Measurement Patterns: User-Oriented Strategies for Dealing with Measurements and Dimensions in Making Processes

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ABSTRACT

The majority of errors in making processes can be tracked back to errors in dimensional specifications. While technical aspects of measurement, such as precision and speed have been extensively studied in metrology, the user aspects of measurement received significantly less attention. While little research exists that specifically addresses the user aspects of handling dimensions, various systems have been built that embed new interactive modalities, processes, and techniques which significantly impact how users deal with dimensions or conduct measurements. However, these features are mostly hidden in larger system contributions. To uncover and articulate these techniques, we conducted a holistic literature survey on measurement practices in crafting techniques and systems for rapid prototyping. Based on this survey, we contribute 10 measurement patterns, which describe reusable elements and solutions for common difficulties when dealing with dimensions throughout workflows for making physical artifacts.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; *Interaction paradigms*; *HCI theory, concepts and models*; • **General and reference** → *Surveys and overviews*; *Measurement*.

KEYWORDS

Fabrication, Making, Measurement, Patterns

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1 INTRODUCTION

Every maker or craft practitioner knows the feeling of frustration during their workflows when parts do not fit together. While some errors can be compensated in subsequent steps, resulting in a minor impact on the final artifacts, in many cases, several parts or the entire object must be discarded. While accomplished makers live by the ethos "Measure Twice, Cut Once" [80], novice makers often struggle to identify the importance and required precision of measurements [8, 9], and its impact on the final outcome [37]. Some errors can be traced back to human mistakes in reading, recording, or calculating, while other errors are harder to trace. Popular examples of less obvious sources of errors include inaccurate calibration of measurement instruments or fabrication equipment or errors caused by environmental effects, such as temperature or humidity. Taking all characteristics into account that might contribute to errors requires significant expertise. Even minor mistakes in dimensions at the early stage of making can propagate through the entire workflow and result in major flaws which only surface at the end when the result does not meet the expectations. In such situations, users face an additional investment of time, material, and effort expenditure for another design iteration.

With the increasing availability of digital fabrication tools, such as 3D printers, laser cutters, and CNC milling machines, one might argue that it becomes easier to fabricate objects with high precision. The opposite is often true, however, as digital fabrication processes require detailed upfront specifications of models before the fabrication process starts. In contrast, during traditional craft practices such as woodworking, design decisions are more ad-hoc and errors or inaccuracies can oftentimes be compensated for in subsequent steps [39].

In contrast to the greater success in engineering and metrology of studying and improving technical aspects of measurement, such as accuracy, cost, and speed [86], the user aspects of measurements and handling dimensions have not received as much attention. For example, how easy is it for actual users to utilize a measurement instrument and get a correct reading? How convenient is it for them to transfer dimensions between digital representations and physical artifacts? Do users understand all implications when choosing a dimension? In the field of HCI and fabrication, Kim et al. [37] observed various types of errors when novice makers measure dimensions of physical artifacts. While only little such research in HCI exists discussing the topic of measurement directly, various systems have been built that embed new interactive modalities and processes, which significantly impact how users deal with dimensions or conduct measurements. For example, systems that automatically inject measurements in CAD models [88], the use of gestures and body measures to express desired dimensions [44], or the use of module building blocks [46] and jigs [47], and 3D scanners [90] to avoid measuring with traditional instruments that are error-prone. While each of these systems presents significant engineering contributions, the implications of these system design decisions on how users deal with dimensions through a workflow are less well recognized as they are often hidden in larger system contributions.

To uncover and articulate techniques to facilitate measurement and handling dimensions, we conducted a holistic literature survey on measurement practices in crafting techniques and systems for rapid prototyping. Based on this survey, we contribute 10 measurement patterns, which describe reusable elements and solutions for common difficulties when dealing with dimensions throughout workflows for making physical artifacts. In contrast to the field of metrology, focussing solely on technical aspects of measurements, measurement patterns offer a structured way to think about measurement-related challenges and solutions from a user perspective and thus offer value in various situations. First, our collection of patterns are useful when engineering novel systems for making, which is similar to how one considers design and interaction patterns when engineering software systems. Second, measurement patterns can be used to understand, review, and improve how users handle dimensions in existing systems. Third, measurement patterns also include practical, even commercially available solutions, that are helpful for makers to simplify handling dimensions while making. Fourth, our literature survey which analyzes articles and systems from the perspective of measurement, offers a starting point for discussion and future work in this area.

The focus of this paper is on dimensional measurements, which include among others, lengths, distances, angles, straightness, and roundness [21, 57]. We examine how dimensions are used throughout crafting and prototyping workflows which, besides sole measurement activities, also include how dimensions are established, transferred, and used. Within the scope of this project, we do not focus on measuring other important base or derived SI units that are relevant to making, such as mass, energy, temperature, or time.

2 BACKGROUND ON DIMENSIONAL MEASUREMENTS

The rate of technological progress throughout history has close ties with the progress in measurement. Archaeological evidence dating back to 2900 B.C. shows that mankind already discovered that for measurements to be useful, standard units need to exist[1]. While originally units were based on body measures of superiors, such as the length of a pharaoh's forearm (the cubit) or the weight of a king, more precise and universal standards were needed to mitigate disputes in trade. Throughout these advancements and the introduction of the international Systems of Units (SI), and the derived imperial unit system, the field of metrology became more established and is concerned with the enforcement, verification, and validation of predefined standards [57]. In practice, metrology also deals with developing methods of measurement, analyzing the accuracy of methods, defining uncertainties in measurement, and investigating the causes of measuring errors and subsequently eliminating them.

The importance of measurement standards and accuracy increased further during the industrial revolution. This time saw a transition from artisan-produced articles in small shops, often referred to as the cottage industry, to mass-produced products in large factories. In contrast to artisan-produced parts that are fine-tuned until they fit, mass manufacturing requires the precise and repeated production of individual parts that have to fit together [4, 68]. Over the past century, thousands of instruments for dimensional measurements have become commercially available, of which the majority are intended for industrial applications [35]. To get a grasp on such a large number of instruments and measurement techniques, various classifications exist in metrology. Some are based on technical characteristics of the method [57], such as whether a quantity is measured directly (i.e. direct measurements) or derived from other related quantities (indirect measurements), while other classifications are based on cost, application, level of precision, or speed [36, 82].

In the mid-twentieth century, the increasing quest for precision parts in weapons and airplanes led to the development of CNC machines [53]. These machines further prioritized precision, repeatability, and upfront design. Over the past decade, digital fabrication machines, such as CNC milling machines, 3D printers, laser cutters, and associated CAD modeling software have become widely available and affordable for makers. While these tools facilitate several aspects of a fabrication workflow, such as avoiding laborious manual craft, they stimulate makers to provide specifications for prototypes using the levels of precision needed in industry. The majority of makers, however, rarely engage in mass manufacturing and especially during the prototyping stages, several exact dimensions might not be known yet or might not even be important.

3 USER ASPECTS OF MEASUREMENTS AND HANDLING DIMENSIONS

As discussed in the previous section, the field of engineering metrology significantly focuses on the technical aspects of measurements. Efforts in metrology focusing on user aspects are mainly concerned with offering more precise readouts, such as the use of dials on calipers instead of vernier scales, or studies on the impact of motor skills on the accuracy of measurements [10]. Early studies on measurement in the field of HCI [37] show that manual measurement and human involvement in the process are one of the main sources of errors. Novices, for example, frequently align measurement instruments incorrectly, even maneuver equipment inappropriately due to a lack of skills and awareness. Besides the actual measurement activity, prototyping and crafting workflows include more activities in which users have to handle, or are confronted

[1]http://msc-conf.com/history-of-metrology

with, dimensions. Examples include, establishing new dimensions, understanding the impact of dimensional choices, converting dimensions between models and artifacts, and taking into account characteristics of fabrication equipment or materials while defining dimensions.

While little research in HCI directly addresses the topic of measurement and dealing with dimensions, various systems have been built that embed new interactive modalities and processes that significantly impact how users deal with dimensions or conduct actual measurements. Examples include, the Moasure system[2] to facilitate and partially automate measurement using IMU sensors and StrutModeling [46] and MixFab [90] that allows for specifying dimensions of shapes using physical objects. These more creative practices for handling dimensions and dealing with precision are oftentimes hidden in larger system contributions and, in contrast to measurement in metrology, are not yet well understood, recognized, or classified. While some of these strategies offer less precision compared to traditional measurement instruments, they ease measurement as they do not originate from metrology and the quest for precision. Our goal is to identify patterns that ease handling dimensions, based on features and tools, embedded in systems for prototyping and crafting artifacts.

