Understanding Uncertainty in Measurement and Accommodating its Impact in 3D Modeling and Printing

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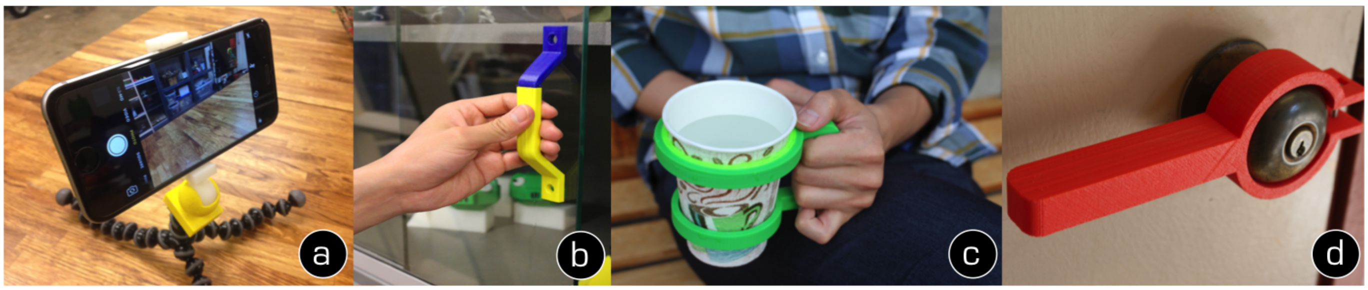


Figure 1: Physically adjustable 3D augmentations accommodate measurement error. From left to right: a tripod mount with ball joint for angle adjustment, an assistive cabinet door handle with a second-iteration update (blue), a cup holder with a flexible ring (light green), and an assistive door lever with an inserted cylinder joint to adjust diameter.

ABSTRACT

The growing accessibility of 3D printing to everyday users has led to rapid adoption, sharing of 3D models on sites such as Thingiverse.com, and visions of a future in which customization is a norm and 3D printing can solve a variety of real world problems. However, in practice, creating models is difficult and many end users simply print models created by others. In this article, we explore a specific area of model design that is a challenge for end users – measurement. When a model must conform to a specific real world goal once printed, it is important that that goal is precisely specified. We demonstrate that *measurement errors* are a significant (yet often overlooked) challenge for end users through a systematic study of the sources and types of measurement errors. We argue for a new design principle—accommodating measurement error—that designers as well as novice modelers should to use at design time. We offer two strategies—buffer insertion and replacement of minimal parts—to help designers, as well as novice modelers, to build models that are robust to measurement error. We argue that these strategies can reduce the need for and costs of iteration and demonstrate their use in a series of printed objects.

DIS 2017, June 10–14, 2017, Edinburgh, United Kingdom.

http://dx.doi.org/10.1145/3064663.3064690

ACM Classification Keywords

H.5.2 Information interfaces and presentation: User Interfaces - *Input devices and strategies*

Author Keywords

Personal fabrication; 3D printing; measurement; uncertainty.

INTRODUCTION

The arrival of consumer-grade 3D printing machines has created new opportunities for consumers to make, create, and innovate [15]. This shift to *personal fabrication* has benefited from, and enhanced, the maker movement: amateurs can not only passively consume 3D models with their personal 3D printers, but also proactively customize, remix, and create original models [18]. Sites such as `Thingiverse.com` facilitate this by allowing people to share parametric 3D models and customize them using the *Customizer* tool.

One popular application arising in the fabrication domain is to augment one's *personal* physical environment. This is common among assistive technology models found online (*e.g.,* [2, 6]). However, if the original designer and the novice modeler who prints the model do not have the exact same object or environment, such augmentations may require further customization to be made usable. For example, a model to make a door knob easier to open by turning it into a lever must be sized for the specific knob that it will be used on. Similarly, a cup holder must fit the specific shape and volume of mug it will be used with.

Many models and modeling tools along with much of the current research in personal fabrication use parameterization to address this customization need. Given a suitably parameterized model (for example based on the diameter of a doorknob), and a correct measurement (of the actual doorknob), the model can be adjusted to the measurement. In theory, the resulting model just fits. This approach is in line with the skills of novices, who may only be comfortable with parameter entry and simple scaling [13]. However, as we will show, in practice correctly measuring a real world object is a surprisingly difficult task for novices and this can have a significant impact on customization of 3D models. Although 3D scanning is an alternative, even then measurements may need to be extracted digitally. Also, the quality of such scans is not dependable, especially given the tools available to novices. In a study described below, we found that issues with user error (such as misaligning instruments and misreading units), measurement instrument precision, and even task definition, combined to make measurement error common. This is compounded by the fact that 3D printing itself is not perfectly precise. For example, some materials shrink slightly as they cool. Put differently, measurements are at best approximations which contain some degree of *uncertainty*. A model that is robust to this uncertainty will be less likely to fail. In this paper we address these problems through:

- Two studies to explore uncertainty in human measurement behavior and categorize common causes of measurement error in everyday measurement practices, as well as the potential for better instructions to reduce error.
- Two modeling strategies that accommodate uncertainty.
- A 3D editor – *FitMaker* – that provides re-usable modular parts that encapsulate these strategies and can be integrated into existing models.
- A demonstration of printed objects modeled using these uncertainty accommodation strategies.

In the next section, we discuss recent trends in making design and iteration for fabrication more accessible to end users. We then focus on measurement error, which represents a design problem in any domain (*e.g.,* [1]). However, in the field of personal fabrication, little or no attention has been paid to the impact of measurement error.

Following that, we characterize the amount of measurement error to be expected. Our first study conducted on Amazon Mechanical Turk shows that across 132 participants, three measurement tasks, and multiple measurement instruments, measurement accuracy ranges from 82%-99% ($SD = 4.4$), meaning that some measurements were off by as much as 18%. Our second study tested whether better instructions could help improve accuracy. Accuracy increased on the low end to 90.8%.

