CustomizAR: Facilitating Interactive Exploration and Measurement of Adaptive 3D Designs

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ABSTRACT

Online 3D model repositories such as Thingiverse offer millions of open source designs that are shared for reuse and remix. Many of the designs are customizable to adapt to real-world objects upon personal needs of varying tasks and physical dimensions. However, it is challenging for novices to discover such designs using text-based search queries, comprehend what each parameter means for customization, locate these parameters on the target objects for measurement, and conduct measurements correctly. These challenges may cause the designs to be incorrectly adjusted, thus failing to function as expected and requiring users to start over, which costs additional time and material. We present *CustomizAR*, a pipeline for facilitating the interactive exploration of adaptive designs and the measurement of real-world constraints to fabricate them correctly. CustomizAR supports the search and discovery of adaptive 3D designs using an object-centric graph-based data structure, and guides users through an interactive measurement process leveraging computer vision techniques. Our technical evaluations and user studies demonstrate that CustomizAR facilitates effective discovery, adjustment, and reuse of adaptive designs that are shared online.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

3D printing, adaptive fabrication, personal fabrication, customizer, parametric modeling, customizable design, computer vision

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1 INTRODUCTION

Personal Fabrication has gained increasing interest among a wide audience over the past few decades because of its unique capability for creating highly-custom objects [17]. To date, personal 3D printers have become more accessible and affordable, and the growth of online 3D model repositories made millions of 3D models available for novices with only a few clicks, reducing the workload of creating new designs from scratch. While some 3D designs can be printed directly without any modification, many require additional refinement to function properly, especially those that interact with real-world objects. As being called *adaptive designs* in this paper, some examples are showcased in Figure 1. In many cases, these designs require measurement of target real-world objects to be correctly customized and properly function. For example, the radius of a 3D-printable mug handle needs to be adjusted to fit mugs of various sizes. Many of these adaptive designs are made following the *parametric design* paradigm, which refers to designs that are intended for variable modification that can change the shape and/or dimension accordingly. Existing tools that support *parametric designs*, including Thingiverse Customizer[1], Fusion360[2], and CraftML [30], allow customization of the original designs to meet individuals' varying design requirements. For example, one of the most popular parametric 3D design tools is Thingiverse Customizer (Figure 2), which is built upon the script-based modeling tool named OpenSCAD.[3] It provides a graphical user interface to facilitate easy adjustment of parameter values and result preview.

However, it remains challenging for novices to discover possible adaptation options from repositories, identify what needs to be measured to modify designs and how to measure them correctly, and digitize the measured values into the corresponding variables [13]. Specifically, (1) the current practice of text-based search interface lacks adaptation-related information that is crucial to explore and discover various adaptation options for the target real-world object. Without sufficient domain knowledge, one might start exploring relevant designs using the target object's name or relevant keywords as the search keyword, and reviewing all possible results from the top hits, which could contain duplicates or irrelevant designs. Next, (2) users may not comprehend what parameters are critical or necessary to change for the intended customization as well as how they impact the design when changed. This includes obscure user experience of comprehending what designer-provided parameters mean in the original design. Furthermore, (3) users often do not

[1]https://www.thingiverse.com/app:22
[2]https://www.autodesk.com/products/fusion-360/overview
[3]https://www.openscad.org/

Figure 1: Examples of adaptive designs on Thingiverse. Many adaptive designs that augment real-world objects are parametric, enabling customization to meet varying needs. For example, a can handle can fit a 16oz or be modified to fit a taller 20oz can.

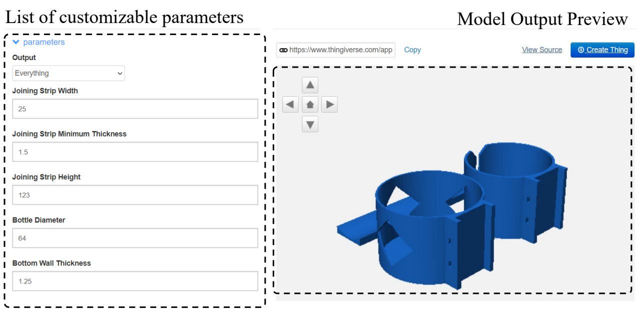

Figure 2: Thingiverse Customizer consists of parametric value inputs and the preview of rendered 3D model

apply the right techniques to measure these parameters correctly and convert them to the required variables in the digital design space [13]. These could result in failed prints and cost additional time and printing materials.

We present CustomizAR, an interactive pipeline that aims to provide an end-to-end solution to support the discovery, measurement, and customization of 3D printable adaptive designs. CustomizAR assists novices to discover adaptive designs among millions of designs available in the Thingiverse repository, and guides

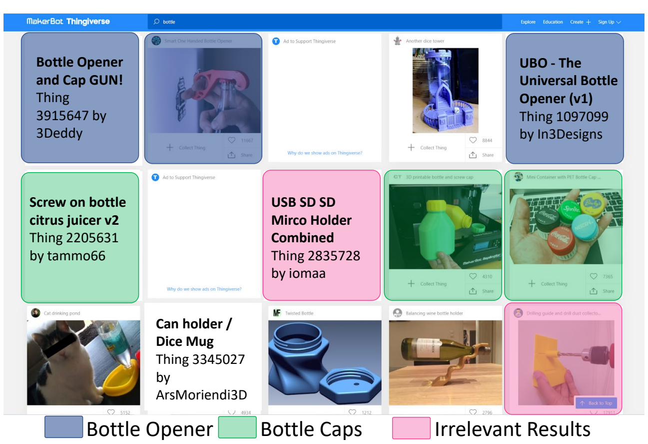

Figure 3: Example Thingiverse search result from *'bottle.'* It returns designs with redundant or irrelevant adaptations. Some images are excluded due to non-commercial license.

them through the customization process of locating parameters, performing measurement, and transferring physical dimensions to the digital design directly, and finally generating a ready-to-print 3D model accordingly. Built upon an organized and connected database of design metadata, CustomizAR automatically determines an associated target object and adaptation type from existing 3D designs, and navigates through the graph-based structure to model adaptation-critical information and the connection that describes relationships among possible target objects, adaptation types, and 3D designs. This structure is then used to support object-centric searching. The front-end mobile application of CustomizAR utilizes the native sensors of modern smartphones to firstly recognize the target object, then overlay auto-detected measurement results of a target object in the camera view. CustomizAR connects the virtual measurements to the physical objects by visualizing results for users to verify and modify if needed, then adjusting the original design file accordingly to generate a new 3D design that is customized based on the users' captured specification.

Through a technical evaluation, we demonstrate that CustomizAR effectively retrieves adaptation information and parameters that require measurement from existing metadata in Thingiverse. We also showcase that CustomizAR supports customization of a diverse set of daily objects. In a user study with 12 participants, we demonstrate that CustomizAR assists novices to effectively discover adaptive designs and reduce the measurement errors compared to the current practice of manual measurement, while identifying limitations and future work which includes adaptation information retrieval, supporting more complex measurement, and additional control and freedom of exploration.

2 RELATED WORK

2.1 Adaptive Designs and Design Remix

Adaptive designs are 3D designs that are created to augment or extend the functionality of existing real-world objects[4], such as the examples shown in Figure 1. These designs have become one popular type of design on Thingiverse. With the help of parametric modeling tools, original models can be customized so that it fits similar target object as in the original design, but with different sizes. This feature was incorporated into Thingiverse in 2013, which has been known to greatly attract users' interests, as the contributing

[4]We will refer to real-world objects that interact with 3D printed adaptive designs as 'target objects' throughout this paper.

authors on Thingiverse increased by almost 600% one year after the introduction of the Customizer feature on Thingiverse [22].

The dramatic growth of 3D printing repositories that are accessible to individuals also attracts the interests of the HCI community, as *Personal Fabrication* has become a popular subfield. Researchers have investigated personal fabrication from various directions including software, hardware, data science, and how the users interact with the existing fabrication systems [2, 6, 18, 28]. Augmented Fabrication specifically focuses on the work which takes place when the design references the existing objects in real life [3]. The study of such augmented (or adaptive) designs and the process is particularly interesting not only because of its interactive nature, but also the direct interaction with the target physical object (*ad rem*) and the object's original context (*in situ*) [19, 29].

