Design of a Precise, Affordable Braille Label Maker for the Blind

by

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ABSTRACT

Braille labels are a simple technology that can enable people with blindness to independently identify objects and spaces in their workplaces, homes and schools. For children learning to read and write, braille labels on their toys and objects in the home and at school could catalyze learning by helping them to associate written words with physical objects. For an adult, identifying objects such as file folders, boxes, and medications is a functional skill essential in the workplace. Labels on these objects leads to an increase in daily efficiency. Yet, even though braille labels present the potential for increased independence and efficiency in the lives of people with blindness, there is no label maker on the market that meets the requirements of users. The goal of this thesis is to design a precise, affordable, language independent, personal braille label maker as a tool for the blind.

The work presented couples methods and tools from both deterministic design and human centered design philosophies. This integrated methodology drove the final design to meet both the precision and human requirements. The two most critical modules in the device are the braille dot embossing flexures and the braille cell indexing ratchet, which both require precision to meet international braille dot standards for the geometry and spacing.

This device is designed to address the needs of Indian users as a beachhead market because of their desire for independence and employment. Furthermore, an educational focus on braille literacy for people with blindness in India motivates the use of this device.

The result of this thesis is a braille label making device with precision alignment between the embossing punch and die and indexing of 6.2 mm, that creates durable braille labels on Scotch Magic™ Tape. The device form factor allows users to independently emboss each of the six dots so that labels can be written in any of the 133 braille languages that exist worldwide. Comprised of only six parts, the entire device is injection moldable out of ABS plastic, which lowers both the variable and fixed costs of part production and mold tooling.

Thesis Supervisor: Alexander H. Slocum
Title: Walter M. May and A. Hazel May Professor of Mechanical Engineering
ACKNOWLEDGEMENTS

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A hearty thank you to my advisor, Professor Alex Slocum, for giving me the opportunity to work on a meaningful and technically challenging project, and for pushing me to constantly learn and grow as a deterministic designer. 1/⊙ = ☺

A big thank you to the MIT-Tata Center and the Tata Trusts for funding this project and my work. Your investment in impactful projects is creating a ripple effect of positive change in India and beyond. Thank you to Dr. Rob Stoner and Dr. Diane Rigos as the leadership of the Center. Thank you to Dr. Nevan Hanumara who guided my work in India and to Dr. Jason Prapas for supporting efforts to actualize this device as a real product.

Thank you to the Precision Engineering Research Group for your camaraderie, design input, and questions. In particular, Kevin Simon thank you for being a friend and mentor; always willing to be a sounding board and ask and answer questions. Thank you to Sally Miller for your friendship and design reviews.

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## NOMENCLATURE

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta_{\text{max}} )</td>
<td>Max deflection of the pawl</td>
<td>[mm]</td>
</tr>
<tr>
<td>( F_v )</td>
<td>The vertical force pushing on the beams transmitted by the columns</td>
<td>[N]</td>
</tr>
<tr>
<td>( l_v )</td>
<td>Length from the base of the beam to the point where the ( F_v ) is applied</td>
<td>[mm]</td>
</tr>
<tr>
<td>( l_B )</td>
<td>Length of the beam from point A to point B</td>
<td>[mm]</td>
</tr>
<tr>
<td>( E )</td>
<td>Modulus of elasticity</td>
<td>[GPa]</td>
</tr>
<tr>
<td>( I )</td>
<td>Area moment of inertia</td>
<td>[mm(^4)]</td>
</tr>
<tr>
<td>( \sigma_{\text{bending}} )</td>
<td>Bending stress of the beam</td>
<td>[MPa]</td>
</tr>
<tr>
<td>( M )</td>
<td>Moment created by the applied force on the beam</td>
<td>[N*mm]</td>
</tr>
<tr>
<td>( c )</td>
<td>The distance from the outermost fibers of the beam to the neutral axis</td>
<td>[mm]</td>
</tr>
<tr>
<td>( \sigma_{\text{flexural}} )</td>
<td>The flexural strength of the material</td>
<td>[MPa]</td>
</tr>
<tr>
<td>( \theta_f )</td>
<td>Slope of the flexure</td>
<td>[deg]</td>
</tr>
<tr>
<td>( l_f )</td>
<td>Length of the flexure</td>
<td>[mm]</td>
</tr>
<tr>
<td>( I_f )</td>
<td>Area moment of inertia of the flexure</td>
<td>[mm(^4)]</td>
</tr>
<tr>
<td>( \delta_b )</td>
<td>Displacement at the tip from the deflection of the flexure and the angular offset of the rigid body</td>
<td>[mm]</td>
</tr>
<tr>
<td>( l_r )</td>
<td>Length of the rigid member</td>
<td>[mm]</td>
</tr>
<tr>
<td>( \theta_f )</td>
<td>Angle at the tip of the flexure</td>
<td>[deg]</td>
</tr>
<tr>
<td>( R_A )</td>
<td>Vertical reaction force at point A</td>
<td>[N]</td>
</tr>
<tr>
<td>( R_B )</td>
<td>Vertical reaction force at point B</td>
<td>[N]</td>
</tr>
<tr>
<td>( M_A )</td>
<td>Reaction moment at point A</td>
<td>[N*mm]</td>
</tr>
<tr>
<td>( \delta_{F_v} )</td>
<td>Deflection of the beam at point B from force ( F_v )</td>
<td>[mm]</td>
</tr>
<tr>
<td>( \delta_{R_B} )</td>
<td>Deflection of the beam at point B from force ( R_B )</td>
<td>[mm]</td>
</tr>
<tr>
<td>( F_{\text{hold}} )</td>
<td>Holding force applied to the tape in the capstan</td>
<td>[N]</td>
</tr>
<tr>
<td>( F_{\text{pull}} )</td>
<td>Force applied to the tape to pull it forward and move the ratchet mechanism</td>
<td>[N]</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Coefficient of friction</td>
<td>[-]</td>
</tr>
</tbody>
</table>
\( \theta \) Wrap angle of the tape around the ratchet [deg]
\( \alpha \) Angle of the pawl surface from vertical [deg]
\( R_1 \) Normal reaction forces between the ratchet and pawl [N]
\( R_2 \) Vertical reaction force acting on the ratchet body [N]
\( R_3 \) Horizontal reaction force acting on the pawl body [N]
\( F_R \) Force applied by the tape pull to the ratchet [N]
\( F_{Beam} \) Force applied on the ratchet by the deflected pawl [N]
\( F_{Unwind} \) Force to unwind 0.75" width Scotch Magic™ tape [N]
\( \eta \) Efficiency of the rollers with tape moving across
\( D \) Outer diameter of the roller [mm]
\( d \) Inner diameter of the rolling element [mm]
\( r \) Repeatability of the elastically averaged coupling [mm]
\( \delta \) Dimensional error of the elastically averaged feature [mm]

ABS Acrylonitrile butadiene styrene
CAD Computer aided design
CNC Computer Numerical Control
COUHES Committee on the Use of Human Subjects
DFM Design for Manufacture
EDM Electrical Discharge Machining
FRDPARRC Functional Requirements, Design Parameters, Analysis, References, Risks, Counter Measures
IAB Indian Association for the Blind
ID Industrial Design
IIT Indian Institute of Technology
IRB Institutional Review Board
LDPE Low density polyethylene
NAB National Association for the Blind India
NIVH National Institute for the Visually Handicapped India
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCMC</td>
<td>Strategies, Concepts, Modules, Components</td>
</tr>
<tr>
<td>USPTO</td>
<td>United States Patent and Trademark Office</td>
</tr>
<tr>
<td>VI</td>
<td>Visually Impaired</td>
</tr>
<tr>
<td>XRCVC</td>
<td>St. Xavier's Resource Center for the Visually Challenged</td>
</tr>
</tbody>
</table>
1.1 Overview

People with blindness and visual impairment wrestle with the stereotype that people with disabilities are not capable of living and working independently. This is simply not true. The physical spaces we live in and products we use were designed with predominantly sighted people in mind, thus it’s not surprising that people without sight must adapt and develop new tools and techniques to navigate, identify and learn. In India, instead of using the word “disability”, it is now common to refer to people as differently abled. Indeed, in the absence of sight, people with blindness use other senses in creative and subtle ways to understand the world around them.

In India alone, there are an estimated 10 million people with visual impairments according to the National Association of the Blind, based on the 2011 national census [1]. Globally, the World Health Organization estimates 36 million fully blind individuals [2]. The visually impaired (VI) experience daily challenges performing tasks that sighted people take for granted, and as a result many depend on family members for help with identification and navigation. Simple tasks, such as identifying food items in generically shaped packaging or differentiating medications in identical bottles are difficult without braille labels or help. A key challenge, still unsolved at scale, is independent non-visual identification of generically shaped objects like boxes, cans, identification cards, important documents, or medication containers.

The question then emerges: how might we enable people with blindness to live more independently within their homes, schools, workplaces and communities?

Many people with visual impairments articulate their need for a simple identification solution. For people who are braille literate, braille tape labels that can be stuck to the objects and identify
them are a simple and accessible solution. Labels are a particularly powerful tool to enable literacy among blind school children. Much early learning in sighted children comes from vision, connecting words with pictures in books, or words written on objects. For a child with blindness, putting braille labels on objects allows them to make the same connection between written word and tactile object.

Numerous state-of-the-art devices attempt to meet this labeling challenge using touch and auditory feedback. However, current label makers on the market do not meet the functional requirements of users, in particular, the price point and ease of use required to make widespread adoption affordable and accessible. The features and challenges of current devices are detailed in the Prior Art Review.

The core innovation of this thesis is to design, build, and test a precise, personal and affordable device that empowers people with blindness to modify their environments with braille labels to make identification efficient, accurate and independent. The Braille-It label maker is a handheld, language independent, personal braille label maker manufactured at a price point accessible to blind persons both in India and globally. Braille-It enables users to quickly label items when first encountered and identified by creating tape labels that can be applied to objects, making quick identification easier in the workplace, in schools and at home.

1.2 Integrating Deterministic and Human Centered Design Methodologies

In order to develop precise machines or products for human use, it is essential to integrate both deterministic and human centered design methodologies. This section will describe both methods and lay out the integrated process followed in this thesis.

“Deterministic design is a catalyst to funnel creativity into a successful design.” [3] The goal of deterministic design is to effectively and efficiently create innovative solutions to technical challenges. Deterministic design starts with strategies, then funnels down to concepts, modules and components – moving from coarse to fine level of detail in the design. Strategies are the high level methods of achieving a given goal, but many types of machines can be used. [3, pp. 1–13] Concepts are ideas for a specific machine that can execute the strategy. Modules are sub-
assemblies within a machine and components are individual parts within the modules. At each level, many creative ideas can be generated and then are evaluated based on functional requirements, design parameters, analysis, references, risks and counter measures. [3, pp. 1-14]

The structure of this thesis follows this course to fine methodology. Deterministic design can be effective in capturing potential strategies and rigorously choosing between them based on an understanding of the fundamental physics that play into the “error budget” of the machine. This methodology mitigates the potential risk of fixating on a cool idea without understanding whether or not it will meet the requirements.

The FUNdaMENTALS of Design [3] teaches a high level process of explore, experiment, create, detail, build and test. As part of the exploration, it is important to assess resources, time, materials, manufacturing processes and people. The designer must also understand the problem, the human stakeholders, the desired outcomes, physics and constraints. Following problem understanding, the process moves through selection of strategies, concepts, modules and components, at each iteration including increasing levels of design detail and analysis.

Human centered design also strives to develop innovative solutions to tough human challenges. It does not always assume a technical solution. The central premise claims that the best way to develop effective solutions is to place the users at the center of the process. This user-centric approach strives to mitigate the risk of solving for the wrong problem, or presenting an undesirable solution, by engaging users at every stage of the process. The IDEO methodology laid out in the Human Centered Design Toolkit [4] articulates an iterative process of Empathize, Define, Ideate, Prototype and Test, that starts with understanding the user needs and allows those insights to inform the ideation, strategy and concept selection.

For projects like Braille-It, which integrates challenging machine and human requirements, it is important to integrate tools from both of these methodologies. Empathizing with the user informs the development of the functional requirements, and user insights drive decision making during the prototyping phase.

This thesis follows the deterministic design process of explore, experiment, create, detail, build and test and integrates important human centered design methods and tools throughout.
Using vocabulary about disability that captures the spirit of the people is challenging. To quote Dr. Nidhi Singal in her report on the education of children with disabilities in India [5] “Disability is a multi-dimensional and complex construct and there is no single universally accepted, unproblematic definition of disability. Not only do definitions differ across countries but these also differ and change within a country with evolving legal, political and social discourses.” While the discourse about blindness is historically framed as a disability, in India, people with disabilities often refer to themselves as “differently abled”, which reframes their blindness as something to live in spite of rather than a reason for excuses. The braille label maker described in this thesis was designed as a tool for independence, to enable rather than disable.

This literature review strives to give a social, cultural, and political context to the mechanical design of this braille label maker. The chapter begins by providing a review of braille code globally and its many languages, then provides particular context on education for the visually impaired in India. The stakeholder analysis gives perspective on the interests of different people and organizations in this braille label maker. Finally, the prior art review documents the current state of the art and demonstrates the technological need for which this label maker is designed.