Even with better instructions, measurement error is still an issue. Thus, we developed two classes of techniques that mitigate uncertainty and thus reducing the number of iterations: flexible buffer insertion; and replacement of minimal parts by adding a joint at the point of uncertainty. We show their values in three kinds of measurements (*i.e.* length, angle, and diameter) and argue that they have diverse and complementary benefits with respect to scale, the amount of expected uncertainty they can accommodate, and the savings in print and iteration time. We demonstrate these strategies in the context of exemplar printed models.

Motivating Scenario

Stacey is a home 3D printing hobbyist who recently injured her wrist and has to wear a splint. She has difficulty with the round door knobs in her home, so she searches Thingiverse for ideas about how to solve the problem. She finds a simple solution—a part that adds a lever to the door knob. She downloads the lever model and prints a test model. However, it is too large, so the lever slips. She measures the circumference of her door knob, but when she loads the model in her 3D modeling software to resize it, she realizes that what she actually needs to know is the radius or diameter. She calculates the diameter, adjusts the model, and prints a new one. However, it fails again because her scaling along the x-axis still did not result in the right dimension. The scaled object shown in the software was based on the outer diameter of the clamp, not inner diameter (of the door knob). She adjusts again, and this time the fit is much closer, but is still slightly too small. This is because she measured the circumference with a tape measure, but did not always align along the maximum circumference. After correcting this, she prints with ABS, which shrinks and warps so much that the lever still does not fit. Undeterred, she makes yet another attempt (her fifth) by estimating how much the lever might shrink and increasing the diameter to compensate. Finally, after four failures, the lever fits.

Had Stacey succeeded on the first try, the time to make this 3D printed door lever would be 3.3 hours (estimated by CuraEngine with normal settings: 20% infill; $0.2mm$ layer height; and $30mm/s$ travel speed) plus minimal customization time. However, with four failures, printing took approximately 13.5 hours and used four times as much filament. Adding in other household obligations, instead of being able to use the door handle on the same day, it could easily take her 3 days to produce.

Although it may sound as though we intentionally exaggerated Stacey's struggles in fitting a 3D printed adaptation to a real world object, in fact the types of errors just described are all quite plausible and common, as demonstrated and quantified by our studies described later.

RELATED WORK

Personal fabrication is entering the mass market. With more and more people owning 3D printers, online maker communities have started to not only create designs, but also share and remix them [18]. A common application of personal fabrication is augmenting real world objects to better fit individual needs, *e.g.,* [6]. However, for novices who just started learning 3D modeling, designing augmentations can be hard for several reasons. First, it may be difficult to design the *right thing* that fits individual needs. Many subtle details arise when augmenting real world objects (*e.g.,* how to attach [5]), which increases the chance of an error. Second, design often involves several iterations (particularly when it is open-ended). Speed is an issue particularly for novices who may need to iterate more because of design errors that are only caught after the model is printed out.

Designing the Right Thing

Designing the right thing for a specific need can be a daunting task for novice designers. One effective way of improving this is narrowing the design space and providing a specialized tool that encapsulates design knowledge about that space. For example, Kim *et al.* created a tool for designing 3D printed moveable picture books for for blind children [14]. In that vein, Reprise system supports the design of assistive augmentations for people with motor impairments [6]; Pteronyms supports design of model airplanes [22]; SketchChair supports design of furniture [20]; and Facade supports design of labels [9]. Alternatively, it is possible to provide tools that abstract away some common aspect of the design process. For example, Encore specifically helps with the sub task of attaching a 3D printed object to a real world object [5]. A variation on that is making the interaction with the modeling tool more intuitive. For example, Tactum allows on-body design with a prototype projected on the arm [7]. These tools share a goal of helping users get to the right design more quickly and easily.

Supporting Iteration

Ultimately, it is reasonable to assume that unless the design space is *highly* constrained, iteration will be a fruitful and necessary part of the design process. Unfortunately, consumer-grade 3D printers are mostly very slow, elongating the iteration cycle. To speed up 3D printing, researchers are experimenting with a range of different printing techniques, such as printing with multiple extrusion heads [10], printing with voxels in parallel in the same layer [11], or using entirely new technologies, such as Continuous Liquid Interface Production (CLIP [4]). On-the-fly printing combines real time design and printing [19]. Low-fidelity fabrication (*e.g.,* [16, 17]) adds an additional speed-up on top of these technologies. Alternatively, a previous print may be patched without a full reprint [21], or reshaped after printing [8].

To summarize, recent work has begun to tackle a wide range of difficult problems that currently stand in the way of widespread uptake of personal fabrication. This work has tried to reduce the need for iteration *via* better design tools, or to speed up the iteration process. However, for the most part, such advances are not based on empirical studies of the problems designers face, nor do they address challenges such as measurement that arise outside of design and printing process.

Measurement for Design

Measurement of existing objects is a long standing necessity in engineering, industrial design, and architecture. A few standard guidelines for beginners along with a precise process to reduce errors is introduced in [1]. To be aesthetically compelling and functionally competent, a protocol for accurate measurement was proposed in the product design area [12]. However, measuring ten times to get a relatively exact value, or stepping through a ten-phase process to reduce error (as suggested in [12]) is not practical, or viable, for novice modelers to follow. It is also possible to use technical solutions to reduce errors. For example, in Facade blind users take a photos of the appliance to be labeled along with a fiduciary marker, and computer vision techniques augmented by crowdworkers are used to extract accurate measurements [9].

MEASURING MEASUREMENT

To understand human practices of measurement and the uncertainty involved, we conducted two studies. The first study was designed to give us an initial glimpse into the measurement practices of everyday users. The second attempted to guide users and improve on the results of our first study.

Study 1: Understanding Typical Measurement Practices

Our first study was designed to elicit information about how people might approach a measurement task on their own. In addition, we wanted to both qualitatively examine what sorts of errors people made in measurement, and quantitatively determine how large they were. Thus, we designed our study to be open-ended for which measurement techniques might be applied, but specific about the target values we expected to get from the process.

Method

To reach a wide sample of people, we deployed the study as an online survey on Amazon Mechanical Turk for four weeks (27 days). The survey tasks included measuring *(i)* the height of an iPhone (specified models only), *(ii)* the angle of a fully opened Mac laptop, and *(iii)* the diameter of a standard lightbulb. These objects were selected to target cases where 3D printed augmentation would apply, such as a phone case, lampshade, and laptop stand. Also, these are each manufactured in standard dimensions, making it possible to compare the reported value with ground truth. Participants were asked to report the model of the object to be measured, so that we could determine the correct measurement. For example, given a lightbulb's manufacturer and model number, we were able to retrieve the physical dimension as reference.

