Unit-Less Measurements with StorySticks++: Rethinking Measurement as Interactive Processes

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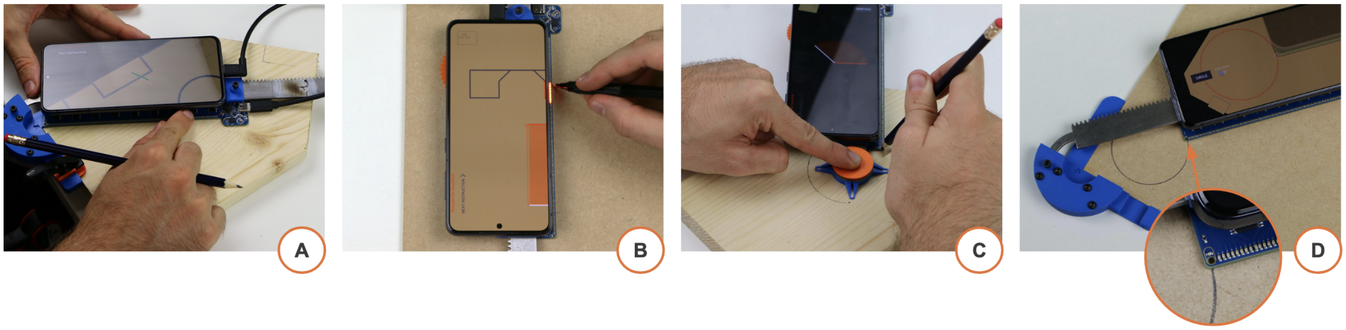

Figure 1: Unit-less Measurements with StoryStick++: (a) aligning the device to mark locations through peep-hole interactions, (b) Marking line-segments by tracing along the illuminated LEDs (c) plotting circles and arcs, (d) capturing geometries by point sampling.

Abstract

Dimensional measurement remains one of the most error-prone activities in making, engineering, and construction, despite the technical precision of modern instruments. Errors frequently arise not from the tools themselves, but from usability challenges: correct alignment of tools, interpreting numeric values, and transferring measurements across media. We introduce StoryStick++, a novel measurement system that rethinks measurement as an interactive, unit-less process. Inspired by story sticks, century-old craft tools using align-and-mark workflows, StoryStick++ replaces numerical readouts with direct spatial interactions. The device enables users to measure, mark, and transfer dimensions without converting to numerical values or standard units. Our system integrates a smartphone-based clip-on with embedded sensing and a series of attachments to support a wide variety of measurement tasks for measuring and marking basic and complex geometries with step-by-step guidance. Together, these contributions offer a new paradigm for measurement; one that emphasizes usability over abstraction and numeric precision.

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CCS Concepts

• **Human-centered computing → Mixed / augmented reality**; **Ubiquitous and mobile devices**; **Interactive systems and tools**; • **Applied computing → Computer-assisted instruction**.

Keywords

Digital-physical workflows, Measurement tools, Smart tools, Dimensional measurement, Interactive fabrication, Unit-less

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1 Introduction

Dimensional measurement is a fundamental activity in diverse fields, including making and engineering practice, architecture, construction, and product design. Yet it is also one of the most error-prone activities. Even small mistakes in alignment, reading, or transferring dimensions can accumulate into major flaws that only surface when parts no longer fit together. Prior research in HCI highlighted that the majority of errors in making processes can be traced back to issues with measurement rather than execution [18, 33]. Even though experienced makers often live by the principle of 'measure twice, cut once,' errors still frequently occur. Novices are especially prone to difficulties such as choosing appropriate measurement tools, the correct alignment of measurement tools, following measurement protocols, reading scales correctly, or transferring dimensions between media. These challenges persist despite the technical precision offered by modern instruments, suggesting that measurement is as much a usability problem as it is a metrological one.

Classical engineering metrology literature frames measurement quality primarily in technical terms like accuracy, uncertainty, throughput and cost [32]. Considerable progress has been made in defining standards, developing reliable instruments, and eliminating sources of uncertainty. However, the user aspects of measurement—the ease with which people can obtain, interpret, and apply dimensions—have received less attention. A growing body of work in HCI and fabrication systems has begun to address these issues [33], introducing interactive tools and workflows that reshape how dimensions are established and transferred. Examples include HandSCAPE [23], which augments a tape measure with IMU orientation sensing and digital readouts, NeoRuler [8], which simplifies numerical readouts and unit conversion by augmenting a ruler with an LED strip, and SPATA tools [45], which integrate measurement instruments with CAD models. These contributions ease specific measurement steps but remain tied to numerical readouts and standard units which are often error-prone and do not address more holistic workflows in which multiple dimensions must be consistently handled, transferred, and interpreted.