With the growth of the maker movement [7], designers and users on Thingiverse also demonstrated this culture by making, remixing, and sharing designs on Thingiverse [22]. The introduction of the Thingiverse Customizer makes this process even more convenient, where the customizable designs, together with the designs generated from these customizable designs, contributed over 45% of all designs on Thingiverse as of 2014 [22]. However, the rapid growth of remixed design from customization did not well contribute to the community and other remix activities, as most of these designs ended up being the 'dead end', with limited user activities based on those designs, which shows a great need to not merely contribute additional customized designs as individual documents, but also to understand both these parametric models and the target reference models of these designs [22]. All these demonstrate the great demand for a pipeline that is based on sufficient understanding of designs metadata in order to facilitate the effective organization and reuse of designs in 3D printing repositories.

2.2 Interactive Systems to Support Novices in Digital Fabrication

Prior literature has proposed various techniques to assist novice users in the fabrication process. Some work aims to understand user intention from given input, and generate adaptive designs accordingly. For example, Reprise generates 3D printable adaptations for the target object based on users' high level intentions (such as the desired types of actions and adaptations) and adjusts certain parameters of the generated designs with sliders [6]. Makers' Marks demonstrates the potential of applying computer vision techniques to understand users' intentions and to locate and approximate users' design requirements [24]. It utilizes annotations with image markers and a sculpted object to help users demonstrate their intentions without requiring professional modeling skills or knowledge. The sculpted object is then scanned, processed, and transformed into a 3D model with functional artifacts that are ready to print. These work inspired us to create a pipeline that could utilize user inputs as well as device inputs (e.g., on-device camera and sensors) to understand user intentions and retrieve 3D information of the target object in order to locate and measure parameters automatically. Instead of trying to reconstruct or generate a new design, CustomizAR primarily focuses on utilizing existing designs in public repositories, which contain a wide range of designs that could be directly customized and reused by novices in daily use cases.

Some other approaches utilize designs in public repositories to avoid having users create models from scratch. For example, Mix&Match enables users to search from Thingiverse repositories via an Augmented Reality (AR) headset to connect virtual models with the physical world [26]. Users are able to adjust models based on the physical context of placement and relative scale. Mix&Match creatively bridges the digital space with the physical space for customizing and adjusting designs. Inspired by this work, we explored similar concepts but primarily focused on discovering and measuring target objects in real life, and applied virtual measurements on top of the detected objects for users to verify the measurement locations. In addition, we enhanced the way users search and discover adaptive designs, thus no longer requiring using a virtual version of the existing text-based search tool.

Other systems propose the idea of reusing the functionality of designs. For example, PARTs promotes the abstraction and reuse of geometries and constraints for the supported adaptation type [10]. This allows designers to create their designs from these preset adaptation types, with constraints checking whether the adaptation will correctly fit the target object or not. PARTs provides a method for abstracting functionality to facilitate reuse, which inspired CustomizAR to apply similar abstractions on adaptation-related information as well. Specifically, CustomizAR focuses on abstracting the design information, including target object primitive shape and design adaptation type, to model key concepts and relationships in adaptive designs. This helps CustomizAR show more organized results (e.g., show results by adaptation type), and supports an object-centric approach to search for adaptive designs.

2.3 Challenges and Techniques for Design Search and Retrieval

Prior work has shown that novice users may face multiple challenges while discovering or using public 3D designs on Thingiverse [2, 16]. Since novice users tend to use online communities to find designs instead of learning 3D modeling, it is important that available design information and metadata should be organized in a clear and easy-to-understand manner to avoid potential confusions [5]. The study on Thingiverse data shows that users often have questions related to designs' printability, functionality, and assembly, which may not always be explicitly included in the design descriptions [15]. Thus, it has been advised that richer metadata, clarifications, and expert tips would be helpful for users in design printing and customization [2]. Based on this finding, one motivation of this work is to retrieve metadata to construct a more adaptation-related data structure to support effective search and discovery.

The problem of search and information retrieval in large collections has been one of the research topics in information systems [20]. The current Thingiverse search interface is primarily based on textual query, with some search filters covering major design attributes, such as categories and community-related features (e.g., 'Things I've Liked'). With no or only few filters enabled, the current interface may return a long list of search results which has been shown to be difficult to navigate, and users are likely to browse only the first page of the result [12]. This becomes a challenge for users to explore adaptive designs, as adaptation-related information, such as adaptation type and target objects, are important to effectively locate the desired design, which unfortunately has not been incorporated into the current Thingiverse search interface or the metadata. The previous work on faceted search proposed a characteristics (facets) based search method [23]. Facets are defined as a set of meaningful labels organized in a way to reflect the concepts relevant to a domain, and have been shown to be more helpful than merely providing a ranked list of result and can improve the search accuracy [9, 21]. Our work utilized a similar idea to retrieve the target objects and adaptation type of the design to help novice users quickly understand what are possible adaptation types before going through each individual design.

2.4 Challenges in Digital Measurement

Another challenge that novice users face is the obstacles to capture the information about the physical object (e.g., measuring target object), and be able to translate it to the digital space [13, 16]. Users may be confused about *what* to measure (which part needs to be measured for which parameter) and *how* to measure (which instrument to use and how to use it) [13]. Taking these into account, we highlight parameters that needs to be measured from the 3D designs to address '*what*' to measure, and then incorporate vision-based measurement techniques to address '*how*' to measure.

To solve the problem of measurement, prior work has utilized different sensors for distance measuring, including stereo cameras [1], structured light depth cameras [25], and time-of-flight (ToF) sensors [8], and have been used in commercial or industrial settings. For example, LiDAR cameras have been used for measurement in logistics.[5] As newly manufactured mobile devices such as iPhone Pro[6] have embedded time-of-flight sensors such as LiDAR, this expands the possibilities of performing more accurate measurements on mobile devices. CustomizAR combines computer vision methods with LiDAR readings to help novice users locate and measure the required parameters for the customization to address the challenges in correctly adjusting and printing adaptive designs.

3 OUR PROPOSED PIPELINE TO SIMPLIFY THE CUSTOMIZATION PROCESS

Many existing online 3D model repositories provide tools for simple customization through editable file format, e.g., Thingiverse Customizer, Fusion360 and its supporting format (.F3D). For adaptive designs, customization may also need object measurement in the physical space and a value translation from physical space into the digital format. Current customization pipelines thus introduce inevitable uncertainties that cannot be easily addressed. Figure 4 (top) demonstrates an exemplar customization pipeline when a user customizes an open-source design from Thingiverse. Both searching and customizing occur in the digital space, and the user takes the sole responsibility from gathering necessary information to transforming them into digital information, which creates gaps between the physical and digital spaces, including retrieving, interpreting, and connecting information between them.

Our goal is to improve the user experience in customization of 3D printable adaptive designs. Inspired by the idea of in-situ customization of scale and orientation to align within the actual use case context [26], we take a step further beyond what users can do in-situ to investigate which part of the manual customization process could be delegated to and facilitated by an interactive system. We start by examining what information can be collected from users' environments, then understanding how reuse and remix of shared 3D models can be improved. Here, it is critical to know how the pipeline could establish context-rich connections between digital designs and target physical objects, such as mapping physical objects with possible adaptive designs that fit for them, and how digital designs interact with or adapt to real-world constraints. Technical solutions could potentially be used to reduce the burdens of the complex steps of the pipeline, such as automatically performing measurements that are necessary for customization for the user, and how different components, both of machines and humans, could all fit into a pipeline.

Figure 4 (bottom) shows a high level overview of the proposed pipeline. Instead of relying on text-based queries, the pipeline should (1) provide intelligent support for users to initiate the customization by retrieving relevant information directly from users' physical environments, leaving the information transformation part to the system, (2) support object-centric, context-rich ways of discovering and suggesting possible adaptations (e.g., holder, cap, coaster) for the given objects, and (3) then retrieve a more relevant and organized set of search results for the users. In this pipeline, users will only need to decide which design to customize and then measure the necessary parameters facilitated by the system, where the system will help users decide what to measure and where to measure, and it will perform the final measurement. Finally, the design should be adjusted accordingly and a ready-to-print custom design can be generated directly.

Our proposed pipeline has four benefits:

- The pipeline reduces users' cognitive burdens in context-switching between the digital and physical spaces, by automating tasks that require information conversion, such as mapping digital parameters to physical objects.
- The pipeline reduces the domain expertise needed for the measurement and customization and also about individual designs (e.g., what is the type of adaptation and what parameters need measurements) by automating the tedious or challenging tasks for novices, which reduces possible human errors from those practices.
- The pipeline reduces possible conversion errors by retrieving information directly from the physical space, and provides a more relevant customization experience based on the user's current environment by showing more organized and relevant designs to improve the quality of the search result.
- The pipeline allows users to focus on discovering their interested creative designs to fit unique customization needs.