Participants were told to measure each item twice (with two different tools or method), so we could observe not only individual skill, but also the uncertainty generated by different instruments and methods. This repetition was done on separate pages of the electronically presented survey to minimize copying. We also asked participants to upload photos of the object and the measurement instrument, showing how they conducted each task. This prevented cheating, and gave us insights about where specific errors might come from. At the end of each round, participants were asked to describe how they conducted the measurement.

Data Preparation and Inclusion Protocol

The study was completed by 62 participants, who each completed multiple measurement trials. We eliminated trials in which participants measured the wrong target (*e.g.,* measured display length instead of the laptop's largest opening angle). We also removed responses lacking valid photos (photos lacking a demonstration of how the participant performed the measurement, duplicate photos, images retrieved from the Internet, and irrelevant photos). In the case of lightbulbs, we removed two trials for which we could not retrieve ground truth by the bulb model name. A total of 10 iPhone length trials, 19 laptop hinge angle trials, and 10 lightbulb diameter trials were rejected for these reasons. Thus, after removing invalid measurements, the total sample size for each task is different.

We also cleaned the data where possible. If numbers were reported without units (or with obviously wrong units such as inches for laptop hinge angle measurement), but we were fairly certain of the correct units, we fixed them. For example, if the participant typed 6.25 without unit for an iPhone 6 Plus's height, we marked its unit as inches, based on a comparison to the real dimension of 6.22 inches.

Next, we converted all measurements for a given task to the same units (*e.g.,* we converted inches and centimeters to millimeters). Finally, we calculated measurement accuracy. Because we allowed multiple models for each task, with different true (ground-truth) values, calculation of average error and accuracy was done with the following formula:

$$E_{d,t} = \frac{\sum_{m_{d,t} \in M_{d,t}} \left\| T_d - m_{d,t} \right\|}{\left\| M_{d,t} \right\|}$$

Where T_d is the correct measurement for device d, $M_{d,t}$ is the set of all measurement instances for measurement instrument t and device d, and $m_{d,t} \in M_{d,t}$ is a specific measurement instance.

Note that our qualitative data analysis considered all completed surveys as well as partial answers with valid photos (same criteria as above).

Study 1 Results: Measurement Approaches and Errors

Overall, participants chose a wide variety of measurement instruments (as summarized in Table 2), some quite surprising (such as a garden spade, eraser, string, electric tape and mug) and others more ordinary (such as a ruler or protractor). Some of the odder choices may have been driven by the requirement to measure each item two different ways. Figure 2 shows distribution of accuracy across the measurement trials. Accuracy was highest for length (leftmost boxplot), with a mean of 98.2%. Since iPhone models range between 123.8*mm* and 158.2*mm* tall, this means that actual errors ranged from 2-3*mm* in most cases (enough to affect the fit of a case, for example). Angle was most variable, with a mean accuracy of 93%. Diameter accuracy ranged from 87.2% to 97.6%. Viewed another way, we can say that the box (or box plus whiskers) in Figure 2 represent the *measurement uncertainty* associated with each task.

Given the presence of uncertainty, we qualitatively explore two sources of error (Table 1): Measurement technique, and measurement instrument limitations. As is demonstrated by the measurement technique section, human judgment plays an important role in measurement uncertainty. For example, people may make errors in deciding *what to measure* and *how to measure*. Similarly, Table 1 demonstrates how *measurement instrument limitations* (such as precision) can affect accuracy.

What to measure?

The very first problem participants encountered was the difficulty of determining the exact measurement target. This was

1. Measurement Technique	**Num**
Not correctly aligned with the start or end of the measurement target	31
Number rounded imprecisely, or in the wrong direction (*e.g.,* 24.9 to 24)	29
Measured the wrong target	23
Reported incorrect units	15
Inappropriate measurement instrument choice	14
Not correctly aligned with the start of ticks of the measurement instrument	10
Incorrect placement of measurement instrument (slanted, not perpendicular, used wrong reference point for angle)	5
Viewer perspective when reading measurement not straight on	5
Incomplete preparation of target object (*e.g.,* did not take out accessory case, measured Mac laptop on the stand)	3
Viewer read the wrong indicator	3
2. Measurement Instrument Limitations	**Num**
Calculation error (*e.g.,* trigonometry, circumference to diameter)	15
Measurement instrument distortion (*e.g.,* curved, stretched)	11
Measurement instrument units too large for sufficient precision	9
Vague reference (*e.g.,* thumb, forearm, screw driver, sharpie, cardboard, eraser)	9
Imperfect ticks (*e.g.,* worn out, hand drawn)	3
Hidden zero tick (causes alignment issues)	2
Short measurement instrument (requiring multiple end-to-end measurements)	1

Table 1: Types of errors and practices observed in the study. *Num* indicates the number of participants with that type of error. Note that this is not an exclusive count. For example, if a participant measured angle with sewing tape by trigonometry, we counted this case in both "measurement instrument distortion" and "calculation error".

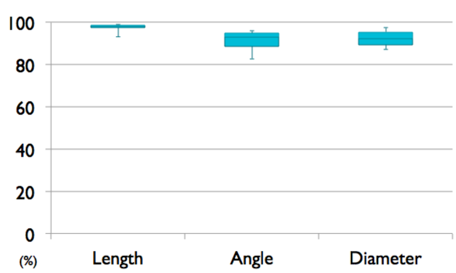


Figure 2: Distribution of measurement accuracy, for iPhone height *(left)*, laptop hinge angle *(middle)*, and base diameter of lightbulb *(right)*.

driven by the fact that real world objects often have curves, bumps, and other design characteristics that make them beautiful or usable, but not necessarily easy to measure.

