TactionTablet: Affordable Tactile Graphics Display

by

Mark E. Vrablic

S.B. Electrical Science and Engineering
Massachusetts Institute of Technology, 2019

Submitted to the Department of Electrical Engineering and Computer Science
in partial fulfillment of the requirements for the degree of

Master Of Engineering In Electrical Engineering And Computer Science
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2020

Signature of Author:____
Department of Electrical Engineering and Computer Science
August 7, 2020

Certified by:____
Kyle Keane
AI Research Scientist, MIT Quest for Intelligence
Thesis Supervisor

Accepted by:____
Katrina LaCurts
Chair, Master of Engineering Thesis Committee

TactionTablet: Affordable Tactile Graphics Display

by

Mark E. Vrablic

Submitted to the Department of Electrical Engineering and Computer Science
on August 7, 2020 in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering in Electrical Engineering and Computer Science

Abstract

This thesis presents the design and manufacture of a new type of refreshable tactile graphics display at a drastically lower cost than existing options. The device, now called the "TactionTablet", uses a single actuator attached to a two-dimensional plotter to raise a grid of individual bumps that lock in place above the tablet surface to form a graphic that can be explored by touch at the user's own pace. The TactionTablet was designed to be built using the tools and supplies available in typical hardware stores and makerspaces, allowing it to be used as a practice project for equipment training.

The core innovation of the device is the evolution from traditional displays using multiple active electronic actuators to a single mobile actuator controlling many passive pins. While this new mechanism is much slower than that of a traditional display, it is also cheaper to produce by multiple orders of magnitude, as adding more pixels does not increase mechanical or electrical complexity. This effectively removes the financial barrier of entry to tactile displays.

The final prototype display produced in this thesis has sufficient resolution to display graphics up to 28 by 29 pixels in size, while being simple enough to build in any makerspace. The plotter mechanism's accuracy and speed are lower than expected, taking two minutes to display a typical graphic, but the ultra low material cost of $32.07 places the device in a class of its own. One complete device has been manufactured during this thesis and all mechanisms validated. In the future the design can be further miniaturized with injection molded pins or a more sophisticated plotter to achieve higher resolutions and likely display braille.

Thesis Supervisor: Kyle Keane

Title: AI Research Scientist, MIT Quest for Intelligence

Acknowledgements

I would like to express my sincerest gratitude to Dr. Kyle Keane for introducing me to the field of assistive technology. Throughout the last five years I’ve had many opportunities to delve deeper into the field and worked on many projects to empower people with disabilities. His extensive experience and connections have proven invaluable to this project, and he always knew exactly who to connect me with to discuss any design problems encountered. His constant support of this thesis during the pandemic has been amazing. This project would not have been possible without him.

I would like to thank all the people with visual impairments who I’ve talked to throughout this project. Lindsay Yazzolino, K. Raghuram, and the children at Project Prakash have all provided great feedback and advice to shape this project into something that is useful to those who need it most. I also extend my sincerest gratitude to all of the other researchers in the field of assistive technology, whose enthusiasm, impactful work, and dedication inspire me to do the most good that I possibly can for others.

I am greatly appreciative to Aaron Yeiser, whose help in writing the firmware and communication interface saved many days of debugging code. Thanks to his ability to write concise and clearly organized programs, the code for this project isn’t something I’m embarrassed to show others.

I also thank Amanda Roberts, whose encouragement has kept my morale high throughout the project and whose continuous proofreading has kept my thoughts written clearly on the paper.

Lastly I would like to thank my parents, without whose love and support I would never have been in a position to succeed.

Contents

Introduction

Due to a lack of assistive technology, blind students have historically had difficulty accessing information that is typically presented graphically in a plot or chart. While text summaries and sonifications are the easiest and cheapest way to make such information more accessible, they cannot be freely explored at the user's own pace and struggle to communicate shape and spatial relations. Comprehension of two-dimensional spatial information is essential to modern STEM disciplines, necessitating serious revision of the aims and capabilities of accessible devices. The TactionTablet makes study of such information accessible by having students touch raised dots that produce a pixelated rendering of any given graphic.

Previous Work

There are a few options for people with severe visual impairments to access visual information. The most common is through an alternative text description given via screen reader or refreshable braille display. This provides a very poor sense of spatial awareness, and limits the user to linearly exploring an interpretation of the graphic they need. The second is a sonification, which attempts to represent visual information through auditory rhythm, harmony, or melody. These can work well when patterns are present, but require extra work to implement properly and are limited to linear datasets with two variables [1]. The third is printed tactile graphics, which offer the greatest sense of spatial awareness, are relatively easy to create from an image, and can be freely explored at any pace; the downside is that they are very expensive to produce except in high quantity, so only mass-produced, published texts are available in this medium.

Although the TactionTablet does not presently achieve a pixel pitch sufficient to display legible braille, its purpose and underlying technology are comparable to a refreshable braille display. Refreshable braille displays are not new, with the first one being created in 1975 at the University of Dortmund [2]. Although there are many nuances to every design, at a fundamental level all refreshable braille displays to date utilise small, powered actuators in every cell. This provides a good reading experience because it allows all cells to refresh very quickly and quietly, but has the drawback of making production very expensive due to the sheer number of mechanical and electrical parts needed. With improvements in manufacturing methods over time that cost has decreased substantially, but despite this refreshable braille displays are still expensive. A 40 cell, single line display costs nearly $3000 today [3], with upcoming models expected to to cut this cost down to $1400 in the near future [4]. Using the traditional design, 40 eight-dot Braille cells require 320 actuators, which in the $1400 device can be optimistically estimated to cost $3 each leaving $500 for the electronics and firmware required to operate it. Further, the actuation mechanism takes up a large amount of space above and below each character, rendering displays with multiple lines impracticable as there would be a large separation between each line. Other companies and projects have attempted to replace this mechanism with radically different ones [5], [6], but their refusal to compromise on refresh speed means that they all use multiple actuators per cell, necessitating a high cost. Because of this, a project that aims to expand the functionality and accessibility of refreshable tactile graphics must take a new approach to this mechanism.

Project Goals

The core innovation of this project is to move from a device with independent actuation of each pin to a device with passive pins controlled by a single mobile actuator. By mounting one actuator on an X-Y plotter and moving it to manipulate one pixel at a time, the manufacturing and control problems are greatly simplified, resulting in huge cost reduction. Since there is only one powered mechanism, displaying multiple lines of text and graphics is possible. Though this mechanism is louder and slower than more expensive refreshable displays, the benefit to people who otherwise wouldn't have access to such technology greatly outweighs these shortcomings. The TactionTablet can be manufactured for under $100 using resources readily available in even a rudimentary makerspace requiring only a basic 3D printer and laser cutter.

This project presented two key challenges. First, to design an inexpensive, passive pin that will lock in place when pushed through a hole, be easily reset, and withstand thousands of use cycles. Second, to design a manufacturing method that uses standard materials available anywhere in the world, and requires only basic maker skills.

Nearly all makerspaces on the MIT campus already use a project to teach students how to use their tools. Since these projects were designed purely as learning exercises, their end product is often not useful; common projects include a circuit board case, or gears mounted on a plaque. As a counter example, the Edgerton Center has a very popular training project in which students build a fully-functional flashlight. This provides anecdotal evidence that learning how to make real world objects engages students in the learning and making process. The TactionTablet aims to take the Edgerton model a step further to engage students at MIT and around the world in public service, teach them about educational methods for the blind, and train them in quality assurance.

While building a TactionTablet, students will gain not only the practical skills of how to safely operate the machines in a makerspace, but an awareness of the impact their work can have in their community. The field of assistive technology has many exciting design and engineering challenges that can measurably improve the lives of people living with disabilities, as well as those of their families, friends, and societal support systems. Studies of people with disabilities indicate that access to assistive technology enhances independence, and can have psychological benefits for the user [7]. Due to the limited market size and funding available to specialized assistive technology products, any innovation that helps a person has a huge impact, even if the device is simple.

To meet these goals, the TactionTablet must:

- be simple enough to build in a makerspace
- be durable enough to withstand small drops or rough transport
- connect to a computer to receive commands to display graphics without requiring user knowledge of software development.
- reset to a known state in the event of power failure
- be easily serviced by someone without an engineering background

TactionTablet Design Renders and Terminology

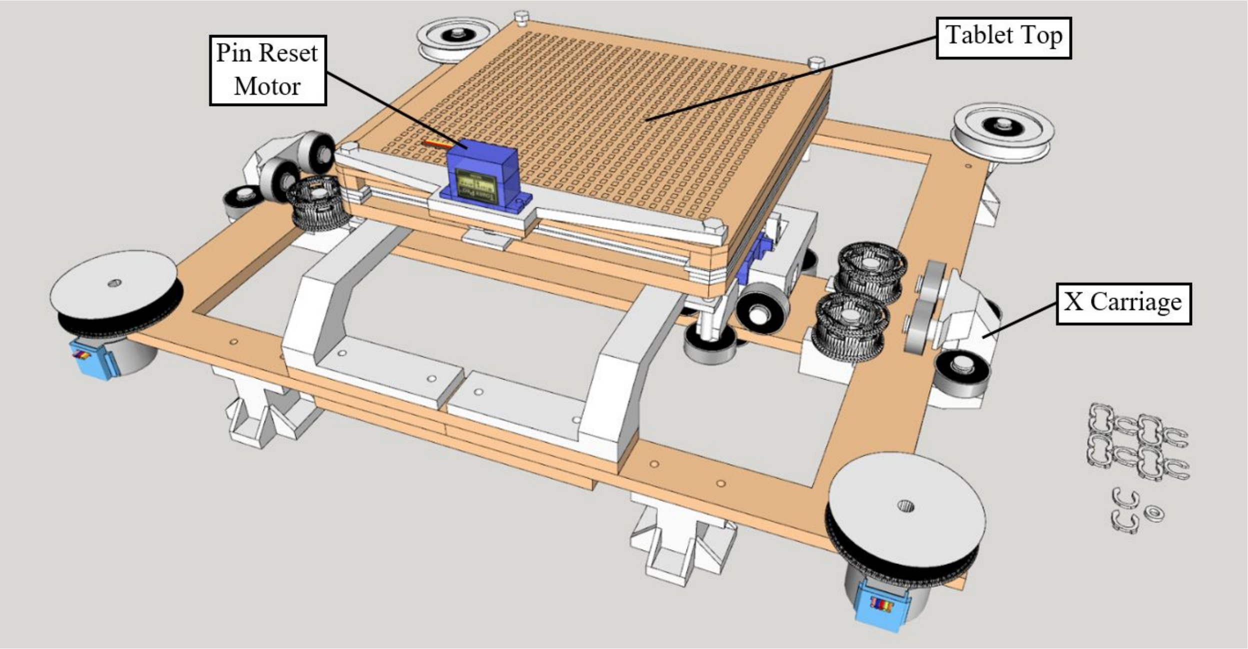

Figure 1: Complete TactionTablet, with tablet top attached to the 2D plotter base