4 METHODOLOGY FOR DEFINING MEASUREMENT PATTERNS

4.1 Dataset and Inclusion Criteria

To define measurement patterns, we looked at existing strategies for dealing with dimensions in crafting and prototyping processes. We used an interpretive research approach [87] and started creating a corpus of literature on processes, systems, and tools for crafting and prototyping. We searched for well-known practices and commercially available systems and tools in crafts and prototyping via Google Search and crowdfunding platforms, such as Kickstarter and Indiegogo. Our search terms included all possible combinations of prototyping, fabrication, craft, measurement, making, and modeling. We then expanded the search using synonyms that appear in the resulting articles of our initial search. Next, we also browsed through books on measurement in crafts [14, 50] as well as more specific craftsmanships, such as woodworking [49, 80] looking at domain-specific procedures or tricks to facilitate measurement. Finally, we searched for state-of-the-art academic literature on crafting and prototyping via Google Scholar, the ACM Digital Library, and IEEE Xplore while using the same search terms as earlier in Google Search.

4.2 Analysis and Synthesis

This extensive search resulted in 36 concrete, practical tricks or tools to facilitate dealing with dimensions and measurements, that we listed in a table. In addition, the literature survey resulted in 157 articles about state-of-the-art systems. Each of these articles presented novel systems or workflows for crafting or prototyping and possibly embedded none, one, or multiple strategies for measurements. Two of the authors independently went through all articles and looked at these articles from the perspective of measurement. This means that we looked beyond the core contribution of these articles and extracted aspects, procedures, or tricks that deal with dimensions or measurements. We completed our table using these novel entries, resulting in 127 entries in total. As many entries include specific features in a large system contribution without a specific code name, we entered descriptions and a representative figure from the article or demonstration video.

In the next stage, two authors independently performed an open-coding process [16, 40] on the 127 entries in our table describing measurement-related challenges they address as well as the essence of the solution represented by the entry. We then collectively reflected on all codes and grouped entries based on common challenges that are addressed as well as the similarity of solutions they represent. Over several group discussions, we then iteratively worked towards 10 overarching strategies that formed the basis of our measurement patterns. We then further defined each measurement pattern by elaborating on what it entails and the measurement challenges it addresses.

5 WHAT ARE MEASUREMENT PATTERNS

Similar to design patterns, used in software engineering [24] and interface and interaction design [79], which describe reusable elements and solutions that can be re-applied for similar contexts and goals, we believe strategies can be developed for dealing with dimensions in systems and workflows for crafting and prototyping. Although we refer to our patterns as *measurement* patterns, they do not solely comprise strategies to facilitate the actual measurement activity. Instead, measurement patterns are strategies for commonly occurring difficulties when dealing with dimensions throughout workflows in which physical artifacts are created. This includes among other techniques for establishing dimensions, understanding the implications of dimensions, transferring dimensions, and considering less well-known fabrication characteristics.

Well-designed systems often implement multiple measurement patterns. Hence, different features of the same systems are frequently used as examples across patterns. When detailing the pattern, we refer to the specific features of a system that implement the respective pattern. Apart from the measurement-related problems that are addressed, strategies presented in measurement patterns can have additional benefits unrelated to handling dimensions, which are not covered in our pattern description. For example, shapes of existing physical objects can be used to make precise fits without explicit measurements (*Pattern 6: Designing with Existing Objects*). As a side effect, this tangible modeling paradigm circumvents traditional CAD modeling operations, often presenting a high barrier to beginners.

Our measurement patterns mainly focus on *process* related aspects, including the benefits and challenges for users when adopting the strategy. Our discussion focuses less on the impact these novel measurement strategies have on the resulting *products*, such as the dimensional accuracy of the resulting artifact. These product-related aspects largely depend on the specific version of the technology that was used at the time of implementation, such as the resolution of a depth camera used for 3D reconstruction (e.g., MixFab [90]).

[2]https://www.moasure.com/

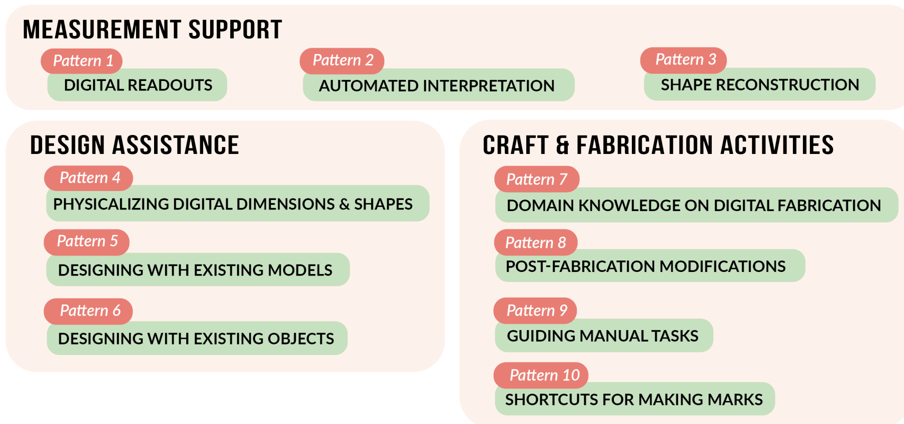

Figure 1: An overview of the 10 Measurement Patterns. The patterns are grouped into three clusters: Measurement Support, Design Assistance, and Craft and Fabrication Activities

To further structure the presentation of the 10 measurement patterns, we grouped them into three clusters based on when the patterns ease the process of measurement in a typical design-then-fabricate prototyping process. As shown in Figure 1, the first three patterns cover techniques that can support actual measurement activities throughout an entire prototyping process. The next three patterns facilitate dealing with dimensions during design workflows. The last four patterns present techniques to ease or avoid measurement activities during craft and fabrication stages of making processes. Every cluster also includes an agenda for future research that is uncovered by the patterns.

Measurement patterns are introduced using the following structure. First, we offer a generic description of the solution presented in the pattern (*What*). Next, we cover the specific measurement challenges addressed by the pattern (*Measurement Challenges it Addresses*). Afterward, a more extensive section, *How to Use*, offers several examples that demonstrate how this pattern can be, and already is, used in a wide range of systems. Finally, we give a brief overview of *Related Patterns* that can be used in combination or offer alternative strategies to address similar measurement challenges. We also use this section to disambiguate similarities with other patterns.

6 MEASUREMENT SUPPORT

The three patterns presented in this section cover techniques to facilitate the process of conducting a dimensional measurement. More specifically, they work towards addressing important challenges users often experience when measuring, such as the correct reading of measurements from instruments, transferring of measured values, and the correct alignment of measurement instruments [37]. We consider traditional analog dimensional measurement tools, such as rulers and calipers, as a baseline during this presentation.

6.1 The Patterns

PATTERN 1: DIGITAL READOUTS

What
Digital readouts of measurement instead of analog readings. This digital reading can be displayed on the measurement instrument itself or on an external device, such as a smartphone or computer.

Measurement Challenges it Addresses
Traditional analog measurement instruments require careful reading to see which tick marks align. These measurement tools often require users to master protocols for reading and handling the instrument appropriately to obtain reliable results. For example, an analog vernier caliper requires combining readings on the main scale with the vernier scale. Solutions covered in this pattern offer numerical readouts that simplify and speed up the instrument's overall operation and reduce reading errors compared to similar measurement instruments offering analog readings.

How to Use
Digital versions of many analog measurement instruments exist, such as calipers (Figure 2a), micrometers, protractors, and tape measures[3]. Digital readouts also facilitate supporting features to permanently or temporarily store readings, such as a "lock" to freeze the current reading and avoid accidental errors when releasing the measurement tool from the workpiece. In addition, many digital measurement instruments automatically convert units or even apply pre-configured scales, such as digital curvimeters. Today's smartphones, with embedded sensors, are also frequently used as digital measurement instruments (Figure 2c).