Literature on the technical aspects of the design analysis is included throughout the narrative in Section 4.2 Design Analysis.
2.1 Review of Braille Code

Braille is a tactile written code that uses a system of raised dot combinations that correspond to letters or contracted phrases in many different languages. English, for example, can be written in print, cursive, or braille. Braille is a manner of writing English, not an independent language. There are 133 global braille languages [6]. Therefore, when referring to a language in braille, it is correct to say English, Hindi or Japanese braille code.

Braille’s raised dot combinations, grouped in cells of six dots arranged in two columns and three rows, are read by gently running a finger over them. Dots are numbered one through six, and there are 64 possible combinations. [7][8] In un-contracted Grade 1 braille, often used for early learners, each cell represents a single letter. Grade 2 braille, also known as contracted braille, represents words or phrases with a single 6 dot cell. Grade 2 braille is more practical because it is faster to read and write and more compact. According to the American Foundation for the Blind, contracted braille is considered standard in the US for use in public spaces. In India, regulations are not currently enforced, but suggestions are made by the Ministry of Urban Affairs and Employment. [9] According to a 1990 UNESCO report titled “World Braille Usage” [6] there are 85 countries globally that have official braille languages with both grade 1 and grade 2, and in some cases more than one language per country. BANA, the Braille Authority of North America, publishes braille codes and guidelines for text, music, math, science and tactile graphics. [10]

![Figure 1: The standard 6 dot braille cell with numbering](image)

![Figure 2: Grade 1 Un-contracted English Braille Code](image)
The braille system was first invented by Louis Braille in 1869 while he was a student at the National Institute for Blind Youth in Paris, France. Previously, students were taught to read raised print, but difficulties embossing the letters as well as reading and writing the complicated geometries were significant barriers to use. Louis was inspired by a night writing code, also called sonography, which was invented at Napoleon’s request for military use at night without sound or light. [12, p. 212]
2.2 Education for the Visually Impaired in India

Education and braille literacy for the visually impaired is emphasized in India with a number of dedicated resources and institutions. The National Association for the Blind (NAB) India [13] has historically played an important role in promoting education for the visually impaired and multiple disability children. The Department of Education at the NAB provides resources and tools to training centers, parent training, educator training, and schools for the blind in addition to running an integrated education program which supports visually impaired children who attend sighted schools. For these children, the NAB provides training to their teachers and dedicated assistants to help the children in the classroom. The Blind People’s Association details this multifaceted system including residential education, integrated education and inclusive education and compares and contrasts the benefits and challenges of each system. [14, pp. 240–244]

The importance of education for the visually impaired is articulated in a 1995 study on childhood blindness published in Eye Nature. The study estimates that there were 1.5 million children worldwide in 1995 with visual impairment, which leads to a total loss of 75 million blind years due to duration of life with the disability. [15]

Looking at education for the visually impaired in India, the National Council of Educational Research and Training [16] publishes the AISES report [17] which reported a 17.36% increase in visually impaired students in the Indian education system between 2002 and 2009. This statistic could indicate that more visually impaired students are attending schools, a desired outcome for integrated education efforts. However, support for these students is lacking; the same 2016 AISES report states that less than 7% of schools offer braille books, slate and stylus, Taylor Frame or abacus, all commonly used tools for visually impaired students. The study cites that approximately 250,000 visually impaired students are enrolled in school in India. [17, p. 38]

Many of the teaching resources and techniques are taught to teachers through seminars and workshops, like the ones developed by the NAB in India. There are a few written resources, including Foundations of Education: Instructional Strategies for Teaching Children and Youths with Visual Impairments [18], which is an informative resource for education theory and methodology regarding education for the visually impaired. These resources explore case
studies, subject specific techniques, assistive technology, and even independent living and social skills.

There are a multitude of stakeholders invested in providing assistance to blind and low vision people including their families, local and international NGOs, government organizations and corporations. The key stakeholders influencing the physical design of the solution are the end users. Investment from other stakeholders will drive the manufacturing and distribution networks for the device.

Each of the stakeholders have different priorities, interests, resources and alliances. This stakeholder analysis presents the stakeholders influential in or influenced by this research with the dual aims of identifying strategic partnerships to cultivate, and building a foundational understanding of the stakeholder network to guide the implementation and business model generation.

2.3 Stakeholder Analysis

This stakeholder mapping provided a foundation for research, and outlines the landscape in which the braille labeler will be implemented. Core insights influenced the physical design of the labeler and guided strategic partnerships, ultimately moving towards sustainable implementation and dissemination of the device to users who need it most.

During the January field work period in 2017, two strategic focus areas were: first, collecting user feedback to iterate and solidify the design and product architecture, and second, developing key partnerships for manufacturing and distributing the device.

Providing resources for the blind is a semi-developed market in which there are a number of institutions and organizations with long term stake and influence who have developed methodologies for their work. One potential risk is that adoption of new technology, like the labeler which is the subject of this thesis, may not immediately fit within currently methodologies and work flows and teachers may be slow to incorporate it into the curriculum. This risk also offers a reciprocal potential opportunity insofar as the market for “low-cost” devices enabling the blind is not saturated with solutions and users could be open to affordable new solutions.
2.3.1 Blind People

Blindness is a complex diagnosis with many different pathologies. Cataract blindness, one of the most common causes, is commonly diagnosed at more advanced stages in the developing world due to a lack of screening. Often caused by untreated diabetes or a lifetime of sun radiation exposure, cataract blindness can often be completely reversed through cataract surgery by implanting an artificial intraocular lens.

Congenital blindness, the highest cause of childhood blindness, is often not fully reversible and has significant adverse effects on “[infant] development, education, and future social, marital, and economic prospects.”[19] Srikanth Bolla, a young blind Indian CEO and MIT graduate, articulates the unnecessary challenges of being dependent and isolated from birth as a differently abled person. [20]

2.3.2 Indian National Government

The Indian national government is significantly invested in providing resources for the blind. Government support for this braille label maker would supplement corporate and NGO resources towards successful distribution and adoption by providing subsidies or schemes for those who cannot afford the device.

The main government entities are the National Programme for Control of Blindness within the Ministry of Health and the Department of Empowerment of Persons with Disabilities within the Ministry of Social Justice and Empowerment. The Department of Empowerment of Persons with Disabilities offers government schemes for the provision of educational scholarships and resources for students and adults to purchase assistive devices.[21, p. 57] They also resource District Disability Rehabilitation Centers to provide financial, infrastructure, administrative and technical support from the Central and State governments to people who are differently abled. [21, p. 75] These district centers are funded 10.2 lakh per year and an extra 7 lakh the first year for equipment.

The National Institute for Visually Handicapped (NIVH) Dahradun trains educators and subsidizes biomedical engineering research for special instruments related to disabilities. Furthermore, the National Institute promotes braille literacy, maintaining the largest library for persons with blindness, operating both the Central Braille Press (est. 1951) and the Regional
Braille Press (est. 2008), and running the workshop for Manufacturing Braille Appliances (est. 1952). [21]

The Department of Empowerment of Persons with Disabilities also funds organizations supporting differently abled events. In 2015 and 2016 the department funded 150 lakhs to the Blind Cricket Association of New Delhi for organizing a cricket tournament, 440 lakh to the Indian Heritage Society of New Delhi for printing yoga books for the visually challenged, and 750 lakh to the Indian Blind and Para Judo Association for the 4th national championship. [21, p. 74] Funding extends to numerous schools for the blind in Andhra Pradesh, Bihar, Chhatisgarh, Delhi, Gujarat, Karnataka, Mizoram, Odisha, Punjab, Rajasthan, Tamil Nadu, Telangana, and West Bengal [21, pp. 194–231]. The current investment in programs and devices indicates potential sources of funding and community level connections for distribution.

Future work might investigate the following questions: Are district centers interested in collaborating on the distribution of this device? At what price point are government institutions willing to subsidize a low-cost braille label maker? What is the government demand for a low-cost label maker? How many devices would district centers or the national departments want to purchase or distribute? How are state governments invested in providing resources for the blind?

2.3.3 For Profit, Non-Profit and Academic Organizations

Within the for profit realm, several companies are uniquely invested in developing technology for the blind and creating job opportunities for people who are differently abled. One example, WORTH Trust, located in Vellore, Tamil Nadu, is a self-sustained rehabilitation organization which includes engineering production centers employing people with disabilities. The profit from this manufacturing then supports both a technical training center and early intervention centers for people with speech and hearing impairment. WORTH is the sole manufacturer of the Perkins Brailler worldwide and the distributor for brailleurs in India.

Another example is Bollant Industries Pvt. Ltd. led by CEO Srikanth Bolla, an MIT alumnus and a blind man himself. Bolla’s trifold company vision is to address employment, economic and environmental issues in an integrated for profit model producing eco-friendly disposable products and packaging solutions for manufacturers. The company primarily employs differently-abled people, providing the necessary skills training to produce high quality products.
Phoenix Medical Systems based in Tamil Nadu is also interested in manufacturing products for the blind. One of Phoenix’s principal products is a smart cane that uses a distance sensor to measure obstacles in front of the cane and vibrates the handle silently to alert the user of obstacles in their path. Currently, the blind cane is the only product for the blind that Phoenix manufactures.

Throughout India there are multiple NGOs committed to providing education, vocational training and resources for blind and low vision people. Among the most influential are the National Association for the Blind NAB [22], the Indian Association for the Blind IAB [23], the National Institute for the Empowerment of Persons with Disabilities and the Blind Foundation for India [24]. The resources these organizations provide are similar, often focusing on primary and secondary education and vocational training to give people basic skills to find jobs in their communities.

Several academic institutions also focus on conducting research and providing resources for the visually impaired. The St. Xavier’s Resource Center for the Visually Challenged XRCVC in Mumbai is led by Dr. Sam Taraporevala, a blind man and the chair of St. Xavier’s Sociology Department. [25] Furthermore, the Assistech Research Group at IIT Delhi developed a Smart Cane as part of their research goal to “serve individuals with special needs through research and innovation in affordable assistive technologies.” [26]

2.3.4 Hospitals and Medical Facilities

Much of the medical community is focused on blindness prevention and optimizing cataract surgeries in an effort to minimize preventable blindness. Amazing developments in surgical cataract procedures occurred over the last several decades. Aravind Eye Care System [27], one of India’s major players, manufacturers intraocular lenses and other surgical tools for cataract surgeries reducing costs significantly from Western supplier. Cost cutting efforts like Aravind’s and technique development by the Himalayan Cataract Project [28] based in Nepal means that a cataract surgery can now be performed for $25 in 10 minutes, completely restoring a person’s sight.

LV Prasad is another major hospital player, promoting a health pyramid model based on widespread “vision guardians” in communities, and service centers with increasingly more services to provide widespread tertiary care and funnel people with complicated cases to “centers
of excellence.” LV Prasad invests in a number of eye health verticals including clinical services, education, research, rehabilitation, eye banks and community outreach. [29]

Although prevention and reversal of blindness is an essential focus for these medical establishments, there are many millions of blind people for whom modern treatments cannot yet fix their blindness. These are the people this project is focusing on, aiming to provide them with another tool to lead more independent lives.
Observations of the stakeholders in the categories presented above are summarized in Table 1: Stakeholder Matrix: Influence Oriented below.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Reason for Exerting Influence</th>
<th>Tradeoffs Confronting Stakeholder</th>
<th>Resources for Influencing Outcomes</th>
<th>Degree of Influence</th>
<th>Actual and Potential Alliance among stakeholders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braille literate blind people</td>
<td>Solution would improve quality of life</td>
<td>Ineffective device, difficult to learn, or breaks easily – no incentive to use</td>
<td>As users and customers they drive demand</td>
<td>High</td>
<td>Work with NGOs and government institutions serving them</td>
</tr>
<tr>
<td>Dept. of Empowerment of Persons with Disabilities</td>
<td>Device enables blind to act more independently – easily distributable solution</td>
<td>Allocation of funds to purchase this solution over investing in other solutions</td>
<td>Strong connections to large user/customer groups influences solution perception</td>
<td>High</td>
<td>Closely connected with most organizations for the blind. Could provide distribution channels and spread solution</td>
</tr>
<tr>
<td>National Institute for the Visually Handicapped</td>
<td>Either due to an interest in the solution’s efficacy or worry about competition</td>
<td>Allocation of resources as investment and providing staff to distribute solution</td>
<td>Large network of people and control over written resources through the printing presses</td>
<td>Medium</td>
<td>High interest in braille literacy, supports the Braille Press. Also facilitates biomedical research and device development.</td>
</tr>
<tr>
<td>Schools and vocational centers for the Blind</td>
<td>Want to use solutions to accelerate student learning outcomes</td>
<td>Might replace current solutions,</td>
<td>Access to large communities of blind and partially sighted people who need solution</td>
<td>High</td>
<td>Most schools receive funding from government schemes to provide education and training and equipment</td>
</tr>
<tr>
<td>LV Prasad</td>
<td>Validate need potential for solution</td>
<td>Solution could compete with other in house innovations, assistive tech not priority</td>
<td>Access to financial and human resources, provides connections, funding and customer perspectives</td>
<td>Medium</td>
<td>Private sector care centers from village level to research facilities. Works with the government and NGOs to build holistic eye care</td>
</tr>
<tr>
<td>WORTH Trust</td>
<td>Would want to gain a contract for manufacturing product</td>
<td>Hires limited number of people, may not have the capacity to manufacture in high quantities</td>
<td>Manufacturing equipment and technical knowledge to produce 10,000 – 50,000 devices</td>
<td>Medium</td>
<td>Connected with government organizations and customers within the visually impaired community in India from prior products</td>
</tr>
</tbody>
</table>
2.4 Prior Art Review

Traditionally, the slate and stylus is the most widespread tool used for handwriting braille. In this method an awl instrument called a stylus is used to depress the dots and cells into thick paper, moving from right to left writing backwards to account for the flipped sheet of paper. This reversal makes learning to read and write more difficult as they are mirrored processes. The slate and stylus is the least expensive tool for writing braille and most widespread in India.