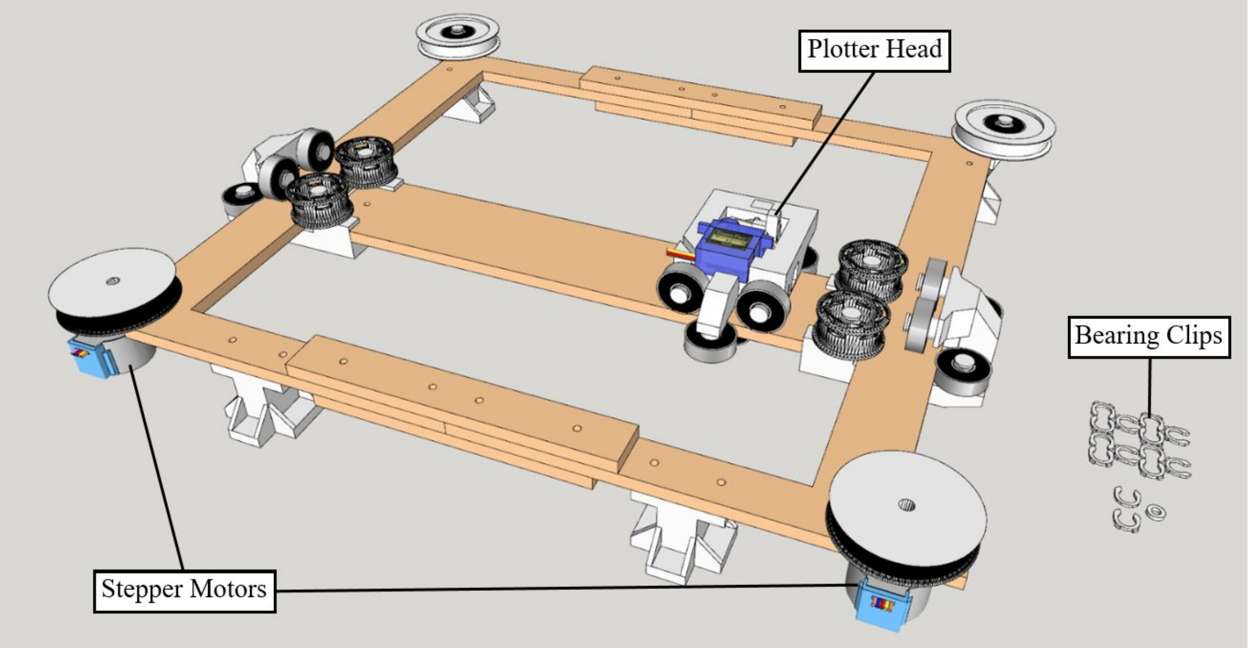

Figure 2: TactionTablet 2D plotter base, tablet top removed

Product Development

The TactionTablet was developed in two separate parts: the 2D plotter base, and the tablet top containing a grid of latching pins. When assembled, the plotter raises the commanded pins to form a tactile graphic which is displayed until an erase command is given. The 2D plotter was expected to be the easier part, as there are already many well-developed designs. The latching pins, however, are entirely new and therefore the more challenging and important part of the TactionTablet design process.

Plotter Base Design

Version 1: CoreXY

Design Process

The first iteration of the plotter was based on nntuan's *CoreXY for LM6UU and linear rail 6mm* [8] and SCOTT_3D's *HyperCube Evolution* 3D printer [9]. It uses minimal, readily available hardware and is easy to assemble. Because it is a coreXY based plotter, movement is incredibly fast and precise [10]. Unfortunately, some major modifications were required for it to work for the TactionTablet. Since it appears to be intended for drawing, there are no limit switches for it to know the plotter head's absolute position. The TactionTablet needs to know where every pin is, so it needs to know when it is at position (0,0). Luckily, the CC Attribution license permits modifications, so mounts were added for limit switches to allow it to find a home position and holes were added to replace the unreliable self tapping wood screws with machine screws and nuts. The next challenge was scaling down the design and eliminating the expensive aluminum extrusion used for the supports. This was accomplished by moving the entire plotter down so it sits on the MDF base and combining the support feet with the motor mount in one 3D printable part.

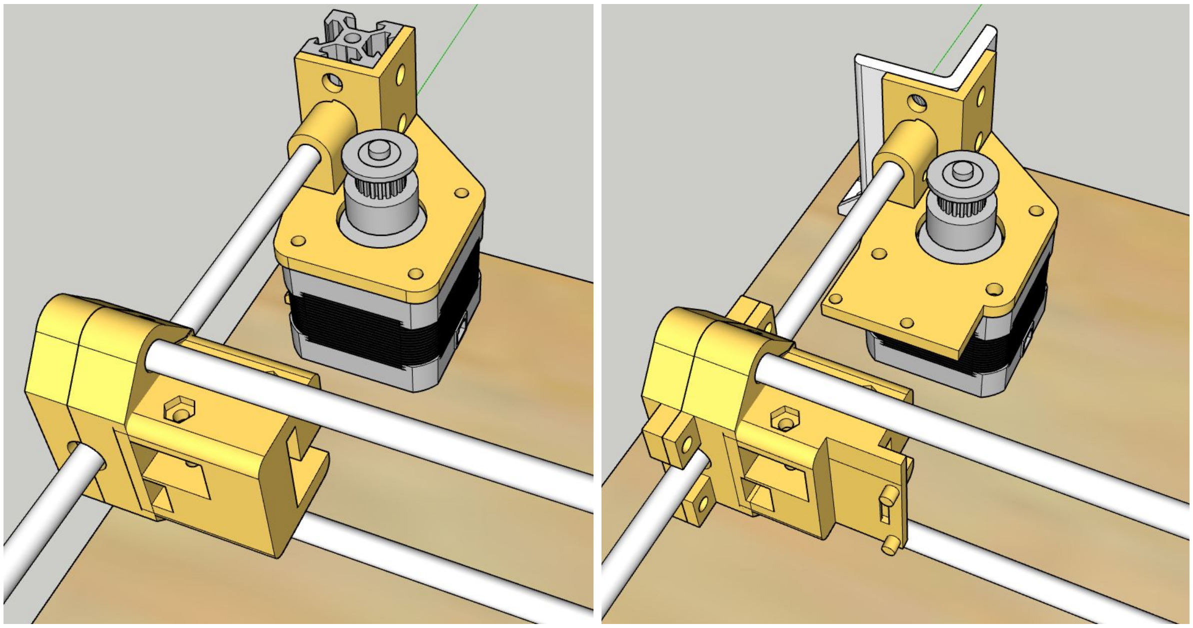

Figure 3: nntuan's plotter (left) and TactionTablet modifications (right)

Challenges Encountered

Unfortunately, this design started to show multiple problems early on. It was relatively expensive to build at ~$65 in plotter parts alone, and its accuracy and speed were wildly dependent on both of the belts being correctly tensioned. Having never built a coreXY plotter before, the only major downside of it appeared to be the relative complexity of threading the belts in the correct pattern. The time and difficulty required to evenly tension the belts, however, is a significant weakness. This difficulty makes the coreXY system a poor choice for the TactionTablet, as ease of construction is a high priority. Further, the multiple large printed parts took a long time to make, and the hardened linear steel rods would take a long time to cut by hand yet be dangerous to cut using power tools. COVID19 ended up being the final tipping point to abandon this design, as it shut down labs across campus including the one this plotter prototype was kept in. Despite this, it is worth noting that this design is capable of achieving much higher speeds than any other plotter design considered. If the TactionTablet were being produced professionally, a CoreXY system like this would be a better option.