3.1 Object-centric, Context-rich Coupling of Digital Designs and Physical Objects

Adaptive 3D designs tend to be object-centric by nature. They are expected to interact with one or more real-world objects after 3D printed. Creating context-rich and object-centric annotations of digital designs could potentially bridge the gap between these designs and physical objects during the design process. Based on this

[5] https://www.intelrealsense.com/lidar-camera-l515/
[6] https://www.apple.com/iphone-13-pro/specs/

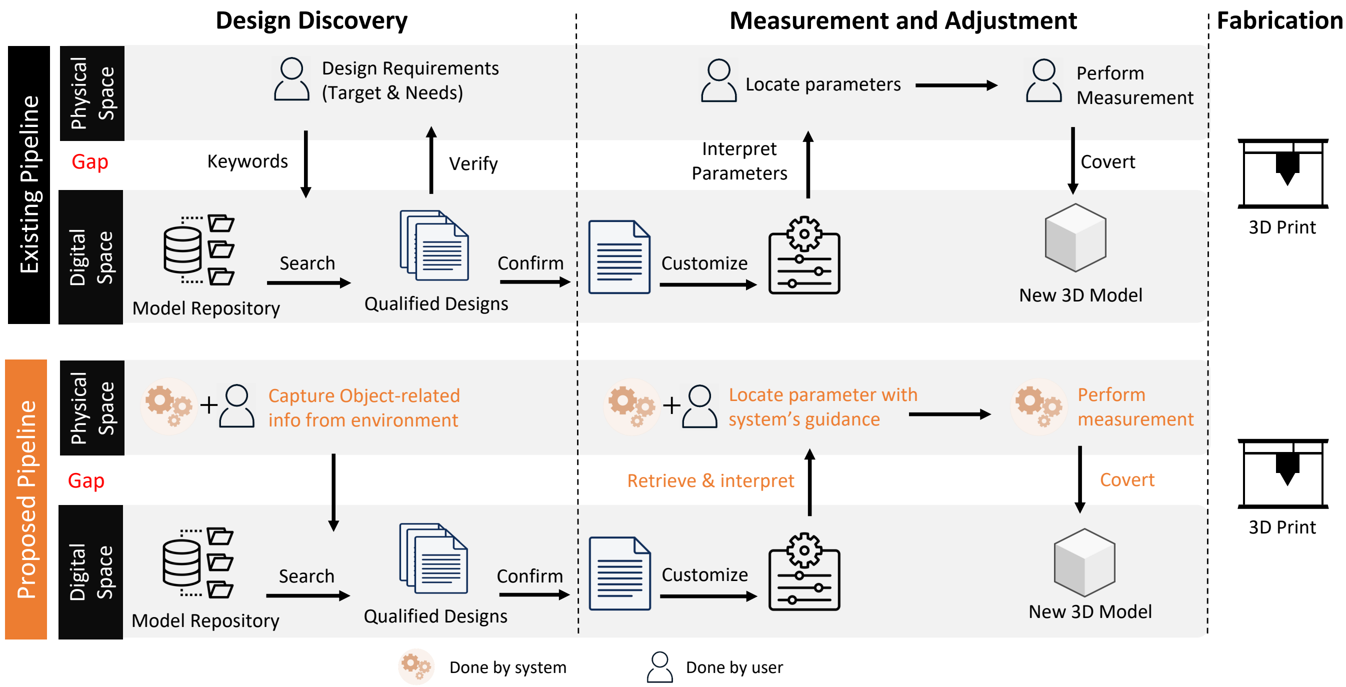

Figure 4: The current customization pipeline using existing repository of 3D design files (top) and our proposed pipeline (bottom). In the existing pipeline users need to deal with the gap between the digital and physical spaces, retrieve, interpret, and convert necessary information between them. Our proposed pipeline aims to bridge this gap semi-automatically allowing users to work with the system collaboratively on various tasks of the customization pipeline.

mapping, the pipeline should act as a proxy to assist the transmission of information, allowing certain tasks to be directly handled by the system instead of requiring user interventions that are often error-prone. For example, having a design repository categorized by the target real-world objects and their functionality enables users to initiate a search by directly capturing physical objects using a camera, providing an intuitive interaction with the customization pipeline. In addition, a mapping between physical and digital information (e.g., parameters) enables the system to automate some tasks such as parameter adjustment.

3.2 Intelligent Measurement Process and Augmenting the Pipeline

While experienced users may have access to more advanced tools given advanced knowledge, novices may experience additional challenges due to limited tool availability and measurement knowledge to perform customization. To mitigate measurement complexity and possible human errors, the pipeline should provide smart guidance in a meaningful way, and perform measurements directly. As more devices are equipped with advanced sensors such as on-device LiDAR or other ToF sensors, users could conduct measurements without traditional measurement tools. Using digital measurement algorithm also implicitly incorporates the measurement method into the pipeline, which reduces the burden of knowing and applying the correct measurement method from users. For example, using the camera and LiDAR sensors , the measurement algorithm could support automatic measurement of common parameters directly from raw sensor readings, including length, radius and angles, without having the users to know how the measurement should be performed. These methods could potentially be reused or extended by other creators in the future without having to create measurement methods for each design from scratch. For example, an automated algorithm to measure the radius of cylindrical objects from LiDAR and camera readings could be applied to various designs that needs such measurement so that end users could directly use this method to capture sizes of target object. Thus, the pipeline allows end users to delegate the problems of where and how to measure to the system, which reduces possible human errors caused by incorrect measurement methods, the need for physical instruments, and the required knowledge and effort for precise measurements.

4 CUSTOMIZAR: AN INTEGRATED SYSTEM TO SUPPORT ADAPTIVE 3D DESIGN

This section describes the integrated CustomizAR system based on our proposed pipeline in Figure 4, using Thingiverse repository as its data source. CustomizAR utilizes on-device LiDAR sensors for measurement, and incorporates multiple steps for customization into an interactive interface:

Step 1. Object Selection: As shown in Figure 5, a user starts the customization by taking a photo of the target object for adaptation in CustomizAR. It then performs object detection using the Microsoft Computer Vision API[7] highlighting known objects. A user can then selects their desired target object by tapping the corresponding bounding box.

[7] https://azure.microsoft.com/en-us/services/cognitive-services/computer-vision/

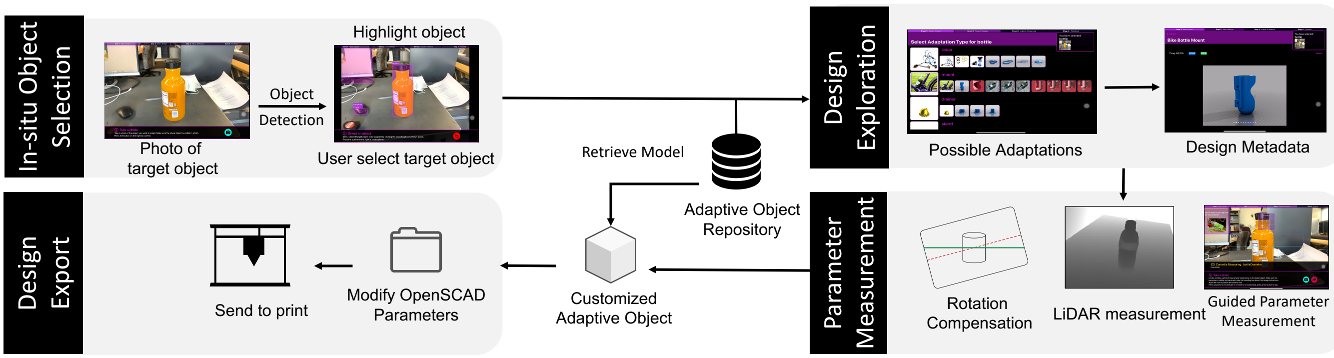

Figure 5: CustomizAR system pipeline of four major steps for (1) in-situ object selection, (2) design exploration, (3) parameter measurement, and (4) design export.

Step 2. Adaptation and Design Exploration: Once the object is selected, CustomizAR prompts a list of possible types of adaptations where the user can explore options of a desired adaptation type (e.g., holder, rack). CustomizAR will return a list of designs under the selected adaptation type for the given target object.

Step 3. Measuring Required Parameters: Once the desired design is selected, the user will measure some design parameters with the help of CustomizAR. CustomizAR will list the predetermined parameters that need to be measured for the customization. For each of these parameters, CustomizAR performs corresponding measurement procedures to detect the region of measurement for the given parameter, calculates the measurement, then prompts the user to verify and, if needed, adjust the ending points of the detected measurement.

Step 4: Adjust and Finish Once the user confirms the measured values, CustomizAR applies them to update the corresponding lines of code in the source file. With that, a customized version of the chosen design can be generated thus to be printed.