Braillers, shown in Figure 8, build off of a traditional typewriter mechanism, but use six keys to actuate the dots, and typically include a space bar, a next line button and a backspace. The Perkins Brailler developed at the Perkins school for the Blind is the industry standard brailler most widely distributed in the US and in India, in collaboration with WORTH Trust [30].
A shorthand braille writer, similar to a brailler, found in some schools in India, but not commonly found in the US, is used to emboss braille on 1-inch-wide strips of paper. This allows a blind person to take notes and then transcribe them later onto a computer, a process observed at the National Association for the Blind in India at their blind workshop in Mumbai.

Electronic braillers, like the Humanware BrailleNote, are the newest and most advanced braille writing technology. Many function as complete computers that allow the user to scroll through applications and documents and functionally use a computer similar to a sighted person, but using audio and tactile braille feedback to navigate and read.

There is no shortage of ideas for braille label makers. A review of patents and products reveals several mechanisms that emboss braille dots on various tapes and strips of paper. The most commonly used devices are shown in Table 2 below. The engineering division at the Perkins School for the Blind keeps a closet full of all the “failed” braille label makers to document the challenge of meeting the full set of requirements and needs of the blind. The two most common complaints are that the labelers are too expensive to be desirable, or that they are too bulky and inconsistent to provide convenient reliable labels.

A label making device, shown in Figure 9, designed by Theodore Moallem, provided the initial inspiration for embossing braille dots on 3M Scotch™ Magic® tape used in this thesis. The device houses two rolls of tape and punches the dots into the tape using the buttons on the upper left in the image.

After conducting preliminary market research and interviews with stakeholders and users, this study determined a set of functional requirements that must be met to fulfill the user needs. A label maker must emboss readable, durable dots, create cells of equal spacing, meet a low cost point for manufacturing and assembly, be portable and compact, and emboss the dots on inexpensive commonly supplied tape. Table 2 compares the best state of the art with these functional requirements.
Table 2: Comparison of state of the art devices based on functional requirements

<table>
<thead>
<tr>
<th></th>
<th>Slate and stylus</th>
<th>Perkins Brailler[31]</th>
<th>Humanware BrailleNote [32]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use case</strong></td>
<td>Full written pages, shorter notes &amp; labels</td>
<td>Full written pages and labels</td>
<td>Notes, contacts, and computer navigation</td>
</tr>
<tr>
<td><strong>Form factor</strong></td>
<td>Plastic or metal thin sheets with pointed awl (Figure 7)</td>
<td>Heavy manual or electric typewriter (top three images in Figure 8)</td>
<td>Keyboard sized device with buttons and braille pin display (bottom right in Figure 8)</td>
</tr>
<tr>
<td><strong>Ease of use</strong></td>
<td>Writing is backwards to reading, simple to use, but a finger is used to align the stylus at the correct location and can often be pricked by the sharp point</td>
<td>Ergonomic key arrangement, standard dots and spacing, reliable quality</td>
<td>Connects wirelessly with computer and provides interface for user with technology, ergonomic keyboard and braille reading cells electromechanically actuated.</td>
</tr>
<tr>
<td><strong>Languages</strong></td>
<td>All braille languages</td>
<td>All braille languages</td>
<td>Software dependent</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>US ($10-20) India (250-350 rupees)</td>
<td>$775</td>
<td>$4,995.00 (sale $2,995)</td>
</tr>
<tr>
<td><strong>Limitations</strong></td>
<td>Backwards writing, large in size, stylus is easy to loose</td>
<td>Heavy, bulky and expensive. Forearms get tired after prolonged use</td>
<td>Expensive and relies on battery power</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>6-Dot [33]</th>
<th>3M / Reizen Braille Labeler [34]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Use case</strong></td>
<td>Dymo tape labels</td>
<td>Dymo tape labels</td>
</tr>
<tr>
<td><strong>Form factor</strong></td>
<td>Handheld plastic exterior with 6 buttons</td>
<td>Handheld plastic with turn dial to choose letters</td>
</tr>
<tr>
<td><strong>Ease of use</strong></td>
<td>6 dots arranged similar to brailler arrangement</td>
<td>Smaller hands have trouble gripping handle, slow to find the letters around the wheel</td>
</tr>
<tr>
<td><strong>Languages</strong></td>
<td>All braille languages</td>
<td>Limited to a single language, and only includes limited characters</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$749.00</td>
<td>$39.95 (some online discounts)</td>
</tr>
<tr>
<td><strong>Limitations</strong></td>
<td>Relies on battery power and Dymo label tape</td>
<td>Only available for English. 3M used to make a similar device.</td>
</tr>
</tbody>
</table>

2.4.1 Patented Prior Art

Several patented braille embossing mechanisms substantiate the current state of the art. Although there is prior art within the realm of this research, the result of conducting a preliminary patent search for similar devices and mechanisms, using the advanced Innography [35] tools as well as the USPTO website, reveals that there is no patented work on a label maker.
using a similar cantilevered beam mechanism that addresses the functional requirements articulated above. Most of the recent braille related patents involve electromechanical systems for embossing, or directly transmitting the braille through actuated pins. Older patents focus on typewriter manifestations. Table 3, shown below, lists most relevant patents in use or in function. The relevance column notes why each patent is relevant to this research.

**Table 3: Patented prior art**

<table>
<thead>
<tr>
<th>Image</th>
<th>Patent No.</th>
<th>Title</th>
<th>Issued</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 9 Left</td>
<td>US8549998</td>
<td>Portable electromechanical braille label maker [36]</td>
<td>2013</td>
<td>6-Dot Braille Label Maker [33]</td>
</tr>
<tr>
<td>Fig. 9 Right</td>
<td>US20090274505</td>
<td>Braille Writer [31]</td>
<td>2009</td>
<td>Updated Perkins Brailler</td>
</tr>
<tr>
<td>Fig. 10 Left</td>
<td>US20120304875</td>
<td>Embossing wheel and anvil for braille printer [37]</td>
<td>2012</td>
<td>Wheel used for embossing</td>
</tr>
<tr>
<td>No image</td>
<td>WO9641320</td>
<td>Touch-readable product and associated process [38]</td>
<td>1996</td>
<td>Assignee Universal Braille Dots Inc.</td>
</tr>
<tr>
<td>Fig. 10 Center</td>
<td>EP0962909</td>
<td>Braille label writer [39]</td>
<td>2000</td>
<td>Solenoid actuation</td>
</tr>
<tr>
<td>Fig. 10 Right</td>
<td>US07996325</td>
<td>Apparatus for embossing Braille labels [40]</td>
<td>1995</td>
<td>Embossing lever and platform</td>
</tr>
<tr>
<td>Fig. 11 Left</td>
<td>US20060118507</td>
<td>Device and method for identifying containers personal to sighted and visually handicapped individuals [41]</td>
<td>2006</td>
<td>Band with embossed braille to identify objects</td>
</tr>
<tr>
<td>Fig. 11 Right</td>
<td>US4079825</td>
<td>Portable braille typewriter[42]</td>
<td>1978</td>
<td>Full sheet typing</td>
</tr>
</tbody>
</table>

**Figure 10:** Images of patented braille related inventions. Left US8549998. Right US20090274505.
Figure 11: Braille related patents. Left US20120304875. Center EP0962909. Right US07996325.

Figure 12: Braille related patents. Left US20060118507. Right US4079825.
This chapter demonstrates the Course-to-Fine design process moving from strategy and concept selection to module and component refinement for the device. Ideas at each level are evaluated using functional requirements and analysis. The following sections enumerate these modes of evaluation and show the decision making process. There is a dual focus on error apportionment and understanding the user journey to meet the precision and human use specifications.

### 3.1 Functional Requirements and Design Parameters

Within the FRDPARRC method [43], functional requirements and design parameters provide the framework for design and decision making in the deterministic process.

There are six key functions of the device: embossing, indexing, cutting, holding, assembly and manufacturability. Embossing is the imprinting of the dots on the tape. Indexing is the movement of the tape at discrete intervals for inter-cell spacing. Cutting, finishes the label and allows the user to put it on the object. Hands must hold the device and apply forces to emboss, index and cut the tape. Assembling the device occurs initially but also when the user needs to replace the tape. The manufacturability of the device significantly impacts the cost of the device.

The overall functional requirements for the device were derived from both the deterministic and humanistic facets of the device functionality. Braille-It is designed to be an easy to use, language independent, personal braille label maker manufactured at a price point accessible to blind persons both in India and globally. Breaking this down, the specifications are laid out in Table 4.
<table>
<thead>
<tr>
<th>Specification</th>
<th>Quantification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makes Braille to precise international standard</td>
<td>Intracell spacing 2.5mm x 6 mm, 2 x 3 grid of six dots</td>
</tr>
<tr>
<td></td>
<td>Dots are of height 0.48 mm and diameter 1.44 mm</td>
</tr>
<tr>
<td></td>
<td>Intercell spacing 2.5 x 1.5, 6.2 mm total</td>
</tr>
<tr>
<td>Hold, dispense and emboss consumable tape</td>
<td>3M Magic™ Tape dimensions and plasticity</td>
</tr>
<tr>
<td>Language Independent</td>
<td>6 dots are independently actuated</td>
</tr>
<tr>
<td>Easy to use</td>
<td>Blind user can accurately reload tape in &lt; 3 min</td>
</tr>
<tr>
<td></td>
<td>Force applied by each finger is &lt; 15 N</td>
</tr>
<tr>
<td></td>
<td>Haptic feedback helps user know when dots are created and cells are accurately spaced</td>
</tr>
<tr>
<td></td>
<td>Braille is written in the same orientation as it is read</td>
</tr>
<tr>
<td>Handheld</td>
<td>Lightweight &lt; 1 kg</td>
</tr>
<tr>
<td></td>
<td>Smaller than 200 x 200 x 200 mm³, fits in purse or backpack</td>
</tr>
<tr>
<td>Affordable</td>
<td>Manufacturable for less than $5</td>
</tr>
</tbody>
</table>

Several heuristics drove the system integration and design of all parts. In particular, working to minimize the number of parts and designing all parts for two-part injection mold manufacturing significantly reduces the cost of mold production, which then reduces the fixed costs. Balancing cost and capability was a significant factor driving the iterative design of the device as well as a deciding factor when selecting strategies, concepts, modules and components (SCMC). When particular features or capabilities did not initially meet these restrictive manufacturing constraints, then alternate modules and components were designed.

Functional requirements resulted from a refinement of the broad specifications. These requirements clustered around the six key actions of the device. For each functional requirement there is a matching design parameter. These functional requirements are tuned to the particular strategy selection of embossing braille dots on tape as laid out in the Design Section.
Table 5: Functional Requirements and Design Parameters

<table>
<thead>
<tr>
<th>Functional Requirements</th>
<th>Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Embossing</strong></td>
<td></td>
</tr>
<tr>
<td>Precise alignment between punch and die</td>
<td>+/- 0.15 mm</td>
</tr>
<tr>
<td>Force applied to die to emboss Scotch Magic tape</td>
<td>10N of Force (See Appendix A.2 Embossing Force Test)</td>
</tr>
<tr>
<td>Repeated elastic bending</td>
<td>$10^5$ cycles estimates the use with a factor of safety of 10</td>
</tr>
<tr>
<td>Embossers fit dot model geometry</td>
<td>Reference dot model geometry</td>
</tr>
<tr>
<td>Dots can be created independently</td>
<td>6 actuators for 6 independent dots</td>
</tr>
<tr>
<td>Force applied to mechanism to transmit embossing force to tape</td>
<td>Determined by spreadsheet cantilever beam calculation</td>
</tr>
<tr>
<td>Haptic feedback indicates dot is created</td>
<td>Tactile and audible click after 10N of force to emboss dot is applied</td>
</tr>
<tr>
<td>Move tape in discrete increments for cell spacing</td>
<td>Intercell spacing of 6.2 mm</td>
</tr>
<tr>
<td>Provide haptic feedback to user that spacing is achieved</td>
<td>Tactile click after spacing is achieved</td>
</tr>
<tr>
<td>Tape exit doesn't interfere with holding</td>
<td>Tape exits device out of the way of hands</td>
</tr>
<tr>
<td>Fingers grip tape and pull to manually index</td>
<td>Geometry allows fingers to grip tape (quantify)</td>
</tr>
<tr>
<td><strong>Indexing</strong></td>
<td></td>
</tr>
<tr>
<td>Easily cut tape</td>
<td>Only need to use one hand and single motion</td>
</tr>
<tr>
<td>Fits in two hands</td>
<td>Meets ergonomic requirements for 5-95% of users ages 15 to 65 [44]</td>
</tr>
<tr>
<td>Dots written in same direction and orientation as they are read</td>
<td>Dots created upwards towards the user</td>
</tr>
<tr>
<td>All buttons can be used simultaneously</td>
<td>All fingers fit on the buttons at the same time</td>
</tr>
<tr>
<td>Extended use does not fatigue user</td>
<td>Keep wrists and hands in neutral (unstrained) position</td>
</tr>
<tr>
<td><strong>Cutting</strong></td>
<td></td>
</tr>
<tr>
<td>Parts must be assembled accurately in the correct orientation</td>
<td>+/- 0.15 mm in the x and y sensitive directions,</td>
</tr>
<tr>
<td>Correct part orientation</td>
<td>Parts designed to only fit one way</td>
</tr>
<tr>
<td>Re-assemble, tape is easy to replace</td>
<td>Can be done without sight in under 5 min, &lt; 10 steps</td>
</tr>
<tr>
<td><strong>Manufacturing</strong></td>
<td></td>
</tr>
<tr>
<td>Low cost</td>
<td>Design for 2 part molds, minimize parts</td>
</tr>
</tbody>
</table>

Some functional requirements constrained the design too much and were eliminated. For example, designs to minimize the distance from the embossing anvil to the tape cutting mechanism, which would reduce the amount of tape used, were eliminated because it was not as important a requirement as the cutting geometry such that the user can grip the tape and pull it...
for indexing and cutting. A second requirement that was expanded was the size of the overall device. Initially, the goal was to make it pocket sized, but eventually, in order to make space for all the mechanisms and integrated attachments, the allowable envelope expanded.

