Design

To validate the proposed abilities and success of this robot, several theoretical calculations were performed and corroborated with empirical success. The significant areas of interest were in physical failure mechanisms and electrical stamina. Determining the right amount of power to provide all of the electronics with proper voltage and current took some honing, but as listed above, three power sources of different voltage and amperage sufficed. As for the modes of failure, the following mathematical analysis defends this final design. Physical data also supports the math below as the real behavior of the robot matched very closely with predicted calculations.

Beam Deflection

One area of concerned failure was the stress caused due to adding weight to the end of the arm. In order to determine if this would be a potential failure mechanism of the robot, presumed vertical deflection was found using simplified measurements.

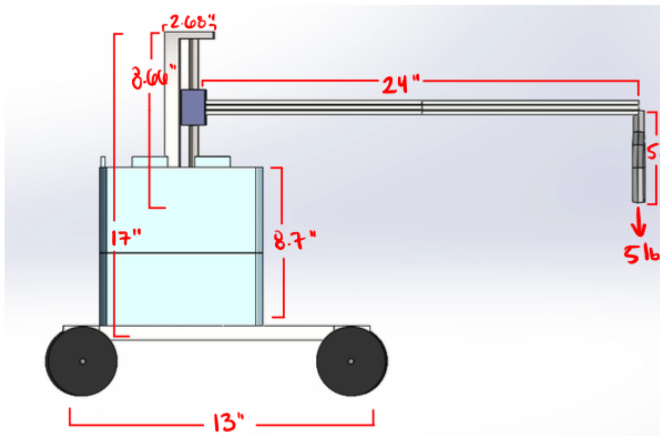


Figure 18: Simplified Robot Model for Beam Deflection Analysis

Castigliano's calculation was used to find the deflection of the arm if a 5lb load was applied to the end.

Moment of Inertia:

$I_{top} = \frac{1}{12}bh^3 = \frac{1}{12}(.7874)(.7874)^3$ $I_{mid} = \frac{1}{12}bh^3 = \frac{1}{12}(3.1496)(2.2047)^3$

$I_{top} = .032032 \text{ in}^4$ $I_{mid} = 2.81269 \text{ in}^4$

Equations:

$M_{top} = Fx$ $M_{mid} = 24F$

Calculations:

TOP SECTION:

$M = Fx$ $L = 24 \text{ in}$

$\partial M / \partial F = x$ $F = 5 \text{ lbs}$

$\delta = \frac{1}{EI}\int_0^L Fx^2 dx$

$\delta = \frac{F}{EI}\left(\frac{1}{3}x^3 \Big|_0^L\right)$

$\delta = \frac{F}{EI}\left(\frac{L^3}{3}\right)$

$\delta = \frac{5}{70GPa \cdot .03\ldots}\left(\frac{24^3}{3}\right)$

$\delta_{top} = 1.0275e^{-5} \text{ in}$

MIDDLE SECTION:

$M = 24F$ $L = 8.66142$

$\partial M / \partial F = 24$ $F = 5 \text{ lbs}$

$\delta = \frac{1}{EI}\int_0^L 24F \cdot 24\, dx$

$\delta = \frac{576F}{EI}\int_0^L dx$

$\delta = \frac{576F}{EI}\left(x \Big|_0^L\right)$

$\delta = \frac{576FL}{EI} = \frac{576(5)(8.66142)}{(70e^6 \cdot .011437)}$

$\delta_{Mid} = 1.26695e^{-7} \text{ in}$

$\therefore \boxed{\delta = 1.04e^{-5} \text{ in}}$

The resulting value of 1.04x10^-5 in indicates no concern for failure at the joint between the arm and the actuator, or anywhere along the arm itself. However, this is a simplified version that did not take into account the nature of the arm-actuator connection. As a safety precaution, the pulley system was added to move the load closer to the base of the arm as a mechanism to limit the torque generated.

Center of Mass

Another concern for the success of this robot was its weight distribution. More specifically, the risk of its front-heavy loading system causing it to topple forward. To guarantee the balance of ELLA, we stipulated that the center of mass of the robot had to be above the footprint of the chassis, no matter how much weight was applied to the end. Again, a simplified model was created as shown below.

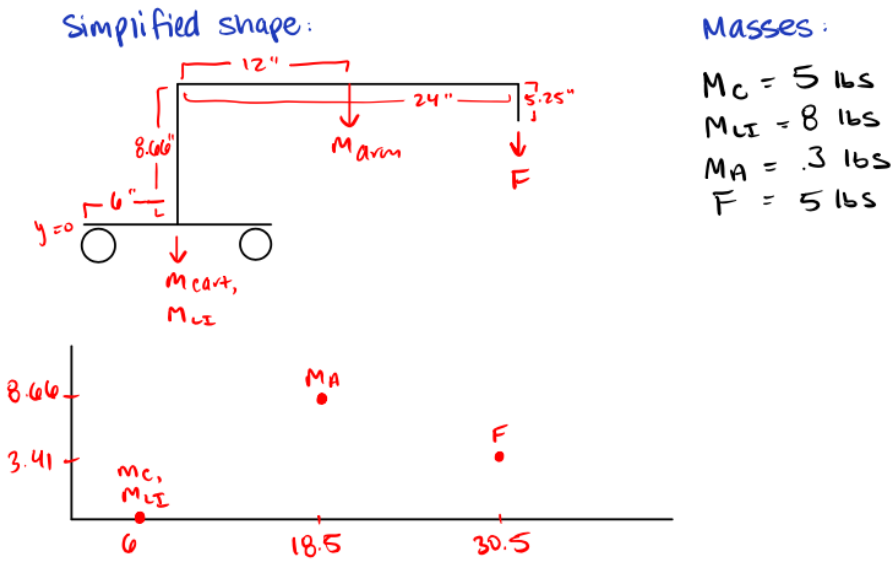


Figure 19: Simplified Shape and Component Center of Mass Plot

Considering the size and weight of each component, the overall center of mass was found, and weight was added to the chassis until it fell in the correct bounds.