4.1 Metadata Design of the Augmented Repository: In/Exclusion Protocol

4.1.1 Retrieving Adaptive Designs. 3D designs in Thingiverse are in many different file formats upon the designer's choice. Not all file formats can be easily fine-tuned by others. For example, the most common file format is STL due to its portability, but it cannot be easily customized. In most cases, they only support some basic manipulations (e.g., change scale, boolean operations, etc.) and do not support fine-tuning of the shape at the parameter level. Designs in OpenSCAD instead provide a room for customization thanks to OpenSCAD's script-based 3D modeling nature, where critical parameters of the design can be defined as variables as in programming. Designers can define necessary variables of the design, such as `bottleDiameter` for a bottle holder design (Thing#: 3057332), then post the source code in order for others to easily adjust and generate a customized version of the model.

As a reasonable start, we define customizable adaptive designs on Thingiverse as adaptive designs that are uploaded by designers with the OpenSCAD source file. 3D models with the original OpenSCAD script contain all the parameters that can be numerically adjusted to change the shape of the design, which can generate a new model based on these parameters. [8] Furthermore, on Thingiverse, the designer can select "This is a Customizer" option when uploading the design and connecting it to the Thingiverse Customizer App. Thingiverse Customizer retrieves all variables appearing at the beginning of the file as parameters (before any function calls or calculations) and transforms these as options to change values using the graphical user interface. CustomizAR takes a similar approach to retrieve customizable designs and parameters to make it consistent with Thingiverse in general. CustomizAR starts by checking whether a design contains OpenSCAD files. Since not all OpenSCAD files are customizable in that they do not contain any variables to change, CustomizAR further filters the result by keeping files which contain at least one customizable parameter. This grants the consistency with how the Thingiverse Customizer determines customizable parameters. As a result, we kept 40,740 designs in total. Designs having multiple OpenSCAD files may have a more complicated structure that requires assembly after printing thus are not included in our initial development.

4.1.2 Retrieve Adaptation-related Information. To augment existing design metadata with adaptation-related information, CustomizAR retrieves the target objects of the design, adaptation type, and customizable parameters for the target objects as the additional adaptation-related information based on the existing metadata, which will be described below.

Retrieve Target Objects and Adaptation Types: Thingiverse currently does not provide designers a field to indicate the target object and/or adaptation type of the given design. Yet, designers often incorporate this information into the title. For example, for 'Customizable Bottle Opener', 'bottle' indicates the target object and 'opener' refers to the adaptation type. Thus, it is possible to further augment existing design metadata with adaptation types and target objects by detecting these entities from existing metadata, and such task is often referred as named entity recognition (NER).

Different approaches have been proposed to solve the named entity recognition task. Traditional approaches such as rule-based NER that analyzes semantic or syntactic rules could be used to recognize entities [14]. Although titles of 3D adaptive designs often present similar sentence structure (e.g., (adaptation type) for (target

[8]Currently on Thingiverse, a design can be marked as customizable using their Customizer interface, if it contains a OpenSCAD file.

object), or (target object) (adaptation type)), creating a rule-based parsing method, such as analyzing part-of-speech tags of words in the title, to understand target objects and adaptation types is still not ideal. The program needs to correctly identify the part of speech tag of the word (e.g., 'stand' is a common adaptation type, but is more generally used as verb) as well as to understand domain-specific vocabularies (e.g., customizer (as in the customizer app), generator (as a program), makerbot (as the 3D printing company)) that may have different definitions in the 3D printing context. Creating a domain-specific dictionary [14] that includes frequently used words in 3D printing domain could potentially improve the performance. However, this may not well adapt to changes happening in the domain, where many new words, including new brand names and new design types, are introduced as community expands.

Thus, we utilized spaCy's named entity recognition system, which utilizes deep learning techniques that combine subword features and bloom embedding for entity recognition, which provides a balance between efficiency, accuracy, and adaptability [11]. We trained the NER model on 1,000 design titles that are randomly sampled among our filtered design files, where adaptation type and target object are manually annotated. When detecting target objects from titles, the system focuses on the most general target object name, which is usually the last noun of the detected target object name. For example, given the model detected target object of 'Makerfarm Prusa i3 Printer', the system will report 'printer' as the target object to avoid keeping too many details. This allows the system to focus on the word that is more broad thus representative of the target object than a specific instance, which increases generality for the design discovery.

Retrieve Measurement-needed Customizable Parameters: In addition to the textual information, the OpenSCAD code files of designs were also parsed to retrieve the variables, customizable parameters, comments, and parameter types. CustomizAR focuses on parameter types of the three most common primitive shapes (cylinder, cuboid, sphere), radius, diameter, length, width, and height. Complex and less common parameters, such as curvatures and rounded corner radius, are not included in the current system. To determine the parameter that needs measurement, CustomizAR starts by extracting all parameters that include one of the parameter types mentioned above in variable name or variable comment. Then, it searches for target object names that were retrieved using NER in the previous step in the variable names and their comments. If the target object name is found in the variable name or its comment, then the corresponding parameter will be mapped to that target object for this design, and will be marked as measurement needed, as it may potentially need adjustment to make the design work. CustomizAR retrieves the corresponding parameters for each of the detected target objects and keeps the parameter type and line number for future use. The unit of parameter is also used for value conversion. Since this is not explicitly required for parameters in OpenSCAD, information of parameter unit is used by CustomizAR only if this is explicitly and clearly mentioned in the code comments (e.g., mm, inch), which is not always the case for OpenSCAD adaptive designs on Thingiverse. Once new values are measured, the program can refer to the line number to make the modification directly. These parameters will also be used for understanding target object primitive shape as detailed in Section 4.1.3.

4.1.3 *Object-centric Approach of Organizing Information.*

Adaptive design discovery is usually object-centric. For example, users may want to discover possible adaptations for a specific target object, or similarly discover possible target objects for an adaptation type. This object-centric nature indicates an alternative and more intuitive way of organizing adaptive design metadata using a graph structure, where nodes and edges are ideal to represent objects, connections, and relationships between concepts.

Figure 6 shows some part of the adaptation graph generated by CustomizAR. The graph contains five types of nodes

1. **Primitive shape node** are three nodes representing cylindrical, cuboid, and spherical objects. Target object which can be abstracted to one of these three primitive shapes will be connected to the corresponding primitive shape node, which could support exploring objects with similar shapes.
2. **Target object node** contains the object name, and is connected to some object adaptations and optionally connected to the primitive shape node. As shown in Figure 6, "Monitor" is connected to a "Monitor Holder" and "Monitor Sun Shield" node, which are possible types of adaptation for "Monitor".
3. **Object adaptation node** represents a specific adaptation for a target object. It connects to a list of designs that falls under this type of adaptation.
4. **Adaptation type node** connects all object adaptation nodes with the same adaptation type. This helps CustomizAR find possible target objects for a chosen adaptation type.
5. **Design node** contains information about a specific design that is necessary for printing adaptive designs, including design metadata and customizable parameters.

This structure abstracts critical concepts and objects as nodes, and uses edges to connect relevant concepts together, allowing CustomizAR to easily discover relevant adaptive designs.

To construct this graph, CustomizAR creates nodes from the adaptation information retrieved by the NER model. To determine the primitive shape of target objects, CustomizAR firstly retrieves parameter types (e.g., radius, length) among designs that involve the given target object, and then counts the frequency of each parameter type. To get common parameter types, the parameters that only appear in a few designs with a frequency lower than 10% of the maximum parameter type frequency of each design was removed. Based on common parameter types, the primitive shape of the target object can be determined as either cylindrical, spherical, or cuboid. If most of detected parameter types of a given target object are radius or diameter only, then the object is likely to be a *sphere*. Similarly, if common parameter types include both radius/diameter *and* height, then it is likely to be a cylinder. If most parameters are length/height/width, then it is likely to be a cuboid. For cases where a dominant parameter cannot be easily determined, CustomizAR will not add primitive shape to the object to avoid confusions. Adaptations that commonly work on one type of primitive shape may be reused on other objects of the same primitive shape. An example could be reusing a bottle holder as a can holder, even though there might be no existing model specifically designed as the can holder. While this may not always work as desired, it still offers potential solutions for the cases where no exact match can be found, which could be listed as secondary results in design discovery stage.