For example, the iPhone 6 has rounded corners and edges (Figure 3a). If a participant does not notice, he or she might

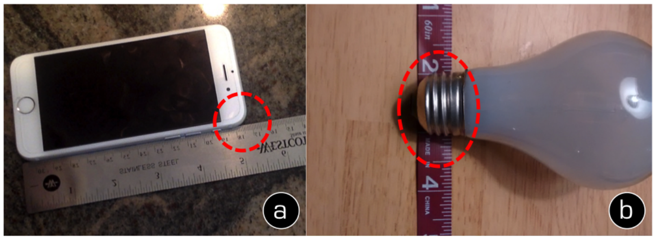


Figure 3: Unclear measurement target. Rounded corners *(a)* and zigzag surfaces *(b)*, make it hard to align the measurement instrument correctly.

not measure from the true top to bottom, especially if the measurement instrument is aligned with the edge of the phone as in Figure 5a. If a participant does notice, then questions arise about what to measure, and how to correctly account for the curve. A participant may also introduce new errors (such as holding the measurement instrument away from the rounded edge, causing an unnoticed slight angle which introduces an alignment error). Most participants chose to measure along the edge rather than the center of the phone which better captures the full length. For example, P32 stated: *"I laid down the phone on the table, and laid down the tape ruler on the side of it."* (P32)

Another difficult example is the zigzag surface of the lightbulb screw base shown in Figure 3b. Should a participant measure at the minimum or maximum circumference? This is not a straightforward question, and depends upon the reason for measurement. In addition, this makes it difficult to align the target and measurement instrument correctly. It is similarly difficult to decide what to measure on a flexible or non-static target such as soft fabric or a piece of yarn.

How to measure?

Table 2 summarizes the range of measurement instruments and frequency of them being used, as well as the average measurement accuracy for each instrument. The table only shows measurement instruments used two or more times; all instances used by only one participants are categorized as "others".

Several participants conducted the measurement tasks with digital applications such as level apps, computer vision applications using a photo of target object with a US quarter as reference, or Adobe illustrator tool path (*e.g.,* Figure 4). Some of these applications function almost identically to a physical measurement instrument once loaded on the screen. Others allow users to manipulate the location of the zero tick to match the item being measured. Some others involve taking a photo, and measurements are then conducted in the application itself. In this case, users specify the reference size using a fiduciary marker, then tap on key points for measurement, possibly with the help of zoom to carefully align. Many digital applications just turn the phone into a measurement instrument, leaving the user with all of the same alignment issues as standard measurement instruments. In addition, the accuracy of photo-based measurement depends heavily on the angle at which the photo was taken (otherwise a perspective error can occur, even with a known fiduciary marker such as a quarter in the image to provide a baseline for size).

iPhone Length(#)	**%**	**Laptop Angle(#)**	**%**
Tape measure (22)	98.2	Protractor (8)	93.0
Ruler (20)	98.7	Protractor app (8)	88.0
US Quarter (2)	98.2	Paper (5)	93.0
Plain Paper (2)	96.9	Tape measure (5)	92.4
Printed ruler (2)	97.4	Image application (4)	94.5
Screen ruler (2)	99.0	Printed protractor (3)	95.8
Other (13)	93.2	Ruler (3)	95.8
Bulb Diameter(#)	**%**	Drawn protractor (2)	88.4
Tape measure (51)	94.8	Lever app (2)	96.1
Ruler (36)	89.8	Compass (2)	88.4
Online ruler (4)	97.6	US quarter (2)	82.6
Other (6)	87.2	Other (11)	93.2

Table 2: Measurement instruments used at least twice (# shows total number of times and % shows average accuracy). Not listed are measurement instruments used only once including: *Length*: eraser, laptop case, cat tape, image application, compass, screwdriver, thumb, caliper, and garden shovel (with embossed ruler ticks); *Angle*: clinometer, eraser, mug, book, screwdriver, speed square, mini draft; *Diameter*: string, screw driver, paper, wire, image application, electric tape.

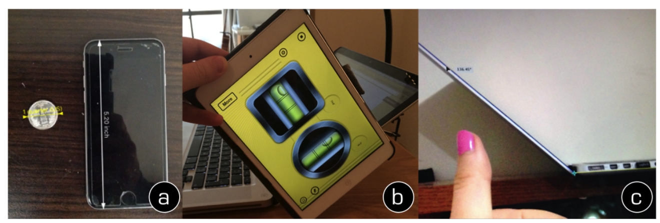


Figure 4: Digital measurement applications used by participants: *(a)* a photo editor with a fiduciary marker for size reference, *(b)* a digital level, and *(c)* Adobe illustrator tool path to calculate the angle between the two lines.

Participants made a variety of errors when using measurement instruments. Most originated from misalignment between the measurement instrument and the target. For example, the tick marked in Figure 5a is not positioned in line with the actual top of the phone. Other variations on this theme included slanted placement of the measurement instrument, not lining up the zero tick on the measurement device to the target correctly (*e.g.,* Figure 5c), or not centering the protractor.

Even assuming correct alignment, errors can occur when reading the measurement with both digital and physical measurement instruments. Especially for physical measurement instruments, reading the measurement requires correctly interpreting tick marks and aligning them with the correct edge of the object. If the observation perspective of users is not straight on, this may cause an error. This type of error is increased when measuring objects with higher curvatures.

Another source of error is selecting an inappropriate measurement instrument. Measurement instruments chosen were sometimes measuring the wrong type of thing (such as using a

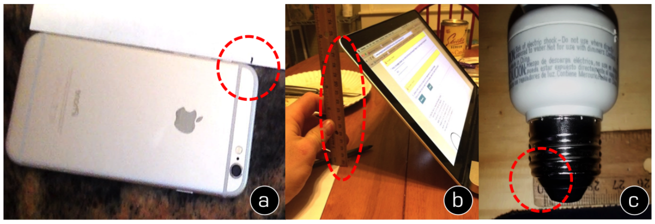


Figure 5: Examples of human choices that might increase error including: *(a)* measuring with paper instead of a ruler; *(b)* measuring angle with multiple lengths rather than a protractor; and *(c)* misalignment of the object with the ruler's tick.

ruler to measure angle Figure 5b). In the most extreme cases, this error also led to issues with the measurement instrument itself. For example, P24 wrote *"I used a hard cardboard like substance and put it on the laptop and folded it according to the angle of the screen and hold it there for few seconds so it does not change its shape."* (P24). Even without a protractor, more precise alternatives were available to this participant had they known they existed and how to use them.