calculation:

$$\bar{y} = \frac{M_C y_C + M_{LI} y_{LI} + M_A y_A + F y_F}{M_{tot}}$$

$$\bar{x} = \frac{M_C x_C + M_{LI} x_C + M_A x_A + F x_F}{M_{tot}}$$

$\therefore$ COM = (12.89, 1.074)

With the final measurements of the robot, the center of mass came out to be located before the end of the chassis. The pulley system helps with this failure mechanism as well, as bringing the load closer to the chassis pulls the center of mass closer as well.

Conclusions and Future Work

Strength of Design

One of the primary strengths of ELLA is the autonomy of the system. The robot performs tasks without the need for human intervention or supervision. At the current state of the project, ELLA will keep running until unplugged. As will be discussed shortly, we have an idea of the mechanism that would allow ELLA to recognize when the task is complete. The autonomy of this robot satisfies our most important customer need – saving time spent doing laundry.

Even though ELLA is fully autonomous, no reprogramming is required for different environments. Since ELLA uses color sensing to move between the washer and dryer, the only difference in installation between households is the arrangement of the lines followed, which is much simpler than updating the code. In the current state, the color green causes ELLA to stop moving, the color blue causes ELLA to move left or right (depending on the phase of the cycle it is completing), and the red color causes ELLA to move in a straight line. As a result, ELLA can be easily set up in any home – of course, provided that we are dealing with front load washers and dryers.

ELLA's other strengths include portability, speed, and the calmness at which clothes are transported. ELLA weighs just under 15 pounds. For the majority of users, this is a robot that can easily be carried into the home. ELLA is also quieter than the typical washing machine. A washing machine is considered quiet when it operates at or below 70dB [4]. ELLA operates at around 50dB. Earlier, we made the assumption that users would be content with a product that makes less noise than the typical washing machine, so we believe that ELLA won't be disruptive sonically.

Lastly, although ELLA transports clothing item by item, it is done at an impressive speed. The speed at which ELLA performed during the final prototype demonstration was suboptimal. More specifically, the speed at which the robot picks up clothing can be increased drastically by altering the speed of the linear actuator, the speed of the stepper motor responsible for sliding the claw across the arm, and the lengths of the pauses between processes. Unfortunately, these speeds were not adjusted in time for the final demonstration.

Limitations of Design

There is a long way to go before ELLA is ready to be used commercially. Most notably, ELLA is unable to open or close the door of a washer or dryer, detect when a washing machine has finished its cycle, or turn the dryer on. This put the autonomy of the entire process into question. We decided not to tackle these problems and to focus on the transportation of clothing – however, this would be an obstacle if anyone were to try to market our current version of ELLA. We made the assumption that the washers and dryers would have a mechanism to autonomously open and close their doors and turn themselves on, which is not realistic.

A large limitation of the current design is that it is not connected to a battery. Instead, the h-bridges associated with the lead screw and wheels are connected to two power supplies. There was not sufficient space on the robot to include the battery we needed, and we decided not to allocate any time or energy into creating a bulky extension to house it. Thus, we ended up having to hold the cords behind the robot wherever it went.

Another limitation is ELLA's ability to recognize when to stop lowering its arm. We attached a color sensor to the claw in order to sense when the claw is in the position to grab clothing. The sensor uses lux measurements, the unit of illuminance, to determine the distance between the claw and the clothing. Although this technique seemed to work well, it may be unreliable in differently lit environments.

ELLA also does not feature a mechanism to find clothes in different locations within the washing machine. In our current design, ELLA is programmed to return to the exact same position in front of the washing machine every cycle. As a result, clothes that are not directly in the center of the washing machine will be neglected.

Lastly, ELLA is unable to recognize when the transportation of a load of laundry is complete, although it is doubtful the robot would ever get to this point. ELLA is programmed to continue the cycle indefinitely, and the user would have to disconnect the Raspberry Pi to stop the process.

Revision Suggestions

In our current design, ELLA saves the user time by moving their clothes from the washer to the dryer. With that said, the original objective was for ELLA to operate in a way where the user would only need to load the washing machine and empty the dryer – that is, the robot would begin and end its task with the user absent. Three features would need to be added in order for ELLA to be autonomous in this way:

1) ELLA can detect when a washing machine has completed its cycle
2) ELLA can open and close the doors of a washer or dryer

3) ELLA can turn the dryer on

These features are challenging to implement, hence we solely focused on the transportation of the clothing. In regards to the first feature, few visual cues indicate that a washer has completed its cycle – there is usually just a small light. It is possible to use auditory cues. In this case, ELLA would conclude that a cycle has finished when the washer stops making noise. However, different portions of the wash cycle are significantly quieter than others. Moreover, we would have to assume that the washing machine is the only entity producing significant noise in its environment. For example, auditory cues would not be very helpful in a laundromat.

