Sharing is Caring: Assistive Technology Designs on Thingiverse

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ABSTRACT
An increasing number of online communities support the open-source sharing of designs that can be built using rapid prototyping to construct physical objects. In this paper, we examine the designs and motivations for assistive technology found on Thingiverse.com, the largest of these communities at the time of this writing. We present results from a survey of all assistive technology that has been posted to Thingiverse since 2008 and a questionnaire distributed to the designers exploring their relationship with assistive technology and the motivation for creating these designs. The majority of these designs are intended to be manufactured on a 3D printer and include assistive devices and modifications for individuals with disabilities, older adults, and medication management. Many of these designs are created by the end-users themselves or on behalf of friends and loved ones. These designers frequently have no formal training or expertise in the creation of assistive technology. This paper discusses trends within this community as well as future opportunities and challenges.

Author Keywords
Assistive technology; design; disability; open-source; personal-scale fabrication; prototyping; 3D printing.

ACM Classification Keywords
K.4.2 [**Computers and Society**]: Social Issues – *assistive technologies for persons with disabilities.*

INTRODUCTION
Personal-scale fabrication tools such as 3D printers can enable the rapid development of low-cost, highly customized physical objects. These features are particularly beneficial to the creation of assistive technologies. An assistive technology (AT) is any item that enables a person with a disability to complete a task that they would otherwise be unable to do. Commercially available AT devices are frequently costly and available in a limited selection. The use of personal-scale fabrication tools to make modifications to existing AT devices and create novel designs is a growing area of interest (Figure 1). This technology affords not only the ability to reduce costs and personalize devices, it can also empower caregivers and end-users of AT to create their own assistive solutions.

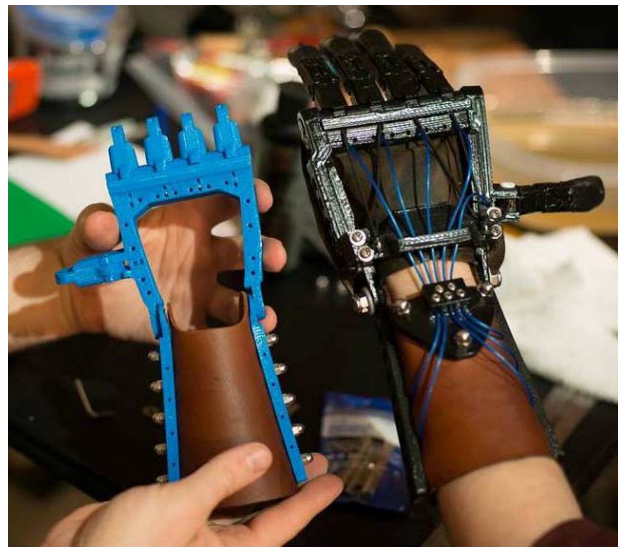

Figure 1. An example of a 3D-printable prosthetic hand, a popular type of assistive technology featured on Thingiverse.com. (Thing # 229620)

Online communities and open-sourced websites have been evolving concurrently with personal-scale manufacturing tools to share models and files. These sites encourage the free and open sharing of 3D-printable designs, allowing for the widespread dissemination of ideas and objects. For this study, we chose to examine Thingiverse.com, a popular open-source design repository and community affiliated with MakerBot, a consumer 3D printer manufacturer. Thingiverse enables anyone to freely download source files

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and registered users can comment on and favorite designs. While Thingiverse supports a variety of file formats that can be used for many types of personal-scale manufacturing (including laser cutting and milling), the majority of the designs are intended for 3D printing.

Our research examines this open design community structure and its impact on do-it-yourself (DIY), or self-designed, assistive devices. This two-part study looks at the existing landscape of AT designs in Thingiverse and looks further into the motivations of these AT designers. We conduct a survey of existing AT designs and present an overview of the variety of AT designs, the disabilities they serve, and the differing complexity involved in fabrication. We explore the motivations, perceptions, and skills of the designers of these items through an online questionnaire. We close with a discussion of the future shape of this community and the challenges posed to technologists to support a successful and more diverse AT-maker landscape.

RELATED WORK

This paper presents a case study of one online community, Thingiverse, and its members' creation and dissemination of assistive technology. The work sits at the intersection of and contributes to the following research areas: assistive technology, personal fabrication of assistive technology, and online maker communities.