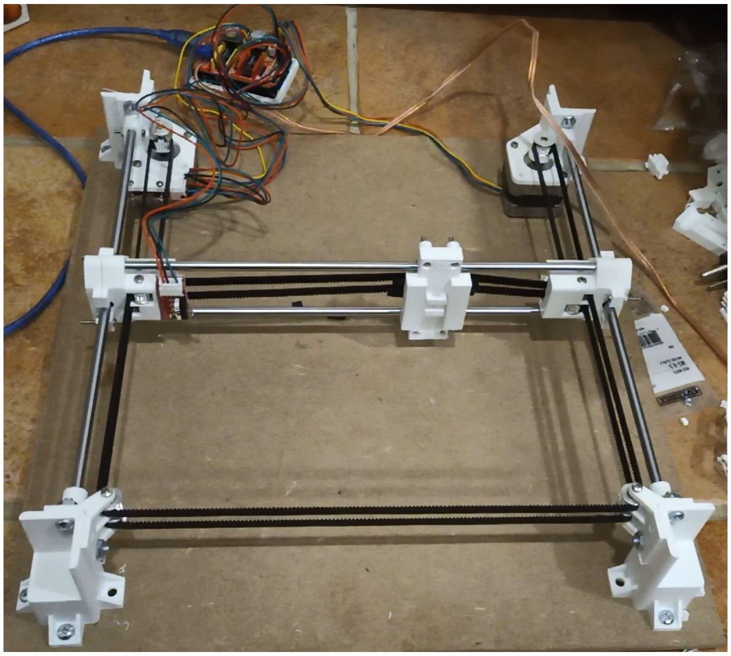

Figure 4: CoreXY plotter prototype

Version 2: H-bot

Design Process

The inspiration for the next design was a low cost, low precision X-Y system commonly used in older 3D printers. It is referred to as an H-Bot because the single belt used for both X and Y motion is wrapped in the shape of an H. The system is rarely found in modern 3D printers and plotters due to its low accuracy which gets worse at high speed due to torque on the moving X axis [11]. Further, since this large torque is applied on the rails, slight errors in manufacturing tolerance can lead to a larger error in positioning, which is particularly undesirable in a 3D printer where submillimeter precision is necessary. As the pitch of pins on the TactionTablet is 5mm, that degree of error is acceptable and can be managed by ensuring the plotter validates its home position after every displayed graphic. The simplicity of construction makes the H-Bot design highly desirable for use in the TactionTablet, which must be buildable in a makerspace.

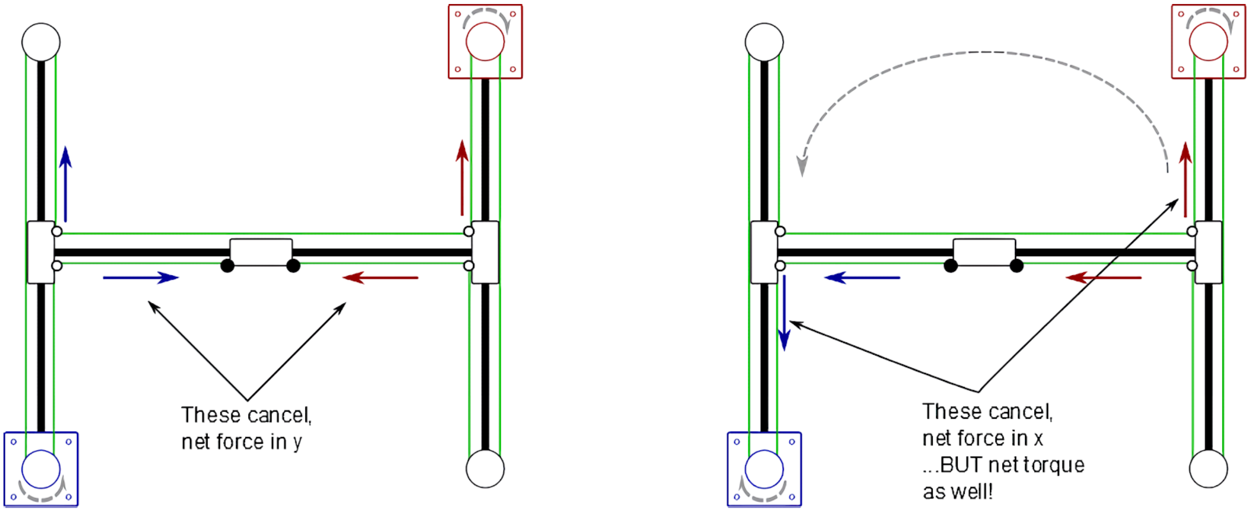

Figure 5: Forces in H-bot during Y and X movement [12]

There are further benefits to using the H-bot design for this application. Since it uses only one belt, balancing the tension isn't a problem. Both motors remain stationary, so they don't work as hard to move the plotter head. Combined with the lightweight plastic and wood design, this allows use of ultra low cost geared unipolar stepper motors which confer their own set of benefits. Besides the lower motor cost, they can be driven with simple and cheap transistor arrays, which allow more precise control over steps taken than could be achieved with a standard GRBL controlled bipolar stepper motor driver. As these motors are intended to be used in air conditioners and fans to direct the air vents in a known position, they are mass produced and reasonably slow. But this also means that they have a built in tension clutch allowing them to slip when they encounter strong resistance to rotation. In the case of an air conditioner this allows the motor to be signaled to rotate to some point beyond fully closed and regardless of where the blades started, the position is then guaranteed to be exactly closed. This saves the extra cost which would be required for a limit switch as well as the electronics to read it. Similarly, for the TactionTablet this principle can be used to eliminate the need for limit switches to home. It also prevents the motors from damaging the high precision parts of the H-bot plotter even if something is stuck in the mechanism.

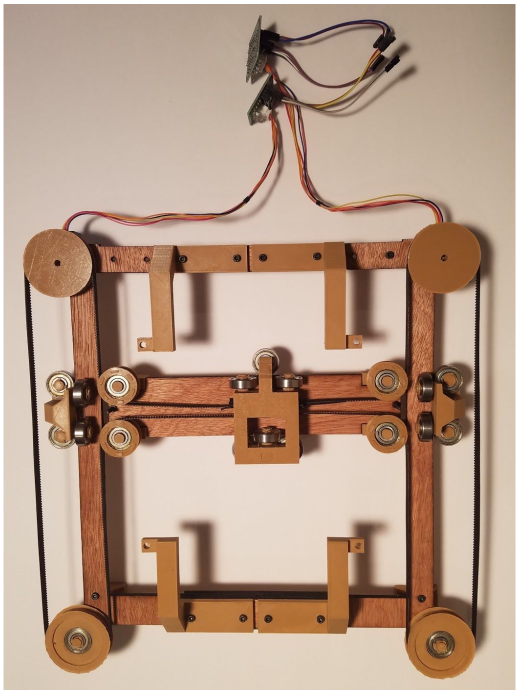

Figure 6: Top view of the first H-bot plotter prototype, note the shape of the belts which form a H

A major goal of this redesign was to avoid the use of hardened steel rods in the linear motion components, as the rods and bearings are expensive and difficult to work with. Browsing bearings by price revealed that skateboard bearings are a standard size and very cheap even in low quantities. These 608zz bearings are somewhat large at 22mm in diameter, but at $14 for 100 pieces with fast USA shipping it was worthwhile to design around the size constraint. There were only a few affordable options to replace the rails. First, small aluminum extrusion; while easier to work with than hardened steel, accurately cutting it would likely be difficult for small makerspaces. Further, since aluminum extrusion isn't uniform on all sides, the bearings would need to be placed very carefully to distribute the load from a single point. The second option was simply laser cut wood, the major benefit of this option being simplicity as the entire frame could be cut in one piece, but with the major drawback of the material's flexibility under tension. For the sake of simplicity wood was chosen as the rails for the design, and the first version of the base was created. Below is a cost breakdown of the plotter buying exclusively from US suppliers, including shipping cost where applicable.

Bill of Materials

Item	Quantity	Supplier	Cost
5mm Utility Panel	12” x 16” (1/24 sheet)	4’ x 8’ Utility Panel at Home Depot	$0.58
608zz Bearing	22	100pc 608zz on eBay	$3.08
PLA filament	~80 grams	1kg Inland PLA at Micro Center	$1.36
Stepper motor and matching driver	2	5pc on Amazon [1]	$5.60
GT2 Belt	1.98m	5m length on Amazon	$4.50
Arduino Nano	1	Available on eBay	$3.63
SG90 micro servo	1	5pc at Amazon	$1.54
M3 screws and nuts	20	100pc variety pack at Amazon	$2.53
		Total	$22.82

Table 1: TactionTablet Base V2 BOM

---

[1] Substantially cheaper from China if shipping time is not a concern

Challenges Encountered

The first iteration of the H-bot design was laser cut using 5mm utility panel on a K40 laser cutter set to 10mA, 2 passes, and 6mm/s. The moving parts required a few iterations of testing different tolerances to tightly fit the wood without impeding the motion of the motors. Of particular note during assembly was the difficulty of inserting the belt into the center holder, which motivated substantial redesign later. Initially a solenoid was used to actuate the pins, but it was large, heavy, difficult to power, and not strong enough to push some of the pins all the way up. The design was modified to accommodate a common SG90 micro servo instead, which provided much more torque for activating the pins at a smaller size and weight. This allowed the actuator on the plotter to use the same model of servo as the tablet on top, simplifying the BOM. The main tradeoff for these benefits was speed, as consistently activating a single pin takes 320ms with the servo but could be nearly instantaneous with a stronger solenoid. For complex graphics using many pins, this adds substantial time to the refresh cycle. Finally, the practicality of cutting 5mm utility panel on a laser primarily designed to engrave things made construction of the base very difficult. The cut's kerf was particularly large due to the long cutting time, poor quality wood, and low power of the laser, and this resulted in dimensional error of as much as 1mm from the design files. The 5mm plywood was of non-uniform thickness, varying by up to .4mm depending on the local thickness of the glue binding the thin sheets of wood internally. This error was unacceptable for the TactionTablet. Because of this the laser would regularly fail to pierce through the wood, requiring a razor and sandpaper to cut through the rest of the way. An additional pass fixed this issue but also resulted in so much charring that the part was unusable.