The second feature may not be as difficult to implement since it is possible to achieve this using our current arm and claw. However, the claw would need to have more degrees of freedom so that it could rotate in a way that allows it to interact with the door. Furthermore, our current claw would likely not do the greatest job of opening a variety of washer/dryer doors. Thus, we would also need to design a new claw that could both effectively pick up laundry and open washer/dryer doors of different varieties.

Implementing the final feature would also be a significant challenge. Different dryers may differ in the positioning and sizing of the ON button, the force needed to press the ON button, etc. Firsty, we would need to be able to see the ON button in order to locate it, meaning we would need some visual representation of the dryer. For example, our robot could include a front-facing camera. Not only do we need to be able to see the ON button, but we would need to differentiate it from the other buttons on the dryer. One way to do this is to read the text associated with each button, assuming that text exists. Next, we would need some tool that could press a button that could be located on any part of the dryer. The tool would need to be able to access at least the front and top sides of the dryer as they are the most likely to feature the button. If we were to use our arm and claw for this function, our arm would need to be able to raise past the height of the dryer and extend as far as the dryer's length. Since this would increase the length of the arm, it may be wise to consider a retractable arm so that there is not a significant increase in torque.

The remaining limitations can be solved quite easily. In order to avoid using power supplies, we could redesign the body of the robot to house a battery. In regards to ELLA's ability to recognize when to stop lowering its arm, we could incorporate a distance sensor alongside the color sensor on the claw, which would be more reliable across varying environments. ELLA's inability to maneuver within the washing machine could be solved in several ways, one of which is to have ELLA pivot once the robot has stationed itself in front of the washer. Another solution would be to design a pattern of colored lines that would allow ELLA to approach the washing machine differently each repetition, both in terms of how central the robot is with respect to the washer and the angle at which the robot approaches the washer. Finally, in order for ELLA to recognize when its task is complete, the robot needs to be able to know when there are no clothes left in the washer. We could use the color sensor on the claw to evaluate the color of various positions in the washer and ensure that they all return the washer's color. With that said, if the user owns a large gray sheet that covers the entire bottom of the washer, this could be problematic.

Appendices

Concepts and Evaluation

Throughout this project, many concepts were investigated, some related to laundry, some not. After it was decided that we wanted to pursue a laundry-related design, we originally thought we wanted to build a robot that would sort clothes into light colors and dark colors. Table 5 outlines the decision matrix for these concepts. Some of the ideas included a bingo ball design, conveyor belt design, shaker, CD reader, and finally, the robot car (see Table 4). In each of the decision matrices to follow, they are weighted on a scale of 1-5, with 1 being the lowest importance and 5 being the highest.

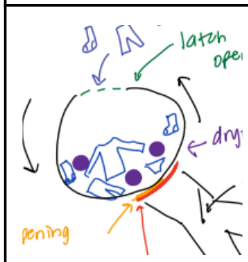
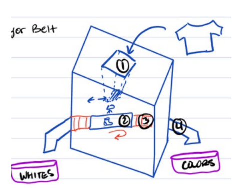
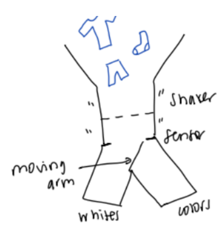
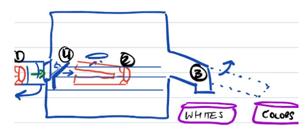
Table 4: Preliminary Design Sketches			
Bingo Ball	Conveyor Belt	Shaker	CD Reader
			

Table 5: Initial Decision Matrix								
Concept Design			Target	Bingo Ball	Conveyor Belt	Shaker	CD Reader	Robot Car (Final Design)
Weight (↓)	lbs	2	50 lbs	70lbs	90lbs	70lbs	100lbs	30lbs
			3	2	1	2	1	5
Size (↓)	ft^3	4	$10ft^3$	$10ft^3$	$20ft^3$	$10ft^3$	$25ft^3$	$5\ ft^3$
			3	3	1	3	1	5

Noise (↓)	dB	1	50dB	50dB	40dB	60dB	40dB	40dB
			3	3	4	2	4	4
Completion of transfer (↑)	%	5	95	n/a	n/a	n/a	n/a	90
			3	n/a	n/a	n/a	n/a	3
Speed of exchange (↓)	mi n	4	10min	n/a	n/a	n/a	n/a	15 mins
			3	n/a	n/a	n/a	n/a	2
Cost (↓)	$	3	$200	$500	$350	$300	$400	$250
			3	1	2	2	2	3
Total				**9**	**8**	**9**	**8**	**22**
Weighted Total (All specifications)				**22**	**16**	**24**	**16**	**66**
Weighted Total (Only shared specifications)				**22**	**16**	**24**	**16**	**43**

When it was decided to pursue a robot that would move laundry from the washer to the dryer, we had to decide how we wanted to design two major components of the system. The first was the type of grabber actuator we wanted to use. Our ideas for the grabber were a claw, a scoop, and a washer bag hook (see table 6). We thought a claw would be good for grabbing individual pieces of clothing, the scoop would be good to grab more clothes at one time, and the washer bag hook would be able to grab all of the clothes at once. The idea behind the washer bag was that the user would put all of their clothes into a laundry bag and then into the washing machine. Then, once the washing cycle was finished, the hook would be able to transfer the bag with all of the clothes. However, we had questions about the efficiency/feasibility of washing and drying all of the clothes in a bag, specifically because of the carrying capacity of the robot. Outlined in table 7 is the decision matrix that ultimately helped us choose to pursue the claw. While the washer bag hook scored better on the decision matrix, we thought it too infeasible for a user to wash and dry all of their clothes in a bag. For this reason, we went with the second highest scoring actuator, the claw.