Assistive Technology Design and Challenges

For the purposes of this paper, we define *assistive technology* as any piece of technology that is designed to increase, maintain, or improve the functional capabilities of people with disabilities, older adults, or people with chronic health conditions [10]. Adopting this broad definition of accessibility allows us to analyze a range of both mainstream and novel assistive technology designs.

While assistive technology has the potential to improve people's lives, gaining access to the appropriate assistive technology can be difficult. Many traditional assistive technology products are expensive and may not adequately meet a user's unique needs [3,14]. Even if an appropriate, affordable assistive technology exists, a user may choose not to use it due to perceptions of stigma or issues of personal identity [16].

Personal Fabrication of Assistive Technology

Because assistive technology must often be customized to individual needs, "do-it-yourself" is not an unfamiliar practice in this area. In some cases, assistive technology products are designed by the users themselves or by family members. Examples popularized by media include Hugh Herr [1], a biophysicist and engineer whose limb loss in a climbing accident led to his advanced research in leg prostheses and orthoses; and Samuel Farber [4,13], founder of the universally designed household brand OXO[1] who identified the need for accessible kitchenware after observing his wife's struggles with arthritis. More recently, personal fabrication has been popularized through the development and availability of user-friendly, low-cost fabrication tools such as 3D printers [5]. DIY or self-designed AT can address several of the pitfalls of traditional or off-the-shelf AT. Devices and modifications can be tailor-made in a way that is often unavailable or pricey for standard AT fittings, end-user involvement can increase buy-in and reduce user abandonment, and some DIY solutions can be made with inexpensive materials that are equal or near equal in robustness to their costly, commercial counterparts.

The potential for personal fabrication to revolutionize assistive technology has been highlighted by several high-profile projects, such as the Open Prosthetics Project[2] and e-NABLE[3]. Despite this potential, few studies have examined the use of modern personal fabrication technologies, such as 3D printers, for creating assistive devices. Hurst and Tobias [9] explored motivations for creating DIY assistive technology. Buehler et al. [2] examined how organizations that served people with disabilities used personal fabrication tools such as 3D printers. Hook et al. [7] have also begun exploring the role of 3D printing as a means to DIY assistive technologies, in particular looking at children with disabilities as designers [6]. Our investigation presents a systematic evaluation of assistive technology creation and dissemination in an online community of assistive technology makers on Thingiverse.

Communities Supporting Making and Fabrication

Many online and local communities have formed around maker practices. In some cases, these communities form "maker spaces" to pool resources and gain access to more expensive equipment [5]. These communities also provide feedback and support for designers and makers. Maker spaces may exist both in the physical world and online. Tanenbaum et al. [17] and Lindtner et al. [12] have studied maker spaces and the interactions around them. Tseng and Resnick [19] studied the design, documentation, and use of designs in the Instructables community and Rosner et al. [15] examined online interactions involving the sharing of design instructions for various DIY projects in the IKEA hacking community. Kuznetsov and Palos [11] conducted a study of six DIY/maker communities (Instructables, Dorkbot, Adafruit, Ravelry, Craftster, and Etsy) and identified structures in the communities that promote sharing, creativity, and independent skill building. Our study is among the first to study an online community with a focus on the creation of assistive technology.

[1] http://www.oxo.com/AboutOXO.aspx

[2] http://openprosthetics.org/

[3] http://enablingthefuture.org/

There are a multitude of fabrication, design, and assistive-technology communities online. In searching for assistive creations in fabrication communities, we identified certain structures, such as design repositories, tutorial sites, and member-focused or forum formats. We also saw open-source and purchase-format design-sharing sites. In tutorial and forum-based communities, we were able to find sites specific to assistive technology and/or personal ability.

We studied the Thingiverse community because it is currently the largest open-source repository, with over 100,000 user-submitted designs for 3D printed, laser cut, or milled objects[4]. Its size and popularity make it a useful lens to investigate the degree to which AT is supported in the mainstream maker movement. It also includes a customizer tool that allows users to "remix," or edit, a previously posted design to improve upon or personalize them, and then share those modifications.