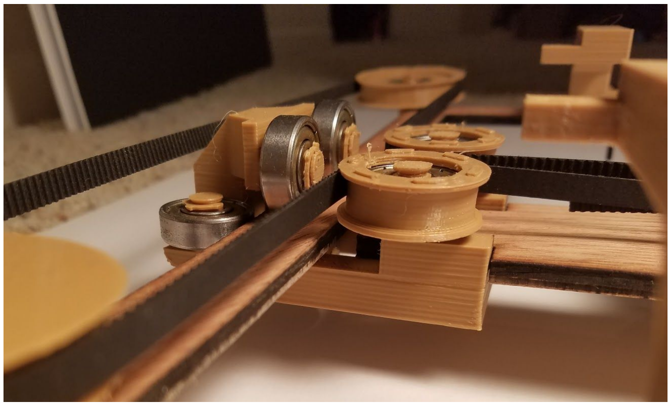

Figure 7: X-carriage size view with clips to hold on bearings

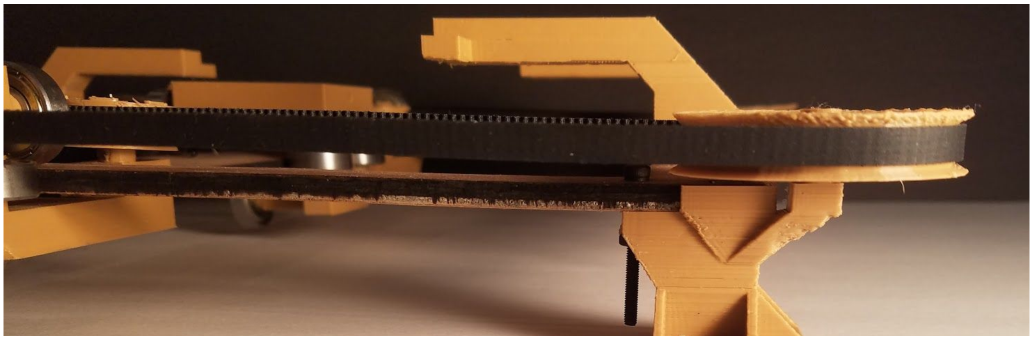

Figure 8: Side view of the cut 5mm utility panel. Note the charred top part of the profile where the laser was able to cut through, compared with the uncharred lower edge, which had to be cut with a razor

This design was functional, but needed two key modifications to work as intended. First, the area accessible by the plotter was smaller than the pin area. Since they were being developed separately, the plotter was only designed to reach the initially planned 10cm x 10cm pin area. Later into the design process of the tablet it was determined that more pins could be used reliably, extending the area the plotter would need to reach. This larger tablet was still compatible with the planned mounting points, but not all pins were in range of the plotter head. This was easily fixed in the next iteration by extending the wooden rails.

Second, the utility panel used for the rails was not strong enough; tensioning the belt caused the whole frame to flex inward. This flexing could likely be fixed by screwing the whole plotter onto a wooden base, but raised durability concerns as the frame would likely deform with time, requiring continuous adjustment of the belt tension. Further, the bearings could wear into the wood and cause further deformation. Given that the panel was also difficult to cut, it was clear that a different material was needed.

Version 3: H-bot

Design Process

For the second major H-bot design revision, all of these issues were addressed. Selecting a new material was particularly challenging, as low powered laser cutters aren’t well suited to cutting wood more than 5mm thick. The material needed to be strong in both the X and Y direction, as the frame is 2cm wide in both. This meant that thin hardwood would not work, as it has a grain in one direction. Most plastics cannot be safely laser cut, and even thick impact modified acrylic would not handle the tension well [13]. The only remaining option was MDF, but it is rarely used for laser cutting since the quality of cut is highly dependent on the brand and batch of MDF chosen. Further, it is only available in thicknesses of ¼” or greater at major hardware stores, and while some users report that this thickness of wood can be cut into functional parts, many have found that the second laser pass needed to cut through this thickness leaves significant charring. After discussing the problem on a laser cutting forum, it turns out that ⅛” MDF is cheap and relatively easy to find at local specialty wood suppliers, even in a small city like Kansas City. Cutting two sheets of ⅛” MDF and stacking them could provide the strength needed, while avoiding the charring that comes with using ¼” wood and two passes with the laser. Despite these concerns, the final material choice for the rails was ¼” MDF, as even with two passes it was dimensionally accurate. The edges were burnt black, but it wasn’t the same severe charring as on the utility panel and plywood. Its bad reputation therefore likely arises from aesthetic rather than functional concerns. Although not used here, the technique of stacking ⅛” MDF to increase accuracy was used on the TactionTablet top pin array.

Setting a K40 laser cutter to 12mA, 2 passes, and 6mm/s yielded a very clean cut on ¼” MDF from Home Depot[2]. The ¼” MDF cut well, and proved to be sufficiently rigid to withstand the belt tension, yet flexible enough to not break when shaken or dropped a few inches. The laser settings may need to be adjusted to accommodate different suppliers of MDF, as infrared absorption can vary between brands. Most makerspaces have higher powered laser cutters, meaning that this practicality is not a concern as the laser will be powerful enough to cut completely through in a single pass regardless of MDF quality.

Other modifications were made to address the issues encountered with the first H-bot version, including a redesign of the belt holders to make assembly and tensioning easier. All wooden parts were enlarged in the X and Y directions to provide extra rigidity. Additionally, the solenoid mount was altered to accommodate a servo and to fit the ¼” MDF. The final bill of materials is included below:

---

[2] Home Depot: Medium Density Fiberboard (Common: 1/4 in. x 2 ft. x 2 ft.), PLU 206092782

Bill of Materials

Item	Quantity	Supplier	Cost
¼” MDF	12” x 16” (⅙ sheet)	Home Depot MDF	$0.31
608zz Bearing	22	100pc 608zz on eBay	$3.08
PLA filament	~80 grams	1kg Inland PLA at Micro Center	$1.36
Stepper motor and matching driver	2	5pc on Amazon [3]	$5.60
GT2 Belt	1.98m	5m length on Amazon	$4.50
Arduino Nano	1	Available on eBay	$3.63
SG90 micro servo	1	5pc at Amazon	$1.54
M3 screws and nuts	20	100pc variety pack at Amazon	$2.53
		Total	$22.55

Table 2: TactionTablet Base V3 BOM

---

[3] Substantially cheaper from China if shipping time is not a concern

Challenges Encountered

These modifications resolved the problems found in the first version of the H-bot plotter, completing its development. The biggest remaining concern with this design was the difficulty of adjusting the belt tension, as with the pin poking servo attached, belt access was severely limited. This was not a major concern, however, as tension could still be easily adjusted using pliers. Accuracy was not great at up to 1mm of positioning error in all directions, but was sufficient as planned for during the design process. In an attempt to increase speed, 28BYJ-16 motors were fitted into the 28BYJ-48 stepper motor mounts. With a lower gear ratio, they could spin 4 times as fast as the 28BYJ-48 stepper motors. Although this greatly increased the plotter speed, due to lack of torque they would lose their position after only a few movement commands and need to go through the homing sequence again. Because of this, 28BYJ-48 stepper motors were selected to be the final motor choice for the plotter.

Tablet Top Design

Early Mechanisms

The unpowered pins are the core of the TactionTablet's function and what makes it unique. Unlike with the plotter, there are no previous versions or other designs to learn from, so a wide range of mechanisms needed to be tested before settling on a final design. Each pin needs to start in the retracted position, be pushed up by the plotter, and stay up when pressed on while being touched. It then needs to be lowered to the retracted position to repeat the cycle. There have been many sources of design inspiration throughout the design process, but the three most significant were machine screws, a retractable ballpoint pen, and an etch-a-sketch.

Machine screws seem like the obvious solution, as they are small, cheap, fit in standard nuts or tapped holes, and can be twisted to different depths. The first designs were based around this idea, with the flat portion of the display consisting of tapped holes with flush M2 screws as pins. However, there is no way to quickly detect and reset all the screws to the retracted position, and the plotter mechanism would need to be much more complex to accommodate the changing height of the screw as it spins. Additionally, since each screw needs to be spun around a fixed axis, the plotter would need to be extremely precise in order to stay centered on the screw head. The additional risk of tightening a screw too far or removing it entirely led to this pin design being quickly abandoned with no physical prototypes being made.

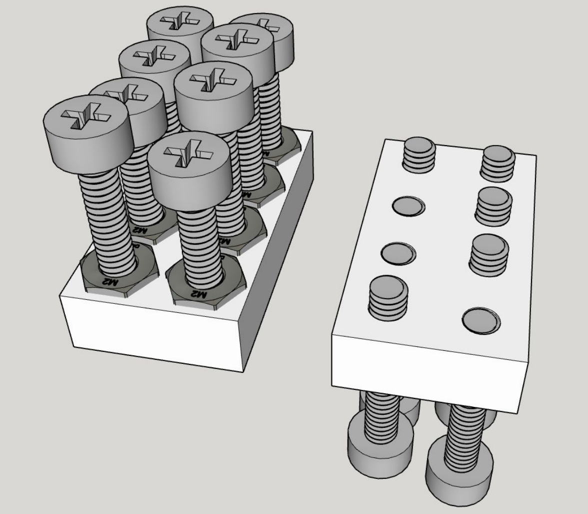

Figure 9: A braille cell designed with M2 screws

The retractable pen mechanism is a better starting point in that there are only two stable positions, it is easy to reset, and it is relatively compact. Actuation still faces the challenge of the pin rotating, therefore requiring a high precision plotter, but that alone is a problem that could be overcome. The bigger problem with this design is that it must be 3D printed due to its unusual shape. Further, with its high level of intricacy it cannot be accurately printed on a standard filament based printer at the desired scale.

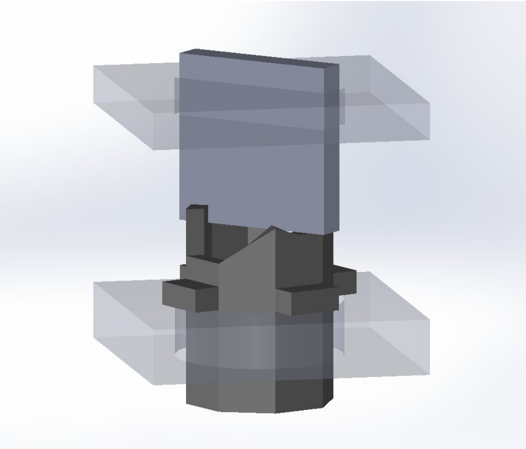

Figure 10: Pen clicker design. The bottom part rotates to move the pin up or down

An Etch-A-Sketch can reset all parts of its screen to a known state by being inverted. Such behavior is particularly desirable for this application, as it requires almost no time to reset, simplifies the software, and allows the moving part of the plotter to operate without any sensors. Combining this with some inspiration from toggle bolts and all the previous designs, a latching mechanism was created which can elastically deform to fit through a hole, then spring back and lock the pin in place on the other side. Moving two grid layers with holes larger than the cross section of the pin allows gravity to pull the pin down into the retracted position, resetting the device.