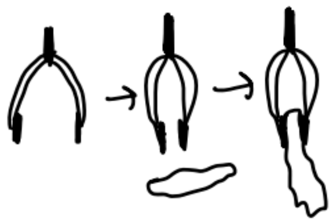
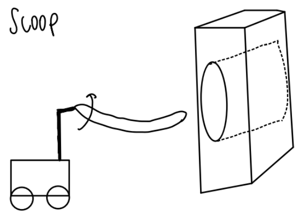
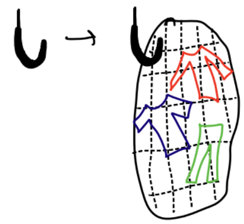
Table 6: Robot Arm Idea Sketches		
Claw/Gripper	Scoop	Washer Bag Hook
		

Table 7: Robot Arm Actuator Decision Matrix

Specifications			Target	Claw	Scoop	Washer Bag Hook	
Size (↓)	ft^3	4	10	10	10	10	
			3	3	3	3	
Washer-dryer exchange (↑)	%	5	95	95	70	0	100
			3	3	1	1	5
Speed of exchange (↓)	min	4	10	10	15	7	
			3	3	2	4	
Cost (↓)	$	3	200	250	250	200	
			3	2	2	3	
			Total	**11**	**8**	**11**	**15**
			Weighted Total	**45**	**31**	**42**	**62**

After we decided which grabber actuator to use, we then had to decide what cart design we wanted to use. Our initial ideas were a physical track, a hard coded path, or color sensors (see table 8). The physical track would work by having a cart travel along a path that would have to be created and installed by a technician. Table 9 outlines the decision matrix for the cart movement. Because of the limited time frame of the project, we thought a color sensor would be a more feasible option than a physical track. Additionally, the color sensors are much more autonomous than if we had hard-coded the path. The color sensors also make the whole system more flexible to any environment. For these reasons, we decided to pursue the color sensor option.

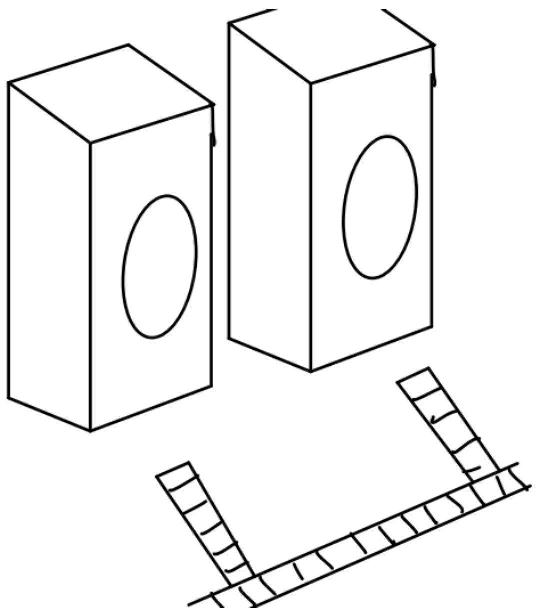
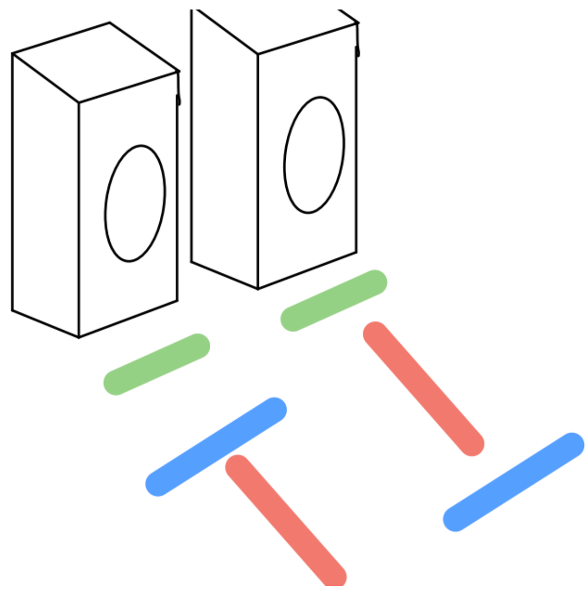
Table 8: Robot Movement Control Idea Sketches	
Physical Track	Color Sensor
	

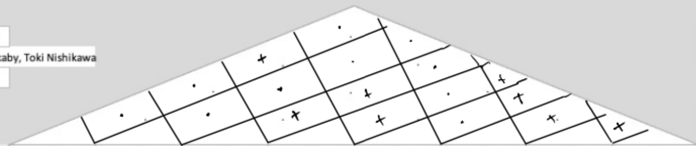
Table 9: Robot Movement Control Decision Matrix							
Specifications			Target	Physical Track	Hard Coded Path		Color Sensor
Size (↓)	ft^3	4	10	15	10		10
			3	3	3		3
Washer-dryer exchange (↑)	%	5	95	95	0	100	90
			3	3	1	5	3
Speed of exchange (↓)	min	4	10	10	7		10
			3	3	4		3
Cost (↓)	$	3	200	250	200		50
			3	2	3		3
			Total	**11**	**11**	**15**	**12**
			Weighted Total	**45**	**42**	**62**	**48**

House of Quality (QFD)

As there were two major phases of initial design, two versions of the house of quality were created. The values and categories in each are very similar as the priorities of each stakeholder remain the same.