As shown in Figure 2b, digital measurement instruments are frequently used in combination with crafting tools, for example, to measure the bevel angle of a table saw. Crafting tools can also embed or be retrofitted with measurement tools[4] to further streamline workflows.

Related Patterns
This pattern solely focuses on the digital readout of a measurement.

[3]https://etape16.com
[4]https://www.reekon.tools

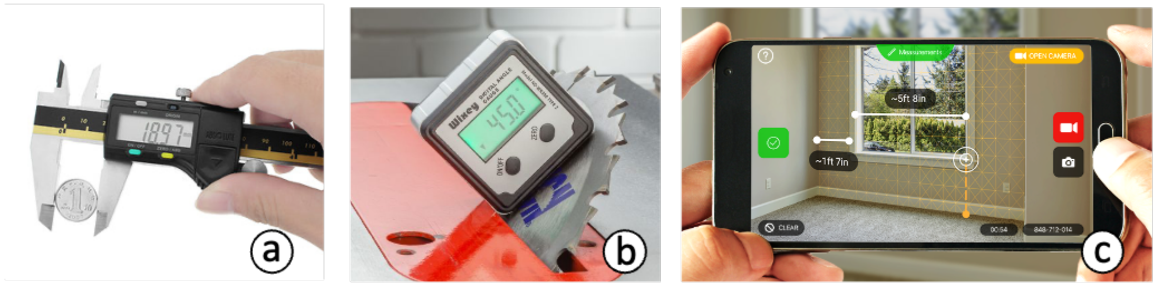

Figure 2: Digital Readouts (*Pattern 1*) of measurements using (a) digital calipers, (b) digital angle gauge (Figure adapted from Lareo [41]), (c) smartphone with measurement app (Figure adapted from Cadbull [13])

Automated interpretation of measured values or associations between multiple measurements is covered in *Pattern 2: Automated Interpretation* .

PATTERN 2: AUTOMATED INTERPRETATION

What

Measurements are automatically interpreted and drive parameters in a digital environment without manually reading or transferring the measurement.

Measurement Challenges it Addresses

Traditional digital or analog measurement tools require users to correctly read and transfer measurements. In both stages, errors might occur as users can incorrectly read measurements as well as translate measurements to a modeling environment. Additionally, automated handling of measurements bypasses continuous switching between different devices and units, such as a measurement instrument and a sketch or digital modeling environment. This pattern thus avoids errors that happen when reading or transferring measurements from a measurement instrument.

How to Use

Some laser distance measurement tools embed basic instances of this pattern by offering functionalities that automatically calculate derived measurements, such as the area or volume, from several distance measurements. In these systems, only the result is interpreted by the user instead of individual distance measurements. A wide variety of systems also exist that combine individual length measurements to precisely digitize complex contours. Examples include Moasure[5] for digitizing outdoor spaces by integrating sampling points as shown Figure 3d and the LT-2D3D Laser Templator[6] for digitizing a countertop by sampling the corners as shown in Figure 3b.

The electronically enhanced tape ruler, HandSCAPE [45], offers a more elaborate implementation of this pattern. In this system, measurements directly drive the dimensions of objects in a digital environment. HandSCAPE infers the dimension that is measured through an embedded IMU sensor. SPATA tools [88] and "Of Instruments and Archetypes" [84] take a similar approach and augment vernier calipers and protractors with sensors to automatically inject dimensions in CAD models which thus automatically resize (Figure 3a). Instead of using instruments optimized for high levels of precision, systems for more coarse prototyping of objects can also leverage this pattern. BodyMeter [44] and ultrasonic glove [31], for example, allow for determining the sizes of furniture using gestures. Sizes represented by those gestures, such as stretching both arms as shown in Figure 3c, combined with simple voice commands, drive the dimensions of a digital model of a desk.

Related Patterns

While reading measurements is also facilitated by *Pattern 1: Digital Readouts* using digital readouts, solutions presented in this pattern eliminate human reading and interpretation of measurements as individual measurements are automatically interpreted by a system.

PATTERN 3: SHAPE RECONSTRUCTION

What

Measuring the dimensions of an object by digitally reconstructing the shape of the object.

Measurement Challenges it Addresses

Traditional measurement instruments, such as rulers and calipers, require precise and correct alignment of the instrument with respect to the object. This alignment procedure is oftentimes error-prone, especially when measuring complex shapes [37]. Instead of measuring an object by requiring the alignment of measurement instruments for every single measurement, this pattern covers strategies to digitally capture the shape of an object, including its sizes, at once. Measurements are then extracted from these digital models, or the model itself can be used in a digital environment for further refinement and processing. This pattern also prevents reading and conversion errors as measurements are not handled by users.

How to Use

Various approaches exist to digitize physical objects. Contact-less approaches include optical systems, such as X-ray tomography, magnetic resonance imaging, depth cameras, LiDAR sensors, or photogrammetry techniques that leverage multiple photos of the same scene (Figure 4b). Many of these systems, such as 3D scanners, have become increasingly affordable and accessible over the past decade, albeit the precision oftentimes depends on the hardware,

[5] https://www.moasure.com
[6] https://www.laserproductsus.com/lt2d3d

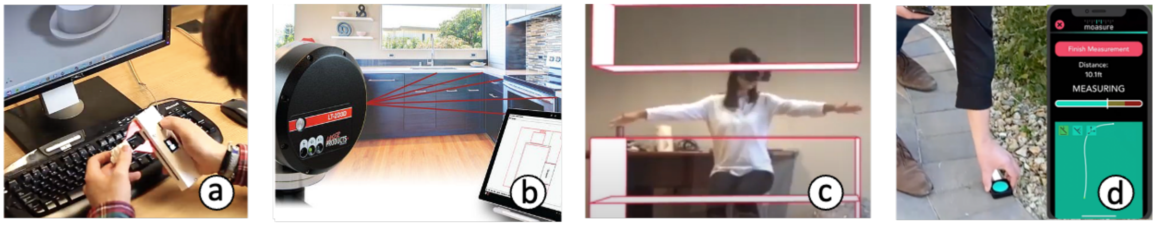

Figure 3: Automated Interpretation (*Pattern 2*) of measurements using (a) augmented vernier calipers (figure adapted from Weichel et al. [88]), (b) a system to digitize intricate contours, such as a countertop[6] (Figure adapted from Evolution Marble [48]), (c) gestures for indicating dimensions (Figure adapted from Lee et al. [44]), (d) a measuring device to digitize complex contours (Figure adapted from Moasure[5]).

the lighting, and material properties. Despite the popularity of 3D scanners, some designers still leverage a 2D flat-bed scanner to digitize dimensions, contours, or proportions of hand drawings or flat imprints of objects. The scanned 2D artifacts typically result in vector drawings that serve as the basis for 3D modeling[7].

In contrast to optical 3D scanning approaches for capturing the contour of objects, Coordinate Measuring Machines (CMM) physically probe the surface of an object. These high-end machines are mainly used in engineering metrology to precisely verify the tolerances of an object with respect to ground truth data (Figure 4a). This typical use of CMM machines often requires a reference 3D model, embedding all measurements. Some CMM machines, however, also support reverse engineering applications in which every detail of an object is probed to reconstruct a 3D model similar to optical 3D scanning approaches.

Shape reconstruction allows for digitizing objects with intricate shapes without requiring manual measurements. Therefore, these setups have been used extensively in the field of HCI to facilitate 3D modeling. Representative examples include MixFab [90], Maker's Mark (Figure 4c) [64], What you sculpt is what you get [33], and KidCAD (Figure 4d) [23]. 3D reconstruction techniques have also been embedded in subtractive digital fabrication machines, such as CNC milling machines [17]. When deployed in these systems, the position, size, and location of holes can be sensed without requiring manual measurements. This information can then be used to precisely position toolpaths with respect to the workpiece without requiring individual user measurements.

Related Patterns

This pattern has similarities with *Pattern 2: Automated Interpretation* that also covers strategies to process measurements automatically. However, solutions covered in this pattern do not require any individual user measurements as the full reconstruction of the object's shape, embedding its dimensions, is created. Furthermore, it is also possible to implicitly use the dimensions of the 3D reconstructed model in modeling operations covered in *Pattern 5: Designing with Existing Models* .