SURVEY OF ASSISTIVE TECHNOLOGY CURRENTLY AVAILABLE ON THINGIVERSE

We completed a survey of existing AT designs shared on Thingiverse. This included manually finding and strictly classifying AT designs. Below, we present our methods of searching and sorting designs to create this dataset.

Search Terms and Procedures

We collaboratively derived a set of key terms related to assistive technology and healthcare needs (Table 1) that included field-specific terms from the literature and colloquial terms to surface as many relevant designs as possible. We then queried the Thingiverse search engine with each term using a desktop browser. Multi-word searches were placed within quotation marks to obtain exact string matches.

We refined our key term list after preliminary searches to ensure coverage. We then added any terms that we did not initially include, but appeared in design descriptions or comments (e.g., "handicap"). Our final list included 173 terms, with 115 yielding appropriate results and 58 yielding none. Search terms not yielding results included "hearing impaired," "motor impairment," "cognitive disability," "paraplegic," "quadriplegic," "Parkinson's," and "Alzheimer's" despite there being numerous designs that might be described by these keywords.

We manually evaluated our search results, totaling over 25,000 "things," for relevance and created a master list of AT designs. For each design, we gathered the "thing" number (a unique ID given to designs on Thingiverse.com), title, designer handle, and the number of likes, makes, and remixes (Figure 3). We categorized each list item according to a set of formal inclusion criteria (Figure 2).

[4] MakerBot, host of Thingiverse, claims it passed the 100,000 mark on June 8, 2013.

Keyword	Frequency
pill (58), pill box (18), pillbox (14)	90
prosthetic (44), prosthesis (17)	61
disabled (14), disability (12), disabilities (10), impaired (1), impair (1), handicapped (3), handicap (1)	42
visual (25), visually impaired (7), visual impairment (1)	33
enable	25
tactile (19), tactile graphic (3)	22
assistive device (11), assistive (9), assistive technology (2)	22
Braille	18
grip	18
wheelchair	17
access (11), accessibility (6)	17
amputee	15
medicine	12
elderly (4), old (3), senior (3), aged (1)	11
cane	10

Table 1. Top 15 keywords that appeared in the complete set of 3D models identified as assistive designs.

IC 1. *Traditional assistive technology products currently available as products or made by therapists:* tools for activities of daily living or math manipulatives for people with cognitive disabilities (6% of designs).

IC 2. *Accessible media:* including tactile graphics with Braille that modeled DNA, atoms, or buildings (11%).

IC 3. *Accessories for assistive devices:* aesthetic toppers for canes, power wheelchair joysticks, or game controller joysticks for people with physical disabilities (8%).

IC 4. *Concept designs and prototypes for assistive technologies:* creative solutions to accessibility challenges or needs that aren't currently addressed by existing products, such as a visionary design of a non-surgical cochlear implant for the profoundly deaf or severely hard of hearing, or a heat-based display (4%).

IC 5. *Prosthetic limbs:* prosthetic hands, fingers, or partial fingers for amputees (17%).

IC 6. *Tools for medication management:* pill-cutting guides or containers for sugar cubes for older adults and people with diabetes (36%).

IC 7. *Other design explicitly intended for disabled or senior users:* spinner rings for people with ADHD (18%).

Figure 2. Example designs from our inclusion criteria (IC). IC 1) Right angle spoon for people with limited dexterity. IC 2) Tactile graphic of Yankee stadium. IC 3) Wheelchair mounted environment controller. IC 4) Prototype to convert images to heat for people with vision impairment. IC 5) Prosthetic hand for users with a functional thumb. IC 6) Pill bottle lid with daily reminder label. IC 7) Ironing guide for individuals with vision impairments.

We categorized the first 100 items collaboratively and the remaining independently. If categorization for an item was unclear, it was discussed with the group. We achieved agreement, often by removing items whose descriptions did not explicitly indicate intended use by people with disabilities or the aging population. The final list contained 363 unique designs uploaded by 273 designers.

Limitations

Despite efforts to cast a wide net, there are limitations to our search approach. We did not conduct an exhaustive search of all Thingiverse designs, but instead chose to search based on a key term criteria. There were also limitations to the website itself, including a search result bug limiting us to viewing only the first 1,032 results of a search regardless of the number of hits. Additionally, the Thingiverse search feature does not include the text found in comments, which might have provided us with more context clues about which designs were intended for assistive use. With any user-generated content, there is the possibility of missed search results due to vague, misspelled, or missing descriptions and keyword tagging by the contributors themselves. Some objects that are assistive tools, like a toothpaste tube key, were excluded from our list because they fell on the edge of our inclusion criteria (thing 35064).