Reliance on numerical values and standard units, such as millimeters and inches, is itself a major source of error. Numerical representations require correct reading and conversion, impose cognitive overhead, such as dividing awkward values, and often demand translating between digital representations (e.g. CAD models) and physical artifacts and vice versa. Research in cognitive science and anthropology has shown that standard units and numerical readouts are cognitively demanding and easily misinterpreted, especially when users must read scales, perform conversions, or carry values across representations [41]. Numerical abstraction lacks the intuitive grounding of embodied or contextual measurements, and can be especially taxing under time pressure or uncertainty [6]. These issues affect both novices and experts. Research has shown that novice makers frequently make measurement and conversion errors in hands-on tasks [18], while even seasoned professionals have caused high-stakes failures, such as the NASA Mars Climate Orbiter loss due to a metric–imperial mismatch [48].

Historically, craftspeople developed alternative *Unit-less* approaches to circumvent common pitfalls when working with numerical values and standard units. One such approach is the story stick: a plain stick on which all dimensions of an artifact are directly marked (Figure 2b). A story stick encodes lengths at a 1:1 scale, enabling makers to align and transfer dimensions directly without interpretation of numerical values or standard units. For example, a single mark might encode the height of a cabinet, while other marks represent the thickness of frames or the height at which to attach a hinge (Figure 2b). This technique avoids many common measurement errors by turning the task of reading and calculating into one of aligning and marking. Story sticks were widely used in 18th and 19th century, as a single stick could encode all the dimensions required to craft an entire artifact [13, 35]. Woodworking shops often had dozens of story sticks hanging on the wall (Figure 2a), each preserving the information needed to faithfully reproduce artifacts over time. From a cognitive perspective, story sticks eliminate the need for abstract numerical reasoning or unit conversion and instead rely on the human strength for analog spatial comparison and real world context. Yet, despite their effectiveness, traditional story sticks also have limitations: they cannot easily represent multiple artifacts, they become impractical for larger artifacts due to their 1:1 scale, they can quickly clutter with annotations, and one needs to know the "story" behind the stick to correctly interpret all marks.

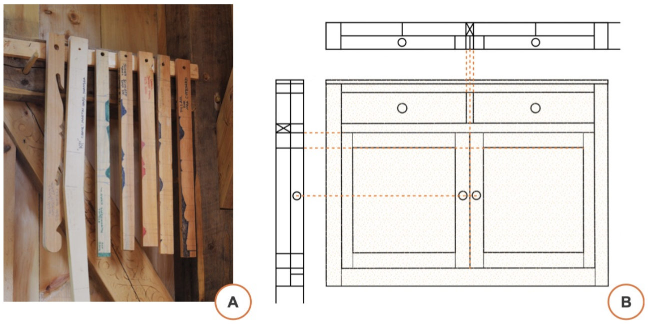


Figure 2: Examples of historical story sticks: (a) storage of story sticks in a workshop. © Popularwoodworking.com. Photo: Peter Follansbee. Used with permission [13]. (b) Story sticks with markings to precisely replicate an entire cabinet.

In this paper, we present StoryStick++ (Figure 1), a novel digital measurement instrument inspired by the traditional story stick that rethinks how dimensions are captured and transferred. StoryStick++ treats measurement as a spatial, embodied, and contextual practice rather than a numeric abstraction. It eliminates the need for interpreting scales or performing conversions, thus directly addressing many of the cognitive challenges identified in the use of standard units. While StoryStick++ addresses some of the core limitations of the original story stick, originating from woodworking, StoryStick++ works on various other materials, including, metal sheets, a cardboard box, modeling foam, ceramic tiles, a leather hide, and a sheet of paper. Our contributions are threefold. First, we introduce a smartphone extension that transforms the phone into a versatile measurement device capable of representing many traditional story sticks and contextualizing the meaning of marks. Second, we develop a set of interaction styles (Figure 1a-c) — allowing for multiple measurements at once, measurements with sub-millimeter accuracy, measurements at different scales from millimeters (making, engineering) to even meters (construction), caliper-style measurements, sampling and measuring of intricate geometries, including circles and arcs. Third, we contribute a software assistant that guides users step by step through measurement