[7] https://www.scan2cad.com/

6.2 Future Research Directions

While the techniques discussed in the three patterns above offer support for measuring, we see several directions for further research in this area. First, similar to technology support for reading (*Pattern 1*) and interpreting (*Pattern 2*) measurements, future generations of measurement tools can offer further assistance to ensure proper usage by novices, such as guiding the alignment of measurement tools. Especially when measuring non-flat or malleable surfaces, technology assistance can bridge knowledge gaps users might have. We envision that such measurement support systems in the future empower, for example, caregivers to precisely measure the hands of people with special needs as input for making custom tools. As the first step in this direction, measurement tools could detect the type of object that is being measured to offer in context guidance. For example, measurement apps on smartphones could assist in precisely measuring a bolt when the system knows a bolt is being measured.

Second, extracting specific dimensions from existing mesh models or models resulting from 3D reconstructions (*Pattern 3*), is oftentimes challenging as many CAD environments only support features to measure the bounding box or the bird's-eye distance between selected vertices for mesh models. While the latest research in computer graphics and CAD explores the automatic conversion from meshes to boundary representations (B-reps) [11], we believe there are opportunities to invent novel easy-to-use digital equivalents of measurement tools for mesh measurements.

7 DESIGN ASSISTANCE

This second cluster covers three patterns to facilitate dealing with dimensions during the design process. These patterns ease measurements by combining strengths from the digital and physical world, oftentimes involving the conversion of physical to digital or vice-versa. As such, these patterns can be useful when realizing a digital design as well as a design on a physical medium. In line with this, Baudisch and Mueller [6] articulated that analog-to-digital and digital-to-analog conversions can often help in fabrication tasks. The patterns covered in this section more specifically show that converting between the physical and digital world also facilitates dealing with dimensions.

Figure 4: Shape Reconstruction (*Pattern 3*) of physical objects using (a) Coordinate Measuring Machines (figure adapted from Centroid CNC [15]), (b) a 3D scanner (figure adapted from bangkokscan [5], (c) a 3D reconstruction of clay model (figure adapted from Savage et al. [64]), (d) the shape of a physical object to create a digital design (figure adapted from Follmer et al. [23]).

7.1 The Patterns

PATTERN 4: PHYSICALIZING DIGITAL DIMENSIONS AND SHAPES

What

Physically representing a digital dimension, contour, or the shape of an entire object to get a better understanding of a digital dimension or shape in relation to existing real-world objects, the environment it will reside in, or the material the object will be created from.

Measurement Challenges it Addresses

When specifying the dimensions of a model, it is often hard to get a feel for how big or small dimensions are with respect to existing real-world objects. For example, once fabricated, an object can turn out too small or too big, demanding additional design iterations to fine-tune dimensions further. To physically represent dimensions, designers frequently take out a ruler or a vernier caliper to roughly see how big or small a dimension actually is. This is however cumbersome as one has to envision the dimension of an existing measurement instrument, outside the context of the rest of the object. In such situations, it is helpful to use techniques covered by this pattern to physicalize dimensions, contours, or the entire 3D model in the real world.

How to Use

While digital fabrication machines, such as laser cutters, milling machines, 3D printers, and vinyl cutters can be used to physicalize dimensions, 2D contours, and 3D shapes, these machines require precise specifications and are time-consuming to use as they are optimized for producing high-quality artifacts. Several novel systems, therefore, include features for more rapid physicalization of measurements, contours, or objects during the design workflow.

SPATA tools [88] embed actuators in vernier calipers and protractors to physicalize lengths and angles present in a modeling environment. Physicalizing a 2D contour or dimensions in a single plane is also done by printing the design at a real scale on a sheet of paper. As shown in Figure 5c, such printouts are frequently used in crafting activities to transfer toolpaths precisely to stock materials without requiring measurements. While this approach is also useful to verify whether a part will fit the remaining space on stock material, some subtractive fabrication machines embed a projector to preview an object's outline on top of stock material [58, 93].

Going further, a number of robotic systems have been built to render 3D objects rapidly. ShapeBots [74], for example, supports features to physically preview skeletons of basic CAD models (Figure 5a). A large number of shape displays have been built with varying resolutions to preview entire 3D volumes [71]. One notable example is Dynablock [73] which supports rapid shape physical formations with undercuts (Figure 5b). In contrast to robotic actuators, researchers also proposed using digital fabrication machines to preview CAD models. Reform [89] embeds CNC milling features to physicalize models in clay and WirePrint [51] accelerates FDM 3D printing to preview shapes of digital models in the real world. While systems supporting robotic actuators inside the materials are generally faster in rendering shapes, systems leveraging digital fabrication technologies offer more resolution.

Related Patterns

Physical representations of digital dimensions, contours, and models can in turn further facilitate dealing with dimensions by designing around these artifacts (*Pattern 6: Designing with Existing Objects*), and by using these artifacts to constrain manual tasks (*Pattern 9: Guiding Manual Tasks*) or to create precise marks (*Pattern 10: Shortcuts for Making Marks*).

PATTERN 5: DESIGNING WITH EXISTING MODELS

What

Instead of modeling a digital object by creating new shapes and dimensions, the model is designed *in relation to* existing models with known dimensions. The shape of the existing digital model thus serves as a reference.

Measurement Challenges it Addresses

Artifacts rarely stand on their own. Objects stand next to other objects or fit in a specific space in an environment. In the maker community, Ashbrook et al. [3] referred to designing models that extend other real-world objects as "augmented fabrication". Matching the sizes or shapes of an existing object traditionally requires many measurements. This pattern covers techniques to design models by leveraging the size and shape of existing digital objects.

How to Use

Existing digital models can be used in a variety of ways to design

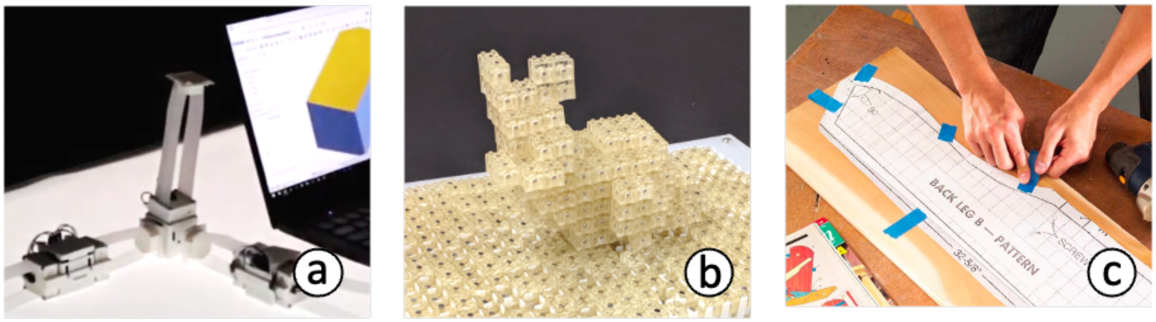

Figure 5: Physicalizing Digital Dimensions and Shapes (*Pattern 4*) using (a) a swarm of self-transformable robots to preview basic CAD models (figure adapted from Suzuki et al. [74]), (b) shape formation systems (figure adapted from Suzuki et al. [73]), (c) a 2D printout of the desired object used as a template (figure adapted from Family Handyman [30]).

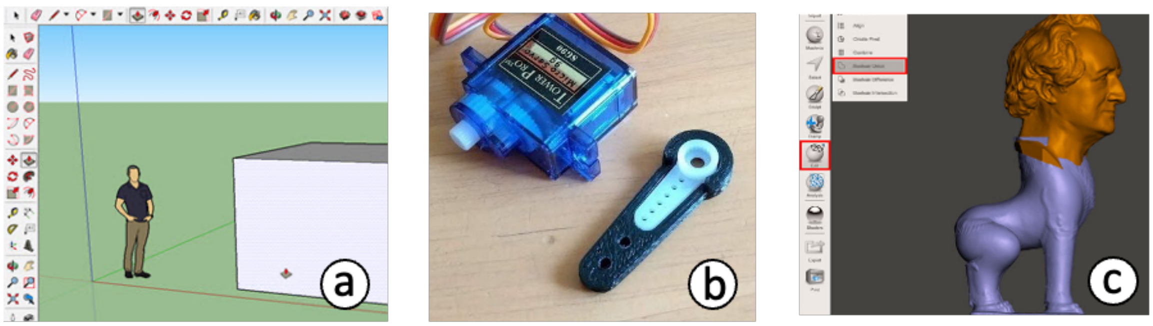

Figure 6: Designing with Existing Models (*Pattern 5*) using (a) a human figure as reference used in Sketchup[8], (b) Boolean subtract operations to mate shapes and ensure a tight fit (figure adapted from Cults3D ©Peaberry [18]), (c) merge operations in Autodesk Meshmixer [65] to combine shapes.

new objects. At a very minimum, existing digital models can serve as a reference for verifying the overall sizes of a model. SketchUp[8] and Kyub [7], for example, respectively show a human figure (Figure 6a) and a coffee mug as reference model. This is similar to how one estimates dimensions using reference objects or body parts, such as steps of 1 meter or a dollar bill.