### 3.2 Strategies and Concepts

Integrating the ergonomic and mechanism design requires an iterative process to prototype and test the overall Strategy, Concepts, Modules and Components (SCMC) as the design evolves from coarse to fine amounts of detail. Proof-of-concept, bench-top prototypes are refined in modules that integrate into an ergonomic product. Selecting the SCMCs is based on the functional requirements.

The key question that underlies this project is: how might we enable blind people to live more independently within their homes, schools, workplaces and communities? One simple answer is to enable them to efficiently and effectively identify objects and spaces. Several strategies could be functional solutions to this challenge, including digital, electro-mechanical and purely mechanical/physical. Braille labels are a relatively simple, inexpensive solution that leverages the prevalence of braille globally and enables a personal, customizable solution.

The core insight was there is a market need for a language independent mechanical braille label maker. Through his work with people with blindness in India, Ted Moallem, a former MIT postdoc, identified this need as a strategic area for innovation. While the trend in assistive technology is heavily weighted towards digital solutions, mechanical solutions are simple to implement and cost accessible.

Braille is written and produced with several primary strategies; embossing methods such as the manual slate and stylus, brailler typewriter and industrial printer are the most common. With the introduction of computing technology, numerous electromechanical braille devices have emerged, most commonly using actuators to elevate or depress pins arranged in cell formations. Thermoforming, displacement and deposition methods are more rarely encountered but are useful in the creation of graphs and other charts, primarily for educational purposes. An alternate identification strategy is using a scanning smart phone application to identify the object, logo or barcode on a product. There are many apps in distribution and being developed that address this need. Table 6 clarifies the strategies described above, and by identifying the advantages and risks
of each strategy makes the selection of a mechanical solution, leveraging labels created with independent actuators clear. In the context of this thesis, the “actuators” are the beams that hold the embossing elements and guide them, but the actual force to emboss is provided by a person’s fingers pressing on the actuators.

Table 6: Identification Strategies

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Concepts</th>
<th>Modules</th>
<th>Advantages</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Labels</td>
<td>Independent actuators</td>
<td>Language Independent</td>
<td>Geometric constraints to fit 6 actuators in small area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integrated, pre-combined dot cells</td>
<td>Geometrically compact embosser</td>
<td>Limited to a single language and slower to emboss</td>
</tr>
<tr>
<td>Digital</td>
<td>Image Processing</td>
<td>Cell phone apps or independent device</td>
<td>Don’t require label creation step or braille literacy</td>
<td>Requires users to own expensive smart phone, need significant database to identify objects</td>
</tr>
<tr>
<td></td>
<td>Scanning bar/QR codes</td>
<td></td>
<td>Doesn’t require braille literacy</td>
<td>Requires smart phone and user still needs to locate the bar code on the object to scan</td>
</tr>
</tbody>
</table>

Moving forward with labels as the chosen identification strategy, the next choice was selecting a label medium. Pressure sensitive adhesive tape was a natural category because it integrates the label with adhesive to stick to objects. Paper strips were also considered but would require an extra step to apply tape or adhesive. 3M Scotch Magic Tape was selected because it meets the cost, embossing force, and dot durability requirements, even though backless adhesives are more difficult to use.

Tapes are comprised of a film/backing combined with an adhesive. 3M Scotch tape is significantly different than most matte tapes, and while the exact composition of 3M Scotch® Magic™ tape is a trade secret, it is known that the film has a higher modulus of elasticity than polypropylene and is made out of a semi-crystalline polymeric material. [45] These properties compliment the physical testing of Scotch Magic tape, which showed that it captured the embossed dot shape better than other tapes and did not tear or break through as easily during embossing. 3M Scotch tape sticks well to a variety of materials including stainless steel, LDPE, polypropylene, and coated natural fibers.
Table 7: Selecting a label medium

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Options</th>
<th>Products</th>
<th>Advantages</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure sensitive adhesive tape</td>
<td>Removable</td>
<td>Dymo compatible label tape</td>
<td>Stiff and holds durable embossed features</td>
<td>Expensive and higher forces required to emboss</td>
</tr>
<tr>
<td></td>
<td>Backing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Backless</td>
<td>3M Scotch Magic Tape</td>
<td>Inexpensive with good distribution channels. Highly elastic film holds dots</td>
<td>Sticky, flimsy tape without backing is difficult to roll through device</td>
</tr>
<tr>
<td></td>
<td>Custom</td>
<td>Custom tape</td>
<td>Material properties match requirements</td>
<td>Expensive to make and distribute</td>
</tr>
<tr>
<td></td>
<td>Generic</td>
<td>Non-name brand tapes</td>
<td>Global sourcing</td>
<td>Tapes with low modulus film backing tear during embossing and do not hold the dot shape.</td>
</tr>
</tbody>
</table>

Creating the braille dots is the first critical module in the label maker. The core strategy question is how to create braille dots on 3M Scotch Tape? Mechanical embossing was selected because it meets the cost requirement.

Table 8: Creating Braille Dots on the Label

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Concepts</th>
<th>Advantages</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Embossing</td>
<td>Low cost and does not require a power source</td>
<td>Requires higher forces provided by the user</td>
</tr>
<tr>
<td>Electromechanical</td>
<td>Deposition</td>
<td>More automatic use and force and indexing done automatically by machine</td>
<td>Expensive to manufacture and assemble, power source necessary</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dots potentially more durable</td>
<td>Heating and cooling of material necessary, slow, and expensive</td>
</tr>
</tbody>
</table>

Flexural and columnar components were considered as the independent embossing mechanisms. Flexural components were selected because they reduced the overall error in the structural loop.
of the mechanism in the x and y sensitive directions, part of the precision requirement, discussed further in Section 4.3.

Table 9: Selecting an Embossing Mechanism

<table>
<thead>
<tr>
<th>Concept</th>
<th>Components</th>
<th>Advantages</th>
<th>Risks</th>
<th>Functional Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Embossing Mechanisms</td>
<td>Flexural</td>
<td>Stiffness in x and y sensitive directions increases precision, high repeatability, injection moldable</td>
<td>Larger footprint and more force required to bend beam and emboss dot</td>
<td>Embossing Forces Assembly</td>
</tr>
<tr>
<td></td>
<td>Columnar</td>
<td>Small footprint, force vertically applied to embossing</td>
<td>Difficult to position precisely, multi-step manufacturing and assembly</td>
<td>Manufacturability</td>
</tr>
</tbody>
</table>

From early user testing and interviews, haptic feedback emerged as an important mechanism in the device allowing the user to know when they have created a dotor indexed the tape. Users wanted to feel and or hear a click after pressing the top buttons. Several ideas for implementing haptics were interesting, such as the column buckling and the wedge shaped slip mechanism. The final prototype at this stage uses metal snap domes that were simpler to implement with off the shelf components for testing the most critical modules. Creative haptic mechanisms integrated into the injection-molded parts is an interesting extension of this project. The prototypes and analysis used to test these mechanism before selection are discussed further in Chapter 4.
Indexing is the second critical module in the mechanism, ensuring repeatable and accurate spacing between the braille cells. An independent rotary mechanism that rolls with the tape and indexes with a ratchet and pawl mechanism was chosen because it ensures exact spacing and is compact within the device. Each of these indexing concepts integrates either a rotary or linear ratchet to provide haptic feedback to the user for each indexed location.

**Table 10: Selecting a Haptic Feedback Mechanism for Embossing**

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Concepts</th>
<th>Advantages</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical and audible click</td>
<td>Buckling columns</td>
<td>Moldable, tunable to desired force</td>
<td>Limited number of cycles, difficult to prototype, not audible</td>
</tr>
<tr>
<td></td>
<td>Wedge shaped slip friction</td>
<td>Moldable, simple geometry</td>
<td>Difficult to tune force</td>
</tr>
<tr>
<td></td>
<td>Moldable snap bridge</td>
<td>Moldable, integrated, one part</td>
<td>Difficult to tune force, high stresses at edges</td>
</tr>
<tr>
<td></td>
<td>Metal snap dome</td>
<td>Premade, reliable and repeatable, specified force, both physical and audible click</td>
<td>Separate pieces that require assembly, discrete forces based on parts available</td>
</tr>
</tbody>
</table>

**Table 11: Indexing Strategies**

<table>
<thead>
<tr>
<th>Strategies</th>
<th>Concepts</th>
<th>Advantages</th>
<th>Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation</td>
<td>Center of tape roller</td>
<td>Could reduce number of parts</td>
<td>Difficult to grip tape reel, small error in spacing as the radius changes when tape is used</td>
</tr>
<tr>
<td></td>
<td>Separate rolling mechanism with ratchet</td>
<td>Exact spacing</td>
<td>Extra part</td>
</tr>
<tr>
<td>Linear</td>
<td>Slider with ratchet</td>
<td>Potential use case</td>
<td>Larger footprint</td>
</tr>
</tbody>
</table>
3.3 User Journey

Designing for users with blindness was a unique constraint for the design of this device. Understanding the potential use cases and scenarios defined the user journey and mechanical design of the device. Physical cues on the device for attachment, orientation and use all required tactile rather than visual indicators for blind users to engage with the tool.

From early interviews, the most important insight was that the tool needed to be used in an orientation such that the direction of embossing, up towards the user, was the same as the direction of reading. Currently, the most affordable braille writing tool, the slate and stylus, requires users to write the mirror of the reading orientation. This mirrored orientation hinders braille learners. Furthermore, most braille students learn to type on a brailler that consists of six keys, one for each dot and a space bar. Each of the braille dots is associated with a particular number and finger. Leveraging this muscle memory, the braille labeler described in this thesis uses the same finger to dot mapping, shown in Figure 13, as the brailler.

Defining the user journey was an essential step in the design process and once determined catalyzed the mechanism design to match the desired use case. Figure 14 details the steps to create a label with the tool.

![Figure 13: Finger to Dot Mapping](image)

- **Step 1:** Hold device and punch first cell
- **Step 2:** Index tape by pulling with hand or pulling device
- **Step 3:** Emboss next braille cell, repeat 2 and 3 until finished with word or phrase
- **Step 4:** Slip finger under tape, grip and pull against cutting edge
- **Step 5:** Stick tape to object

![Figure 14: User journey creating a label](image)
It was also important to think about how a blind user would replace the tape after a role is finished. Qualitatively, the tape is replaced by first opening the top of the device, removing the embossing anvil piece, sliding the tape off the roll, then clicking a new roll into place. The end of the new roll is then pulled up and across the anvil and rollers and threaded down through the device and out the bottom, where it is stuck on the cutting ledge. The anvil is then pressed down and the top with the beams attached is oriented and pressed down to connect the Legos™.

Moving forward with commercialization it is important to determine the broader user journey surrounding the use of the device, including where do users buy or obtain the device? How do they learn how to use it? Where do they put the labels and how do people engage with them?