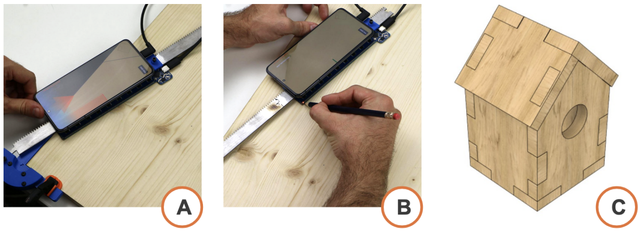


Figure 3: Marking the outline of the front panel of the birdhouse on the stock material by (a) configuring the angle and displacement of StoryStick++ by following step-by-step instructions, (b) plotting a corner mark next to an illuminated LED. (c) A 3D-render of the fully assembled birdhouse as reference.

activities, automatically interprets and converts dimensions, and embeds procedural knowledge about measurement tasks. Together, these contributions outline a new perspective on measurement instruments: one that considers measurement as an interaction technique, giving equal weight to usability and accuracy.

2 Walkthrough

Figure 1 shows the StoryStick++, a smartphone clip-on that extends your phone with diverse measurement capabilities. The clip-on embeds edge LEDs (Figure 1c) enabling precise inputting and outputting of length dimensions to and from digital representations on the mobile device. The StoryStick++ is precisely tracked on top of a workpiece. The smartphone's display offers a peephole display [49] to visualize technical plans on top of the workpiece and transfer markings. As demonstrated in the Walkthrough below, when used in combination with mounts and attachments that come with StoryStick++, our system is a powerful tool for easy measurement and marking of basic and complex geometries, such as the birdhouse in Figure 3c.

Step 1: Marking the panels on stock material. Once the vector graphic files (SVG files) for the birdhouse are uploaded to StoryStick++, our system guides the user with marking the outlines of all 7 panels on the stock material. Figure 3 shows how StoryStick++ offers step-by-step guidance to mark the outline of the front panel. Our system uses the polar coordinate system to allow for plotting all points from a single corner. StoryStick++ offers visual on-screen guidance using arrows to precisely orient and move the StoryStick++ to the different marks (Figure 3a). When a mark is approached, the edge LED near that location is illuminated enabling precise transfer of the position to the workpiece (Figure 3b). When the corners of all panels are marked as well as the center point for the bird entrance hole, the stock material is cut along these marks using a panel or plunge saw.

Figure 3b.

Step 2: Marking detailed features. Next, the compass attachment is mounted and positioned at the center point of the entrance hole as shown in Figure 4a. The user then sets the correct radius by extending StoryStick++ along the rail until the white guide line on the edge of the smartphone display aligns exactly with the orange target line (Figure 4b). After inserting a pencil in the alignment hole, the circle is traced by sweeping the device around the pivot point (Figure 4c).

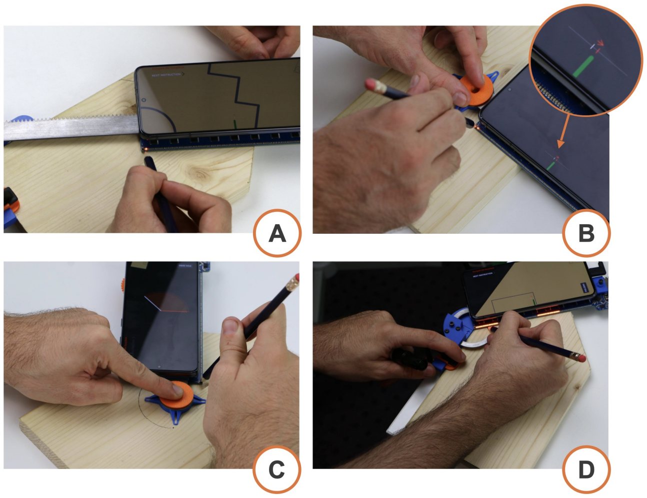


Figure 4: Marking detailed features on the front panel of the birdhouse: (a) the centroid of the entrance hole, (b) setting the radius on StoryStick++, (c) plotting the entrance hole by following the onscreen instructions, (d) marking the outline of the finger joints, using the lit up LEDs.