Specific features of existing models can also be used to establish a new design. For example, attachment holes in an existing model of a bracket for a motor can be projected onto a new design to precisely match the layout of the holes without measuring. Alternatively, one can also use a Boolean subtract operation, available in many CAD environments, to exactly mate the shape of an existing object and ensure a tight fit (Figure 6b). Especially for Commercially-Off-The-Shelf (COTS) products, an increasing number of highly detailed CAD models become available via manufacturers and distributors, such as McMaster-Carr[9] or through CAD community platforms, such as Thingiverse[10] and GrabCAD[11].

Another popular modeling technique that fits this pattern is to adapt parts of an existing 3D model into a new model. Within the maker community this is oftentimes referred to as patching or remixing objects [22, 54, 69]. For example, to design a custom horn for a servo motor, one can merge a custom-designed shape with a CAD model of a standard servo horn available online[12]. Without taking any measurements, the resulting horn design will precisely fit the servo. Niche CAD environments have become available that prioritize features to mix and patch existing objects (Figure 6c), in contrast to, designing objects from scratch and specifying new dimensions [63, 65].

Related Patterns

When a physical object is available instead of an existing digital model, *Pattern 3: Shape Reconstruction* can be used first to devise a 3D digital reconstruction and later apply this pattern for creating other related digital models. Alternatively, *Pattern 6: Designing with Existing Objects* can be used to design directly in relation to the existing physical object.

[8]https://www.sketchup.com
[9]https://www.mcmaster.com
[10]https://www.thingiverse.com
[11]https://grabcad.com
[12]https://www.thingiverse.com/thing:2484552

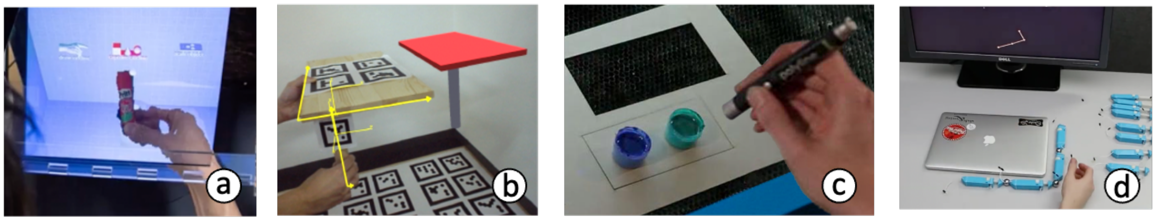

Figure 7: Designing with Existing Objects (*Pattern 6*) using (a) Augmented Reality environments to shape and preview models in relation to physical objects (figure adapted from Weichel et al. [90]), (b) tangible primitive shapes (figure adapted from Lau et al. [43]), (c) reference objects to trace a toolpath (figure adapted from Meuller et al. [52]), (d) tangible modeling using struts and hubs (Figure adapted from Leen et al. [46]).

PATTERN 6: DESIGNING WITH EXISTING OBJECTS

What

Modeling in the physical environment by leveraging shapes and dimensions of existing physical objects. This pattern covers two classes of frontier technology: mixed-reality modeling and tangible modeling.

Measurement Challenges it Addresses

Precisely designing a digital model to fit an existing real-world object or available space in an environment requires many precise measurements and design iterations. By designing a model at full scale, using for example mixed-reality or tangible modeling tools, the sizes or shapes of existing physical objects or available spaces can be matched by aligning the digital model with the physical environment. As such, many measurement steps and potential measurement errors are avoided.

How to Use

A wide variety of mixed reality modeling systems exist in which models can be designed at real scale, using spatial 3D input, for example, to fit an existing object or an available space in an environment [26, 96]. MixFab [90] and Mix&Match [70], for example, contribute augmented reality environments in which digital models are shaped and previewed in relation to existing physical objects (Figure 7a). Similarly, RoMa [56] demonstrates how one can trace around a person’s finger in mixed reality to specify the size and shape of a teapot ear. LÁrtisan Électronique [83] uses the real-world environment as a reference and allows for shaping pots at actual scale using hand gestures. Instead of using hand gestures or virtual reality controllers, other relevant input modalities have been explored to design in the context of existing physical objects. Situated Modeling [42], for example, tracks tangible primitive shapes that are used as stamps to compose digital models in the context of existing physical objects or the available space in an environment (Figure 7b). Modeling-in-Context [43] allows users to design 3D models by sketching objects on top of a 2D photo of an environment. An accurate 3D model is then created from the 2D sketch lines once the user specifies geometric constraints between lines and the dimension of a single edge. We also identified this pattern in a feature of the Constructable system [52] that allows users to define the toolpath for cutting a hole by tracing around an existing cup that will precisely fit inside (Figure 7c).

This pattern also covers techniques that are often referred to as *tangible modeling* in design and HCI communities. These systems allow for modeling objects in physical space by crafting with materials or primitive shapes after which a 3D digital reconstruction of the object is created. Some systems offer raw materials, such as clay [27, 33, 64, 89] or paper [92] for designing a physical shape while other systems offer primitive shapes that can be composed as building blocks [25, 28, 32, 46]. Some systems are developed for designing surface models [28, 32] while others optimize for skeleton models [20, 46, 91]. Some systems allow for shaping materials by hand while other systems require manual tools, such as a knife [92] or a hand-held filament extruder [76].

Some systems use generic 3D reconstruction techniques, covered in *Pattern 3* , to digitize the tangible shape and construct the digital model [64, 90]. Other tangible modeling systems seamlessly embed tracking using electronics [25, 32, 46, 92]. Also the speed and thus the frequency of updates in this digitization stage varies across systems. Some systems offer digital reconstructions of 3D objects in real-time, such as StrutModeling [46] shown in Figure 7d. Other systems only digitize the shape once when it is finalized [33, 64].

Related Patterns

Pattern 3: Shape Reconstruction is often used in tangible modeling and mixed-reality modeling environments to digitize respectively a crafted tangible model or an existing physical object. In turn, the resulting digital model can help when designing other models as presented in *Pattern 5: Designing with Existing Models* .

7.2 Future Research Directions

The discussion of the three patterns on design assistance open several novel directions for future research. First, besides the use of actuators, physicalizing digital dimensions and shapes can also be achieved using digital fabrication machines, as discussed in *Pattern 4: Physicalizing Digital Dimensions and Shapes* . One should however avoid fabricating a complete first version of the design as a way of physicalizing all dimensions for easy verification. Such a full design iteration requires more significant time and material investments compared to fabricating small templates that physicalize several dimensions of a design. Modeling environments in

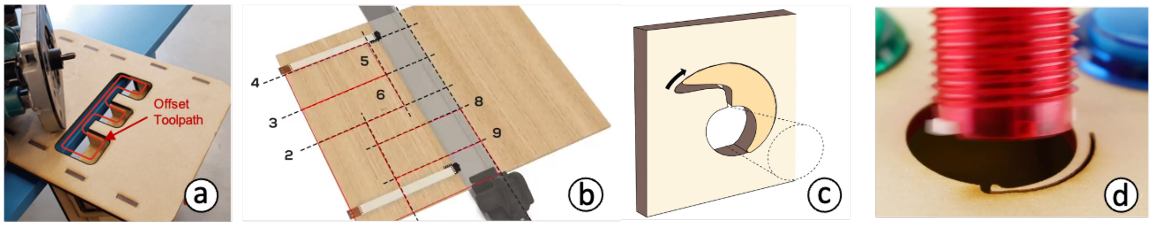

Figure 8: Domain Knowledge on Digital Fabrication (*Pattern 7*) using (a) automatically generated toolpaths that compensate for the copy ring of a plunge router [47], (b) knowledge about the guillotine cut restrictions during nesting, (c-d) springs and adjustable mechanisms to ensure a tight fit of laser cut joints and assemblies (figures adapted from Roumen et al. [61, 62]).

the future could guide users in extracting and realizing minimalistic templates that are fast to physicalize and allow for effective verification of dimensional choices.