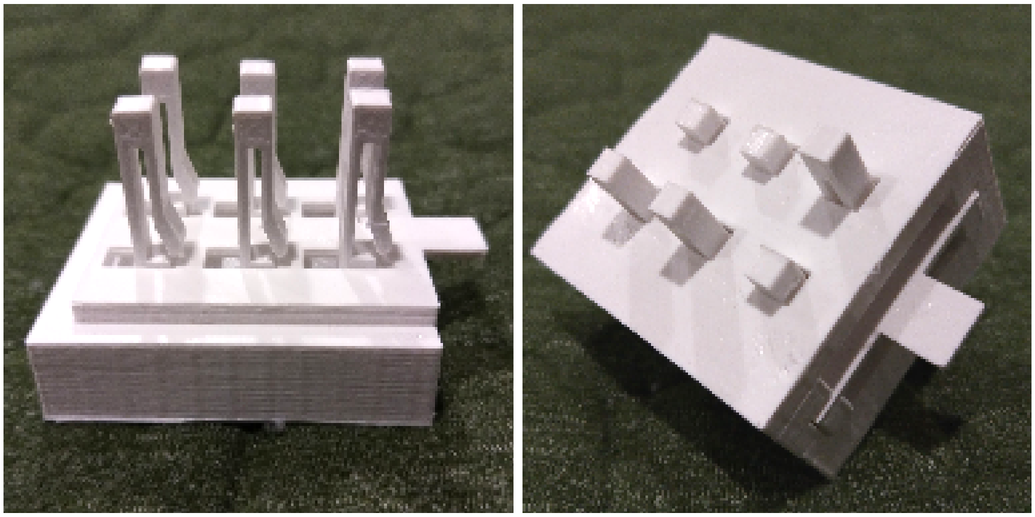

Figure 11: Large scale latching pin design prototype

A fully functional prototype was created with six oversized pins to demonstrate the concept and has been in use as a fidget toy. Although the pins in the large scale model were 3D printed, they could be laser cut at a smaller scale. It has shown no wear or failure in the 6 months of use since. Despite this, the biggest concern with this pin design was still durability, as the whole pin must elastically deform to fit through the hole. Due to its reliability, this design was selected for the device moving forward, and pin durability was closely monitored as the scale was lowered.

Iterating on Pin Design

To this end, material choice for the pin was very important. The pins had to be made on a laser cutter, as 3D printing so many would take too long. Unfortunately, this proved to be a huge design limitation, as there are only so many materials that can be safely laser cut, and fewer that can be cut into intricate parts [13]. The two most likely candidate materials were acrylic and acetal (Delrin) as they are both available at the desired thickness of 1.4mm (0.55”) and can both be safely laser cut. Acetal appeared to be the best choice at first, as its durability and flexibility are far superior to that of acrylic. Unfortunately, there were a few major drawbacks to its use in the TactionTablet. Due to uneven cooling during the extrusion process, the material is under internal stress which causes substantial warping when cut into small shapes. Further, since the thinnest section of a pin is only 1mm wide, the ability of the material to easily bend worked against it, as the pin struggled to hold its shape well enough to stay up. The final drawback for acetal is price - it’s only available online with expensive shipping thanks to its large size and is therefore substantially more expensive than acrylic. Acrylic is the typical material choice for laser cutting, as it leaves the cleanest edge of any plastic and so can achieve the finest details. It unfortunately has a reputation for being extremely brittle, especially in large sheets. While warping is still a problem in acrylic, it is less severe thanks to the increased rigidity, especially for small parts. Further techniques can be used to minimize warp and will be discussed later. As for the brittle nature of acrylic, when cut into small pieces the behavior changes substantially and it becomes reasonably elastic for all but very sharp bending motions. It is still more delicate than acetal, but doesn't deform as easily and will not snap when the arm is pushed all the way in. Ultimately, despite the durability drawbacks, acrylic was the best choice for the pins.

The first prototype was made using .055” acrylic for the pins and .110” acrylic for the grid which they fit in. The working area of the tablet was 20cm x 20cm at the time, and after the first part of the grid was cut it became immediately clear that this area needed to be reduced, as while the pins could be successfully cut at this scale without warping, the large size and high hole density of the grid led to severe warp.

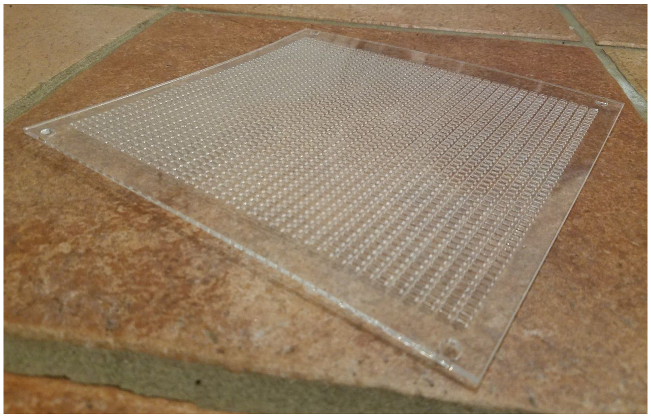

Figure 12: Warped tablet top

With a quarter the pin count of the 20cm x 20cm grid, a 10cm x 10cm grid was created with the same hole and pin dimensions. This time, the grid didn't warp substantially, and the prototype could be tested. The results were very underwhelming and the prototype had many flaws. The tolerances used were too tight so the friction of the grid against the pins was high enough to keep the pins up even with the grid in the reset position. With only 10 pins inserted the amount of force required to keep the grid out of the reset position was too high to apply by hand. A solenoid or servo certainly could not provide the necessary force to maintain the latching position with all 540 pins inserted. The pins could be pulled all the way out of the top or fall out if turned upside down.

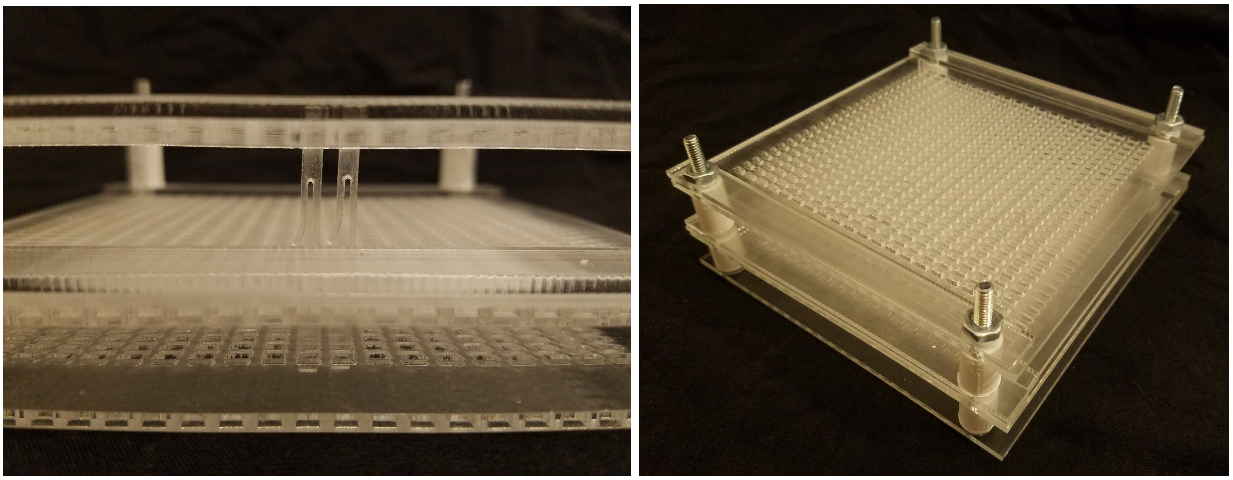

Figure 13: First working prototype with 2 pins inserted

Finally, with the large top grid being made of acrylic, it was very brittle and quickly broke when dropped from a height of a few inches onto a table. The final issue with this design was in the design process used to create it. Rather than modeling the whole top part of the tablet and pins in 3D, they were modeled in 2D on a sheet with no thickness. This meant that there was no easy way to visualize how any changes made would impact surrounding parts until physically building the entire assembly.

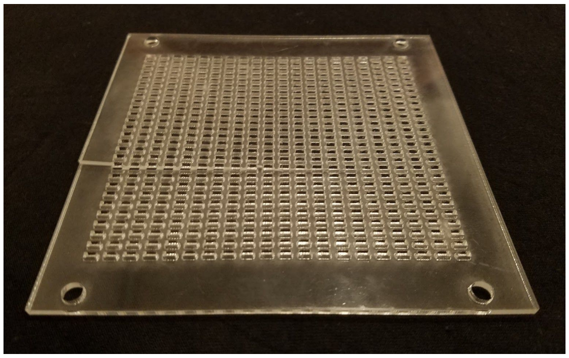

Figure 14: Cracked grid from the first prototype being dropped

All these problems were addressable and could be fixed in the next iteration. Unfortunately, the coronavirus pandemic shut down all labs at this point in the design process, necessitating a big shift in workflow, as the Epilog laser cutter previously used was no longer available.