Statistics About Designs

Our search process identified a variety of designs to solve accessibility challenges (Figure 2). The category with the most designs was IC 6, tools for medication management, which had 130 things of the total 363 and was dominated by pill boxes, bottles, dispensers and accessories like tops and dividers (107 things). The category with the second most designs was IC 5, "prosthetic limbs," which had 61 things and was dominated by prosthetic hands, hooks, and related parts (41 things).

The majority of designs either mimicked or replaced devices that are already available on the commercial market, such as splints, tactile graphics, prosthetics, and pillboxes. Many of these came at lower cost (e.g., prosthetic prints run in the hundreds of dollars instead of in the thousands). But for other items, cost savings are not so clear (e.g., pill boxes, which can cost less than \$10 on the commercial market).

Many items were highly specialized, thus not commercially available, enabling people to have more control over inaccessible environments or inadequate medical care. For example, one designer created an adapter to fit their child's preferred Vortex inhaler mask to an incompatible PARI JuniorBoy SX compressor (thing 237169). At least one item was designed because its commercial vendor had gone out of business and was no longer available to consumers (Trautman Hook, things 2194 and 2114).

As we discuss in greater detail in following sections, the value of creating these designs extended beyond the utility of the thing itself. For example, on design profiles, we found that some designers expressed enjoyment in the process of invention (e.g., "I love to invent," thing 324072) or pride in who made the item (e.g., "Designed by two dyslexic students. :) :)", thing 186338).

In Figure 3, we highlight several designs with high numbers of likes, makes, and remixes. While these metrics are not an explicit statement of the popularity of an item, it is one way to discern if a design is receiving attention within the Thingiverse community. Prostheses dominated our list in terms of likes, with four (things 261462, 242639, 92937, and 380665) of the top five most liked AT designs being variations on prosthetic hands, but made up less than 17% of the total AT designs. Despite being relatively complex prints, the prosthetic hands were also printed several times as indicated by their high number of makes.

Figure 3. Overview of the top 5 items with respect to likes (top row), makes (middle row), and remixes (bottom row) among the 363 AT designs identified. Likes accrue when account holders click the "Like" button on a design profile. Makes accrue when an account holder clicks the "I made one" button on the design profile to indicate having made a copy. Remixes accrue when account holders click the "Remix it" button on a design profile. This figure illustrates the popularity of prosthetic hands and pillboxes in our dataset. All counts are publicly viewable on Thingiverse.com and were gathered August 2014.

This perceived popularity may be due in part to media coverage of open-sourced prosthetics resources.

Designs like the spinning ring fidget (thing 188275) and the pill boxes (things 201304 and 273754) also received a high number of makes, which might be linked to their universal appeal as everyday items (i.e., the fidget is intended for sensory or attention issues and pill boxes are for medication, but both items can be used by anyone for other reasons). The most remixed item, a model of an atom with tactile information on the surface (thing 114247) includes an accessible version with Braille labels, but it may be among the most remixes and makes due its versatility as an instructional aid (i.e., the design offers the ability to print a model of any atomic element with the correct information about each already programmed into the remix options).

Publically Available Designer Information

We surveyed the publically available information about the designers in order to understand more about them. Of the 363 models that matched our inclusion criteria, 273 were created by unique designers. According to each designer's profile, 258 of these designers are individuals, and 15 belong to groups or organizations. Most designers (215), only uploaded a single design, 33 designers uploaded 2, and the most active designer uploaded 13. Of the 166 designers who disclosed their location in their profile, 93 were in the United States.

To help users manage objects they find interesting, Thingiverse allows users to create collections on their profiles. A collection is a group of related models either created by the owner of the profile or by other designers. 104 designers had a collection of models that met our inclusion criteria as assistive technology. While this survey was helpful, we had many remaining questions about designers that we investigated with a questionnaire.