Quality Function Deployment

Project title: Laundry Sorter Robot
Project leader: Olivia Goss, Julia Huckaby, Toki Nishikawa
Date: 30-Sep-22



Correlation:

+	.	-
Positive	No correlation	Negative

Relationships:

9	3	1	
Strong	Moderate	Weak	None

	1: low, 5: high	Desired direction of improvement (↑,0,↓) Functional Requirements (How's) →		↓	↓	↑	↑	↑	↓	↓	↓	Competitive evaluation (1: low, 5: high)	
	Customer Needs	Importance Rating		Footprint (ft^3)	Noise Volume (dBs)	Accuracy of Color Judgement (%)	Single Piece Selection (%)	Fully Completed Loads (%)	Weight (Lbs)	Price ($)	Sporting Speed (clothes/min)	Hand Sorting	Laundroid
1		Samsung	Household User										
2	Safe	5	4	1	1	0	0	0	3	0	1	5	1
3	Innovative	5	3	3	9	3	1	3	1	0	3	1	5
4	Efficient sorting tool	3	4	3	1	9	3	9	0	0	0	5	3
5	Worthwhile investment	3	5	9	3	9	9	3	1	9	9	1	2
6	Longterm Solution	3	5	3	1	0	0	0	1	0	0	1	1
			Importance: Samsung	65	65	69	41	51	26	27	47		
			Importance: User	85	55	90	60	60	25	45	58		
			Target	6	70	100%	100%	100%	20	150	20		
			Threshold	10	100	98%	90%	95%	40	200	15		
			Competitor: Hand Sort	-	0	100%	100%	100%	-	-	10		
			Competitor: Laundroid	-	-	-	-	-	-	-	-		

Figure 20: Laundry Sorter QFD

Quality Function Deployment

1: low, 5: high	Desired direction of improvement (↑,0,↓) Functional Requirements (How's) →		↓	↓	↑	↑	↑	↓	Competitive evaluation (1: low, 5: high)			
Customer Needs	Importance Rating		Footprint (ft^3)	Noise Volume (dBs)	Fully Completed Loads (%)	Weight (Lbs)	Price ($)	Transfer Speed (min)	Hand Transfer	ELLA Robot		
	Samsung	Household User										
Safe	5	4	1	1	0	0	0	3	0	1	5	1
Innovative	5	3	3	9	3	1	3	1	0	3	1	5
Efficient sorting tool	3	4	3	1	9	3	9	0	0	0	5	3
Worthwhile investment	3	5	9	3	9	9	3	1	9	9	1	2
Longterm Solution	3	5	3	1	0	0	0	1	0	0	1	1
		Importance: Samsung	65	65	69	41	51	26	27	47		
		Importance: User	85	55	90	60	60	25	45	58		
		Target	6	70	100%	100%	100%	20	150	20		
		Threshold	10	100	98%	90%	95%	40	200	15		
		Competitor: Hand Sort	-	0	100%	100%	100%	-	-	10		
		Competitor: Laundroid	-	-	-	-	-	-	-	-		

Figure 21: ELLA Robot QFD

Bill of Materials

The following table includes all materials used to manufacture ELLA, their quantity, cost per unit, and the total cost. The overall cost to produce the current prototype of ELLA was approximately $600. As was discussed previously, there are many changes that could be made to make ELLA easier to mass-produce, which would also decrease the cost.

Table 10: Bill of Materials

Vendor	Item Name	Quantity	Cost/unit	Total cost
RobotShop	MakeBlock Robot Gripper	1	$32.99	$32.99
Amazon	Mecanum Wheel 4wd Metal Robot Car Chassis	1	$99.99	$99.99
Amazon	Linear Guide Slide Table Ball Screw Motion Rail 300mm 12" Stroke	1	$92.99	$92.99
Adafruit	RGB Color Sensor with IR filter and White LED - TCS34725	2	$7.95	$15.90
Amazon	Male/Female Jumper Wires	20	$0.37	$7.49
Amazon	Befenybay Small V-Wheel with Plate for 2020 Aluminum	1	$17.89	$17.89
Adafruit	INA169 Analog DC Current Sensor Breakout - 60V 5A Max	1	$9.95	$9.95
Amazon	FYSETC Ender 3 S1 3D Printer Stepper Motor 42-40 Nema 17	1	$13.88	$13.88
Amazon	300mm 2020 Aluminum Extrusion 12 inch V Slot Aluminum	1	$19.99	$19.99
Adafruit	TCA9548A I2C Multiplexer	1	$6.95	$6.95
Amazon	GT2 Timing Belt Pulley	1	$14.19	$14.19
Amazon	Aluminum Straight Line Connector	4	$2.22	$8.88
Amazon	Jumper Wires	120	$0.04	$4.80
Amazon	Marble PLA Filament	1	$19.99	$19.99
Amazon	Silver PLA Filament	1	$21.99	$21.99
Amazon	Hot Glue Sticks	5	$0.60	$2.92
Amazon	M5 Slide in T Nut	6	$0.16	$0.96
Amazon	H-Bridge Motor Driver	3	$2.80	$8.40