Finding a Cheap Laser Cutter during a Pandemic

The most affordable laser cutter for a home user is a very common Chinese built 40W CO2 laser often referred to as a “K40” or “3020” laser. They sell for $270-$400 shipped and are intended to engrave Japanese Hanko stamps. Because they weren’t intended to cut material, they forgo many of the features of proper laser cutters commonly found in makerspaces, such as an air assist, active water cooling, and high dimensional accuracy. The work area is correspondingly small and the focal distance fixed. Despite being sold as an engraver, they do have enough power to cut if a 800mm 40W CO2 laser tube is installed and the above features added. The maker community has rallied behind this machine, and with a little work all necessary features can be added to achieve 90% of the functionality of the professional machine for less than 10% of the price. All laser cutting from this point was performed on a “K40” modified following the advice at www.k40laser.se. Despite these modifications, the machine still has two major drawbacks when compared to a professional one. The first is that in a high temperature and high humidity environment like Kansas, where this laser was used, it can only be run for roughly 30 minutes twice a day, increasing the time it takes to make one complete TactionTablet top to nearly 3 days. The second is that the power output is lower than a professional machine, so while the cuts are very precise, they are wider, less accurate, and often require more than one pass to cut all the way through a material. A professional machine would be able to cut the same complete TactionTablet top in less than an hour.

Figure 15: K40 laser cutter

The laser cutter was set up next to a window to exhaust the fumes. A drag chain was added to the laser head with 3D printed parts and a fish tank bubbler compressor was used to provide an air assist to extinguish any flames. Without an air assist, soot could settle on the lens, causing it to heat up and shatter. A laser head was 3D printed to direct the air to the focal point of the beam. Since the lens has a fixed focal length, the top of the material must always be exactly 50.8mm from the lens regardless of the material's thickness. To accomplish this, a vice grip was built with springs such that the top was fixed to the correct focal length. With this addition, any cutting material inserted into the clamp was guaranteed to have the correct focal length.

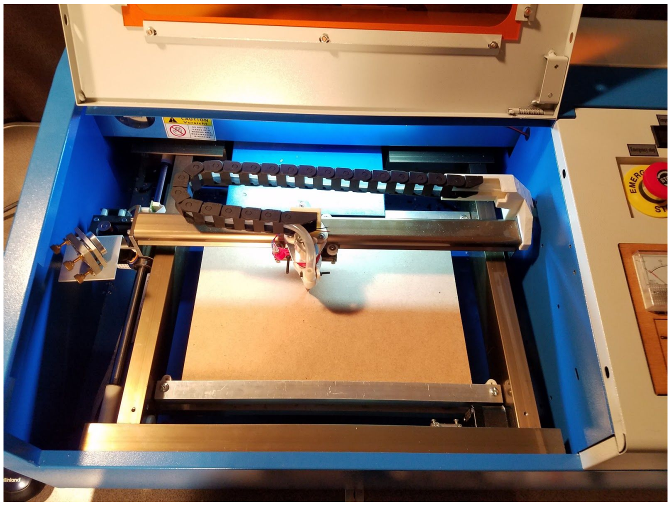

Figure 16: Cutting area and 3D printed laser head

On a professional laser cutter, the type and thickness of material are entered into software, which calculates the necessary power automatically. By contrast, the power supplied to the K40 cannot be changed by computer input, so power levels need to be determined manually by trial and error. Before each cut, the power and alignment must be entered manually on the cutter itself. As a side effect the exact current and cutting speed are always known, which is beneficial for documentation purposes. In a similar vein, the machine has no safety features. Laser temperature must be closely monitored throughout the cut to prevent permanent damage to the machine, and safety glasses must be worn at all times to protect against any beam reflections which may escape through the air inlets. To keep the coolant below its maximum temperature of 21℃, a small mini fridge was modified to hold the reservoir as shown in figure

18. A coolant flow sensor was added to monitor the flow rate and power down the laser in the event of pump failure.

Figure 17: Laser power controls

Figure 18: Laser cooling system with flow sensor

Refinement of the Tablet Top with a K40 Laser

With a new laser working, the design was fixed one issue at a time, and the tablet top was recut. With such a long delay between the previous iteration and this one, there was plenty of time to make design changes. Leaving the lab space also provided an opportunity to source different materials. The acrylic grid which had broken in the previous prototype was instead made from 5mm utility panel. Since the wood is not prone to warping, the size was increased to 17 cm x 17 cm. For the pins, acrylic was unfortunately still the best option, especially with a weaker laser. Fortunately, when comparing all the options nearby, Lowes had a special variety of impact modified acrylic designed to be less brittle. This turned out to be the perfect material for the pins, as it is more flexible and durable than standard acrylic.

This iteration worked better, but the laser still failed to cut every hole perfectly in the 5mm utility panel due to the wood's inconsistent thickness, so some holes were too small or would need to be sanded for the pin to fit correctly. Doing this for every single hole would be impractical, so it became clear that a different material was needed. At this point in the design process, the inconsistent 5mm utility panel was also causing problems in the plotter, and MDF was selected as a replacement for it. Since it had proven to be a good replacement in the plotter, it was also used to replace the tablet top. Due to the tighter tolerance on the grid, ⅛" MDF was cut and then layered to create the needed ¼" sheets.

Method to Reliably Cut TactionTablet Pins

Cutting the pins on a weak laser like the K40 is somewhat difficult, as the accuracy is low and the laser moves too slowly to cut a pin in one pass without melting the surrounding material. If using a nicer laser, kerf compensation should be turned off. The K40 software does not support this feature, so kerf was accounted for in the TactionTablet files instead. The following method was developed to reliably cut pins:

1. Place a sheet of .08" impact resistant acrylic on top of a sheet of utility panel, plywood, or MDF. Put this onto the laser bed.
    - Any material partially composed of adhesive should work as long as it leaves a sticky surface when burned by the laser. In testing, utility panel worked most reliably.
2. Set the laser power to 80% of normal cutting power for .08" acrylic and have it cut a single batch of pins. The laser should never cut all the way through the acrylic; if this occurs, either reduce the power or increase the speed.
    - For a K40, use cutting speed 18mm/s and current of 12mA.
3. Decrease the laser power and run a second pass to cut through the remaining acrylic while burning the top layer of plywood, releasing some of the glue which holds it together. If the wood beneath cannot be seen burning, the power should be increased. This adheres the pins to the bed and prevents them from blowing away or warping.
    - On a K40, use cutting speed 18mm/s and current of 5mA.

4. Remove the pins from the plywood. This should be done by hand and require a little force.
5. Put the pins in a container of soap and water and stir to remove the sticky residue. Rinse and dry the cleaned pins.

Pin Reliability Improvements

Having identified a reliable method for cutting the pins, the pin design could be iterated upon to improve the latching mechanism's consistency. Instead of testing all of the pins on a fully populated grid, a smaller cutaway containing only six pins was 3D printed. Since the pin and hole dimensions were the same as on the full size TactionTablet, the pins behaved exactly the same on this smaller model. Multiple cutaways were produced and a different pin design installed in each, allowing closer study of the impact of changing pin geometry on functionality.

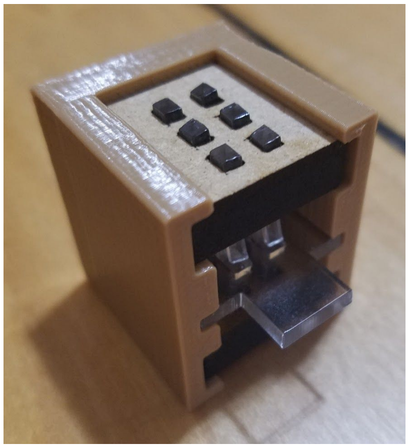

Figure 19: Small cutaway of grid for testing pin designs

The original pin design had a tendency to stay in the upward position even with the grid in the reset position. Since the pins rely on gravity moving them to the downward position, any friction with the grid prevents them from falling down. Modifications were made to the tolerances of the grid as well as the pin design to ensure that they would reset to the downward position despite their low mass. It was also found at this stage that shaking the reset grid a few times from the reset position to the locked position resulted in more pins being reset. This was taken advantage of and a lip was added to the edge of each pin to ensure collision with the grid during reset. This way, the pin would move down even if there was friction with the static holes. This was very effective, and meant that friction was only a concern immediately after the pin was pushed up, as the lip would be too high to make contact with the moving reset grid. Luckily, there was an easy solution to this problem; when the pin is touched from above as it is during normal use, it moves slightly downward, causing the lip to make contact with the grid if there is friction, ensuring a reliable reset. The downside to this is that every pixel of any graphic displayed must be touched at some time before or during the reset to guarantee retraction.

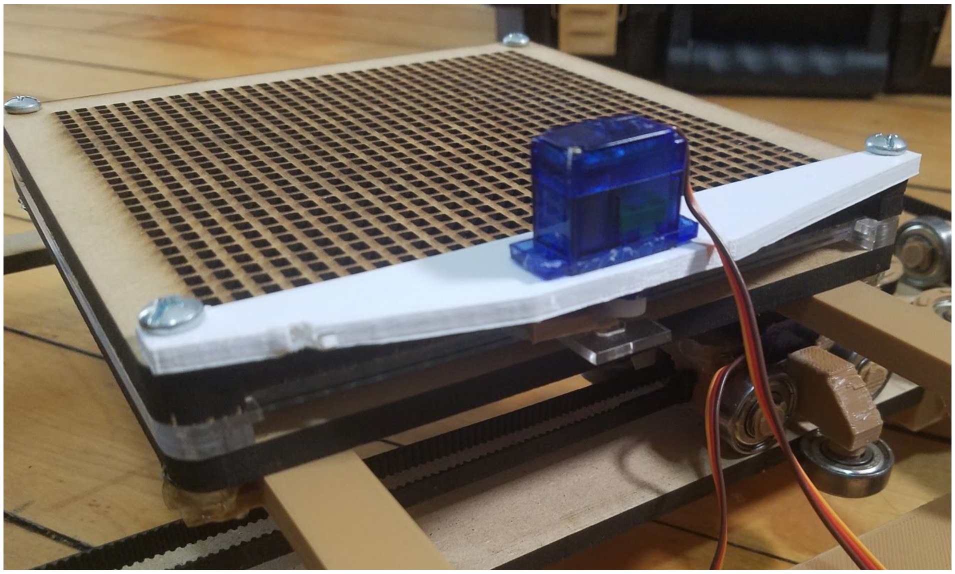

Figure 20: Complete TactionTablet top with reset servo

The bill of materials for the tablet portion can vary substantially depending on the success rate of cuts. Even professional grade laser cutters often require tuning speeds down to produce details as fine as in the pins, and no matter how well executed the cut, there will likely be a few pins that do not work perfectly. Cutting extra pins is therefore highly recommended.