Construction Requirements

We observed a diverse range of construction requirements for items in our dataset in terms of the amount of assembly required prior to use, what tools were used to manufacture the part, and whether or not the object required extra parts (i.e. string, bolts, or rubber bands). 98% of all items in our dataset were designed to be 3D printed, 30% do not require any assembly prior to use, and almost 28% require assembly and additional parts (Table 2).

Construction requirements are an important consideration for adoption as these can impact the cost, difficulty, and time required to build the technology. For example, single-part designs are likely faster and less expensive to produce than designs consisting of multiple parts, and can be manufactured using only one machine. Single part designs are also attractive, as they only require the end user to control the fabrication machine, increasing the likelihood that those with limited abilities will engage in making AT.

While designs that require assembly and additional parts may be more technically complex, the effort and materials required for assembly may deter some individuals from attempting to make them. For example, many of the prosthetic hands require significant assembly and specific external parts that may reduce the likelihood that the target user would undertake this project. However, the fact that a bottle opener only requires a single part to be manufactured and that it is "ready to go" after printing increases the chance that an end user would make it (Figure 4).

No assembly required	One 3D printed part	29.8%
	One laser cut part	0.3%
Some assembly required	Multiple 3D printed parts	40.5%
	Multiple laser cut parts	1.3%
	Multiple 3D printed and laser cut parts	0.3%
Some assembly required and extra parts	3D printed parts	27.5%
	Laser cut parts	0.3%
	3D printed and laser cut parts	0.0%

Table 2. Summary of assistive technology items currently on Thingiverse broken down by construction requirements.

Figure 4. Example items with different construction requirements: 1) knife assistant for limited dexterity (no assembly required); 2) a wearable pill box (some assembly); and 3) cup holder (assembly and extra parts).

QUESTIONNAIRE TO UNDERSTAND WHY PEOPLE DESIGN ASSISTIVE TECHNOLOGY

While the Thingiverse website encourages designers to include stories about the objects, we could not find much information about the motivations for designing these objects. In order to gain a deeper understanding of why these objects were being designed, we invited these designers to complete an online questionnaire. We contacted all 273 designers to participate in our questionnaire and received 70 responses (25.6% response rate) over a two-week period. Participants were added to a raffle for a $100 gift card as compensation for their efforts. The questionnaire took approximately 15 minutes to complete and contained both closed and open-ended questions. Respondents were asked to provide demographic information and to describe the motivation, process, tools, and outcomes of their designs.

Self-reported Designer Demographics

We asked designers for more details about themselves, including information about any disabilities they might have (Table 3), age, occupation, and experiences with 3D modeling and assistive technologies.

Over 48% of designers had a career in a STEM (Science, Technology, Engineering, and Mathematics) field, including engineers, programmers, and information technology specialists. Fewer than 13% reported health care occupations, such as neurologist or dentist. Students made up approximately 14% of the respondents, and less than 3% of respondents indicated 3D printing expertise as their career. The remaining 14% included a wide range of careers, such as an artist, a realtor, business professionals, and teachers.

The designers reported ages between 18 and 71 with the mean age 37 and 18.8% being over the age of 50. The majority of designers (>76%) reported that they had no disability. The top three reported personal uses for AT were medication management, physical or motor impairments, and learning disabilities (all fewer than 1% of our sample).

Design and Printing Process

To better understand the history and use of these models, we asked about the process of designing and printing their objects. We found the majority of users (59%) reported that it took a day or less to create and finalize their designs. Most respondents reported building their designs on a personal 3D printer, as opposed to in an office or at a public maker space. All but 9 designs were successfully printed at least once, 46 were printed more than once, and none of them were printed more than 5 times. Of the designs that weren't printed, all respondents reported that they did not have access to a 3D printer. Several users indicated that their design was novel, in part or in whole. Often users had submitted designs that closely resembled other designs on Thingiverse or objects outside of Thingiverse such as in an AT catalog. In most cases, we could not discern if users were unaware of the existence of the other objects or if they merely perceived their own design to be truly unique.

Motivation for Designs

In order to understand the motivation for designing these objects, we asked questions about why and for whom designs were created. These open-ended question asked respondents to describe the motivation behind their designs in their own words.

We analyzed these responses using open coding with six categories. To further differentiate between these motivation categories we provide brief descriptions of each, along with a quote from one of the respondents.