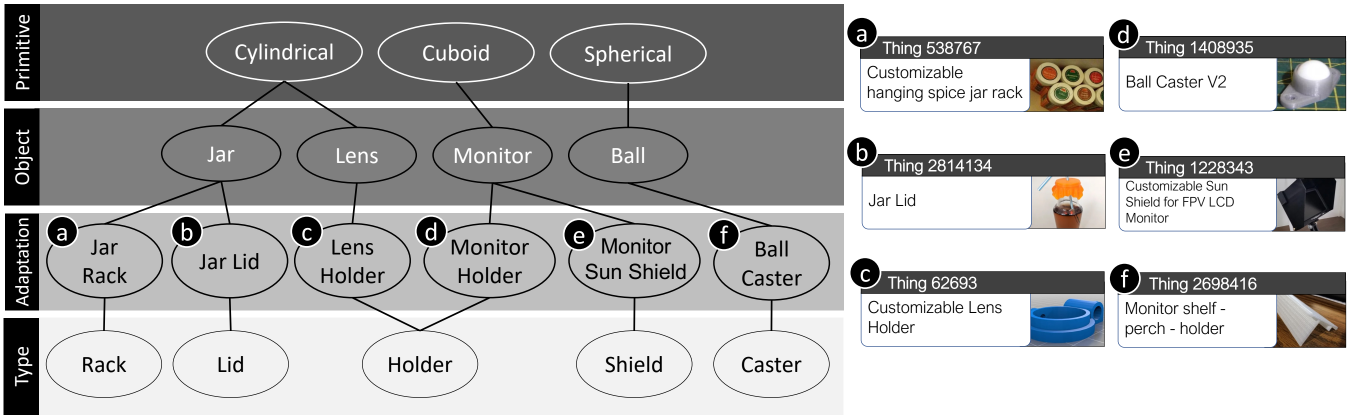

Figure 6: Partial adaptation graph generated by CustomizAR. The plot shows example nodes grouped by node types, including primitive shape nodes, object nodes, adaptation nodes, adaptation type nodes, and Thing design nodes. Each adaptation node can connect to multiple qualifying designs. For demonstration we only show one for each adaptation as an example.

As a result, the graph contains 2,599 target object nodes and 1,566 unique adaptation type nodes, where each target object has an average of 2.675 adaptations (SD = 4.474). This graph structure allows an object-centric way of performing adaptive design search and exploration. As discussed in Figure 5, given the detected objects from the camera view, user can now directly select the target object to initiate a search or possibly select multiple objects to initiate a more complex search. In both cases, it can now be approached by directly performing a graph search to find possible adaptations.

4.2 Facilitating Vision-based Measurement using On-device Sensors

CustomizAR provides a vision-based measurement method to help users locate the region of interest, then performs the measurement automatically using on-device sensors in real time, such as ToF sensors or stereo cameras. They are capable of retrieving 3D coordinates by combining distance and camera intrinsics. CustomizAR runs on the iPad Pro 11' with a LiDAR sensor, which conveniently captures 3D information that is critical for measurement but difficult to retrieve from single 2D image without known reference object. While there exist similar apps (e.g., Measurement app on iOS), they do not necessarily give low-level direct control on measurement procedures that are needed for customizing 3D adaptive design, and also do not support fine-tuning to mitigate potential errors. CustomizAR directly adopts raw sensor readings, including depth map from LiDAR, camera intrinsics, and inertial measurement unit (IMU) values. This enables the system to perform measurement directly on 3D coordinates of pixels, and the method applies to other devices that are capable of retrieving distance or 3D coordinate of pixels. We expect that the accuracy of measurement will be increasingly improved upon the advances of hardware specs.

4.2.1 Measurement Interface. Figure 7 illustrates the measurement process where CustomizAR guides the user through the measurement of a customizable parameter. CustomizAR first asks the user to roughly locate the parameter on the target object (Figure 7 left) and take a picture to be used by CustomizAR. To simplify the measurement, the user is asked to point the camera to the side view of the object which contains the given parameter that needs to be measured, and keep it roughly parallel to the reference line as seen in the middle of the Figure 7 (A). A guidance figure is shown on top of the screen to assist the user to position the device accordingly. Once selection is confirmed, CustomizAR auto-detects the measurement range of the parameter, and provides its measured value (Figure 7 B). CustomizAR also displays the handle at the end of the detected parameter location informing the user to manually adjust if needed. CustomizAR will then recalculate the measurement in real time. Once confirmed, CustomizAR records the measured value, and continues to the next parameter that needs measurement.

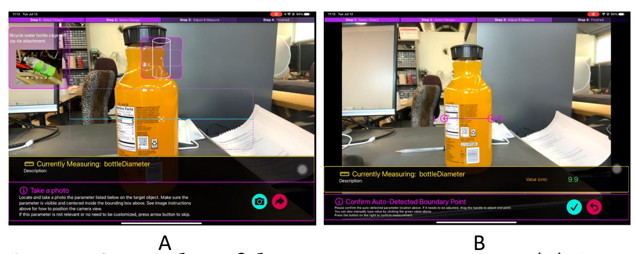

Figure 7: Screenshot of the measurement process. (A) A user roughly indicates the measurement location and (b) the system shows auto-detected measurement range and value.

4.2.2 Determine Edge points. To determine where the values for the parameter input needs to be measured, CustomizAR prompts the user to place the target object on a flat surface and position the device horizontally. It detects the left and right edges of the objects using the depth information. This is achieved by detecting a sudden change of depth value between pixels along the reference line. To increase the robustness of the detection, CustomizAR utilizes IMU data, determining the *yaw* of the device (assuming the device is in landscape mode and the object is placed on a flat horizontal surface) in order to correctly measure horizontal parameters (e.g., bottle radius) when the device is not in the perfect horizontal mode.

Once CustomizAR detects the parameter ending points, it plots them on top of the image taken when the measurement was initiated, with two handles on the end for users to manually adjust if needed. It helps users visually verify if the detected edge points are correct. When the given handle location has a depth significantly different from the rest of the pixels near the ending point for that parameter, CustomizAR will try to snap the user-provided location to a pixel having a closer depth value to the rest of the pixels for the given parameter within a 3x3 grid. This is added to further reduce the error introduced by not accurately moving the handle. If such pixels cannot be found, CustomizAR prompts the user that the given point may not be located on the target object, and asks the user to provide another handle location.

4.2.3 Measurement. Given two pixels of the colored image, CustomizAR translates their locations to 3D coordinates relative to the center of the camera using the camera intrinsic matrix. With the 3D coordinates of the two ending points, it can directly calculate the Euclidean distance of the parameter as the measurement value. The accuracy is highly dependent on the hardware, including noise, resolution, and target object materials (e.g., transparent/reflective surfaces). The current implementation is based on the depth map with a resolution of 256x192 for iPad Pro 11'. For future devices with high-resolution sensors, CustomizAR will become more precise, especially for parameters with smaller values.

5 TECHNICAL EVALUATION

5.1 Evaluation of Adaptation-related Information Retrieval

We first evaluated the named entity model, described in section 4.1.2, that was trained to retrieve information about target objects and adaptation types from design titles. We started by manually annotating target objects and adaptation types for 100 random customizable designs that were retrieved from Thingiverse as the test set, which also contains titles without target objects or adaptation type for diversity. We applied the trained model on the test set to compare the detected results with the ground truth.

Table 1 shows the precision and recall for entity-level evaluation of the detection result. With a training set from Thingiverse repository, the model can detect both the common objects and 3D printing related items (e.g., detect “Prusa” (printer) in “Prusa endstop mount” as the target object and ignore “Customizer” (Thingiverse Program) in “Keychain Customizer” as the adaptation type). While the model can capture most adaptation types in the test set, current model tends to have false positives that reduces the precision of the detection result. Besides misclassifying words as target objects, this is also caused by not correctly determining the range of a target object entity. This could happen for objects with a long but designative name such as brands (e.g., “Raspberry Pi 3 Model B+” or “Sunpak 6200 tripod”, in the later case the model detected “Sunpar” and “tripod” as two target objects). The diversity of target object names and how they are referred in the title also reduce the detection accuracy, especially when the designer uses an abbreviation or a nickname for the target object, such as “i3” as for “Prusa i3” (Thing#: 199171), or “Pi” for “Raspberry Pi” (Thing#: 2525426). Possible errors of detecting target objects and/or adaptation types may negatively impact user experience, especially in the design discovery stage where the system cannot suggest correct designs, even though such designs exist in the repository. However, the model still shows promising result and potential to apply automatic retrieval of adaptation-related information from existing documents. As the current model only utilizes title for detection, utilizing other detailed textual information including design description, tags, and comments in this retrieval process would potentially improve the performance on this task. In addition, asking designers to directly provide such information before publishing designs would also help their designs to be easily discovered by others.