Second, feature-based modeling using 2D sketches and 3D modeling operations is the dominant technique for precision engineering modeling in CAD. In contrast, more research is needed on techniques for precise 3D modeling in mixed reality. As covered in *Pattern 6* , existing physical objects can help in establishing the dimensions of a design while modeling in mixed reality. However, creating precise perspective drawings remains challenging particularly when the digital world is overlaid, and depth perception is cumbersome [34]. Future research can, for example, explore techniques to automatically extract dimensions from objects in the user's field of view and make these immediately available as overlaid features when modeling new objects in mixed reality. This is partly similar to features in Object-Oriented Drawing [95].

8 CRAFT AND FABRICATION ACTIVITIES

The four last patterns, presented in this section, cover techniques to ease or avoid measurement activities during the craft and fabrication stages of making processes.

8.1 The Patterns

PATTERN 7: DOMAIN KNOWLEDGE ON DIGITAL FABRICATION

What

Procedures that suggest or account for fabrication-related characteristics during the design process in order to increase precision in fabrication without requiring additional measurements. Examples include automated compensation for laser or milling kerf, or material properties, such as warping and shrinkage while designing a model.

Measurement Challenges it Addresses

All fabrication procedures come with domain, machine, and material-specific characteristics that have to be considered when producing an artifact. For example, saws, laser cutters, and CNC milling machines have a kerf — or the width of the material that will be lost when cutting that is highly dependent on the type of material being cut (e.g., wood vs. thin acrylic sheet) and the machine's physical setting (e.g., milling bit diameter, laser power, and speed). Similarly, some 3D printing filaments, such as ABS, shrink significantly while cooling due to changes in temperature, causing inaccuracies. Beyond the machine and material characteristics, one has to consider, for example, the material's physical dimension, such as the material thickness when creating finger joints. Oftentimes, characteristics that are specific to fabrication procedures, are not known, not accurately measured, or compensated for. This pattern covers systems that embed domain knowledge to automatically consider these characteristics when designing artifacts. By doing so, these systems compensate for several measurements or dimensional considerations which designers traditionally handle manually.

How to Use

In many industrial production facilities, a wide variety of advanced software and hardware systems exist that embed procedures to account for production characteristics. For example, state-of-the-art CAM tools for thermoforming compute and compensate for distortions to ensure proper alignment between visual textures and the thermoformed shape [67]. Also originating from industry is the wide variety of CAM software for CNC milling that supports features for offsetting toolpaths to compensate for milling kerf. Similarly, high-end table saws come with software to optimize nesting parts on sheet material and take into account the guillotine cut restrictions these machines have (Figure 8b). Such features also avoid users having to puzzle with parts and their dimensions to find an optimal configuration for positioning all items on sheet material.

Within the maker community, systems like Kyub [7] dynamically adjust the design of finger joints when changing the thickness of sheet material. Roumen et al. introduces the idea of embedding cantilever springs [62], or sliders, bearings, and gear aligners [61] in a design to compensate for laser kerf as shown in Figure 8c-d. Over the past few years, domain-specific design environments have been developed to account for characteristics that impact dimensional accuracy when working with power tools. Carpentry compiler [94], for example, supports features to compensate for saw kerf. JigFab [47] additionally adjusts the toolpath of plunge routers for milling kerf (Figure 8a).

Related Patterns

Instead of compensating for fabrication-related characteristics during the design stage to achieve precise fittings and dimensions, *Pattern 8: Post-Fabrication Modifications* covers techniques to further fine-tune objects after fabrication. *Pattern 9: Guiding Manual Tasks* also

Figure 9: Post-Fabrication Modifications (*Pattern 8*) using (a) clamps to compensate for inaccuracies (figure adapted from Kim et al. [37]), (b) using heat to shrink a 3D print around an existing object (figure adapted from Sun et al. [72]), (c) embedding adjustable mechanisms in a design to allow for fine-tuning of sizes after fabrication (figure adapted from Kim et al. [37]).

leverages domain-knowledge on fabrication but uses this information to guide users in manual tasks.

PATTERN 8: POST-FABRICATION MODIFICATIONS

What

An object, embedding mechanisms, to allow for further fine-tuning after its production in order to improve dimensional accuracy and realize a precision fit.

Measurement Challenges it Addresses

Designing objects with a precise fit can be extremely challenging, especially for novice makers. Besides requiring precise dimensions, one needs to consider the clearance and all characteristics of fabrication machines, materials, and the environment. This pattern covers techniques for fine-tuning the dimensions of objects once they are fabricated. Using these techniques can resolve inaccuracies and allow for post-fabrication modifications.

How to Use

We identified three common techniques to allow for post-fabrication modifications. First, Embedding adjustable or compliant mechanisms in objects to fit parts of various sizes. Examples include hose clamps for tight mechanical connections and cable glands for waterproof fittings of electrical cables of various sizes. Several systems have been developed that facilitate embedding compliant mechanisms for post-fabrication fine-tuning. For example, the FitMaker [37] design environment supports embedding soft insert and clamps in designs to compensate for inaccuracies post-fabrication (Figure 9a). ShrinCage [72] demonstrates how heat can trigger shrinkage of a 3D printed object to realize a tight fit with other objects (Figure 9b). Instead of shrinking, TFcells [38] embed microcell structures in 3D printed objects to realize joints that allow for adjustments upon heating. In HotFlex [27] heat is also used to change the shape of a wristband after it is produced.

Second, a modular object design can be used to allow for replacing parts that might not fit and need a redesign. FitMaker [37] supports such modular object design as shown in Figure 9c.

Third, subtractive fabrication methods can be used to remove regions of objects that do not fit after which a new add-on is attached. Teibrich et al. [77], for example, contribute a new fabrication machine supporting 3D printing and milling features to patch objects without requiring a complete redo.

Related Patterns

To mitigate the need for modifications once an object is fabricated, *Pattern 7: Domain Knowledge on Digital Fabrication* covers techniques to compensate for fabrication-related characteristics during the design process.

PATTERN 9: GUIDING MANUAL TASKS

What

Constraining or guiding the wide variety of possible actions that one can take in crafting or assembly activities to reduce the number of measurement activities. Even when using digital fabrication techniques, this pattern can be used to eliminate measurements involved in the manual assembly of fabricated parts.

Measurement Challenges it Addresses

Crafting activities, such as molding clay or traditional woodworking offer a lot of freedom but are also very error prone when precision is desired. For example, a handheld drill can create holes in almost any place on the material's surface, at angles, and at various depths. When precise results are desired, such as a hole under a precise angle with an exact depth, significant skills and various precise measurements are needed. Assembly activities, sometimes considered crafts, have similar difficulties. When various parts with similar shapes exist, measurements are needed to identify parts and attach parts in the right configuration (e.g. perfectly straight). This pattern covers techniques to constrain or navigate the large solution space often present in crafting and assembly tasks.