	Target User	Designer
Allergies	1	0
Cognitive	7	1
Coma	1	0
Dexterity	15	1
Elderly	11	2
Learning	2	2
Medication Users	14	6
Physical / motor	23	5
Reading	0	1
Sensory	6	0
Temporary injury	3	1
Visual	11	1
None	**9**	**53**
Declined to Answer	**8**	**4**
Multiple Answers	**42**	**8**

Table 3. Self-reported respondent and target-user abilities.

I Made This for Myself

"I have tendonitis and ulnar nerve damage (repetitive stress injury) and was curious if I could improve the ergonomics of my Magic Trackpad by changing its angle similar to how 'vertical' mice help traditional mouse users with similar wrist/hand problems."

The ability to self-design assistive technology is highly empowering. Our questionnaire found that 13 designers created AT designs for their own use. This is particularly significant when considering the high rate of user abandonment in AT, which may be reduced if the end-user has a direct role in the design and creation of their AT [9]. While we were encouraged to see some self-designers, this was not as common as we had hoped. Increasing the number of self-designers might be accomplished in the future by increasing awareness of making assistive technology or by providing more accessible software and hardware tools for the creation of these designs [8].

I Made This for Someone I Know

"My aunt came to me for help, because she was having difficulty moving my uncle around whenever he had mini seizures. Since he had a walker anyway, she needed a way to push him around when he can't help himself."

Making an object for someone the respondent knew was the most common response with 24 designers indicating that they created AT designs for friends, family members, and other acquaintances. This included designs for aging parents, partners with disabilities, and children. Given the range of disabilities reported, it is difficult to say with confidence why more disabled users were not self-designing. Possible reasons could be the perceived difficulty of 3D modeling and fabrication, leading end-users to approach friends or family members with existing engineering or computer skills. Depending on ability, end-users may not have accessible design tools to create designs, but we did not fully explore this in our questions.

A close relationship with the end-user enables these designers to have a discourse. The designers would, in theory, be familiar with the user, task and environment. These are key factors in creating a positive user experience. A dialogue with the intended user has the potential to design for the individualized needs of specific disabilities. Ways to promote this dialogue could include community efforts to pair designers with end-users or finding ways to support this connection through the design sharing web sites more implicitly.

This Was a Personal Challenge

"I want to create useful objects. This bracelet I've designed, can contain medications, a note with dangerous allergens, or emergency phone numbers for elderly ill people."

13 respondents reported their motivation to create the design as wanting a personal challenge. They described wanting either a test of their ability as a 3D designer or they simply identified what they perceived as a need and created an object to fill that need. These respondents likely did not talk to anyone with the disability they were attempting to address, and had to guess preferences. This begs the question, should these types of AT designs be encouraged and/or dispersed? With little or no AT training and no contact with the end-users, it is difficult to say what if any value these items have to the disability community at large.

This Was Required for a Class or Competition

"I created this design for an undergraduate course I was taking in engineering design. The concept was to create a pillbox that could keep track of medication usage throughout a week (or weeks)."

Only five respondents indicated that they created and uploaded their designs as part of a contest or as required by a classroom assignment. The pitfalls of the previous category apply here, as well. As with the designers creating items for others, for these projects to have any impact it might be more appropriate to pair contestants and students with individuals with disabilities or related support organizations. In this way, students and contestants can still tackle interesting design challenges, while bolstering the applied outcome of their projects. This might improve designs and increases visibility for accessibility issues.

This Was Part of a Research Project

"I did my Masters thesis designing and printing objects for two children with blindness to help them in school and see if having a 3D printer in school is a good resource."

Only six respondents indicated that they participated in research and/or development as their occupation and that this was the motivating factor in the creation of their design. Open source sites like Thingiverse present an excellent opportunity to the academic and research community to share their work, as these respondents have. We hope to see more research labs creating and open-sourcing their designs in the future to help spread awareness of the possibilities of building AT and to advance these designs with end-user input.

This Isn't Intended for a Disability

"Creating adapters to join different products that fulfill the same use, but utilize proprietary measures."

Despite keywords, descriptions, and our inclusion criteria, eight respondents indicated that they did not perceive their design as targeted to a person with a disability. Examples of this perception included the appropriation of pillboxes as anything-goes storage containers or understating a dexterity aid as simply "useful". These examples are an interesting mix of universal design issues and "Accidentally AT" objects, a concept we describe in the next section. This may be indicative of an issue of the visibility of disabilities in the maker community at large.