As shown in Figure 4d, instructions now guide the user to position StoryStick++ along the edge of the front panel to mark the outline for the finger joints. The edge LEDs light up all regions with cut-outs. StoryStick++ ensures these regions are marked with sub-millimeter accuracy to ensure precise fit of the joints. After marking, the entrance hole and finger joints can be cut with a band saw or fretsaw.

Step 3: Ad-Hoc Aesthetic Modifications. After assembling the parts, we find the birdhouse to have a somewhat conventional and rigid appearance. To create a softer and more distinctive aesthetic, we decide to round off the sharp corners of the roof. Since we do not have a specific radius in mind, we begin by sketching a rough arc freehand on one corner of the roof panel using a pencil (Figure 5a). Next, StoryStick++ is mounted in the corner of the workpiece, and the alignment hole is positioned at three sampled points along the sketched arc (Figure 5b). These points are digitized, allowing the system to infer the precise arc radius that best fits the sketch. StoryStick++ then automatically calculates the center point of this arc, which can be marked back onto the panel. Using the compass attachment, we pivot at this center and redraw the refined arc on the workpiece (Figure 5c). The fitted arc is then reused to replicate the same corner profile on the remaining roof corners.

3 Related work

Instead of measuring individual dimensions with handheld tools, modern metrology increasingly digitizes entire objects using contact or contactless acquisition. Contact approaches such as Coordinate Measuring Machines (CMMs) probe surfaces point by point, while contactless systems rely on X-ray tomography, magnetic

Figure 5: Rounding the edges of the roof panels of the birdhouse by (a) making a freehand sketch of the rounded corner, (b) capturing the sketched arc by sampling 3 points with StoryStick++, (c) plotting the redefined arc on all corners of the roof.

resonance imaging, depth cameras, LiDAR sensors, or photogrammetry, as well as domain-specific setups such as laser-based kitchen countertop templating [20]. All of these techniques aim to ease, speed up, and increase the precision of measurement by automating the full measurement workflow, from locating features, to capturing values, to storing and analyzing them digitally. In interactive systems and interactive fabrication research, similar measurement activities are often embedded into broader design, fabrication, or sensing workflows and thus remain implicit. To make these strategies explicit, Ramakers et al. [33] analyzed these interactive systems and uncovered ten measurement patterns, describing user-oriented strategies for dealing with measurements and dimensions in making processes. Building on this perspective, we structure our review into three strands: (1) the historical and cognitive foundations for unit-less measurement instruments, (2) smart measurement tools that embed sensing and computation, and (3) situated design and fabrication approaches that establish dimensions in context rather than through explicit numerical measurement.

3.1 Historical and Cognitive Foundation for Unit-less Measurement Instruments

Across cultures, people have long favored concrete, embodied measures over abstract units. Traditional societies used body-based or context-specific scales—like hand-spans or "stone's throw"—aligned with human perception and task needs, documented in at least 186 cultures [6, 17]. Similarly, crafts and engineering domains developed tools to bypass abstract units by directly transferring dimensions from one object or template to another. For example, woodworkers, metalworkers, and construction workers use contour copiers (Figure 6a) to trace complex profiles, pen scribes (Figure 6b) for tracing offset contours, pinch sticks (Figure 6c) to measure span openings, and bevel gauges (Figure 6d) to replicate angles without reading numerical values. Adjustable story sticks (Figure 6e) capture multiple distances using movable stops, sometimes with built-in angle bisectors. The planimeter, used in civil-engineering, traces a shape's perimeter to derive area through physical integration. Analog computing tools also exemplify unit-less reasoning: the slide rule replaces arithmetic with spatial alignment on logarithmic scales, offloading mental computation to visual perception. These tools like story sticks and nomograms keep measurement in the world, not in the head, solving problems through direct physical manipulation.

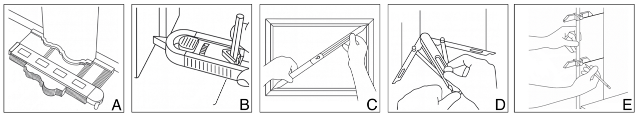


Figure 6: Unit-less crafting tools: (a) a contour copier, (b) a scribe, (c) a pinch stick, (d) a bevel gauge, (e) a story stick.