Measurement Instrument Limitations

Our final category of error is driven by the limitations and characteristics of the measurement instruments used for measurement. Limitations that arose in our study included instruments that could change shape if used incorrectly, measurement instruments on which it was hard to interpret tick marks accurately, as well as precision limitations.

Changing length: Measuring tape (used for sewing) is easily curved or bent, which may introduce error (*e.g.,* Figure 6a). Flexible measuring instruments need to be tightly wrapped or flattened. Also, using yarn, string, or electrical tape to measure length can lead to errors, because they can stretch, and it is hard to define the starting point (*e.g.,* Figure 6b). On the other hand, if the measurement instrument is shorter than the target, the user has to combine multiple measurements (*e.g.,* Figure 6e), which may introduce overlaps or slight gaps.

Difficulty interpreting tick marks: Blurry tick marks from old or worn out measurement instruments make it hard to read the labels accurately. Similarly, sewing measure tape with a hidden zero tick is hard to read (*e.g.,* Figure 6c and d).

Precision: The measurement instrument may lack the precision needed for correct specification of a 3D model. For example, multiple participants used body parts, such as *"I used my thumb and it was one thumb length which was equivalent to an inch."* (P11) and *"I know my forearm is 30cm in length, so I took a thick thread and measure the size of the bulb. I took three measures with the thread and put them aside separately. Then I converted each thread's length into centimeters by fitting them in my forearm."* (P59). While many measurement units derive from body parts (foot, cubit, *etc.*), the precision of using body parts as reference is limited, and human variability makes such measurements error prone. P59's strategy to address this by measuring multiple times is unlikely to significantly improve things. Overall, 11

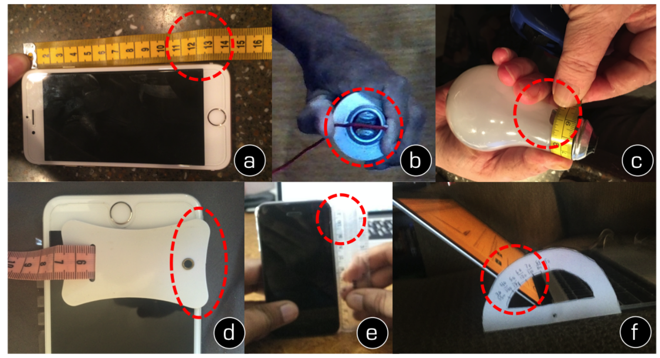


Figure 6: Measurement instruments limitations can increase the chance of error, including: *(a)* tape that is not naturally flat; *(b)* stretchy string; *(c)* requiring calculation (diameter derived from circumference); *(d)* hidden 'zero' tick, making correct alignment difficult; *(e)* shorter than the item being measured (introducing potential gaps or overlap); *(f)* difficult to align precisely.

measurements involved measurement instruments that are limited in precision For example, one participant used a spade that showed inch marks but no precise divisions below that to assess length. Another used an eraser: *"I placed the eraser upright on the laptop (90 degrees) and tilted it until it touched the monitor. It appeared to be halfway down, making it an additional 45°, and 45 + 90 = 135."* (P36). Other examples included a screw driver, sharpie and piece of cardboard.

Measurement instrument limitations can be compounded by user error, such as faulty calibration of calipers, the curved tape in Figure 6a, the over-stretching string in Figure 6b, or calculation errors.

Limitations and Discussion

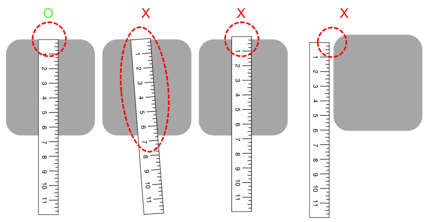
Our study only provides an estimate of the potential of measurement error. We have incomplete information about ground truth (in the case of laptop angle, where age could affect maximum possible angle). Also, photos may not all have shown actual measurement instrument position during measuring. Despite these limitations, our study shows that measurement error is a potentially significant factor even when good measurement techniques are used. For length, average error was about 2%, which is probably due to the fact that it is the most familiar of the measurement tasks we set. Although this accuracy is high, it translates into a real world error on the order of $2-3mm$, which for many augmentations would cause failure. For other types of measurements, average error was 10.5%, a much larger problem. Our next study explores whether we can reduce error by providing simple instructions.

Study 2: Improving Measurement Process

Although not available in all situations, one possible way to reduce errors is to provide well-designed instructions for taking measurements. To test whether this could significantly reduce error rates we developed a set of instructions for measurement and tested their impact on measurement error based on the type of errors and common factors leading to incorrect measurement we found in Study 1. We designed the instruction set to be general for a variety of measurement goals and objects,

Instructions for Length Measurement

1. Identify the [measurement target] you plan to measure.
2. Remove any accessories that could impede exact exact measurement.
3. Place the item to be measured and the measurement instrument on a flat surface.
4. If your measurement instrument is flexible (*e.g.,* tape measure), flatten it and make sure it is not curved or over-stretched.
5. Place your measurement instrument on the object along an axis that has no indentations, bumps, or other artifacts that could affect measurement.
6. Align the edge of the item to be measured with the "zero" tick of your measuring instrument correctly.



7. Hold the measurement instrument to the surface of the object and read the length straight off the instrument.

Table 3: Instructions to improve accuracy of length measurement. Similar instructions were provided for other tasks.

but specific to either length, angle, or diameter. An example is given in Table 3, which describes a set of instructions for length measurement. Unlike existing complete measurement instruction (such as [1]), the instructions were designed to be simple enough that participants were likely to read them through.

Method and Data Preparation

The study method was very similar to our first study, with the addition of instructions and a scenario, both meant to motivate more accurate measurement. We told participants to imagine they are measuring with the intent of augmenting the measured objects (*e.g.,* designing an iPhone case, or selecting a lampshade for the lightbulb). Similar to Study 1, we required that they upload a photo of the measuring task for verification. We used the same rubric to eliminate incorrect photos.