### 3.4 Modules and Components

Embossing and indexing are the two critical modules that form the core of the labeler mechanism, while cutting and holding are the two additional modules that weren’t critical but are very important to the use of the device. Table 12 shows the components that form each of the modules. For each of these components specific functional requirements were defined and used to refine the design. Both the design of the components and the integration into the device were taken into account during iterative system integration.
<table>
<thead>
<tr>
<th>Critical Modules</th>
<th>Components</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embossing</td>
<td>Flexures</td>
<td>Embossing mechanism with positive die</td>
</tr>
<tr>
<td></td>
<td>Anvil</td>
<td>Anvil with negative die features</td>
</tr>
<tr>
<td></td>
<td>Alignment Connector</td>
<td>Aligns the flexures with the anvil</td>
</tr>
<tr>
<td></td>
<td>Finger columns</td>
<td>Transmits force from fingers to flexures</td>
</tr>
<tr>
<td></td>
<td>Haptic Feedback</td>
<td>Provides click feedback after dot is created</td>
</tr>
<tr>
<td>Indexing</td>
<td>Roller</td>
<td>Rolls as the tape is advanced out of the tape, reduces friction</td>
</tr>
<tr>
<td></td>
<td>Ratchet</td>
<td>Attached to the roller and indexes the rolling movement</td>
</tr>
<tr>
<td></td>
<td>Pawl</td>
<td>Engages with the ratchet to stop it after each increment, provides click haptic feedback</td>
</tr>
<tr>
<td>Additional Modules</td>
<td>Cutting edge</td>
<td>Serrated edge to cut the tape</td>
</tr>
<tr>
<td></td>
<td>Sticking edge</td>
<td>Ledge before cutting edge on which the tape sticks when device is not in use</td>
</tr>
<tr>
<td></td>
<td>Loop for finger to grip tape</td>
<td>Allows user to grip tape and pull out to cut or index</td>
</tr>
<tr>
<td></td>
<td>Hand grip</td>
<td>Ergonomic form factor fits range of hand sizes and allows hands to transmit force to the device to emboss and index</td>
</tr>
<tr>
<td>Holding</td>
<td>Ratchet Holder</td>
<td>Slots aligning the ratchet and allowing it to roll</td>
</tr>
<tr>
<td></td>
<td>Anvil connector</td>
<td>Aligns and connects the anvil to the body piece</td>
</tr>
<tr>
<td></td>
<td>Tape holder</td>
<td>Aligns and locates the tape</td>
</tr>
</tbody>
</table>
CHAPTER 4

PROTOTYPING AND TESTING

After determining high level strategies and concepts enumerated in Chapter 3, the device was iteratively developed through physical prototyping, modeling, analysis, user feedback and testing. Different ideas for modules and components were iterated and found to work, or indicated that the next prototype needed to pursue a different option. This section details the prototype iterations, master model development, design analysis, user testing and system integration.

4.1 Prototypes and Modeling

Iterative prototyping and testing was a core part of the development of Braille-It. Early prototypes validated user interest in the device and identified the most critical modules described in Table 12 in Section 3.5.1. This section details the high level changes made for each prototype and shows the progressive development and refinement of the device. The detailed description of the final design and individual components is in Chapter 6 of this thesis.

Early prototypes tested the flexural embossing mechanism strategy and validated tolerancing for 3D printed Legos™ as an elastically averaged attachment and alignment mechanism. These earliest prototypes, shown in Figure 15, use both custom and off the shelf Lego™ components.

Figure 15: Early version 1 prototype with actual and 3D printed Lego™ interfaces
Braille-It underwent eight significant iterations shown in the following images. Within each of these iterations numerous versions were modeled and physically prototyped. The cross section views of each prototype show the internal components of the design, but all of the prototypes enclose the tape and mechanisms in an ergonomic exterior.

There was a significant jump from prototype 1, shown in Figure 15, to prototype 2 in Figure 16. The multifaceted leap represents the combined impact on the design of insights from detailed user interviews and assessing “failed” label makers. Prototype 2 introduced a vertical stack of the embossing beams (red) and embossing anvil (blue) above the white tape roll to make holding the device easier for users. The gray body piece tests an ergonomic shape with the flexural beams exposed on top. The prototype moved away from a Lego™ dominant design to incorporating the Lego™ type connections within the body to enable snap-together ease with the high precision created by elastic averaging. Prototype 2 also tested the braille standard sizing for the punch and die. Several fillets with different radii were considered for the tip of the embosser to create a strong dot. These dot samples were given to users to evaluate. The blue hexagonal die is both the anvil and together with the green torsion spring forms the indexing mechanism. At the bottom of the gray base is an experimental connector using two flexures with an interior pin.

Figure 16: Prototype 2 cross sectional view and held in a user’s hands
Prototype 3, in Figure 17, introduced the green button cover that interfaces with the fingers and the flexural beams as a parallel coupled system. The body of the device is about 2/3 the width of the previous prototype in an effort to make it pocket sized. The white arched embossing anvil is static rather than rotating to reduce alignment error between the punch and the die, and an experimental ratchet mechanism is inserted at the center of the tape with flexural arms to grip the tape and an internal ratchet. Furthermore, connector features half the size of standard Lego's™ were implemented to allow for a smaller footprint at the connection lip. Several beam orientations and geometries were prototyped to locate the force from the green column closer to the tip of the beam. Although the interior ratchet indexing mechanism was promising, it introduced an error in the intercell spacing, because the diameter changed when tape was consumed. This error was deemed unacceptable for users.

Prototype 4, in Figure 18, replaces the center ratchet in the previous prototype with the white roller between the blue beams and red body. It also cuts in on the side to reduce tape waste and create a space for fingers to grip the tape and pull it out of the device. This prototype was also designed to be pocket sized, but minimizing the components reduced performance and was more
difficult for larger hands to use. Prototype 4 was the first to incorporate haptic feedback via a clicking slip off mechanism between the green columns and the blue flexures. While the clicking was satisfying, it did not transmit enough force to the beams to emboss dots, it was difficult to tune to a required force, and the click gradually reduced as the edge of the ledge wore from use.

In response to the cramped ergonomic design of prototype 4, prototype 5, in Figure 19, returned to the horizontal tape and anvil layout, with an ergonomic exterior skin. This elongated design allowed for extended button flexures that are easier to press, but user testing revealed that Prototype 5 was not a desirable shape. The key insight was that it is important to indicate directionality of the device (bottom, top, right side, left side) to the user via the design. Without visual cues blind users need tactile indicators showing which is the top and bottom of the device and how it should rest on a table. Users also described the device with words like fragile, easily breakable, and insecure. This was very different than the feedback from sighted users who liked the curvy design and mentioned that it felt good in their hands. This difference in opinion highlighted the specific needs of people with blindness and their unique perspective of the tactile experience of an object, whereas sighted people were biased by the visual appearance.

Figure 19: Prototype 5 - Section view on the right and an assembled view with transparent top to see interior
Prototype 6, in Figure 20, returned to the vertical stack, but widened the finger buttons on top and enlarged the ratchet tape roller in yellow. Two rollers were added on either side of the embossing anvil to provide rolling instead of sliding friction to reduce tape drag and prevent the dots from being compressed by edge loading. Off the shelf clicking buttons were also added between the green top buttons and the embossing flexures to provide repeatable haptic feedback. This prototype was challenging for users to replace the tape and reassemble because it came apart into many small pieces. In particular, holding the two body halves and the rollers and ratchet while inserting the tape was particularly challenging for people with blindness. Tape indexing was also frustrating because there was no source of tension after the roller so the tape remained stuck on the roller and wrapped onto itself, making removal of the label difficult. Figure 21 shows several detailed views of the design including the connectors on top of the base parts and the beams and the long buttons on top. The non-symmetric embossing beams in the second image from the left attempted to bring the haptic buttons closer to the tip of the embossers, but instead caused torsion of the beam which significantly reduced the embossing.

Figure 20: Prototype 6 cross section and hand holding prototype

Figure 21: Four images of Prototype 6 showing the embossing beams with elastically averaged connectors, the rolling-indexing anvil and the long top buttons.
To address the assembly challenges of the previous prototype, Prototype 7, in Figure 22, moves from a two-piece body to a monolithic base part. A single base configuration removes the alignment error between the two base halves, which was propagating error to the connected beam part. The monolithic base also makes assembling and replacing the tape much easier for blind users by reducing the number of parts. The embossing anvil is separated from the base into its own piece that also serves to constrain the tape roller in the body. Creating a separate anvil piece also shortens the structural loop between the flexures and the anvil. Although not obvious from the cross-section, this prototype makes a significant jump in ergonomic form factor that is built on for the final version. Prototype 7 also moves back to full sized Lego™ type features for attaching the buttons, beams, anvil and base, but it reduces the number of connection points. It also simplifies the off the shelf clicking buttons to bistable metal snapdomes that can be selected based on a desired click force and feel. Snapdomes occupy a much smaller footprint than the previous buttons, allowing the buttons to transmit force closer to the tip of the embossing beams which increases the mechanical advantage of the coupled system. Furthermore, prototype 7 changes the flexural mechanism from a full cantilevered beam to a living hinge design moving the center of rotation towards the base and stiffening the tip between the loading point and the embossing tip. This is analyzed in Section 4.2.1. From
the top in Figure 22, in the cross section view the buttons are shown in red, the embossing beams are yellow, the anvil and rollers are green, the tape roller is white and the base is blue. The second image shows a cross section view of the top part of the device. The image depicts the interlocking stack up of elastically averaged connectors on the left and right sides, the stackup is also shown in the third and fourth images. The fourth image shows the spacing of the upper dots, in light gray, alternating with the smaller bottom columns outlined in black. The interference between the dots and columns creates the elastically averaged connection described further in Section 4.2.3. Finally, Figure 23 depicts a user using the device to make a label. Detailed feedback from users led to the changes manifested the final design iteration.

The final prototype 8, in Figure 24 and Figure 25, demonstrates both high level changes and detailed component refinement. This prototype was built from a master model integrating all the insights from previous prototypes. The blue anvil piece integrates the entire tape spooling pathway which simplifies assembly and replacement of the tape for the user. The tape roller was
eliminated by integrating it into the embossing anvil and moved to the side to create space horizontally for the ratchet mechanism and the bottom opening. The pawl part of the ratchet assembly was also integrated into the anvil piece. The bottom opening was designed to hold and cut the tape while allowing a user to access and grip the tape. Furthermore, the body is a monolithic part that is closed as a unified exterior by the button top. The green beams are connected to the button top by snap hooks on the left and right sides that hold together the top assembly with the snap domes preloaded in between the coupled flexures. Details of the final design and use are expounded upon in Chapter 6.

Figure 25: Section view of the final prototype
4.2 Design Analysis

Analytical models informed design decisions for features and components in the device with deterministic functional requirements. In particular, the design of the two most critical modules were governed by a Flexural Beam Model, presented in section 4.1.1, and a Capstan Ratchet Model detailed in section 4.1.2. This section also presents the elastic averaging mechanism used for alignment, and ergonomic analysis.

4.2.1 Flexural Beam Model

The flexural beams at the core of the embossing mechanism require stiffness in the x and y sensitive directions and compliance in the z direction, and must fit within the given geometric constraints of the braille dot matrix. It is also important for the beams to repeatedly bend elastically without fatigue to the hinges. Analysis of the beam was divided into two beam scenarios: the cantilevered deflection and the fixed-roller configuration during embossing.

A flexural beam model was developed to calculate the deflection at the tip of the beam, and the max bending stress along the beam. This model enabled quick dimensional analysis of varying beam geometries. For prototypes 1 through 6, the embossing beams were modeled as a continuous flexure with bending along the entire length of the beam. Prototyping and the beam model showed that to achieve the desired deflection of 1mm with a relatively low applied force while also maintaining a low stress ratio at the base of the beams, the beams needed to be longer than 30 mm. The deflection at the tip of the beam was calculated assuming Euler-Bernoulli beam theory using the formula for a cantilevered beam with a force applied at some distance $a$ from the base of the beam as shown in Figure 26. The formula for the max deflection is therefore:

\[
\delta_{\text{max}} = \frac{F_{\text{v}}l_{\text{b}}^2}{6EI} (3l_{\text{b}} - l_{\text{v}})
\]  

Figure 26: Cantilevered beam model with concentrated force $P$ [45]
Where $\delta_{max}$ is the max deflection, $F_p$ is the force applied to the beam, $l_p$ is the distance from the the base of the beam to the point at which the force is applied, $E$ is the modulus of elasticity, $I$ is the area moment of inertia, and $l_b$ is the length of the beam.

The maximum bending stress, at the base, was calculated using the following equation:

$$\sigma_b = \frac{Mc}{l} \tag{2}$$

Where $\sigma_b$ is the bending stress, $M$ is the moment generated by the force $P$ acting at length $a$, $c$ is the distance from the outermost fibers to the neutral axis, and $I$ is the same area moment of inertia as Eq. (1). Using the max bending stress, a stress ratio was then calculated to understand bending stress compared to the allowable stress calculated from the flexural strength of the material. The flexural strength is a material property defined as the stress in a material just before it yields in a flexure test. The flexural strength is also referred to as the modulus of rupture, bend strength, or transverse rupture. [46, p. 40] For ABS plastic the flexural strength is 60.6 – 73.1 MPa [47] and mechanical testing suggests that fatigue failure for ABS occurs between 11 and 22 MPa. [48] Thus, the stress ratio is:

$$stress \ ratio = \frac{\sigma_{bending}}{\sigma_{flexural}} \tag{3}$$

This stress ratio was used as a design tool to evaluate beam designs and maintain a ratio less than 0.2, calculated by computing the ratio of the stress at which fatigue failure occurs over the flexural strength for ABS plastic as referenced above.

Although a single flexural member was sufficient, in order to make the device smaller while orienting the beams in a circle to increase stiffness, a hinge was added at the base of the beam, shown in Figure 27. To account for this new topology, the parametric beam model was extended.

![Cross Section View of Beams with Hinge](image)
to include a beam-based flexure joint coupled with a rigid body, as proposed by Teo et al. [49] and shown in Figure 28. In this model, a short flexural segment allows for deflection, while the forward part of the beam acts as a stiff stage to transmit the force from the snap dome to the embossing tip.