Amazon	Arduino MKR 1010 WiFi	3	$39.23	$117.69
Adafruit	Raspberry Pi 3 - Model B	1	$35	$35
MakerStock	3mm Acrylic, Transparent Blue	1	$10.95	$10.95
Amazon	12V 10A Power Supply	1	$20.99	$20.99
Amazon	12V 5A Power Supply	1	$9.89	$9.89
Amazon	ZipTies	50	$0.02	$1.37
			Total	**$596.04**

Concept for Production

To make a manufacturable final product, several changes need to be implemented to simplify and speed up the building process. First, the body of the robot should be made from a material other than 3D printed PLA. While PLA was a fairly simple material to work with for the prototype, a lot of sanding needed to be done to ensure the parts fit together. To cut down on the modifications needed, a material such as injection molded plastic could be used. Additionally, there were several issues encountered regarding the abundance of wires, microcontrollers, and H-bridges used. In the final product, it would be useful to have custom-made PCBs.

The electronics used for the prototype were fairly robust. The linear actuator and claw both worked well for the prototype, and it is suspected that they could also work well in a final product. The arm of the prototype, which was assembled out of 2020 aluminum extrusion, was a strong material to use, but required connecting pieces. To simplify this process, aluminum extrusion of a fixed and calculated length should be used. Connected to the aluminum extrusion were some aluminum brackets that supported the bearing for the timing belt pulley system. A custom made part would be better to use, and could be manufactured from aluminum.

Technical Drawings

As the final robot had a multitude of components, the technical drawings highlight the main assembly and parts specifically designed for the robot that cannot be easily purchased or recreated.