Table 1: Evaluation of Named Entity Recognition Model on Retrieving Adaptation-related Information

	Target Object	Adaptation Type
Precision	0.62857	0.85185
Recall	0.72527	0.87341

5.2 Parameter Selection of Target Objects

We next evaluated the performance of CustomizAR capturing parameters that require measurements of the target object for customization, which is detailed in Section 4.1.2. In this task, we focused on the recall and precision of the detection results from both the parameter and the design level, and summarized the challenges that caused mis-classification. To start, we used a randomly retrieved set of 100 customizable adaptive designs, and manually highlighted parameters that need a measurement. We then compared the ground truth with the detection results. CustomizAR reaches a precision of 0.7934 and a recall of 0.6919 on detecting all parameters from all 100 designs that need users' measurement. CustomizAR successfully highlighted all measurement-needed parameters for 70 of the 100 test designs (only count the designs where all measurement-needed parameters were selected by CustomizAR).

While the evaluation shows some success of retrieving parameters that need to be measured, it also reveals several challenges of covering all parameters. The most common problem is not able to cover parameters of all target objects or components (e.g., camera lens of the camera). While many design titles clearly state the target object(s) for better visibility to other community users, there are also many designs that include extra target object(s) (e.g., a filament spool holder is to mount the holder onto the 3D printer frame, but “3D printer” is often omitted in the title). Such objects not appeared in the title could be found from representative images or using common/domain knowledge, but it is challenging for CustomizAR to detect them automatically. For example, a Toothbrush Holder/Sanitizer (Thing#: 4207458) has two target real-world objects, toothbrush and a sanitize jar, which is not explicit in the title but can be found from images. Some designs also need measurement of subcomponents, such as the camera location in the cell phone for a phone case. The connection between the camera and the cell phone may not always be explicitly mentioned in the code, which introduces challenges of determining the relevance. Thus, it needs additional interpretation of the design functionality and target object hierarchy to increase the performance of capturing the important parameters that need measurements.

5.3 Measurement

5.3.1 Measurement Accuracy. We measured diameters of 10 different cylindrical objects and lengths of 10 different sized cuboids, analyzing the error from the measurement of various target objects. The tasks include two types of parameters (curved: diameter and radius, and straight: length, height, and width) that CustomizAR can measure. The objects used for this evaluation cover a variety of items that are commonly found in daily life, including bottles, cans, package boxes, and large cases. We measured each parameter 5 times in a dining room without using a clean background, and manually holding the device to perform the task. This is to simulate the real-world usage that a user may not hold the device and measure the parameter perfectly in front of a pure background.

Figure 8 shows the error for the 20 parameters we measured. For diameters of cylindrical objects, most measurement errors were within the ±0.5 cm range (as shown in Figure 8 A). The absolute measurement error has a mean of 0.392 cm, and its 25th, 50th and 75th percentiles are 0.125cm, 0.3 cm and 0.5 cm respectively. For cuboid length, the measurement errors are shown in Figure 8 B. The mean absolute measurement error is 0.548 cm, and the 25th, 50th and 75th percentiles are 0.125 cm, 0.4 cm and 0.6 cm respectively.

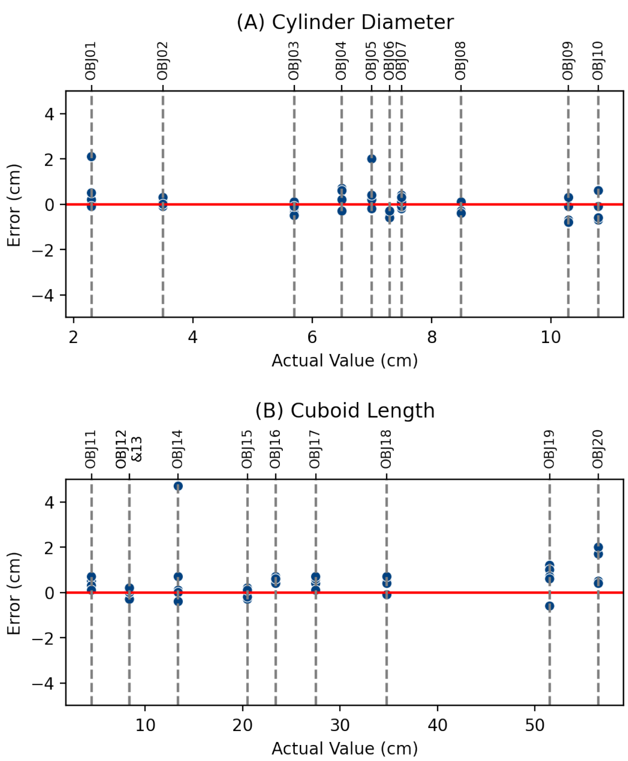

Figure 8: Measurement error for cylinder diameter (top) and cuboid length (bottom). Most measurement errors are within the +/-0.5 region with a few outliers.

Note that as the actual parameter value increases, errors also tend to increase and become diverse especially when the device is not perfectly aligned. While CustomizAR compensates some amount of rotation depending on how the user holds the device, the error might be amplified. We also tested reflective objects using

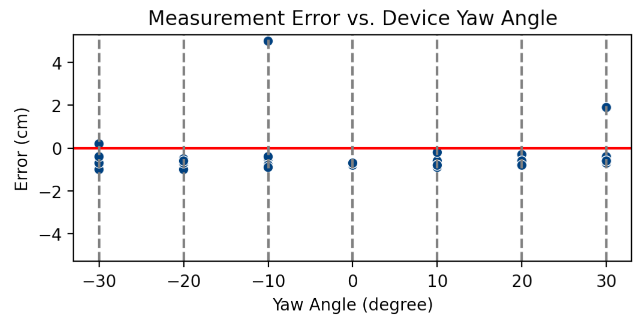

Figure 9: Measurement error for different device yaw angle. The error distribution is similar, showing the effectiveness of CustomizAR's rotation-compensation feature.

the same procedure. We measured a reflective stainless steel pot that is highly reflective and a coke can which is less reflective. The measurement result is less stable and accurate, where the mean absolute error for pot and can is 6.18 cm and 1.14 cm, higher than the error seen in non-reflective objects.

This evaluation demonstrates the utility of on-device sensors to perform measurement for daily objects. Increased errors with reflecting surface introduce possible future improvements, such as a more robust sensor fusion pipeline to utilize other sensor information (e.g., camera, ultrasonic sensors) to collectively perform boundary point detection and measurement. In addition, as more and more mobile devices are equipped with advanced time-of-flight sensors, utilizing a high-resolution sensor, such as high-resolution LiDAR, can also increase the accuracy of the measurement.

5.3.2 Rotation Compensation. We performed another evaluation specifically on the rotation compensation. In order to analyze the accuracy with tilted device, we fixed the pitch and roll angles of the device using a device holder, and changed the yaw angle from -30 to 30 degree with a step size of 10 to simulate different rotation cases. As an example, we measured the diameter of a bottle in all of these cases, iterating 5 times for each. The results are plotted in Figure 9. While there are a few outliers, the measurement errors have a similar distribution among all 7 cases, and CustomizAR was able to compensate rotational errors to increase measurement accuracy.

6 USER EVALUATION

To understand how well the CustomizAR can support users, we conducted a user evaluation with 12 participants. We are specifically interested in how CustomizAR can support users, especially novices with no or limited 3D printing background, to (1) search, (2) discover, and (3) perform measurement/adjustment of adaptive designs. The user evaluation covers both qualitative and quantitative analysis, including semi-structured interviews, surveys, and design discovery and measurement tasks and performance measure. The study was approved by the University IRB board.

6.1 Participants & Procedure

We recruited 12 participants through a bulk email sent to the authors' institution. Table 2 summarizes participants' demographics. The study covers a list of tasks to simulate possible situations while

Table 2: User Study Participant Demographics. The frequency of options for experience is: None: 0 times; Few times: less than 3 times; Sometimes: 3-10 times; Regularly: 10-20 times; Very Frequently: more than 20 times (none selected this option).