A total of 79 crowd workers completed the survey, 27 workers on iPhone, 26 workers on laptop, and another 26 workers on lightbulb respectively. With the same data inclusion protocol as Study 1, 22 valid responses were collected for iPhone (5 failed attempts), 18 for Mac laptop (8 failures), and 21 for lightbulb (5 failures). All responses included units, which were required as a part of the instructions.

Study 2 Results: Improved Practice

Table 4 summarizes participants' measurement practices. We saw particularly large improvements in angle measurements, and no significant improvement in length measurements. Negative and positive 1% changes are likely within the range of natural variation. When we examined the images participants submitted, we could see that some of them very carefully followed our instructions to use a flat surface during measurement, and carefully aligned the zero tick of the measurement instrument with the correct location on the item to be measured. Some new strategies we saw included: using measurement instruments with more precise units (such as *mm*), and using background lighting to help with alignment.

iPhone Length(#)	**%**	**Laptop Angle(#)**	**%**
Tape measure (10)	98.3	Digital app (10)	93.2≫
Ruler (9)	98.3	Protractor prints (5)	94.1<
Sewing tape (2)	97.7<	Protractor (3)	96.5≫
Digital app (1)	99.4		
Bulb Diameter(#)	**%**		
Tape measure (10)	94.9		
Ruler (6)	90.9>		
Sewing tape (5)	90.8		

Table 4: Range of measurement instruments and accuracy. Where possible we show comparison with the previous study (>= 1% increase; ≫= 10% increase; <= 1% decrease).

These improved practices led to improvements in average accuracy, which increased from 93% to 96.7% due primarily to an improvement in the minimum from 82.6% to 90.8%. However, not all users exactly followed the instructions, and many of the bad practices found in the first study were still repeated (Figure 7). For example, flexible measurement instruments were still bent Figure 7a, and measurement instruments were still misaligned with the target Figure 7b & Figure 7c.

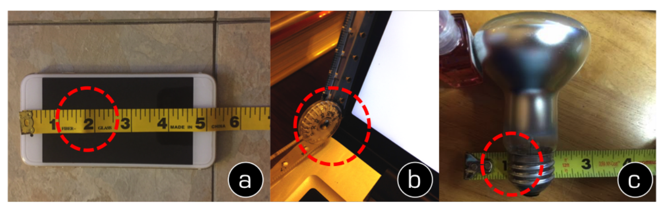


Figure 7: Participants tried to follow instructions, but still made errors. Measurement instrument is: (a) curved; (b) mis-centered; and (c) not aligned at zero tick.

Limitation of Study and Discussion

Our first study showed that measurement is a surprisingly error-prone process. Even digital tools cannot overcome all sources of error. Although accuracy is high in some cases, inaccuracies as low as 1% could still pose problems for 3D model fit, and in any case better instructions did not eliminate errors. In the end, the impact of uncertain measurement depends on the application. Certain adaptations require precise measurements to function correctly and safely, whereas others can handle some amount of imprecision. For example, some imprecision for a lampshade is acceptable, as gravity helps to hold it in place as long as it is narrower than the widest part of the bulb. Thus, a set of solutions to measurement uncertainty should function under a range of precision requirements (as well as a range of measurement error).

STRATEGIES FOR ACCOMMODATING UNCERTAINTY

As our studies have demonstrated, measurement error is likely to be an ongoing problem that better instructions or even digital measuring applications alone cannot completely solve. The current *status quo* is to work around this problem with iterations through a prototyping process. However in the realm of 3D printing, iteration can be quite costly. Novice modelers or casual users are unlikely to behave like expert designers, who are accustomed to and can afford multiple design iterations to improve a prototype. Instead, they are likely to become very frustrated after one or two failed prints.

We make a case for a new design principle—**accommodate measurement uncertainty**. We argue that designing with this principle in mind will reduce the negative impact of uncertainty and reduce iteration. We propose two accommodation strategies that can be applied not only to the design of a new model but also to the modification of an existing model. They are: *(i)* inserting modular joints for replacement of minimal parts, and *(ii)* adding flexible buffers. These strategies involve integrating geometric structure specifically for handling regions where uncertainty may arise. Such modules could either be importable modules (for novices) or quickly built from scratch (for experts). We introduce the strategies below, and present a tool in the next section which allows users to import any off-the-shelf model and insert these strategies into the model to accommodate measurement uncertainty.

Strategy 1: Modular Joint/Clamp Insertion for Partial Replacement

Inserting a modular joint or clamp allows part of an object to be replaced, or adjusted slightly, after the first print is completed. For example, a lampshade mount needs to be big enough to fit above a bulb's neck, but not slide down. This could be designed separately from the remainder of the lampshade, so that the entire lampshade does not need to be reprinted if there is a measurement error.

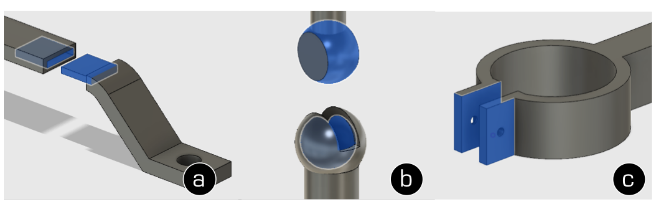


Figure 8: Joints (in blue) can accommodate uncertainty. Shown are applied examples for modifying: *(a)* length; *(b)* angle; *(d)* diameter. Both (a) and (b) support adjustment or replacement, while (c) supports only adjustment.

Joints and clamps can be characterized by the degrees of freedom they provide, and thus allow adjustments in multiple directions in addition to replacement [3]. As an exemplar of modular joints, we designed three types of joints, a simple connector (one dimension; Figure 8a and Figure 9); a ball joint (two dimensions; Figure 8b and Figure 10); and a clamp (one dimension; Figure 8c). A connector joint can also be used to make slight adjustments to length as illustrated in Figure 9, while a ball joint can be used to make adjustments to angle (without reprinting) and a clamp to diameter (without reprinting). These positions can be finalized using glue (in the first two cases) or a bolt (in the latter case). In the case of the connector and ball joint, where the model has been split into two parts, the user also has the option to reprint another version of one part as a replacement, instead of printing the whole model again (shown in Figure 8a).