Human cognition strongly favors embodied, spatial strategies over abstract numerical reasoning. People mentally represent magnitudes on an internal "number line," which leads to systematic biases, for example, identical addends like 2+2 are processed more quickly and confidently than equivalent but varied sums such as 1+3 [12]. Our working memory is also limited, typically holding only about 7 items, making it prone to overload during multi-step calculations or under time pressure [28]. Even highly skilled individuals frequently struggle with unit conversions. Research results show that even engineering students and science teachers often fail basic metric conversions [10, 27]. One infamous example is NASA's Mars Climate Orbiter, lost due to a mismatch between imperial and metric units [48]. Kim et al. [18] similarly observed how novices misread units, misaligned tools, or introduced errors during intermediary calculations, such as converting a measured circumference into a diameter. These issues are not inherent to measurement itself but stem from the cognitive fragility of abstract number handling. In contrast, people perform surprisingly well on comparable tasks when information is embedded in physical tokens or visual layouts [3, 41], highlighting the benefits of perceptual and contextual grounding.

3.2 Smart Measurement Instruments

Several systems embed sensors into measurement instruments to facilitate measurement activities and embed novel interactive opportunities. Early explorations on augmenting measuring tools, such as ShapeTape [1] and later SensorTape [7], use a bend- and twist-sensitive strip used to manipulate curves in 3D models. Several research and commercial measurement tools also embed sensing to automate the interpretation of measurement and reduce manual transfer of numerical values. HandSCAPE [23], for example, extends a tape measure with orientation sensors and automatically interprets the measured length and angle. Going further, Moasure [29] integrates an IMU in a handheld device so users can walk around an area to record multiple vectors; by integrating these vectors, the system digitizes perimeters or complex contours. Similarly, smartphone AR ruler applications [4] use on-board smartphone cameras and depth sensors to overlay virtual measurement lines on a live view of the environment. More recently, commercial tools such as NeoRuler [8] have emerged, offering a hybrid digital ruler and caliper. Similar to StoryStick++, it displays measurements via an LED strip, but still presents users with numerical values and is primarily focused on automated unit and scale conversion. SPATA tools' [45] actuated calipers and protractors offer bidirectional transfer of measurements between physical and digital worlds. While SPATA tools [45] focuses on individual measurements in isolation, StoryStick++ embeds intelligence and guidance to support complex measurement and layout tasks and reasons about measurements in relation to other measurements or a digital model.

3.3 Situated Design and Fabrication

Instead of performing explicit measurement activities, dimensions can also be established implicitly by designing, fabricating, or crafting objects near existing real objects. These approaches are often referred to as situated (in-situ) design [11, 38] and fabrication [5, 16, 34, 42–44, 51] as the dimensions of surrounding objects and the world are used indirectly to design digital and physical objects.

3D scanning has been widely used both to digitize existing artifacts and to support in-situ design. Some systems capture clay-sculpted forms [36, 46] or physical objects [14] to create new digital artifacts. Building on this, interactive systems such as MixFab [47] and Mix&Match [40] combine 3D scanning with mixed reality technologies to design 3D models in relation to the real environment. AR-based tools further extend these ideas by integrating parametric modeling directly into the user's environment. CustomizAR [25] guides novice users through customizing parametric CAD models to fit real physical environment: it overlays measurement instructions on camera views and uses LiDAR to extract dimensions which are then used to adjust the digital model. Similarly, pARametric [11] is an AR modeling tool in which users freehand sketch objects at full scale and the system automatically infers dimensions from the surrounding environment. RoMA [31] is an AR-based system paired with a 3D-printer that fabricates the model in the same workspace as the designer edits it, turning the emerging print into a tangible, in-situ reference. Beyond integrating parametric modeling into the environment, recent AR systems also use body gestures themselves as a way to express measurements. BodyMeter [22] lets users specify the dimensions of furniture through full-body poses combined with simple voice commands. Similarly, pARam [38] allows users to position and preview a parametric CAD design through AR and then adjust parameters through mid-air gestures.

Another form of situated design can be understood as tangible modeling tools. StrutModeling [24] merges measuring and modeling by providing sensor-augmented struts that serve both as construction elements and as real-time digital input devices, resulting in a skeletal frame representation of the design. Complementing this approach, BrickStARt [39] is optimized for modeling the surface of objects through tangible modeling: users first assemble a rough in-situ model from LEGO bricks to represent the desired object and to test its fit, stability, and ergonomics. After iterating on the physical mock-up, the LEGO model is scanned with an AR headset for digital refinement before it is fabricated.