	Background	Gender	Age	Experiences in		
				3D Printing	3D Modeling	Thingiverse
P1	Computer Science and Engineering	Male	23	Sometimes	Sometimes	None
P2	Plant Science	Female	31	None	None	None
P3	Nutrition	Female	21	None	None	None
P4	Public Health	Female	20	None	None	None
P5	Human Resource Development	Female	22	Few times	Few times	Few times
P6	Industrial Engineering	Male	26	Few times	None	None
P7	Engineering	Male	19	Few times	None	None
P8	Educational Psychology	Female	26	None	None	None
P9	Industrial and Systems Engineering	Male	20	Sometimes	Sometimes	None
P10	Biology	Female	21	None	None	None
P11	Computer Science	Female	24	Regularly	Regularly	Sometimes
P12	Statistics	Male	29	None	None	None

customizing adaptive designs, and compares the feedback and results of participants using Thingiverse and CustomizAR. If using Thingiverse, participants were given a tape measure as the physical measuring tool to follow the conventional measurement process. While experienced users may have more advanced measurement tools and knowledge, this study aims to study novice experiences, where the access to various precise measurement tools is limited, and users may not have sufficient knowledge about what to use and how to use them precisely. This includes cases where novices do not have access to 3D printers and advanced measurement tools and simply want to customize a design and print it through third-party printing services. Our study used a within-subject design in which participants used both CustomizAR and Thingiverse interface for searching, discovery, and measurement tasks in a counterbalanced order. First, the participants were asked to fill out a pre-survey about their demographics. Then, one author gave an overview (5 minutes) to show the complete procedure of using Thingiverse and CustomizAR for searching, measuring, and adjusting an adaptive design. Participants were allowed to ask any questions or clarification until they become clear about the general procedure of using both systems. In the end, the participants filled out a post survey about their preferences and user experiences, which also collects participants' feedback and suggestions for improvement.

Searching. This task is to evaluate users' experience and performance of CustomizAR compared to Thingiverse by simulating that users already have a clear idea of what to 3D print for the given target object. Participants were given the image and the general description about design context, including real-world target object and adaptation type. Then, participants were asked to alternatively try two different systems to customize the design for actual 3D printing. In this task, there were 6 different customizable adaptive designs given; four of them have a bottle as the target object, and the other two have a box as the target object. We gave participant 4 different bottles and 2 different boxes as target objects for the designs above. The order of which object to use was counterbalanced among all participants. Participants were expected to find the exactly same design given by the researcher and asked to conduct the measurement task that we will detail in the measurement section.

Discovery. This task is to simulate the cases where the user does not have a clear idea of what to print in mind and would like to explore possible adaptive designs for the given object. To simulate an example case, participants were given a tin can, which is a cylindrical object commonly found in daily life. They were asked to imagine a scenario (e.g., in the dining room) where they want to print an adaptation for this can, and then try to think of a general idea of *"what to print"*. Once participants are ready, they were asked to use both Thingiverse and CustomizAR to discover possible adaptive designs and choose a design they like, and ideally, close to their initial idea. After trying both systems, participants were asked to provide feedback and explain challenges they encountered.

Measurement. This task is to evaluate the performance of CustomizAR's measurement function in a real use case. Every time after the participant selected a design for 3D printing using either Thingiverse or CustomizAR, they were asked to measure necessary parameters of the target object using a tape measure (for Thingiverse) or the measurement program (for CustomizAR). Participants were directed to perform measurement tasks for all the objects (i.e., 4 bottles and 2 boxes that were used in the search task, and the tin can used in the discovery task) given in the search and discovery tasks. The measured values were recorded and compared against the ground truth to evaluate the error.

6.2 Findings

Here we summarize qualitative feedback on CustomizAR's performance on searching and discovering adaptive designs. We also analyzed the measurement values from the user study to show the strengths and weakness of CustomizAR's measurement module. One limitation of our user study is the limited sample size. Conducting a larger scale study covering a diverse set of user scenarios could be beneficial to further verify the generalizability of the results, specifically about users' preferences and feelings of the system.

6.2.1 Convenience vs. Confidence: Trade-offs and Users' Preferences. While measuring digitally using CustomizAR seems to be more accurate, stable, and easier, users' preferences are still mixed. Of 12 participants, 7 preferred CustomizAR for measurement, primarily because of the easiness, speed, and no extra tools needed as it is readily-available anytime with their smartphones.

> *"I assume that not everyone will have the ruler ready. You don't need to worry that you do whether you have a ruler or not if you are using the app so it's worry-free you just need to take pictures."* (P8)
> *"I just prefer iOS system [CustomizAR]. I am just not used to this kind of measuring tape. For boxes it is easy but for bottles measuring edges is not easy, like this could be curved, and I don't know where I should stop (if using ruler) for this measurement. At least for me it is not easy to use tape or ruler."* (P11)

In contrast, 5 participants still prefer manual measurement, even as a way to double-check the measurement. Participants showed their trust and confidence of measuring parameters by themselves, and thus prefer manual measurement over CustomizAR.

> *"Measurement is more accurate if I measure it myself. I can actually seeing it, and I am not sure if the technology is more accurate, even though they (the measurement) can be modified."* (P5)
> *" I just trust myself measuring it, until like some application like that gets a little bit more advanced, and less margin error when you measuring it.* (P8)
> *"Personally I have a tape measure that I keep in my car, so I would measure it with that (CustomizAR), and then I would run over my tape measure, just to verify, like secondary."* (P10)

This implies that achieving convenience and accuracy of the measurement process is critical, as it establishes the trust between CustomizAR and the user. Users would rely on the automatic measures if they do not need to worry about the possible errors. Also, more transparency about what the system is doing could also contribute to the trust between automatic programs and users.

6.2.2 Exploration Freedom Grants Inspirations. CustomizAR prioritizes its accuracy and relevance for search results, such as showing designs that are *highly* related to the given target object. The results are also grouped by adaptation types for easy exploration of relevant results. This helps users quickly explore possible adaptations of the given target object. Of all 12 participants, 7 prefers using CustomizAR for searching and exploring possible designs, mostly because it shows organized and relevant results, and more intelligent (e.g., using object detection to select target object). As P10 mentioned, "everything is clearly labeled for its purpose", "convenient and fast", where in contrast Thingiverse results are "a little overwhelming...There's so much stuff so many different things and pictures and I don't know what I am going to be printing."

Although most of participants prefer CustomizAR for exploration, 5 participants preferred Thingiverse over CustomizAR.

> *"I would say the iPad [CustomizAR] is more relevant, but the [Thingiverse] website does have more choices. [Relevant result] is good for searching, but for the discovery I wouldn't say it is as good as the website."* (P4)

Some participants added that the freedom of using free text entries makes them feel that Thingiverse is better for searching and discovery. While they appreciate the easiness and speed of using CustomizAR, it only shows limited results of *what CustomizAR believes relevant*, instead of giving users the freedom to explore a diverse set of possible results that can inspire them, giving a sense of control which will be detailed as follows.

6.2.3 Users Want More Sense of Control for Iteration. The diverse filters and the opportunity to tune the search query catered the impression of more control. Participants felt that they were able to precisely tune the search query, apply filters, even if the initial search results are not as relevant as CustomizAR results.

> *"For discovery, the user is limited by what adaptations the app thinks is applicable to the type of object. [...] your creativity is limited by the [detected] object."* (P6)
> *"When searching for adaptations, I liked how there were various filters to fine tune your search. Although the technology [CustomizAR] is unique, [...] various filters available when searching on the interface. "* (P8)

These reveal that users prefer to first explore then change, fine-tune, and refine results for iterations, with additional terms. This illustrates that showing more inclusive results in addition to the exact match is still an important design implication.

Participants also mentioned the sense of control for parameter measurement. As mentioned in section 4.2, CustomizAR automatically detects the boundary point. Users can adjust detected results, and CustomizAR will auto-correct possible error, which may override the user-provided point and make users feel less in control of the result. As P7 mentioned, "[Detected Line] ought to trust the judgment of the user over the software." This shows important design considerations to allow users to have more control over what should or should not be done during the customization procedure.

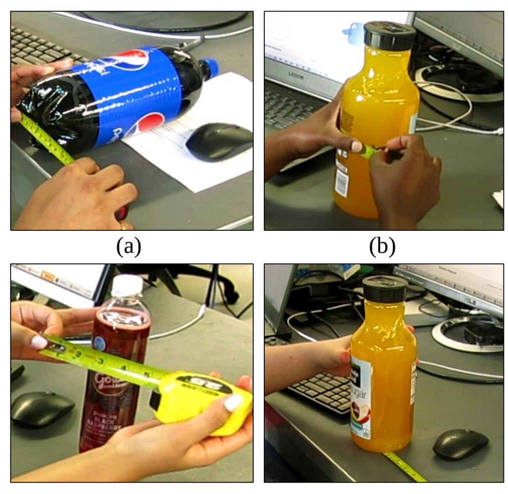

Figure 10: Human errors during cylinder diameter measurement. (a) measuring from curved bottom, (b) measure circumference and divide by 3, (c) horizontal estimation, and (d) not aligning well with the tape measure.