Figure 28: On the right a beam based flexure joint coupled with a rigid body, on the left a beam subjected to a moment end load [44]

To find the total displacement of the combined flexure and rigid body, the slope at the tip of the deformed flexure is found and then used to calculate the displacement at the end of the rigid member. It is assumed that the moment is constant across the length of the flexure because the length of the rigid body is much greater than the length of the flexure. The slope of a cantilevered beam with an applied end moment is:

\[
\theta_f = \frac{Ml_f}{EI_f} \quad (4)
\]

\[
M = F_v l_v \quad (5)
\]

Where \( \theta_f \) is the slope of the flexure, \( l_f \) is the length of the flexure, \( E \) is the modulus of elasticity, \( I_f \) is the area moment of inertia of the flexure cross-section, and \( M \) is the applied end moment calculated by multiplying the vertical force \( F_v \) by the distance from the base that the force is applied \( l_v \).
Using $\theta_f$ from Equation 4, the total deflection at the tip of the rigid body is calculated as the sum of the vertical displacement of the rigid member and the displacement of the flexure.

$$\delta_b = l_r \tan \theta_f + \frac{M l_f}{2 E I_f}$$

(6)

Where $\delta_b$ is the total deflection at the tip of the rigid body, $l_r$ is the length of the rigid body, $\theta_f$ is the slope of the flexure, and $I_f$ is the moment of inertia of the flexure. As described in Equations 2 and 3 above, the bending stress in the center of the flexure can be calculated and compared to the flexural strength.

As mentioned in the first paragraph of this section, analysis of the beam was split into two scenarios. The second scenario is modelled as a fixed-roller beam configuration as shown in Figure 29. This model determines how much force needs to be applied to the beam, to emboss the dot with approximately 10 N of force, documented in Appendix A.2 Embossing Force Test. Solving for $F_v$, in Eq. (7) gives the force required to emboss a dot with a force $R_B$ given a particular parametric beam model.

$$F_v = \frac{2 R_B l_v^3}{l_B^2 (3 l_B - l_v)}$$

(7)
4.2.2 Capstan Ratchet Indexing Model

The indexing mechanism is comprised of a ratchet and pawl, as shown on the right in Figure 30. The tape is routed with the adhesive side up from the tape roll up and over two rollers on either side of the embossing anvil and then down past the ratchet roller with the adhesive side facing the roller and then out past the tape ledge and cutting edge. The wrapping of the tape around the rollers and ratchet is both a risk and a useful countermeasure. The capstan effect from the tape wrapping around the embossing anvil is mitigated by adding the rollers, but the same effect is used to pull the ratchet counterclockwise forcing the pawl upwards.

The capstan effect explains how a holding force can resist much larger load forces when a line, rope, belt or tape is wrapped around a static element. The relationship between the forces is based on the wrap angle of the tape or band. The capstan formula is [3]:

\[ F_{\text{hold}} = F_{\text{pull}} e^{\mu \theta} \]  

(8)

Where \( F_{\text{hold}} \) is the resulting force exerted at the end of the capstan, \( F_{\text{pull}} \) is the applied tension on the tape, \( \mu \) is the coefficient of friction between the tape and the ratchet material, and \( \theta \) is the total angle that the tape is in contact with the ratchet roller.

A coupled capstan ratchet model informed design decisions for the ratchet and pawl. In particular, it was important to determine the angle of contact necessary between the tape and ratchet to provide a frictional hold between the two, while overcoming the force of the pawl. Furthermore, the model validated the depth of engagement between the ratchet and pawl, and the angle of the pawl surface. These parameters ensure repeatable indexing functionality of the module.
Figure 31 depicts the ratchet in yellow, rollers in green and tape in gray, where the tape is threaded through the device as shown in Figure 30. The forces on the tape are shown as they correspond to Eq. (13). To find the wrap angle $\theta$, first, the ratchet force needs to be determined because it is equal to the $F_{pull}$. The ratchet force is the horizontal force necessary to deflect the pawl upwards such that it moves above the depth of engagement, and it is dependent on the friction between the two materials and the angle of contact.

To determine the angle of the pawl contact both the critical angle at which an object will begin to slide and the resultant force necessary to actuate the pawl for a given angle were considered. For a given coefficient of static friction there is a critical angle at which an object will begin to move, governed by Eq. (14), where $\mu$ is
the coefficient of static friction and \( \alpha \) is the critical angle at which two objects will overcome friction. Figure 32 shows the line of correlated angles and coefficients of friction.

\[
\alpha = \tan^{-1} \mu \tag{9}
\]

Assuming that the coefficient of friction for ABS plastic on ABS plastic, is approximately 0.2 \cite{50}, Figure 32 estimates that 12 degrees is the minimum possible angle of the pawl surface. By calculating the horizontal pull force \( F_R \) necessary to overcome the pawl force for a range of angles, an angle for the pawl contact is selected greater than the minimum value.

The maximum \( F_R \) occurs when the pawl is fully deflected. The force to deflect the pawl beam by 1.5 mm is calculated using the following equation:

\[
F_{Beam} = \frac{3\delta_{max}EI}{l^3} = \frac{3 \times 1.5 \times EI}{17^3} = 1.63 \text{ N} \tag{10}
\]

For a length of 17 mm, a height of 1.5 mm, and width of 2.75 mm. This value is then used as a max value to oppose the force of the ratchet.

To calculate the max \( F_R \), a simplified model, as shown in Figure 33, was analyzed. The external forces acting on the system are the force of the ratchet \( F_{Ratchet} \) and the force of the beam

![Figure 33](image-url)
$F_{Beam}$. The sum of forces in the $x$ and $y$ directions for the two bodies resulted in the series of four equations shown in Eq. (15), which were solved numerically for a range of angles.

$$
\begin{bmatrix}
\mu \cos \alpha - \sin \alpha & 1 & 0 & 0 \\
-\mu \sin \alpha - \cos \alpha & 0 & 0 & 1 \\
\sin \alpha - \mu \cos \alpha & 0 & 0 & 0 \\
\mu \sin \alpha + \cos \alpha & 0 & -1 & 0
\end{bmatrix}
\begin{bmatrix}
R_1 \\
R_2 \\
R_3 \\
F_R
\end{bmatrix} =
\begin{bmatrix}
0 \\
0 \\
F_{Beam} \\
0
\end{bmatrix}
$$

(11)

$\mu$ is the coefficient of friction of ABS plastic on ABS plastic, $\alpha$ is the angle of the pawl face from vertical, $R_1$ is the equal and opposite reaction force between the ratchet and pawl, $R_2$ is the upwards reaction force of the ratchet support, $R_3$ is the horizontal reaction force of the pawl, $F_{Beam}$ is the downward force of the beam when it reaches max deflection from the ratchet, and $F_R$ is the desired force applied by the ratchet to overcome the pawl force.

Figure 34 demonstrates the resulting force necessary to overcome the pawl force for a range of angles as calculated in Eq. (16). Selecting a pawl surface angle of 50 degrees, four times greater than the critical angle, requires a pull force of 2N. Selecting a lower pull force reduces the necessary wrap angle around the ratchet.

Before calculating the wrap angle, the holding force $F_{hold}$ must be calculated for the tape. The holding force is the force to unwind the tape from the roll, $F_{Unwind}$ multiplied by an efficiency value of the rollers $\eta$ [3]. $D$ is the outer diameter of the roller, $d$ is the small diameter of the rolling element both measured in millimeters, and 0.2 is the coefficient of friction between ABS plastic and ABS plastic.

$$
\eta = \frac{F_{out}}{F_{in}} = \frac{D-d \mu}{D+d \mu} = \frac{10-3*0.2}{10+3*0.2} = 0.89
$$

(12)
The rollers have an efficiency value because there is rolling friction between each roller and its support. The efficiency \( \eta \) is squared because there are two rollers. \( F_{\text{unwind}} \) is calculated based on the unwind force value on the Scotch® Magic™ Tape 810 product sheet of 0.7 N/cm [45]. For 0.75 inch wide tape, \( F_{\text{unwind}} = 1.47 \) N. Therefore,

\[
F_{\text{hold}} = \frac{1}{\eta^2} F_{\text{unwind}} = \frac{1.47}{0.89^2} \text{ [N]} = 1.86 \text{ N} \tag{13}
\]

Finally, the wrap angle \( \theta \) of the tape around the ratchet is calculated using Eq. (13) rearranged to solve for \( \theta \).

\[
\theta = \frac{-1}{\mu} \ln \frac{F_{\text{hold}}}{F_{\text{pull}}} = \frac{-1}{0.8} \ln \frac{1.86}{F_{\text{pull}}} \tag{14}
\]

The necessary wrap angle \( \theta \) for a range of pull forces is plotted in Figure 35. The ratchet force calculated by Eq. (16) and shown in Figure 34 is 2 N for a 50 degree pawl surface, with a factor of safety of 2, the force is 4N. Therefore, the wrap angle of the tape around the ratchet roller required for a pull force of 4 N is 56 degrees.

The total minimum force necessary for the user to pull is the combined force to unwind the tape plus the amount of pull required to overcome the pawl force. This total force is approximately 5.86 N as shown in Eq. (20).

![Figure 35: Wrap angle required for a range of forces](image)

\[
F_{\text{pull(total)}} = F_{\text{ratchet}} + \frac{1}{n^2} F_{\text{unwind}} = 4 \text{ N} + 1.86 \text{ N} = 5.86 \text{ N} \tag{15}
\]
4.2.3 Elastic Averaging for Alignment and Attachment

Elastic averaging is a method of coupling two parts in which the two solid bodies are significantly over-constrained with a large number of relatively compliant members. When preload is applied to the system, the elasticity of the compliant members allows them to deform slightly. The deformation of the members averages the positional error of each individual contact over the total sum of contacts in the part.

Legos™ are an example of an elastically averaged coupling with low-stiffness elements. Slocum and Weber evaluated the repeatability of press-fit Lego™ Duplo™ assemblies and found in an experiment with 2 blocks and 72 contact points that the repeatability in the x direction was $8.15 \mu m \pm 2.484$ and in the y direction $10.95 \mu m \pm 2.759$. [51, p. 26] Using Lego™ features as the elastic averaging geometry for the braille label maker increases the repeatability of the connections between the base, anvil, beams and buttons. Figure 36 shows the contact points on the bottom columns in the left image, and the top contact points on the right. The opposite side of the part has an equal number of contact points, thus, each part has 28 points of contact.

The repeatability of an elastically averaged connection is approximately inversely proportional to the square root of the number of contact points. Eq. (21) demonstrates this relationship where $n$ is the number of contact points, $r$ is the repeatability of the coupling and $\delta$ delta is the positional error of the elastic feature. A first order estimate can use the manufacturing tolerance for $\Sigma$. For the Protolabs™ ABS Lustran material [52] the manufacturing tolerance is $+/- \, 0.08 mm + 0.002 \frac{mm}{mm}$. Therefore, the repeatability is estimated at $15.1 \mu m$ as calculated in Eq. (21). This seems reasonable as the same order of magnitude as measured by Slocum and Weber. [53]

$$r = \frac{\delta}{\sqrt{n}} = \frac{0.08}{\sqrt{28}} = 0.0151 \ mm = 15.1 \mu m$$ (16)
4.3 Ergonomic Analysis

Ergonomic dimensions and use scenarios for the device informed the industrial design and form factor of the device. Figure 37 shows some of the ergonomic data used to size the height of the device, determine the radii of the grip curvature and model the finger spacing of the buttons all to fit a range of hand sizes. [44] This ergonomic data was validated by user testing with a range of hand sizes.

![Figure 37: Ergonomic Hand Data for Woman and Man][43]
Figure 38 demonstrates the fit of the final prototype with two different hand sizes. For reference, the small woman hand is in the 1st percentile for a small woman, where the palm length measures 3.4”, while the large man hand palm length is the mean length at 4.1”.

![Figure 38: Small woman hands on the right and large man hands on the left holding the device demonstrates range of fits.](image)

The curvature of the left and right sides of the device were dimensioned to allow for adjustability up and down based on the hand size and length of fingers. In Figure 38, the left image shows the woman fingers flat across the top of the device, whereas in the right image the man’s fingers are more curved. The thumb also has a range of grip surfaces on or under the ledge. The force to actuate the beams is provided by the index, middle, and fourth fingers opposing the force of the thumb and palm on the device. The opposing forces in a wide pinch grip allows the fingers to apply more force than they would independently. This grip is a combination of a palmar pinch and a wide grip as commonly defined in ergonomic literature.

The mean press forces for males and females are 50.90 and 35.20 N respectively, while the palmar pinch is 62.88 and 45.45 N. [54, p. 24] For the purposes of this thesis, the total press force was designed to be less than 10 N.
Chapter 5 presents the final design of the prototype. The underlying parametric master model is presented in Section 5.1. Each of the components are described in detail as well as features of the system integration. Facets of the design for manufacturability and initial estimates for the fixed and variable manufacturing costs are presented in Section 5.4. Evaluating the design based on the functional requirements shows that this device meets and exceeds the user specifications for precision, affordability, usability, and portability.

Figure 39: Rendering of the final design

The final prototype design, shown in Figure 39, consists of four structural pieces, the body, buttons, beams, and anvil, a ratchet and two identical rollers; which totals 6 distinct parts for the entire device. These parts encompass 15 components as laid out in Table 12. Figure 40 shows a
cross section view of the prototype on the right and a sketch view with interior components on
the left.