How to Use

The first set of systems uses visual instructions to reduce measurement activities in manual tasks. The augmented power drill in Drill Sergeant [66], for example, eliminates a number of traditional measurement steps by projecting feedback on orientation and drilling depth above the drilling spot (Figure 10a). In a similar vein, Sculpting by Numbers [59] and Being the Machine [19] illuminate regions on a workpiece to guide users in respectively removing and adding material (Figure 10b). Visual instructions during assembly tasks

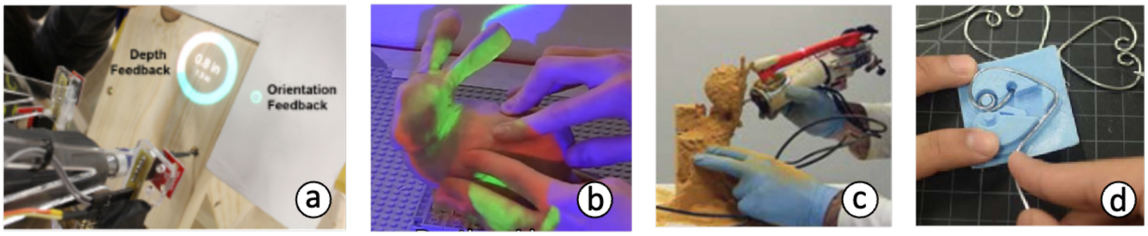

Figure 10: Guiding Manual Tasks (*Pattern 9*) using (a) projection techniques to communicate feedback around the work environment (figure adapted from Schoop et al. [66]), (b) projection techniques to communicate instructions (figure adapted from Rivers et al. [59]). Physically constraining the degrees of freedom using (c) actuators to make adjustments during operation (figure adapted from Zoran et al. [97]), (d) 3D printed jigs (figure adapted from Torres et al. [81]).

also help to identify parts with similar shapes instead of requiring measurements for identification. StackMold [85], prints out a template for matching parts that are too small to fit labels. RoadKill [1] goes further by engraving a visual instruction language on the frame that holds all parts together to ease both part identification and assembly. Beyond identification, Atifakos et al. [2] embed IMU sensors in parts of furniture and their system offers feedback to ensure parts are assembled straight instead of requiring the use of a try square.

A second popular set of techniques to reduce measurement activities in crafting tasks are the use of constraints to physically reduce the degrees of freedom in crafting activities. Various reconfigurable jigs are commercially available, such as box joint jigs for producing dovetail and finger joints[13] using hand and power tools. While these jigs still require some measurements to precisely configure them, the JigFab system [47] further eliminates measurement by outputting custom laser-cut jigs based on a digital design of the desired artifact. Similarly, ProxyPrint [81] uses 3D printed jigs to reduce the degrees of freedom involved in wire-wrapping (Figure 10d). Instead of using tooling, researchers also reduced the degrees of freedom of crafting tools by embedded actuation mechanisms that stop or retract the tool when making inaccurate movements. Examples include Free-D [97] (Figure 10c) and Shaper Origin [60]. Adroid [78] takes this approach a step further by equipping a robotic arm to limit the movement of power tools.

The use of constraints to physically restrict assembly activities to only valid configurations is often referred to as Poka-yoke and Design for Assembly methodologies [75]. Such techniques make assemblies fool-proof and avoid measurement steps typically needed for identifying and correctly aligning parts [55].

Related Patterns

In many ways, the techniques covered in this pattern use domain knowledge in fabrication and craft to guide users during manual tasks. *Pattern 7: Domain Knowledge on Digital Fabrication* similarly uses domain knowledge in fabrication to account for fabrication-related characteristics during the design process.

[13] https://www.rockler.com

PATTERN 10: SHORTCUTS FOR MAKING MARKS

What

Precise marks are frequently needed on a workpiece to align or cut parts accurately. Various techniques exist in practical geometry to simplify or even avoid measurement activities when making marks. For example, drawing the diagonal of a rectangle to find the center point instead of measuring the width and height. Some other techniques may require additional tools, such as a pair of compasses to bisect an angle. While these techniques are frequently used in crafting activities, similar concepts can also be applied in CAD modeling environments.

Measurement Challenges it Addresses

Precisely marking a workpiece often involves complex measurement procedures that are tedious and error-prone. For example, setting out two perpendicular lines over a long distance on a piece of land or translating the curvature of a wall to a tabletop counter to realize a tight fit after cutting. This pattern, therefore, covers techniques to create marks by translating the measurement challenge into a simpler, mathematically equivalent, operation.

How to Use

Over centuries, techniques have been developed to transfer dimensions and shapes instead of using measurements. As shown in Figure 11c, one can use a washer to precisely transfer a profile to a workpiece that has to precisely fit the profile after cutting. More advanced tools, such as contour gauges (Figure 11d), a Veritas transfer scribe[14], and angle-izer template tools are commercially available to transfer more intricate contours. Another well-known technique to transfer physical shapes is by casting a negative mold over the top of the original object. This mold then allows for duplicating (parts of) the shape in various casting materials. One interesting ancient but oftentimes forgotten transfer technique is the use of story sticks. As shown in Figure 11a, this is a plain stick with many marks that encodes all dimensions of an object. A well-thought-through story stick allows for duplicating an entire object without requiring any measurement instruments.

When a desired dimension or contour is not available and is difficult to obtain, many measurement techniques exist to simplify

[14] http://www.veritastools.com/products/Page.aspx?p=86

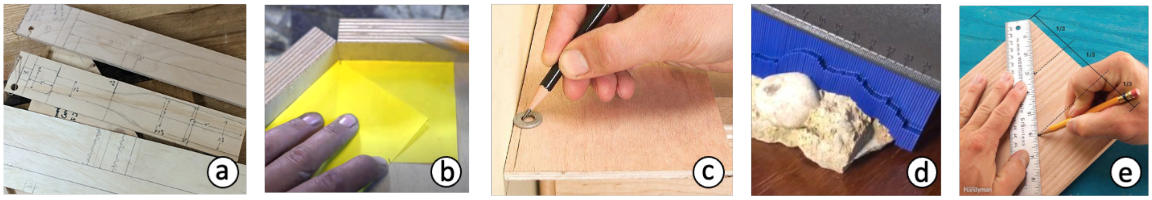

Figure 11: Shortcuts for Making Marks (*Pattern 10*) to avoid or simplify measurements using (a) story sticks that encode all dimensions of an object, (b) sticky notes to find the miter angle, (c) washers to transfer profiles, (d) contour gauges, (e) a mathematical trick to divide a piece into equal parts (figure adapted from Family Handyman [29]).

the measuring process. For instance, the miter angle to realize a precise fit between two boards, such as baseboards, can be determined by locating the intersection point of two sticky notes that are aligned with the boards as shown in Figure 11b. Alternatively, specific tools, such as an angle divider tool or Starrett miter saw protractor can be used. Setting out a straight angle over longer distances is rarely done using a try-square. Instead, construction workers memorize the 3:4:5 ratio from the Pythagorean theorem, for setting out straight angles using length measurements. Similarly, it is oftentimes tedious and error-prone to divide a workpiece into three equal parts, when working with dimensions that are hard to divide by three. As shown in Figure 11e, this can be facilitated by aligning a ruler diagonally with the workpiece to a number that is easier to divide by three. Custom tools have been developed to facilitate this procedure even further, such as center finders and Fibonacci gauges.

Related Patterns
When starting with a digital model instead of a physical object, *Pattern 4: Physicalizing Digital Dimensions and Shapes* can first be used to physicalize digital dimensions or shapes before using techniques in this pattern to transfer them onto the workpiece.

8.2 Future Research Directions

While the techniques covered in the patterns in this section, reduce the number of measurement activities involved in the craft and fabrication of artifacts, we see several directions for further research in this area.

First, *Pattern 7: Domain Knowledge on Digital Fabrication* covers several techniques that account for fabrication-related characteristics while designing objects. We believe more fabrication domain knowledge can be embedded in modeling tools to further increase the accuracy of fabricated artifacts without requiring additional measurement activities. CAD and CAM environments can, for example, support and stimulate guidelines and best practices for specific digital fabrication machines to ensure the fabricated object precisely matches the dimensional accuracy of the digital model. When designing for 3D printing with Fused-Deposition Modeling (FDM), for example, the next generations of CAD design environments could only allow for designing with sizes that are multiples of the extrusion width or thickness.

Second, the mechanisms to enable post-fabrication adjustments (*Pattern 8*) and the tooling to constrain manual tasks (*Pattern 9*) have limited to no design tool support which makes both techniques time consuming and oftentimes hard. We see significant potential in novel features for CAD environments to facilitate designing tooling as well as mechanisms for post-fabrication adjustments. Furthermore, we also see potential in translating some of the tricks in craft, for making precise marks (*Pattern 10*), to novel tools in digital environments to facilitate modeling and establishing dimensions.