DISCUSSION AND FUTURE CHALLENGES

In this section we extrapolate from our findings and contemplate the deeper meanings and future exploration of open-sourced AT designs.

Diversifying the Designer Population

More than half of our respondents reported that they had no formal training in 3D modeling and personal fabrication tools. Given that the current wave of these tools, especially 3D printers, are targeted to novice users, this finding did not surprise us. Several respondents described themselves as self-taught, learning techniques such as 3D modeling by watching videos on youtube.com and experimenting with open-source design tools. While this finding suggests these activities are not just for professionals, we observed that the average designer has a technical background.

The majority of respondents were members of the STEM and health care community, with fewer than 36% reporting occupations outside of hard science or technology fields. While many of these designers claimed no previous experience with modeling tools, it is important to recognize that 3D modeling, 3D printing, and personal fabrication have roots in engineering and that the formal skills of an engineer may supplement their informal use of these tools. This might indicate a need to encourage a wider variety of people with differing skills to utilize rapid prototyping.

Out of a group of 69 designers creating assistive designs, more than 76% of the designers reported that they had no disability themselves and less than 1% had any formal training in assistive technologies. While this might be alarming for a trained accessible technologist, we consider it an opportunity. There is clearly room to extend more support to alternative users, both in creating accessible tools and helping to democratize this technology for a more heterogeneous group of end-users.

As we discussed earlier, the ability to create customized and inexpensive assistive devices is a tremendous benefit to persons with disabilities, yet judging from the distribution of designers in our study, this group is not completely represented in the current make-up of 3D designers and makers. This is not to say that the engineers and technologists lending their skills to the AT cause are unwelcome. Instead, we pose the question, how do we diversify these designers and create more opportunities for designers with disabilities to self-design and become further incorporated into the making movement? Does this call for changes to fabrication tools or design repositories or both?

Actionable steps to support this goal might include simplifying tools, creating alternative design interfaces, or providing a new delivery system for tutorial information. Technologists should consider the abilities and goals of these potential AT-makers and work with them to uncover best practices for fabrication tool design.

Finding Assistive Technology On Thingiverse

Accidentally Assistive Technology

In classifying items using our inclusion criteria by assistive technology type or target user ability, we created the "Accidentally AT" subcategory. These had incidental keywords or were not perceived or intended as assistive objects by their designers. An example of an item in this category was a handle for soda cans, which enables a user with limited hand mobility or dexterity to grasp a cylindrical cup. The design description contains no language or keywords related to disability or being an assistive device. The reason we found this object was because our search term "old" was a substring within the word "holder". Nothing about the description indicates that this is an assistive device, but drinking aids are a very common tool used by persons with motor or dexterity impairments. Conversely, there is a similar cup-holding Thingiverse design with explicit disability keywords such as "tremor" and "handicap".

We saw multiple examples of objects in this category with information that would assist an individual with a visual impairment, however these were not designed with this audience in mind. For example, we found a special gaming die with custom tactile markers for eyes-free verification of a role.

From our analysis, the language used to describe objects is important. We feel these examples beg the larger question of whether or not items on Thingiverse should be tagged in a consistent way to indicate they are intended as or have been used as an assistive technology. Is this simply a matter of visibility or can a greater argument be made for universal design? A keyword from the non-AT cup holder was "useful", perhaps indicating support for more inclusive designs benefiting a range of end-user populations. There is a unique balance between highly personalized and universally useful AT design. A prosthetic limb may require careful customization to be both useful and comfortable for the wearer; meanwhile, a cup holder need only be scaled to fit the right beverage and/or hand size to be used by a variety of people. In both cases the base design can be shared, modified, and recreated to benefit others. Labeling one as assistive and the other as useful could be seen as arbitrary or even exclusionary. This is a sensitive subject as there may be negative stigma attached to tagging items as assistive technologies.

How Are Models Different from Tactile Graphics?