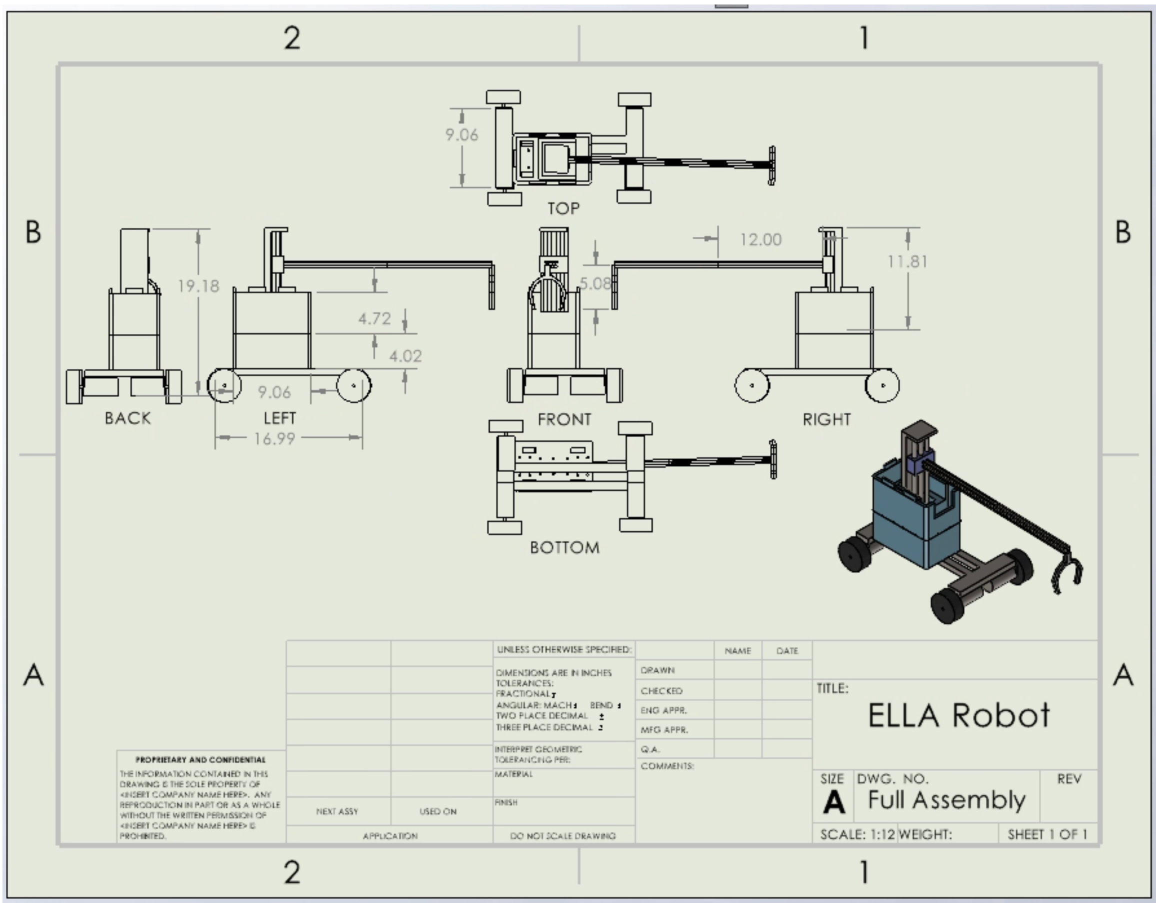


Figure 22: Technical Drawings for ELLA Assembly

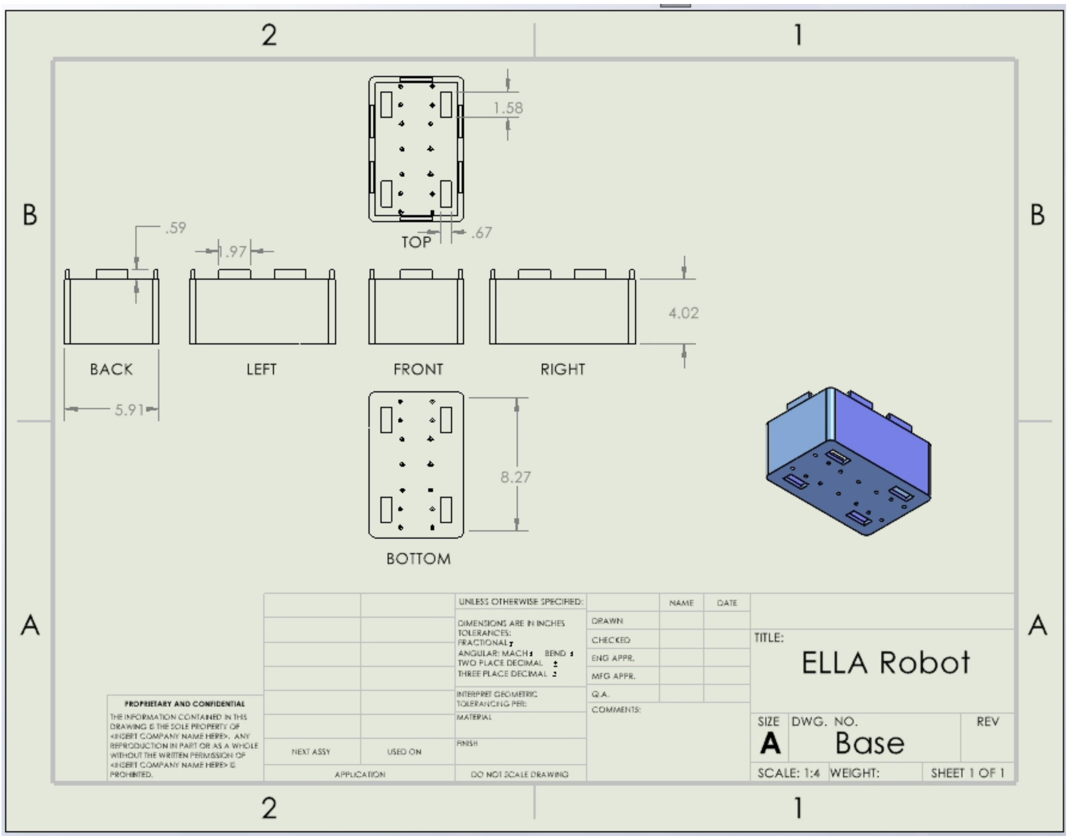


Figure 23: Technical Drawings for ELLA Base

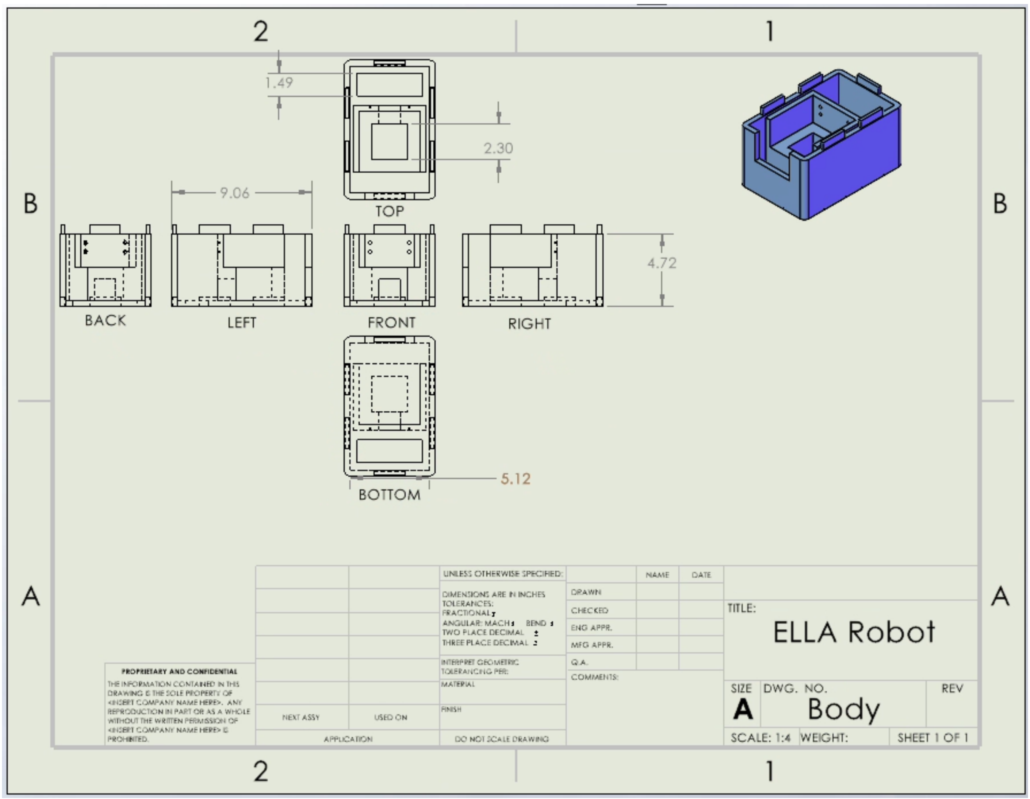


Figure 24: Technical Drawings for ELLA Body

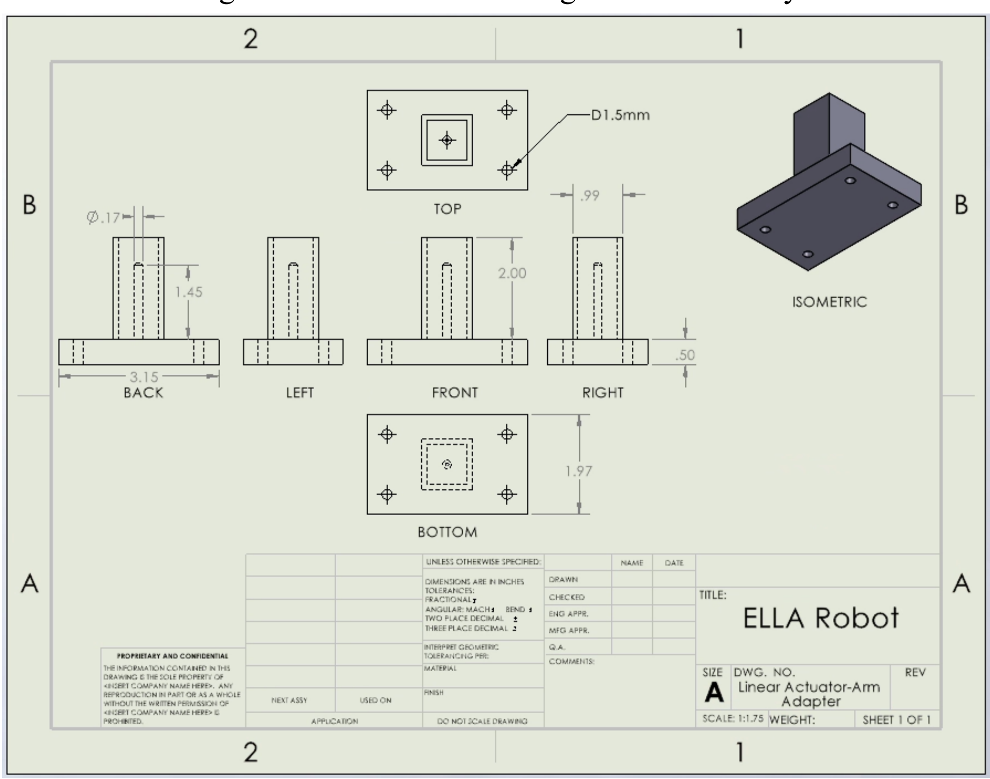


Figure 25: Technical Drawings for Linear Actuator-Arm Adapter

User Guide

ELLA is a very intuitive robot to use. As aforementioned, one of the primary strengths of the design is the autonomy. When a customer first purchases ELLA, the idea is that an engineering technician would come to the house/location that ELLA was to be used in. The engineering technician would analyze the space and place the color-coded tape on the floor. This allows ELLA to be very flexible to any environment. After the tape is put on the floor, the user's intervention is finished. ELLA will follow the lines and complete the transfer of laundry with no other help.

In the current prototype of ELLA, the robot is running on power from a corded power supply. In a later version of the project, ELLA would be battery operated, which would make the whole system cordless, increasing the autonomy.

Gantt Chart

The following table provides an overview of the project timeline. Not included in this table is the final week of September, which is when we were originally given the project assignment. However, in this week, no progress was made that contributed to the final ELLA design, so it has been omitted for clarity.