Bill of Materials

Item	Quantity	Supplier	Cost
.080" impact modified acrylic	9" x 24" [4]	Duraplex Acrylic Sheet at Lowes	$6.99
⅛" MDF sheet	12" x 24"	Metro Hardwoods KC[5]	$0.73
#10-24 screw and nut	4	50pc combo pack from Menards	$0.26
SG90 micro servo	1	5pc at Amazon	$1.54
		Total	$9.52

Table 3: TactionTablet Top BOM

---

[4] ½ a standard 18" x 24" sheet

[5] $11.68 for a 4' x 8' sheet at time of writing

Software

Device Firmware

Since the TactionTablet uses unipolar stepper motors and ULN2003a drivers, it is not compatible with standardized open source firmware like GRBL. Custom firmware was written to drive the stepper motors based on serial input over USB. Python was chosen to do the translation from graphic to serial output for its balance of simplicity and power. A major advantage to writing the firmware from scratch was the resulting high degree of control over the steppers, which enabled homing of the axes without using a limit switch or current feedback. Instead, the motors take a step, turn off, step again, turn off, and repeat the process until the head inevitably runs into the wall at the home position. The motors continue stepping until the axes would be in the home position if they were starting in the furthest point from it, ensuring that the head returns to home every time. Since the motors are turned off after each step, they slip back when they hit a wall, preventing damage. With a duration of 56 seconds, this process takes significantly longer than it would if limit switches or current sensing were used, but only needs to be run once on bootup, as the position is remembered for as long as the device is powered on and is validated after every image. Further, the tablet is nearly silent during the homing routine. Therefore, this inconvenience is worth the significant savings it provides in both cost and complexity.

Computer Software

The TactionTablet receives low level commands over serial for all functions. Therefore, the computer it is connected to needs two pieces of software - one to generate a graphic of correct size for the TactionTablet screen, and one to take the pixels from that graphic, convert them to commands the tablet can understand, and send them over. All processing is done on the connected computer, where optimization is easier and more advanced calibration can be implemented to account for nonidealities in the plotter.

Generating Compatible Graphics

At present there are two ways to generate graphics of the correct size for the TactionTablet. The first is to input an image into a Python script which will resize and process it using OpenCV, displaying the result both on-screen and on-tablet. To prevent a confusing excess of pins from being activated the software draws an outline of the input image, as shown in Figure 21. This works well for many graphics, but in selecting a threshold for pin up versus pin down many fine details are lost. This includes thin lines on graphs, which are otherwise one of the best use cases for the TactionTablet. Graph images should instead be converted using a line drawing algorithm, which will prioritise inclusion of these fine lines in the graphic output. Due to lack of software experience, this has not been implemented.

.

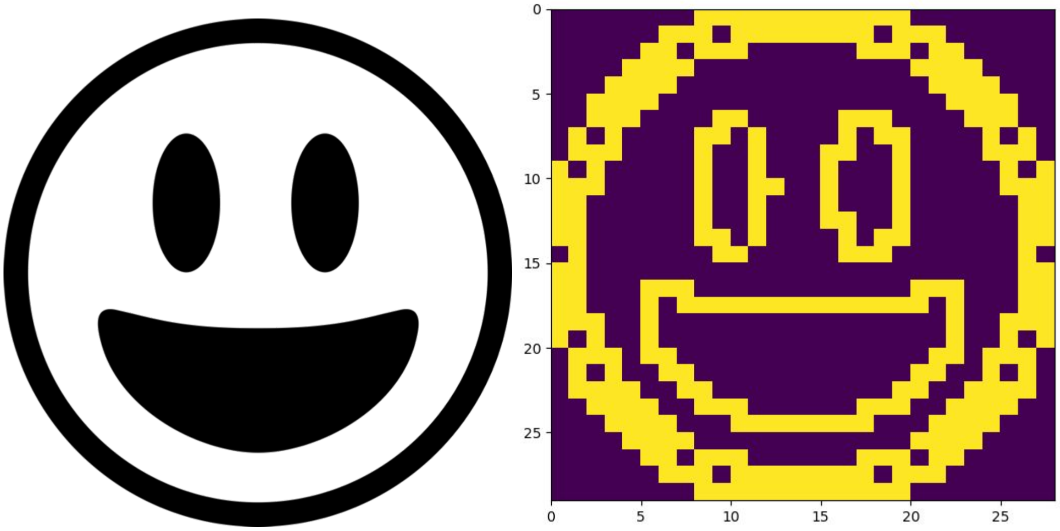

Figure 21: High resolution input image (left) and TactionTablet compatible output (right)

Instead, a second Python script was created to generate graphs compatible with the TactionTablet from their equations. This second option allows for generation of graphs without needing to worry about thresholding or line width

Calibrating Position and Sending Data to the TactionTablet

This part of the software has the most complexity, as it takes the pixels from the compatible graphic generated by the previous program and maps them to a sequence of steps across the tablet's grid. This code includes optimizations to account for slop in the plotter mechanism and increase repeatability of positioning, including two homing routines to: (a) find zero from a completely unknown position; and (b) validate the zero position between drawings without taking the time of a fully blind homing cycle. Not every TactionTablet built will have perfectly tensioned belts nor parts of exactly the same dimensions. Therefore, to increase reliability pins are always approached from the same direction before being poked. A raster pattern is followed for only the area that contains graphics. The plotter first hovers one pin to the left of the desired pin, then moves to the right to poke it and all subsequent target pins in the row. This process is repeated for the remainder of the raster. The program also supports drawing axes in a separate cycle from the image raster, which saves movement time when drawing larger graphics with horizontal or vertical axes.

Completed TactionTablet Assembly

Combining the Tablet Top and Plotter Base

With the plotter base and tablet top complete, the complete device could be assembled. Each half was tested independently during design with no major issues. The only issue found when combining them was that if the plotter arm pushed too hard, it would pop the tablet out of its mounts. This was prevented in software by reducing the arm's maximum reach, and in hardware by adding screws nuts to the bottom of the tablet. These screws made it harder to remove the tablet from the plotter, but prevented this failure mode when displaying larger images where the repeated application of upward force could slowly move the tablet top up and out of its holder.

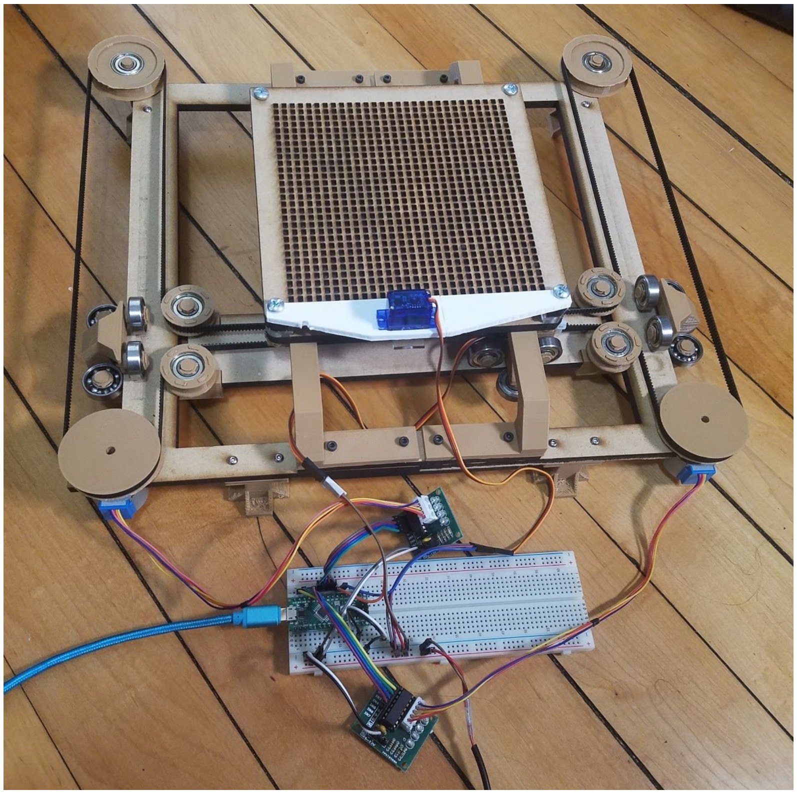

Figure 22: Complete TactionTablet without baseboard

To secure the electronics and increase the tablet rigidity, all parts should be screwed into a wooden base. Due to the pandemic this final step was unable to be completed for the TactionTablet prototype, as it requires access to power tools. Instead, a flat piece of styrofoam was cut to size and used as a base to ease transport of the device. It is also used during operation when a flat surface is unavailable. Luckily, completing this step with wood is not strictly necessary as it doesn't impact the device functionality, only it's durability. A video of the tablet in operation can be found at https://youtu.be/XImc5XEBQ9U.