4 StoryStick++ Design Rationale and Interaction Metaphors

Insights from history and cognition, covered in Section 3 directly inform the design of StoryStick++. Rather than reporting measurements as abstract numeric values, StoryStick++ employs spatially grounded "align-and-mark" interactions: the user aligns the device with the object and marks or measures features directly, without resorting to numerical values. The system automatically captures the resulting dimensions in context of the geometry and performs geometric computations (for example, calculating the geometry's area similar to the planimeter), thereby eliminating the need to interpret or manipulate numerical values. Importantly, StoryStick++ provides clear, step-by-step visual guidance so each action is explicitly guided. In doing so, it replaces the strong reliance on tacit measurement knowledge, such as plotting auxiliary construction lines that are essential for some measurements, or always zeroing an instrument before use, with guided procedures.

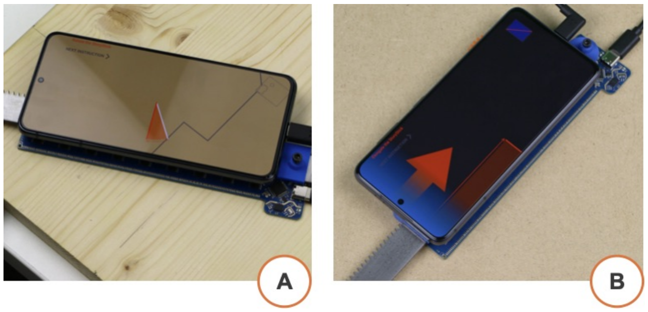


Figure 7: (a) StoryStick++ uses a peephole display metaphor showing the workpiece and markings, (b) arrows guide the user to off-screen marks.

Key behind StoryStick++'s unit-less interaction paradigm is a close coupling between the physical and digital world, allowing measurements to be recorded and interpreted in relation to both worlds without conversion to numeric values and standard units. To enable this, StoryStick++ adopts several established spatial interaction metaphors in Human-computer Interaction, such as Peephole displays [49] and off-screen content visualisation [2, 15, 50].

We treat the workpiece as a continuous digital workspace, of which the user sees and interacts with only a localized segment through the StoryStick++ device. As users slide the tool across the workpiece, the smartphone reveals a 1:1 view of the digital workplan and accompanying markings, akin to looking through a peephole at a larger hidden structure (Figure 7a). The edge LEDs, in addition, bridge the gap between the display and the workpiece, enabling markings to be accurately transferred with minimal parallax error.

As workpieces and plans are larger than the StoryStick++ core, the majority of marks will fall outside the current viewport and users navigate StoryStick++ to marks. To make users aware and draw their attention to off-screen marks, we leverage established off-screen content navigation techniques, including arrows [50]. Figure 7b illustrates how visual guidance directs the user to slide StoryStick++ upward along the guiding rail to reveal the next mark. Future versions could incorporate alternative visualisations such as Halo [2] or Wedge [15], to further ease and improve off-screen content navigation.

These metaphors also address a few core limitations of traditional story sticks: (1) StoryStick++ can represent very long story sticks using the peephole display metaphor. (2) StoryStick++ replaces the need for storing many story sticks as all markings are represented digitally. (3) The peephole display allows for an infinitely large digital space to clearly tell and visualize "story" behind each mark and visualize measurement procedures.

Figure 8: Using the StoryStick++ core unit to measure (a) the length of an object, (b-c) the angle between two sides of an object.

5 The StoryStick++ Unit-less Measurement Device

5.1 StoryStick++ Core Unit

The StoryStick++ core unit, shown in Figure 8a connects to a smartphone via USB. The edge LEDs on the StoryStick++ core unit enable dimensions to bridge the bezel of the mobile device and ensure seamless transfer of dimensions between the physical and digital world. Figure 8 illustrates how the core unit can be used to (a) measure lengths and (b-c) measure angles. Unlike traditional story sticks, StoryStick++ contextualizes each measurement in relation to a digital model, making the “story” behind the marks more interpretable and reducing ambiguity in both reading and use.

While the StoryStick++ core unit can be used on its own to measure and mark basic dimensions up to 140 mm (approximately 5.5 in), its capabilities are significantly extended when combined with our mounts and attachments. Notably, the core unit also embeds a small alignment hole as visible in Figure 1c, a precision opening used for plotting or point sampling (Section 6). While present in the core unit, the alignment hole is only functionally accessible when attachments are used.