In deciding how to define and categorize assistive designs, we struggled to define what constituted a tactile graphic. There exist official guidelines for when and why to provide a tactile graphic [18], but in this domain, there is no clear distinction between a tactile graphic and any other 3D model. For example, is a model of the Sphinx a tactile graphic or "just" a model? If a model of a famous monument is a tactile graphic, then is a 3D bust of a stranger also a tactile graphic? With these questions in mind, we opted to exclude many 3D models that could have been considered tactile graphics using our inclusion criteria. Without printing and testing each item, we had no way to confirm what information could be conveyed by these designs in tactile form, and thus excluded models that did not explicitly state that they were for a population with a disability (such as a visual impairment or a learning disability that benefits from tangible interactions).

Filtering Spam Generated by Thingiverse's Customizer

The Thingiverse tool Customizer offers designers the ability to quickly and easily modify an existing design. By providing modifiable parameters with an existing design, any Thingiverse user can create a customized ("remixed") design with a few clicks. While helpful for customization, this tool generated a lot of duplicate objects creating a "spam" effect. Users frequently made indistinguishable duplicates of objects from Customizer. For example, we found over 100 pillbox designs that are almost all remixes of one or two basic seven-day pillboxes. These identical objects were created by users who made a copy of the original design and then saved their copied creation without making any changes. Only a handful of users made significant modifications to these designs. We still included pillbox designs in our findings, as they are a form of medication management, but it is important to note how this scenario can create remix bloating.

Another trend we felt added noise to the AT collection was adding Braille to objects without any apparent discretion. The Customizer allows designers to engrave or emboss text onto designs from a selection of fonts, including a Braille font. This generated several objects with Braille added seemingly at random with no particular benefit to a visually impaired end-user. One example was a bracelet with Braille text around the outside. While this may have value as a means to express oneself in Braille, it is unclear how this would be considered as an assistive technology. This complements our earlier finding that the vast majority of AT designers in this space had little or no training in assistive technology.

The Customizer offers valuable modification features, but it can create noise that overwhelms search results. This spam may frustrate users and prevent the discovery of beneficial designs and design modifications. As the Thingiverse community continues to grow, it is important to consider the impact of this tool to ensure quality designs that are easy for end-users to find. Technologists could consider this a special case search, in which searching fabrication designs for a subset of assistive designs may differ from other search behaviors or repository structures.

Measuring the Impact of Designs On Thingiverse

We feel the presence of these AT designs on Thingiverse speaks to a potential for more empowered end-users self-designing assistive solutions, there are also questions to be asked about the visibility and perception of making AT. With over 100,000 designs on Thingiverse, the 363 designs we identified make up less than 0.004% of the total designs available for download. Within our AT design set, there are several items that go unsung while others receive phenomenal attention. One of the more advanced prosthetic hand designs was prominently featured by the Thingiverse site during our initial design audit. It garnered hundreds of likes and over a dozen reported makes. Other items, such as exaggerated bottle openers to help persons with limited dexterity, may only have a handful of likes and no makes. This is especially interesting when considering the complexity of the prosthetics (multiple prints and external hardware) when contrasted against a bottle opener designed for users with limited dexterity (single print ready without modification or additional hardware) that can be printed in a short window of time and can be adopted for a variety of persons and abilities.

While the measures we describe give us a sense of the popularity of these designs with Thingiverse members, we are unable to measure the ultimate impact these AT designs had for their target users. Thingiverse supports comments on designs, but there were no end-user testimonials rating or discussing the designs.

Without this information, it is unclear if these designs made any significant or lasting impact. We feel testimonials and user experiences with these designs is crucial to further cultivate a community resource for assistive technologies, as this feedback will likely encourage users to try this technology.

CONCLUSION

In this study, we explored the existing community of assistive technology designers within Thingiverse.com. We found several AT-related designs spanning a range of ability and that the majority of the AT designers do not themselves have disabilities, nor do they have any training in assistive technology. We discussed strategies for diversifying the designer population and identified areas where open source AT on Thingiverse might be improved. We also discussed the current and potential impact of designing AT objects and sharing their designs freely online. Our suggestions included creating more communication between existing designers and the community of users with disabilities, promoting more visibility of AT designs with appropriate keywords and features for open-sourced sites, and the creation of accessible tools for users with disabilities to self-design assistive solutions. We believe there is a future in open-sourced designs to become a valuable source of solutions to persons with disabilities. We hope the technology community provides more access and support to persons with disabilities and to see this community grow.

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