Table 11: Gantt Chart

TASK TITLE	% OF TASK COMPLETE	October				November				December			
		1	2	3	4	1	2	3	4	1	2	3	4
Brainstorm Home Robot Improvements	100%	■	■										
Narrow Down Designs	100%		■	■	■	■							
Initial CAD Model	100%				■	■							
Initial Parts Order	100%			■	■	■	■						
Initial House of Quality	100%			■	■								
First Prototype and Presentation	100%	■	■	■	■	■	■						
Construct Large-Scale Model	100%					■	■	■	■	■	■	■	
Review & Iterate First Design	100%					■	■	■	■	■	■	■	
Settle on Final Design	100%						■	■	■	■			
FEA/CFD Analyses	100%							■	■	■			
Final Parts Order	100%						■	■	■	■	■	■	
Build Large-Scale Prototype	100%						■	■	■	■	■	■	
Prepare for Demo	100%						■	■	■	■	■	■	
Final Wrap-Up	100%						■	■	■	■	■	■	■
Final Report and Evaluation	100%											■	■

References

[1] “Laundry by the Numbers.” *Soap Opera Laundromats*, 9 May 2022.

[2] *Activities of Daily Living - Statpearls - NCBI Bookshelf*, 19 November 2022.

[3] “How Many Gallons of Water Do Washing Machines Use?”, Maytag, 22 July 2019.

[4] “Top 5 Quietest Washing Machine on the Market.” *Zen Soundproof*, 1 Aug. 2022.

[5] “6Smart Dial Washer with FlexWash™ .” *Samsung Electronics America*.

[6] Dhar, Payal. “Robot That Can Do Laundry by Itself.” *New Scientist*, 25 May 2022.