6.2.4 Measuring Real-world Objects Using Traditional Tools is Challenging. As also known in prior work, participants found it hard to accurately measure the target using a tape measure, especially for cylinder to get its diameter [13]. Participants utilized different ways of getting diameter, which introduced diverse types of error cases. Figure 10 shows four different examples of how participants measured diameter, where the participant (a) measured the diameter from the curvy bottom of the soda bottle, (b) measured the circumference instead and divide the value by 3.14 or 3 to estimate diameter which introduces computation errors, (c) roughly measured the diameter from the side view without aligning the starting and ending points of the measurement correctly, and (d) put the bottle on top of the ruler but not aligned well with the center to measure the diameter precisely. Each of these attempts implied potential measurement errors, demonstrating how a simple but common measurement task can be directly impacted by the limitation of the available measuring tool and human error. However, participants also proposed alternative approaches that could increase accuracy. With more advanced measuring tools, the human error shown in Figure 10 could potentially be reduced.

> *"[The measurement results could be more accurate if I could] use something like a caliper, to get even finer measurement".* (P8)

Some participants also suggested that alternative parameters to infer the original parameter may help for measurement.

> *"[On Thingiverse] there weren't alternative parameters (for instance circumference instead of diameter), ... [this] would also be of use, especially for round objects".* (P7)

To compare the accuracy of CustomizAR with manual measurement, we collected measurement values of using the tape measure and CustomizAR. It can be found that for diameters, the measurement error in CustomizAR is lower than the error introduced by manual measurement overall. The mean absolute measurement error for the bottle diameter measured by Thingiverse is 0.66 cm (SD = 1.09 cm). In contrast, the mean for CustomizAR is 0.51 cm (SD = 0.66), which indicates that CustomizAR could generally be more accurate and stable. However, when measuring box width, height, and length, tape measure could be better, as the tape measure performs well to measure straight lines. For the box length, error from manually measured value using a tape measure (mean = 0.13 cm, std = 0.1 cm) is generally lower than the error from CustomizAR (mean = 0.41 cm, std = 0.3 cm) which is partly due to the low hardware/sensor resolution, noise introduced into the implementation of CustomizAR, and the insufficient error correction algorithm, which we will discuss in the limitation section.

The current study design aims to evaluate novices' experiences, where access to measurement tools and instructions are limited. 3D printing professionals and advanced hobbyists may have access to advanced measurement tools and have more experience and knowledge measuring parameters, and thus additional studies are required to compare the performance of all levels of users and conclude a result that could be generalizable.

7 DISCUSSION AND FUTURE WORK

The technical and user evaluations show promising results of utilizing CustomizAR to assist users with adaptive design discovery, measurement, and customization. Specifically, CustomizAR provides relevant results that assist users in exploring adaptive designs for objects, and reduces the challenges and human errors while measuring parameters that may affect functionality of 3D prints. At the same time, these evaluations also reveal several challenges and insights, which we summarize and discuss below to provide possible directions for the future work.

7.1 Result Relevance vs. Exploration Freedom

As we discovered in user evaluation, users may have different preferences in exploration freedom. We prioritized search relevance over coverage in CustomizAR's current implementation, as we hypothesized that it would be beneficial to support users to discover designs in large online repository that does not have proper organization. While the relevance of the result was appreciated by a majority of participants (7 out of 12), as shown in the study, 5 of them still prefer a mixture of exact matches and possible relevant results to have more choices that they can decide on, which gives a feeling of "online shopping" (P4). This might be more critical for discovery, as the user may not have a clear idea in mind; less-relevant ideas also potentially play a role in giving some users additional inspiration of what to print, especially in a casual setting [4]. This finding shows the importance of further leveraging CustomizAR's shape abstraction method in section 4.1.2, to provide other indirectly related designs based on the similarity of target object shape. This could give users more choices and ideas, while maintaining an acceptable relevance of the results. At a higher level, this reveals a important consideration in system design, which is to allow users to configure how the results are represented or filtered (e.g., showing more relevant results or showing more diverse results), to satisfy the preference of a larger and more diverse group of people.

However, it is worth to notice that the limitation of our current user study and system design could also contribute to the feeling of having less control. Factors such as technology used (iPad vs. laptop), input method (touch vs. type), and the overall familiarity with each interface (camera interface vs. traditional search bar) are not rigorously compared in the study, but could implicitly impact user experience. In addition, the current study is designed to evaluate daily use cases primarily for novices. 3D printing professionals and hobbyists may have different preferences on user's control on different parts of the procedure, including 3D model adjustment, measurement tool/method selection, level of result relevancy, and more. Thus, it could be helpful to study the impact of these factors on a larger scale with diverse use cases to fully reveal users' needs and preference of discovering adaptive 3D designs.

7.2 Measurement Accuracy and Error-mitigating Methods

While our technical evaluation showed that CustomizAR is able to measure parameters of primitive shapes with a relatively stable and accurate result, it still incurred several millimeters of measurement error. While this may not directly impact designs such as a battery case (Thing#: 57281) as the target object is not tightly fit in the design, several millimeters of error may not always work for designs that cannot easily tolerate measurement errors, such as a bottle holder that is tightly attached around the bottle (Thing#: 1527777).

Different approaches could be used to ensure fitness. One approach is to use soft materials as a buffer or apply post-processing techniques to mitigate potential errors and give more flexibility on interacting interfaces [13, 27]. This may require special material and model processing in order to correctly apply buffer to the printed design. Another improvement is to use high-resolution sensors or utilize multiple sensors and perform sensor fusion to increase measurement accuracy directly. Multiple cameras, as well as time of flight sensors, can be used collaboratively to retrieve the depth of critical pixels for measurement, which could provide more robust results than relying on a single sensor for measurement. For example, using RGB frames in addition to the depth map to locate parameters could also improve the measurement accuracy, especially when depth sensors may not work as expected (e.g., measuring reflective surfaces).

7.3 Complex Parameter Measurements and Reuse of Previous Measurements

CustomizAR currently supports the measurement of common parameters of primitive shapes as a reasonable starting point. While this can handle a considerable amount of adaptive designs for practical use, advanced cases require more complex measurement techniques, such as curvatures. In these cases, using more advanced sensors and vision techniques could help. In addition, getting additional input from designers about what could be measured alternatively can also simplify the measurement problem.

Future work could also investigate reusing previously measured values of existing designs, as measurement itself usually costs time and effort and may contain different types of errors from different sources. With the approval from users who have measured the target object and verified the correctness of the adjusted print, CustomizAR could provide an option for these users to share the details of the target object and the measured values for other users to reuse these measurement values. With sufficient users contributing their measurements, a database of target object details (e.g., parameters, measurement values, etc.) could be built, which not only contributes to the fabrication community, but can also be used by other fields as well, such as supporting 3D reconstruction of common objects in computer vision community.

7.4 Retrieving Adaptation Information from Textual Information

As mentioned in table 1, the performance of detecting target objects from the title using named entity recognition is limited. This is because the current method can process titles consisting of relatively clear and simple words, not handling long titles with many descriptive words, for example, 'lm8uu ao x motor end side print version holder' as in Thing#: 28776 on Thingiverse. In addition, it does not handle nested target objects. Designs such as 'Camera tripod leg stick cap' may introduce additional confusion for the entity recognition model to determine the most relevant object and the relationship between these possible target objects in the title. Future work could focus on better understanding the sequence of target objects, and decompose large nested object names into smaller components. This could also help with the measurement process, since CustomizAR can combine this with object detection to precisely highlight part or components of the target object that needs to measure, such as focusing on 'lens' in 'Camera lens', instead of measuring the whole object.

8 CONCLUSION

We presented CustomizAR, a pipeline for discovering and customizing adaptive 3D designs that are open-sourced for reuse. CustomizAR provides end-to-end support for users to print adaptive designs, which can reduce the amount of required prior knowledge and human errors in the measurement. Our technical evaluation demonstrated that CustomizAR can effectively retrieve adaptation related information from existing metadata on Thingiverse, and is able to measure parameters of common primitive shapes. Our user evaluation showed that CustomizAR was able to support users in design search and discovery with more relevant and organized results, and was capable of assisting users performing necessary measurements with less human error. These evaluations also informed future improvements of CustomizAR, including measurement accuracy using additional on-device sensors and target object decomposition and understanding. The qualitative feedback from the user study also revealed a number of critical system design considerations, such as balancing relevancy and diversity of search result, and granting users freedom and control over the discovery and measurement procedure. Overall, CustomizAR demonstrates an integrated pipeline for customizing adaptive designs in the 3D printing community, which shows its value in supporting users with various backgrounds in personal fabrication.

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