Figure 40: Sketch and cross-section views of the final prototype

To better understand the integration of the components and functionality in the final device,
Figure 41 and Figure 42 identify the parts and integrated components.

Figure 41: Components of the final prototype labeled
Figure 42: Right section view with labeled components

Evaluation of the design based on the functional requirements, presented in Table 13 demonstrates that this prototype meets all the functional requirements in Chapter 3.
<table>
<thead>
<tr>
<th>Functional Requirements</th>
<th>Design Parameters</th>
<th>Final Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precise alignment between dot and cup</td>
<td>+/- 0.15 mm</td>
<td>Repeatably makes good dots, precise alignment not measured</td>
</tr>
<tr>
<td>Force applied to cup to emboss scotch magic tape</td>
<td>10 N of force</td>
<td>10 N</td>
</tr>
<tr>
<td>Repeated elastic bending</td>
<td>$10^5$ cycles estimates the use with a factor of safety of 10</td>
<td>Yes, initially validated by max tensile stress calculation at the base of the flexure and SolidWorks simulation</td>
</tr>
<tr>
<td>Actuators fit dot model geometry</td>
<td>Reference dot model geometry in Figure 50. Dot diameter of 1.44 mm and height of 0.48 mm.</td>
<td>Yes</td>
</tr>
<tr>
<td>Dots can be created independently</td>
<td>6 actuators for 6 independent dots</td>
<td>Yes</td>
</tr>
<tr>
<td>Force applied to mechanism to transmit embossing force to tape</td>
<td>Determined by cantilever beam calculation</td>
<td>Yes, applied by fingers to buttons</td>
</tr>
<tr>
<td>Haptic feedback indicates dot is created</td>
<td>Tactile and audible click after 10 N force to emboss dot is applied</td>
<td>Snap dome clicks at force higher than needed for dot formation indicating dot is created</td>
</tr>
<tr>
<td>Move tape in discrete increments for cell spacing</td>
<td>Intercell spacing of 6.2 mm</td>
<td>Yes</td>
</tr>
<tr>
<td>Provide Haptic feedback to user that spacing is achieved</td>
<td>Tactile click after spacing is achieved</td>
<td>Yes, ratchet and pawl clicks after spacing is achieved.</td>
</tr>
<tr>
<td>Tape exit doesn’t interfere with holding</td>
<td>Tape exits device out of the way of hands</td>
<td>Yes</td>
</tr>
<tr>
<td>Fingers grip tape and pull to manually index</td>
<td>Geometry allows fingers to grip tape</td>
<td>Yes, spacing determined by human ergonomic dimensions</td>
</tr>
<tr>
<td>Cutting</td>
<td>Easily cut tape</td>
<td>Only need to use one hand and single motion</td>
</tr>
<tr>
<td>Holding</td>
<td>Meets ergonomic requirements for 5-95% of users ages 15 to 65</td>
<td>Yes</td>
</tr>
<tr>
<td>Dots written in same direction and orientation as they are read</td>
<td>Dots created upwards towards the user</td>
<td>Yes</td>
</tr>
<tr>
<td>All buttons can be used simultaneously</td>
<td>All fingers fit on the buttons at the same time</td>
<td>Yes, for 1-99% of adult users based on ergonomic ranges [44]</td>
</tr>
<tr>
<td>Extended use does not fatigue user</td>
<td>Keep wrists and hands in neutral (unstrained) position</td>
<td>Yes</td>
</tr>
</tbody>
</table>
In the final prototype, the tape is routed from the roll up and over the two white rollers and blue anvil, but below the green flexural beams, as shown by the yellow line in Figure 43, where the dots indicate the adhesive side of the tape. After passing over the left white roller, it passes to the right of the blue ratchet and out the bottom of the device. While not in use the tape sticks to the protruding cutting ledge. The process of loading the tape is shown in Figure 44. Image 1 shows the placement of the tape on the tape roller. Image 2 shows a hand pulling the tape up and over the rollers with the sticky side upwards. Next, image 3 shows the end of the tape threaded through the cutout at the bottom of the device. Then, in image 4 the embossing anvil piece is aligned with the base piece and pressed together to engage the elastically averaged Lego™ like connection. Image 5 shows the user holding the device and sticking the tape to the cutting ledge.
One of the risks of using backless tape was that it would stick to components within the device. The sticky side of the tape faces upwards on top of the anvil so that the positive dots are formed on the non-sticky film. Only the small punch points come in contact with the tape reducing unnecessary stick. Then, on the ratchet, reciprocity uses the stickiness of the tape to rotate the roller when the tape is pulled downwards thus displacing the pawl and creating the ratchet click which indicates the tape was moved one cell width.
5.1 The Master Model

The master model for the device assembly and parts is a single part file with sketches, planes and surfaces that is included in the child parts at the top of the feature tree and drives the shared dimensions and features of the child parts. When changes are made in the master model they propagate down to the sub parts creating a robust CAD model that streamlines changes and iterations. The master model only needs to include dimensions, reference planes and surfaces that will be shared among two or more parts, without the clutter of part specific features.

As depicted in Figure 45, the industrial design (ID) geometry and global equations are both inputs into the master model. The ID geometry for the exterior or skin of the device is created separately as a solid body, surfaces or combination of both and imported into the master model. Likewise, a document containing the global equations is imported into the SolidWorks equations as a text file. This equation file, documented in Appendix A.1 Dimensions for the CAD Model, is included in all the component files. When a component is made, the first step in the feature tree is to import the master model and global equations. The master model is located by making the front, right and top planes of the two parts coincident. The individual component is then built out from these references. When creating an assembly of parts that are associated with a master model no mates are required because they will automatically align as referenced.

The master model for prototype 8, detailed below, includes the following sketches: front plane, braille dot location, punch and die geometry, beam orientation, circular Lego™ features and circular Lego™ like groove.
Figure 46 and Figure 47 show the front plane sketch in the final master model for the Braille-It device. As annotated in Figure 47, the front sketch defines the z-height stack-up of the button thickness, button height, beam thickness, and snap height all referenced off the top split plane, co-planar with the embossing surface of the anvil. Each of the locating points in this sketch were used to locate planes in the components. These planes were used to cut the solid body ID geometry and to define feature extrusions and cuts. Furthermore, the front sketch locates the tape, ratchet and roller centers and diameters.
Figure 48: Master Model Sketch of Lego Features [mm] [deg]

Figure 48 shows a top view of the master model sketch for the circular elastic averaging features which propagates to the buttons, beams, anvil and body sub parts. The Lego™ diameters are based on actual Lego™ dimensions and the spacing ensures the elastically averaged connection between the groove and the dots.

Figure 49: Master Model Sketch of Beam Orientation, Length and Force Point [mm] [deg]

Figure 49 illustrates the separation between the flexural beams and the points of connection, embossing and force applied on the beams. The radial spacing of the beams maximizes the space between the beam tips (slightly more than 1mm) for moldability, but brings the tips together to emboss the dot pattern according to international braille standards. Figure 50 illustrates the
braille standards as implemented in the model. The tape offset sizes the embossing dies larger than the punch to press the tape into the desired shape.

The master model places the dot pattern symmetrically at the center of the model to indicate its critical function and to facilitate the building of the parts and features around it symmetrically.

Figure 50: Master model sketch of the dot spacing and size [mm]
5.2 Component Level Detail

The final configuration of this label maker includes six distinct parts shown in Figure 51. Each of these components is shown in detail in the following section. Whenever possible, features and functionality were combined into fewer parts to reduce the number of molds necessary to manufacture the device.

Figure 51: The six components that comprise the final device
5.2.1 Embossing Beams

The embossing beams, shown in Figure 52, are the core innovation of this device. The connected flexural design maintains the relative relationship of the beams to one another, and the stiffness of the exterior connector, analysis shown in Section 4.2.4, was considered to reduce Abbe errors at the embossing tip of the beams. The final beam design incorporates a hinge mechanism instead of a continuous bending beam, which moves the center of stiffness and rotation of the beam towards the base and allows for shorter beams and a stiffer tip to transmit the forces from the buttons through the beams to the tape, this is analyzed in Section 4.2.1. The parametric values for beam geometry were selected using the Beam Bending Model presented in Section 4.2.1.

Six independent actuators allow the label maker to be language independent, but the risk of independent actuators is that there will be error between the embossers and the anvil. The flexural component mitigates this risk of misalignment by designing for stiffness in the x and y directions in the plane of the page, while allowing compliance in the z direction for embossing. This stiffness is actually designed for in the circular stage that connects the flexures, because it is the component that experiences forces that might cause distortion from attachment to the body of the device.
The geometry of the hinge was selected based on the deflection and stress analysis presented in Section 4.2.1, as well as considering lifetime repeatability and moldability.

Alignment between the beams and the embossing anvil is the most sensitive part to misalignment or error. As documented in the functional requirements, Table 13, the allowable misalignment is maximum of 0.15 mm. The Lego™ connector between the beam and anvil parts mitigates the risk of error in the attachment mechanism, as quantified in Section 4.2.3. The same connector is used to align the button part with the beams, so that the force columns from the buttons align with the snap domes assembled towards the tip of the beams. Since the button and the beam parts do not need to come apart for replacing the tape, a snap hook feature was added to more permanently connect them.

5.2.2 Anvil

![Anvil top and side view annotated](image)

The embossing anvil, in Figure 53, incorporates several functional components into the same part, including the embossing die, roller captures, the pawl part of the ratchet, and the tape holder. As shown in the image, the part is injection moldable with a two-part mold pulling from the top. Integrating the tape pathway into a single part that is removable from the device made replacing the tape easier with fewer steps. The two rollers on either side of the anvil hold the tape slightly above the anvil surface, reducing friction and eliminating the capstan effect as the tape winds up and over the anvil. The tape roll snaps onto the tape holder and is held horizontally by a flexural capture, labeled in Figure 53 as the horizontal tape restraint. The pawl is located to
engage with the ratchet roller inserted into the body piece, and surrounding the pawl is a protective barrier to prevent the pawl from snapping off during assembly.

5.2.3 Base

The base, shown in Figure 54, forms much of the ergonomic exterior as well as incorporates the cutting mechanism, ratchet capture, and alignment for the anvil and button parts. The anvil rough alignment ledge blocks the anvil part from being inserted the wrong direction, while the LegoTM connector ensure the fine alignment via elastic averaging. The rough alignment lip at the top of the part helps locate the button part, which as it is pressed down locates precisely also using LegoTM connectors. The ratchet capture is a rounded slot sized for a smooth sliding fit between the ratchet rest and the capture. When the ratchet was uni-directional, the two captures were different lengths to only allow for assembly in the correct orientation, but when the ratchet became symmetric so too did the ratchet captures.

In the right image of Figure 54, the hands are placed on the right and left sides of the device with fingers pointing upwards to engage with the buttons. The tape comes out through the bottom of the device and sticks to the ledge before the cutting edge. The cutout finger loop allows the user to insert their index finger and thumb to grip the tape and pull it out from the device to index.
5.2.4 Buttons

The button part, shown in Figure 55, completes the ergonomic exterior with the base part, provides the human interface with the dots, and couples the force applied by the human fingers through columns, down to the snap domes and embossing beams. The columns to beam connection, detailed in Figure 56, shows where the finger tip applies force to the top button, the column that transmits the force from the button through the snap dome to the embossing beam, which engages with the tape and embosses the dot. When sufficient force to emboss the dot is applied, the metal bistable snap dome suddenly collapses and makes a clicking noise alerting the user that the embossing step was successfully completed and the force can be removed.

This side view also shows the green snap hooks as they engage with a lip on the button piece. It also shows the engagement between the the buttons and the lip around the rim of the base
piece as a rough alignment guide. Furthermore, Figure 56 shows how the rollers are slightly raised above the blue embossing anvil to hold the tape up during indexing.

5.2.5 Ratchet

The ratchet, in Figure 57, sits in a groove in the base and is rotated by the tape applying a tangential force to rotate the roller. The intermediate slots across the length of the roller allow the part to be injection molded without sink throughout the thickest sections. Design for manufacturability features like draft are not shown in these images, but will be added once the design is finalized. The ratchet is the only part that is not two part moldable because of the overhangs on the ratchet grooves.

![Symmetric Ratchet Groove](image)

**Figure 57: Ratchet Side and Top View Annotated**

5.2.6 Rollers

The rollers reduce friction between the tape and the avil and align the tape with the tape alignment groove. The groove for the dots creates a cavity for the dots to sit without being

![Tape Alignment Groove](image)

**Figure 58: Rollers Annotated**
pressed flat as the tape comes off the anvil. This part could be designed for injection molding, but in its current configuration it is more efficient to machine it.

5.3 System Integration

Using elastic averaging or kinematic features to achieve precision alignment of parts relative to one another is a theme throughout the design and central to the system integration. Two-part alignment, both rough and fine, of each part was designed to make assembly easier. By providing coarse alignment blind users are able to generally orient the part and then with the application of force to the parts the elastically averaged Lego™ features slightly deform and provide fine alignment of the parts. Originally, only the fine alignment of the Lego™-feature based parts was incorporated, but through user testing of the assembly of the device it was observed that even for parts with non-critical alignment requirements, these features greatly facilitate assembly. These alignment features can also be used as datum features to measure parts to verify dimensions after manufacturing.