9 USING MEASUREMENT PATTERNS WHILE MAKING

The following scenario demonstrates how measurement patterns can be used to alleviate issues in handling dimensions throughout a workflow in which Sam, a maker, builds the custom display shelf shown in Figure 12a. As the scenario focuses on makers, we only use systems, tools, and tricks, covered in the measurement patterns, that are commercially available at the moment and left out state-of-the-art solutions with a lower TRL level.

Sam starts with a wooden plank of 150 cm. When holding the plank against the wall to envision its position, she notices that the wall is slightly curved. To ensure a tight fit with the wall, Sam leverages *Pattern 10: Shortcuts for Making Marks* and uses a washer and pencil to transfer the curve of the wall onto the plank (Figure 12b). A Jigsaw is now used to cut the plank along the pencil curved path (Figure 12c). Sam would like her favorite plant to hang from the shelf through a hole, as shown in Figure 12a. As the pot has an intricate conical shape that is hard to measure, she leverages *Pattern 3: Shape Reconstruction* and creates a 3D reconstruction of the pot based on photos taken from several angles (Figure 12d). Sam also quickly models the shelf in her favorite CAD environment and loads the 3D reconstruction of the pot to experiment with various positions. She now leverages *Pattern 5: Designing with Existing Models* and conducts a Boolean subtract operation between the two solid geometries to realize a hole in the plank, exactly matching the contour of the pot (Figure 12e). To create this same hole in the actual shelf, she leverages *Pattern 9: Guiding Manual Tasks* and laser cuts a template that is used to constrain a plunge router for precisely cutting the hole eliminating the need for manual measurements (Figure 12f). When a plunge router or laser cutter is not available, *Pattern 4: Physicalizing Digital Dimensions and Shapes* can be used to print the shape of the hole on a sheet of paper and transfer it to the shelf for cutting using a jigsaw. Sam screws two brackets to the shelf for mounting it to the wall. To precisely transfer the exact spacing between the two brackets to the wall for drilling the holes, Sam leverages *Pattern 10: Shortcuts for Making Marks* . She therefore sticks a piece of paper tape between two brackets and

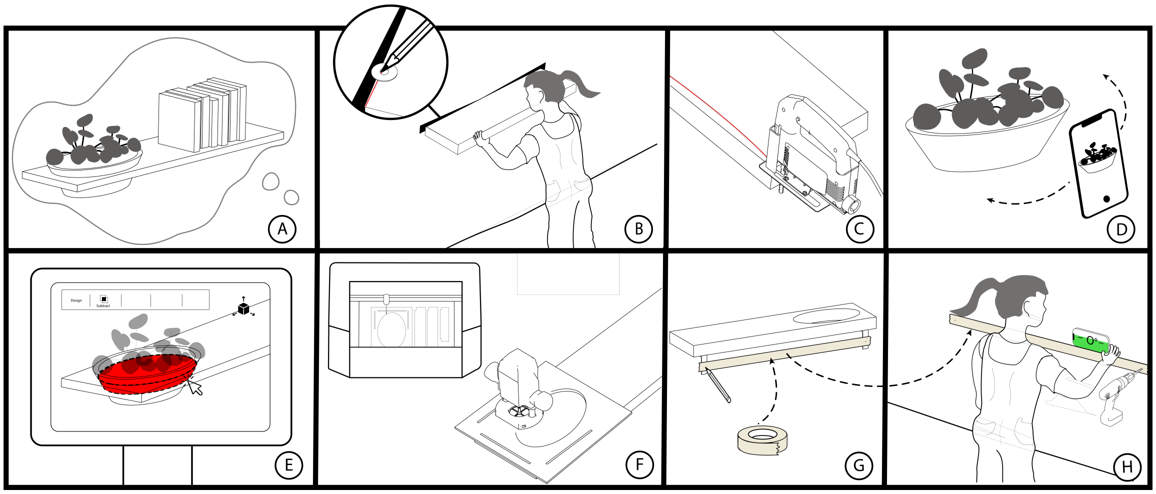

Figure 12: Using measurement patterns in a workflow for making a display shelf: (a) the envisioned result, (b) transferring the curve of the wall to the plank, (c) cutting the plank in a curve, (d) 3D reconstructing a pot, (e) using a CAD environment to create a hole for the pot in the plank, (f) laser cutting a template for cutting the hole in the plank using a router, (g) transferring the spacing between the brackets to the wall using paper tape, (h) leveling the paper tape.

marks both holes on the paper tape as shown in Figure 12g. The paper tape is now attached to the wall, marking the exact position for drilling the holes. As a final step, she uses the spirit level app on her smartphone to verify the paper tape is leveled correctly, thereby using *Pattern 1: Digital Readouts* (Figure 12h).

10 DISCUSSION

The discussion on the user aspects of measurement in this paper offers a starting point for looking at engineering contributions from the perspective of measurement. Using this perspective, measurement is an elementary aspect in any stage of the making process. While many techniques, presented in measurement patterns, the process of handling dimensions is automated, implicit, or simplified, examples covered in Section 6.2 show that additional approaches in the future could also focus on guiding or educating users to become better at measurement. Each of the three categories, in which we clustered the measurement patterns, includes opportunities for novel technical research uncovered by the patterns. In the remainder of this section, we offer a higher-level discussion on how one could use and build upon measurement patterns in the future.

First, system designers, engineers, and tool builders can use our measurement patterns when building new or improving existing systems, tools, or workflows for crafting or prototyping. We believe that throughout such an engineering process, one should consciously consider when and how end users will be exposed to activities that involve dimensional measurements. Similar to interaction and software engineering patterns, measurement patterns help in identifying measurement-related challenges and provide known solutions to deal with measurements and dimensions. To further support and streamline this process in the future, methodologies to assess the user aspects of measurement in engineering contributions could be devised.

Second, makers can use measurement patterns to find a proper system, tool, trick, or workflow to help with their crafting or prototyping projects, as shown in Section 9. While all measurement patterns include a generic description of the challenges they address, it might sometimes still be demanding to identify the measurement challenges in very practical problems that one is facing. Oftentimes, multiple measurement patterns, or a combination of techniques in different patterns, might collectively present a solution. For example, the scenario in Section 9 uses both *Pattern 3* and *Pattern 5* to define the shape for the hole to fit the pot. However, a clever marking technique might also exist now or in the future, as part of *Pattern 10*, directly transferring the contour of the pot to the shelf. We believe that, similar to software engineering patterns, one gains insights into how measurement patterns apply to concrete problems, through practice. To get makers familiar with our measurement patterns, in the future we plan on making an interactive online gallery of all the measurement patterns, including the technical strategies they present. It is also important to mention that several of the systems, discussed in measurement patterns, are research contributions and might not be available yet to makers. The discussion and examples covered in our measurement patterns, however, extract the essential elements from these systems from the perspective of measurement. We believe this is a step towards translating state-of-the-art contributions to practical systems and tools that can be brought to makers.

Finally, the structured overview provided in this work can lead to new insights and the development of more measurement patterns. One possible next step is to extend our measurement patterns, currently focusing on dimensional measures, to user-oriented strategies for dealing with other physical quantities, such as force, mass, or stress. Many of these physical quantities can however also be used to establish dimensional measurements. For example, using analytical methods to determine the maximum size of a wooden table that can carry a certain weight. Traditionally, such approaches have been used to optimize the design of artifacts. More recently, novel generative design techniques allow for the automated generation of design solutions based on higher-level problem definitions [12].

11 CONCLUSION

This paper reports on an extensive literature survey of crafting and prototyping practices from the perspective of measurement. While measurement-related activities are one of the major sources of errors while making, our results show that little research in HCI directly addresses the topic of measurement. In contrast, various systems have been built that embed new interactive modalities and processes that significantly impact how users deal with dimensions or conduct measurements. These more creative practices for dealing with dimensions are oftentimes hidden in larger system contributions and, in contrast to measurement in metrology, are not yet well understood, recognized, or classified. Based on our literature review, we contributed 10 measurement patterns which are reusable strategies to commonly occurring difficulties when dealing with dimensions throughout workflows in which physical artifacts are created. We hope this work also raises awareness about the importance of user-oriented features for dealing with dimensions during a workflow. Hence, we hope that analogous to design patterns, measurement patterns offer guidance to system engineers to consciously consider different strategies for how users deal with dimensions throughout a crafting or prototyping workflow.

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