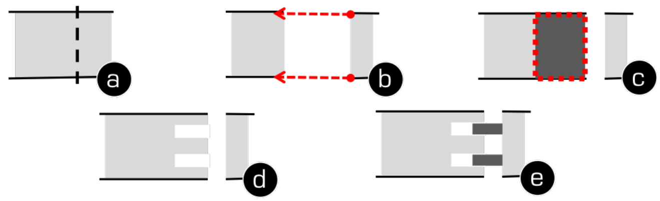


Figure 9: Operations to adjust length of a model: *(a)* Slice the model in two; *(b)* translate one part perpendicular to the slicing plane; *(c)* extend the model to fill the gap; *(d)* create female slots by subtraction; *(e)* create male joints by union.

Figure 10: Operations to insert a modular ball joint in a model: *(a)* Slice the model in two; *(b)* subtract space to create room for the joint and add the female connector; *(c)* add the male part.

To insert a joint or clamp, a model is split at the insertion point and then the male and female connectors are attached so that the model can be assembled once printed. For example, for the ball joint Figure 10, the male part would be inserted through a parallel slot, and be twisted in 90 degrees to be locked in position for later adjustment of angle (shown in Figure 8b).

The clamp is created using a pair of planks and cutting out a segment of the cylindrical part of a model. In this case, a bolt and nut are needed to pull the planks together at assembly time.

Strategy 2: Flexible Buffers

Our second strategy is a flexible buffer which can be added to a model. Such a buffer can support a small diameter or length adjustment. This structure can be printed in a soft material such as NinjaFlex. Because a different material is used, to maintain integrity of the model, it is ideal to use buffers for very small scale (millimeter) adjustments. This approach is effective for example for a cup holder or phone case.

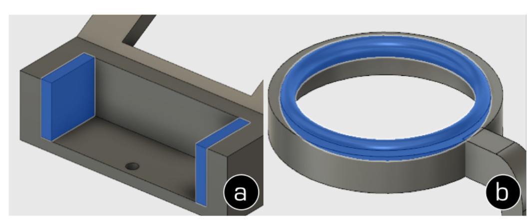


Figure 11: Two buffer designs (in blue). Shown are buffers that flex *(a)* in a linear direction and *(b)* in diameter.

We created examples for length and diameter, shown in Figure 11. The added buffer structures are highlighted in blue. If a dual-extruder printer is available, hard plastic can be used for the main structure and a flexible, soft material can be used for the second extruder for printing the buffer. Alternatively, the two structures can be printed separately and glued together. This technique is also allows replacement of the buffer if it is the wrong size without reprinting the entire object. A further advantage of the buffer approach is textural: Buffers can be designed to reduce slip.

FITMAKER: AN UNCERTAINTY ACCOMMODATION TOOL

The designs showed above represent conceptual solutions to the problem of uncertain measurement. As described, these concepts could be used by an experienced 3D model designer. However, there are thousands of 3D models online on sites such as `Thingiverse.com` that were not designed with these principles in mind. Many of these models are downloaded and used by novice modelers who have little ability to modify them (and are also more likely to make measurement errors than experienced designers).

To address this, we developed *FitMaker*—a parametric tool which allows novice modelers adapt off-the-shelf 3D models to handle uncertainty. FitMaker includes a library of modular components that modify geometries of off-the-shelf 3D models, implemented as a plug-in in open-sourced 3D modeling engine CraftML[1].

FitMaker provides a library of parameterized models for addressing uncertainty. As of now, the library includes a simple linear male-female connector, ball joint, and jigs as illustrated in Figure 8. The library is extensible, meaning that new modules for alteration of physical properties can be added. As CraftML is an open-source 3D modeling engine, any users with the skillset to model modular components with the required operations in mind, can contribute to the enrichment of the library.

Walkthrough

To demonstrate how FitMaker works, we describe a hypothetical user, Stacey, a fabrication enthusiast who has limited time and modeling skills. Stacey's daughter is having a hard time opening a sliding cabinet door because the handle is too high.

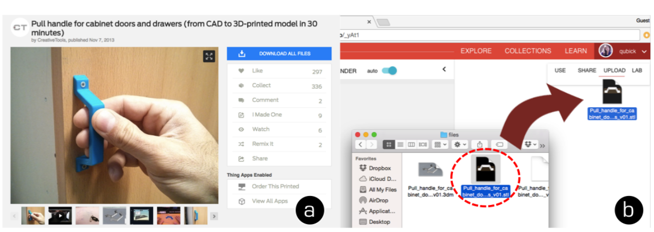


Figure 12: Stacey starts by searching for desired 3D models from online repositories, to download *(a)* and import a model. Next she loads a modular component for addressing uncertainty from the library *(b)*.

Step 1: Search Off-the-shelf 3D Models
Stacey searches for 3D handle designs from popular online resources, such as Thingiverse or GrabCad. Any 3D model available online and numerous CraftML designs could be also used. She finds a satisfying example, but is concerned that it may be the wrong size. She realizes that simply scaling it before printing will not only change the size of the handle but also the bolt hole, making its shape oval.

Step 2: Import STL and Modular Component
Instead, Stacey imports the handle model into CraftML. She clicks the *Insert* tab to search the CraftML library for a modular component that can be used to adjust length. Clicking the button "insert" from the popup browser confirms selection of the connector module.

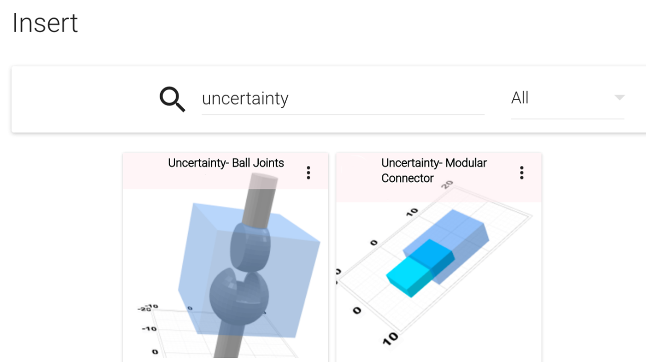


Figure 13: Stacey clicks the "insert" button to see modules available in library for handling uncertainty. Shown are the ball joint, linear joint and jigs for clamp.