Figure 59: Alignment Guides between the Buttons and Beams and Anvil and Base
5.4 Design for Manufacturing

To meet the key affordability specification, design for manufacturing was an essential part of the design process and integrated from the start of the strategy selection and throughout the design and prototyping stages. Often, manufacturability considerations were a make it or break it factor when deciding between features and design implementations. The key criteria for designing for manufacturability (DFM) are eliminating undercuts, draft angles on surfaces, part wall thickness for mold flow and preventing sink during cooling, minimum mold feature requirements, and material selection.

The primary manufacturing process for this braille label maker is single shot injection molding. The parts shown in Section 5.2 are all moldable with this two-part process, validated by interactive quotes provided from Protolabs® [52] and SolidWorks draft analysis, shown in Figure 60. Based on the Protolabs® specifications, vertical faces require a minimum draft of 0.5°, while most surfaces need 2° and shutoff surfaces require 3° of draft. Once the part design is finalized for molding, the required drafts will be added to the surfaces.

![Figure 60: Example SolidWorks Draft Analysis for the Ratchet and Base Parts, Draft of 2°, Green is positive draft, Yellow requires draft and Red is negative draft.](image)

Wall thicknesses are also important for moldability. Designing above the minimum value ensures good flow of the material through the mold, while keeping walls under the max value prevents sink from occurring. All parts meet the recommended thicknesses for all three plastics.
The recommended wall thicknesses for several materials considered are [52]:

<table>
<thead>
<tr>
<th>Material</th>
<th>Recommended Wall Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>1.143mm – 3.556mm</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.762mm – 2.921mm</td>
</tr>
<tr>
<td>Prolyproylene</td>
<td>0.635mm – 3.81mm</td>
</tr>
</tbody>
</table>

The DFM accounted for both the moldability of the part and the machinability of the mold. Maintaining consistent interior corner radii in the mold allows for fewer tool changes during computer numerical control (CNC) machining.

A challenging feature to machine into the mold are the wedge cutting grooves at the bottom of the base part. The smallest cutting diameter at Protolabs™ would nearly eliminate the grooves. An alternative strategy is using a wire electrical discharge machining (EDM) process with a minimum width between the grooves of 0.020", about 0.5 mm, to create the groove geometry in the mold. The addition of an EDM process would add about $1,000 in cost to the mold. A second alternative is to remove the grooves from the mold and instead design for a metal cutting insert to be assembled post-injection molding. Projecting the cost of assembly for an insert, with a heat staking operation to secure the insert as well as manufacturing the insert, it is more cost effective to pay for the upfront fixed cost of using wire EDM in the mold manufacturing.

The fixed cost of molds can be reduced both by designing relatively simple molds and reducing the total number of molds. Integrating multiple components into the same part is both efficient and cost effective. In future designs the button and base pieces that could be connected by a living hinge, eliminating a mold as well as a need for alignment between the two parts. Several parts such as the rollers and the ratchet could be made in a family mold, in which multiple parts are connected to the same runner within a single mold.

Mold quotes from Protolabs™ were requested for all the parts. Molds would be manufactured out of aluminum for small to medium size production runs. The quotes also included cost per part for lot size of 1,000 parts. Mold costs were also discussed with several injection molding manufacturers in India and the per part cost was approximately two times the material cost to include labor and overhead. In India, ABS plastic costs around 80 rupees per kilogram. From these estimates a part cost was calculated for manufacturing in India for comparison with
Protolabs™. The part volume was measured from the SolidWorks models. These estimates for mold and part costs are shown in Table 15. The rollers are not quoted for molding because they were designed to be machined from round stock. Setup and tooling costs for the rollers are not yet quoted.

Table 15: Mold and per part costs for all six parts in the device

<table>
<thead>
<tr>
<th>Part</th>
<th>Mold Cost ($)</th>
<th>Part Cost Protolabs™ ($)</th>
<th>Part Mass [kg]</th>
<th>Part Cost India ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body</td>
<td>$6,655.00</td>
<td>$3.98</td>
<td>0.0479</td>
<td>0.120</td>
</tr>
<tr>
<td>Beams</td>
<td>$3,295.00</td>
<td>$2.40</td>
<td>0.014</td>
<td>0.035</td>
</tr>
<tr>
<td>Buttons</td>
<td>$4,290.00</td>
<td>$2.43</td>
<td>0.0159</td>
<td>0.040</td>
</tr>
<tr>
<td>Anvil</td>
<td>$3,800.00</td>
<td>$2.40</td>
<td>0.0162</td>
<td>0.041</td>
</tr>
<tr>
<td>Ratchet</td>
<td>$5,365.00</td>
<td>$2.31</td>
<td>0.0086</td>
<td>0.022</td>
</tr>
<tr>
<td>Rollers x2</td>
<td>-</td>
<td>-</td>
<td>0.0019</td>
<td>0.010</td>
</tr>
<tr>
<td>Total</td>
<td>$23,405.00</td>
<td>$13.52</td>
<td>0.1045</td>
<td>0.266</td>
</tr>
</tbody>
</table>

It is clear that manufacturing in India would be much less expensive on a per part cost basis. The advantages of working with Protolabs™ is that they have online quotes available and a good reputation for strong customer service and production quality. Quoting the molds and production with Indian manufacturers is an important next step for this device because it reduces the cost of manufacturing parts by more than 50 times comparing the Protolabs™ and Indian total device costs. Table 16 shows an estimate for the cost per device including the fixed mold cost distributed over the number of parts. This shows that for 20,000 devices the per device cost would be $1.52. To estimate the per device cost at medium scale production the fixed and variable costs were summed and divided by the total number of parts.

Table 16: Cost per part estimate at scale

<table>
<thead>
<tr>
<th>Number of Parts</th>
<th>10000</th>
<th>20000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Cost</td>
<td>$23,405.00</td>
<td>$23,405.00</td>
</tr>
<tr>
<td>Parts Cost</td>
<td>$2,664.16</td>
<td>$5,328.33</td>
</tr>
<tr>
<td><strong>Per Device Cost</strong></td>
<td><strong>$2.61</strong></td>
<td><strong>$1.44</strong></td>
</tr>
</tbody>
</table>
6.1 Future Work

Future work for the device broadly encompasses user testing, finessing the design, manufacturing, business plan development, international patents applications, and creating a supply network and partnerships with distributors.

All known changes to the design are completed, such that the device is ready to 3D print two to five devices for testing with users. In depth interviews with a small group of select users will reveal insights that lead to a finessed iteration of the design. Design for manufacturing changes are also added. After this round of design changes, the device will be ready for a first round of aluminum mold production to manufacture twenty to thirty devices for an in-the-field user study.

In this study, the device should be given to braille literate people with blindness for several weeks and data about the ergonomic form factor, lifetime of the components and use cases for the labels should be gathered at several points throughout. Interesting data would include:

- How many labels did they create?
- What did they label? What did they not label? Why not?
- When and where was the device used? At work, school, home or in public places?
- When users first started creating labels with the device how much instruction was necessary to teach them how to use it? What was the most effective form of instruction?
- Did users intuitively hold the device in the correct orientation? Did they consistently hold it in an incorrect orientation?
- Would they rate the buttons as difficult, moderate or easy to press? Would users rate the tape as difficult, moderate, or easy to pull?
- Did users notice and like the haptic feedback mechanisms?
- What complaints did users have at the beginning? After several weeks?
- After using the device for several weeks, how did users grip, emboss and index with the device? Was the use at the end of the study different than at the beginning?
- Was the user journey as presented in the User Journey, Figure 14? How was it different?
- Generally, what feedback did users offer? Are there consistent categories of feedback?

The study should be conducted in both India and the US to compare data for a range of user segments. IRB approval of the study protocol is necessary as well as cultivating partnerships with local organizations to facilitate data gathering and user followups.

A second study on the efficiency of object identification with and without labels would further inform the value proposition of the device. In this study, two boxes of similarly shaped objects, one with labeled objects and the other without labels, would be placed in front of the blind user. The user would first be asked to identify the objects in one of the boxes and then the objects in the other box. Alternating which box was identified first would eliminate bias from information gained in the first round of identification. For each box, the user would be timed and the accuracy of the identification would be recorded. Although not unique to the Braille-It device, quantifying the efficiency and effectiveness of object identification with labels would provide concrete evidence for this thesis’ claim that a braille label maker enables people with blindness to live more independently.

Concurrent to user testing, developing a business plan, marketing and pricing strategy, and distribution network with regional partners would validate the market need for an affordable braille label maker. Obtaining international patents is also important to protect the intellectual property of the device. Ideally, a company with incentives to produce and globally distribute this device would license the technology and actualize the product in the market.
6.2 Conclusion

The goal of the label maker detailed in this thesis is to enable people with blindness to live more independently by facilitating the efficient and effective identification of objects using braille labels. While labels are commonly accepted as a useful tool, current labeling solutions are not widely used because they don’t meet user requirements; in particular, they are expensive and language limiting. This thesis presents the development of an innovative label making tool, from inception through manufacturing, designed to be affordable, precise, personal and usable for all 133 braille languages.

Integrating methods and tools from both deterministic and human-centered design paradigms catalyzed the development of this device, grounded on user centered insights, that met the cost and precision requirements. Time spent with users across India pinpointed the requirements particularly important for users in developing markets, such as the cost and availability of the tape used in the device. The resulting Braille-It labeler shows potential to be faster, cheaper, and more usable than the current state of the art, and highly desirable by braille literate people with blindness in Indian, American and global markets. This label maker is a precise, handheld, language independent, personal braille label maker that enables people with blindness to live more independently.
REFERENCES


[22] “nabindia | National Association for the Blind.”.


Appendix A.1 Dimensions for the CAD Model

"tape-diameter" = 54mm
"tape-ID" = 25mm
"tape-dist.-emboss-plane" = 37mm
"bottom-wall" = 18mm
"dot-bottom-plane" = 0.5mm
"dot-height" = 0.48mm
"beam-thickness" = 3.2mm
"snap-height" = 0.25mm
"button-height" = 10mm
"dot-offset" = 1mm
"top-height" = 2mm
"dot-spacing" = 2.34mm
"beam-length" = 35mm
"beam-angle" = 60deg
"press-pt-length" = 6mm
"dot-diameter" = 1.44mm
"dot-radius" = 0.51mm
"tape-thickness" = 0.15mm
"beam-width" = 12mm
"bcircle-dia" = 97mm
"index-dia" = 19.74mm
"index-vert" = 10mm
"index-horz" = 15mm
"tape-center-offset" = 19mm
"lego-column-radius" = 3mm
"lego-dot-radius" = 4.80mm
"lego-dot-height" = 1.8mm
"lego-pitch" = 8mm
"lego-deg-separation" = 5.2deg
"lego-groove-width" = 4.82mm
"anvil-height" = 3.2mm
"roller-length" = 25mm
"roller-end-length" = 3mm
"roller-end-radius" = 1.5mm
"roller-dia" = 10mm
"roller-free-fit" = 1mm
"roller-roll-fit" = 0.25mm
"tape-width" = 22mm
Appendix A.2 Embossing Force Test

<table>
<thead>
<tr>
<th>Force Applied [g] (+/− 30 grams)</th>
<th>Test</th>
<th>Dot Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>600</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>800</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
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<tr>
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<td>5</td>
</tr>
<tr>
<td>1,100</td>
<td>10</td>
<td>5</td>
</tr>
</tbody>
</table>

Determining the force required to emboss defined braille dots was a key metric for the functional requirements, and an input for the force stack up that the user needs to apply to the button to emboss the dot. The force was applied to the embossing beam, which was then pressed 3M Scotch® Magic™ tape into the anvil. The dots were then evaluated on a qualitative scale of 1 to 5, where 1 is barely existent and 5 is a fully formed dot. The force of deflecting the beam 1mm was measured independently, and roughly equals 150 grams. Thus, the calculated force to fully emboss a braille dot on Scotch® Magic™ tape with the punch and die as designed is approximately 1000 g of force.
Appendix A.3 IRB Oral Consent

An image of the COUHES approved oral consent document used in all user interviews.

Given that this study will be focused on seeking opinions and observations, we are requesting permission to employ a simplified oral consent that will explain the reason for the study, the voluntary nature and the protection of confidentiality, without impeding the discussion format. It is also specifically tailored to use simple language for ease of translation.

The proposed oral consent is as follows:

My name is Hilary Johnson and I am a graduate student at the Massachusetts Institute of Technology working with the Tata Center for Technology and Design. My master’s thesis work focuses on designing a device to enable people who are blind to create their own Braille labels that they can stick on everyday objects.

If you are willing, I would like to speak with you about how you identify everyday objects, ask you to test a prototype device and explore how you might use it. I expect that this will take about a half hour and I will appreciate your insights and feedback, positive or negative. You will not receive any compensation and cannot keep the device.

Please feel free to not answer any questions and I am happy to stop the discussion or testing at any point, participation is completely voluntary. I will take notes and may ask your permission to photograph how you hold or use the device. Your privacy will be respected and I will keep your personal information confidential. If you are willing to give more feedback in the future, I would like to write down your contact information.

The best way to contact me is by my email address hilaryj@mit.edu if you have any questions, comments, or follow-up.