Bill of Materials

Item	Quantity	Supplier	Cost
¼" MDF	12" x 16"	Home Depot MDF	$0.31
608zz Bearing	22	100pc 608zz on eBay	$3.08
PLA filament	~80 grams, 20% infill	1kg Inland PLA at Micro Center	$1.36
Stepper motor and matching driver	2	5pc on Amazon [6]	$5.60
GT2 Belt	1.98m	5m length on Amazon	$4.50
Arduino Nano	1	Available on eBay	$3.63
M3 screws and nuts	20	100pc variety pack at Amazon	$2.53
.080" impact modified acrylic	9" x 24" (½ standard sheet)	Duraplex Acrylic Sheet at Lowes	$6.99
⅛" MDF sheet	12" x 24"	Metro Hardwoods KC[7]	$0.73
#10-24 screw/nut	4	50pc combo pack from Menards	$0.26
SG90 micro servo	2	5pc at Amazon	$3.08
		Total	$32.07

Table 4: Complete TactionTablet BOM

---

[6] Substantially cheaper from China if shipping time is not a concern

[7] $11.68 for a 4' x 8' sheet at time of writing

Shortcomings and Future Improvements

The reliability of the pin reset cycle could be improved. Despite graphics being drawn reliably, if each pin is not touched during a use cycle there is always a chance that friction with the grid will prevent a pin from being reset, resulting in an erroneous pixel in the next graphic. Using a laser cutter with tighter tolerance than the K40 may prevent this problem, but it may also be an inherent limitation of cutting the grid from a composite wood like MDF. Adding a thin spring or grid to press down on the top of each pin during reset could solve this problem in future designs. Implementation of this solution is currently impractical due to the poor manufacturing tolerances on the K40, the added complexity for only slight improvement in usability, and limited equipment availability.

With professional manufacturing methods such as injection molding or higher end laser cutters, this pin pitch could be scaled down far enough to display readable braille. In its current form, however, braille text is oversized and nearly unreadable. This was confirmed with an early prototype of braille 3D printed at the minimum pitch the laser would allow for. During user testing it was proven to be legible, but was likened to a puzzle, taking time and effort to read the short phrase “The quick brown fox jumps over the lazy dog”. Such braille would therefore likely do more harm than good, especially to somebody still learning to read it. This confirmed that the TactionTablet as manufactured in a makerspace would not be a replacement for a standard cell based braille display.

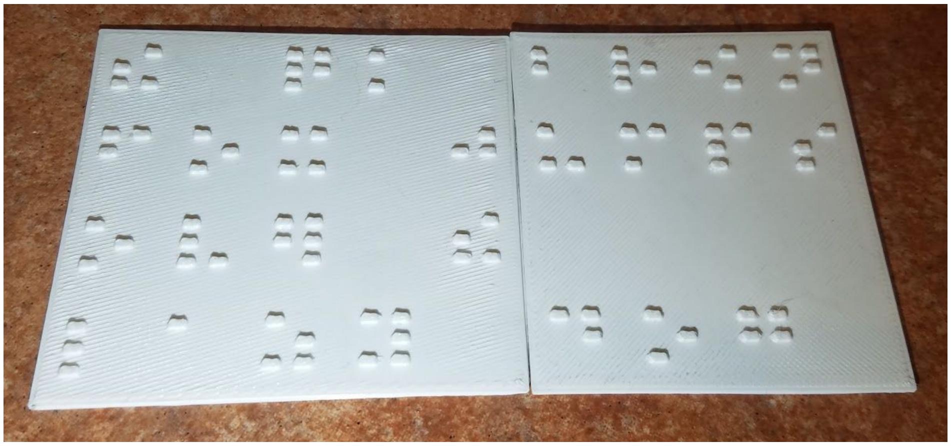

Figure 23: Braille 3D printed at the pitch of the TactionTablet

The tablet top could be modified to achieve standard braille spacing by angling pins inward so they form 2x4 cells of pins with spaces between adjacent cells, but building such an addition would require manufacturing tolerances tight enough that it would likely be more worthwhile to just make the entire grid at a lower pitch.

Plotter mechanisms are very common and have already undergone extensive research and cost optimization. The design chosen for the TactionTablet is well suited to it for its simplicity and low cost, but not for speed and accuracy. The H-bot would not be the right choice if the device were to be manufactured in high quantities, as the tolerances of the final plotter were worse than expected. Although the accuracy was improved in software, it required the motors to run slowly negating the high speed H-bot designs can achieve due to both motors being stationary. Further, the improvement in accuracy provided by always approaching the bottom of the pin from the same direction added even more time to the already slow image drawing process.

A coreXY or modified quadrap[8] plotter like that used in the Ultimaker line of open source 3D printers would likely work best in a professional manufacturing environment. Either of these designs would be able to provide excellent speed and accuracy for relatively low added cost, but the higher design complexity rules them out of the makerspace [14]. A better balance for a makerspace tablet would likely have been to use the simplest mechanism out there: separate X and Y axes with independent motors. This would theoretically have a significant speed penalty compared to the H-bot since the Y axis would need to carry the entire X carriage assembly including a heavy motor, but the extra accuracy provided by this design would allow the motors to run at full speed with high positional certainty. Acceleration curves could also mitigate the impact of the extra X carriage weight in this design.

Another option would be to produce only the tablet top in the makerspace, and source a commercial plotter for the bottom section, as many designs of plotter are mass produced for use in 3D printers, DVD drives, inkjet printers, and more. However, some degree of customization would likely be required to attach the pin poking mechanism, which may prove difficult.

The software could be improved as well, by implementing line drawing algorithms to trace images more accurately than possible with the binary thresholding and resize interpolation built into OpenCV. This would prevent graphics from having gaps between otherwise continuous shapes, and mitigate the large clusters of poked pins that currently form when there is a thick line or grey area. The raster pattern currently used to poke pins could be replaced with a nearest neighbor pattern to save time in movement, but the time savings of this would likely be minimal unless a more accurate plotter is used, as the pins must always be approached from the same direction with the current design.

---

[8] No official name for this design of plotter exists, it’s instead referred to as Ultimaker or Zortrax, the two most popular 3D printers to use this design.

Conclusion

The TactionTablet and its innovative pin latching mechanism will dramatically change the way that refreshable tactile graphics are made while allowing the technology to reach more users due to its low cost. The prototype display has sufficient resolution to display graphics while being simple enough to build in even a poorly equipped makerspace[9]. Despite the shortcomings in the plotter mechanism's accuracy and speed, its simplicity makes it a good candidate for the makerspace and its ultra low cost prices the device in a class of its own. This design can be further miniaturized with injection molded pins and a more sophisticated plotter, to achieve a low enough pixel pitch to display braille. This project is just the starting point for the TactionTablet, and with the mechanism proven the project can move forward to reach as many people as possible.

---

[9] The laser cutter and 3D printer used to produce the prototype had a combined cost of less than $400

Bibliography

[1] L.M. Brown, S.A. Brewster, R. Ramloll, M. Burton, and B. Riedel, “Design guidelines for audio presentation of graphs and tables,” In Proc. 9th International Conference on Auditory Display, 2003, pp. 284-287

[2] Papenmeier, “Milestones - Papenmeier Rehab Technology,” *papenmeier-rehatechnik.de*, 2020. [Online]. Available: https://www.papenmeier-rehatechnik.de/en/about_us_milestones.html.

[3] New England Low Vision, “Braille Display Focus 40 5G,” *New England Low Vision*, 2020. [Online]. Available: https://nelowvision.com/product/braille-display-focus-40-5g/.

[4] Orbit Research, “Orbit Reader 40 - Braille Display, Book Reader, and Note-taker,” *Orbit Research*, 2016. [Online]. Available: http://www.orbitresearch.com/product/orbit-reader-40/.

[5] X. Wu, H. Zhu, S. Kim, M.G. Allen, “A Portable Pneumatically-Actuated Refreshable Braille Cell”, In Proc. Transducers 2007 International Solid-State Sensors, Actuators and Microsystems Conference, 2007, pp. 1409-1412.

[6] Polymer Braille Inc., “SBIR Phase I: Full-Page Electronic Braille Display”, *Small Business Innovation Research (SBIR)*, , 2012. [Online]. Available: https://www.sbir.gov/sbirsearch/detail/392063.

[7] World Health Organization, “Visual Impairment and Blindness 2010 Fact Sheet”, *World Health Organization*, 2011. [Online]. Available: https://www.who.int/blindness/data_maps/VIFACTSHEETGLODAT2010full.pdf.

[8] N.N. Tuan (nntuan), “CoreXY for LM6UU and Linear Rail 6mm by nntuan,” *Thingiverse*, Sep. 13, 2018. [Online]. Available: www.thingiverse.com/thing:3098626.

[9] S. Alford (SCOTT_3D), “HyperCube Evolution by SCOTT_3D”, *Thingiverse*, April 18, 2017. [Online]. Available: https://www.thingiverse.com/thing:2254103.

[10] I.E. Moyer, “CoreXY Theory,” *CoreXY*, 2012. [Online]. Available: www.corexy.com/.

[11] J. Vasquez, “CoreXY The Two-Axis Gantry - Part 2”, *Double Jump Electric*, 2016. [Online]. Available: http://www.doublejumpelectric.com/projects/core_xy/2014-07-15-core_xy/.

[12] iquizzle, “Ultimaker to Hbot conversion”, *Google Groups: H-bot and CoreXY 3d printers*, Nov. 17, 2013. [Online]. Available: https://groups.google.com/forum/#!topic/h-bot-and-corexy-3d-printers/NKVKtzYIHLg.

[13] Mediawiki contributors, “Laser Cutter Materials”, *ATX Hackerspace*, Feb. 14, 2019. [Online]. Available: http://atxhs.org/index.php?title=Laser_Cutter_Materials&oldid=8541.

[14] "Cartesian Printer - Motion Platform - Research 1", *Makkusu*, May 22, 2016. [Online]. Available: https://maxdesign1990.wordpress.com/2016/05/22/gmtech-printer-motion-platform-research/.