Step 3: Scaling and Rotation
Once both parts are imported, Stacey has the opportunity to adjust the position of the handle and connector with sliders until they are lined up as shown in Figure 14. If the default size of the connector is too large or too small, she is also able to adjust parameter sets that define physical dimensions of the connector, as shown in Figure 15.

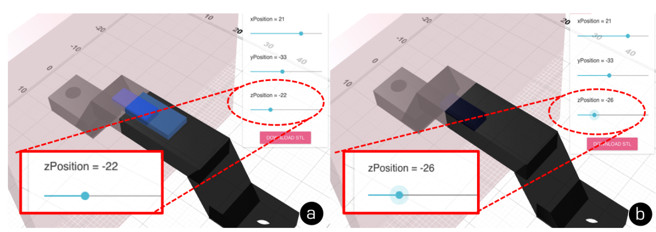


Figure 14: The connector is in the wrong place, cutting through the wall of the handle *(a)*. Stacey adjusts the z-position of the connector to place it inside the cabinet handle, by moving the slider to adjust the location of inserted module *(b)*.

Whenever parameters related to the location, rotation, and physical dimensions are adjusted, CraftML shows real-time adjustments in the model. Stacey can pan and rotate the scene to check whether the modular component is safely inserted, as illustrated in the geometry operation diagrams (Figure 9-10).

Step 4: Export 3D Models and Fabrication
When the model is ready, Stacey can export it for printing. She can assemble the handle and attach it to the cabinet door for her little daughter. If the handle turns out too short, Stacey

[1] https://craftml.io

Figure 15: Stacey widens the joint, to strengthen it, by adjusting a parameter. If she feels the inserted male connector is too narrow *(a)*, she can increase the width of both the male connector and the female slot *(b)*.

can go back to CraftML to modify the model for reprinting as shown in Figure 16.

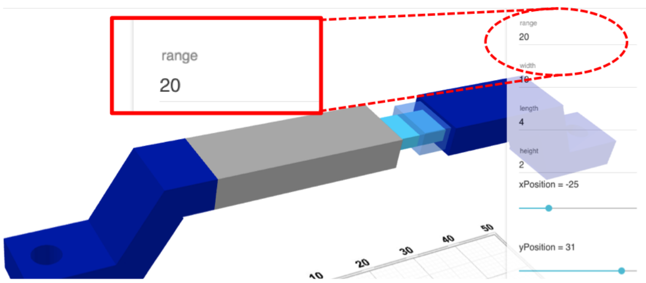


Figure 16: Stacey can modify the model for reprinting, without affecting other parts of the model. The gray part shows the extended piece, whose length is controlled by the range parameter.

Examples

To demonstrate FitMaker's usefulness in addressing uncertainty, we created a set of diverse printed examples, shown in Figure 1 on the first page. These were chosen based on real world augmentations found on Thingiverse. We focused on models that were liked more than 50 times by community members. Note that we did not test items used in our studies; those were selected because the dimensions were standard, allowing us to validate the ground truth with factory manuals and not because of their need for uncertainty accommodations. In contrast, our approach is ideal for augmenting less well defined items, such as cups, door knobs and utensils, that require measurement.

Our examples demonstrate the use of ball joints for a phone camera stand (with angle adjustment), connectors for a cabinet handle (with length adjustment), clamps for a door knob, and a buffer (with diameter adjustment).

Length uncertainty: We implanted a connector joint into an assistive cabinet handle from our scenario (Figure 1b). In the figure we show how this allows part of the handle to be reprinted if the handle is too short (the replacement part is shown in blue). This example highlights the power of the tool to reduce iteration time, allowing users to reprint partial models, rather than the entire part.

Angle uncertainty: We integrated the ball joint into a phone attachment for a tripod. This application highlights the fact that uncertainty may not only arise from user error, but also from the task. The ball joint allows repeated adjustments of angle (Figure 1a), accommodating uncertainty in how the tripod will be used in the future.

Diameter uncertainty (b): We used a buffer to create a cup holder that can accommodate diameter uncertainty. In this case, the height at which to measure may be unclear (Figure 1c). This also demonstrates a situation where uncertainty is contextual– the cup chosen in the moment.

Diameter uncertainty (a): We printed an assistive door lever with an inserted cylinder joint, to adjust diameter and clamp the knob tightly with a bolt (Figure 1d). This example highlights the potential value of combining methods – a buffer could help with a door knob that is not perfectly round and reduce slip, improving the reliability of the solution.

Discussion of FitMaker

The above four examples demonstrate the range of contexts in which uncertainty might arise, and the value of our solutions for addressing them. Here we discuss additional topics surrounding FitMaker's usage.

Need for Automation One challenge for future work is to improve the tool so that it can automatically generate modular components that are intelligent about how they integrate with existing objects. For example, a tool could automatically resize components to fit a specific model, identify an optimal location or direction of insertion, or alert the user if they intersect some other part of the object.

Solidity of Model Inserting a joint or buffer requires segmenting a model into two parts, raising concerns of mechanical rigidity. Our cabinet handle print was assembled without glue and in use in a public setting for 3 months. No fragility issues arose. A more formal evaluation could provide additional confidence in each design.

Applicability Depending on the target object's characteristics, there are limitations to the techniques that users can apply. For example, the original model might be too small to fit a ball joint or buffer. However, since the frustration of iteration mostly comes from long printing tasks, we would expect our strategies for reducing iteration time to have more benefits for large model prints.

CONCLUSIONS

We presented two studies exploring the types and degree of measurement errors for length, angle and diameter by novice modelers. We showed that measurement is an inherently uncertain process and argue that accommodating such uncertainty will make it easier for novice modelers to successfully customize physical augmentations to real world objects. To this end, we presented two accommodation strategies for modelers and developed a parametric tool for novices to insert these strategies into existing off-the-shelf 3D models. We demonstrated through a series of examples how such strategies might be used.

ACKNOWLEDGMENTS

This research is supported by NSF Grant No. IIS-1453771.

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