5.2 Mounts and Attachments

StoryStick++ comes with several mounts and attachments shown in Figure 9, including (a) a guiding rail, (b) a corner mount, (c) an edge mount, (d) a compass, and (e) a jaw. Unlike the StoryStick++ core unit, the mounts and attachments are all passive and thus do not include sensing or computational elements. Guiding rails (Figure 9a) are available in different lengths, including 22 cm and 44 cm (approximately 8.7 in and 17.3 in) in our current prototype. Guiding rails enable measurements that exceed the physical length of the StoryStick++ core. In the future, longer rails, such as 1 meter versions, could further expand the system's applicability to meter-scale tasks, such as those encountered in construction. In addition to extending the measurement range, the rails improve precision by tracking the position of the core unit at sub-millimeter (4 mils) resolution. A built-in thumb roller allows for fine-grained displacement along the rail, while a locking screw can temporarily fix the core unit in place during measurement or marking. Guiding rails are also compatible with all other attachments and are frequently used in combination.

The corner mount (Figure 9b) attaches to the guiding rail and precisely aligns the StoryStick++ with the corner of a flat work surface. An off-the-shelf clamp can be used to temporarily secure the device to the workpiece, preventing accidental shifts that could lead to misalignment from the corner. The mount incorporates a concealed 90-degree hinge, allowing the StoryStick++ to reach any position on the workpiece by pivoting in exactly the corner of the workpiece. A set screw allows for locking the orientation of StoryStick++. The corner mount plays a critical role in tracking the position of StoryStick++ relative to the workpiece, ensuring that all measurements are interpreted in the correct spatial context. As such, it is often used during the initial measurement steps to establish a reliable reference point, ensuring that all subsequent measurements are accurate and consistent with respect to this corner.

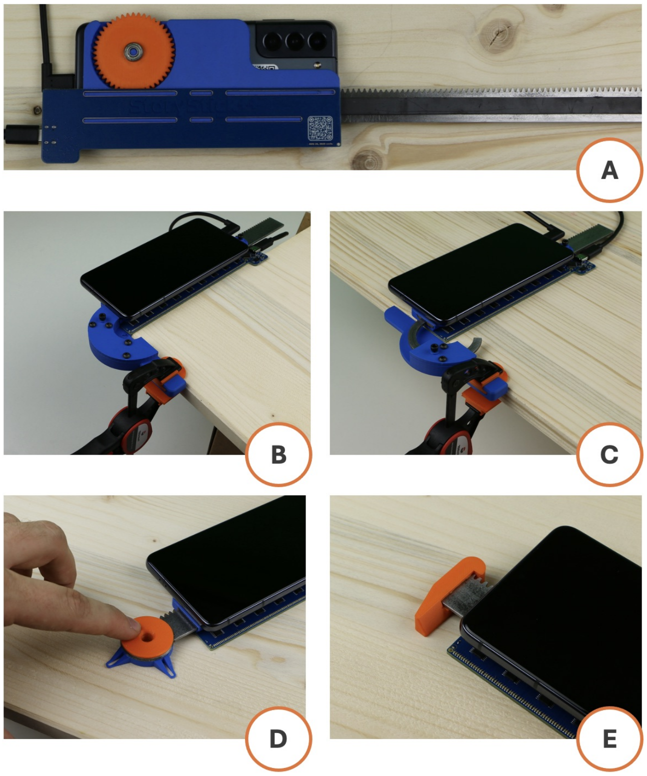


Figure 9: StoryStick++ mounts and attachments: (a) the guiding rail, (b) the corner mount, (c) the edge mount, (d) the compass, (e) the jaw.

The edge mount (Figure 9c) has a similar design to the corner mount but can perfectly align with a straight edge of a workpiece. Like corner mounts, it attaches to the guiding rail, supports clamping, and embeds a concealed 180-degree hinge that allows StoryStick++ to reach any position on the workpiece, and a set screw to lock the orientation. As the edge mount can align StoryStick++ with any line segment on a workpiece, it is particularly useful for quickly and precisely measuring and marking line segments.

The compass attachment (Figure 9d) similarly attaches to the guiding rail. Its pivot point can be positioned anywhere on the workpiece. The compass attachment is particularly useful for precisely plotting circles and arcs.

Lastly, the jaw attachment (Figure 9e) also fits on top of the guiding rail and allows for caliper-style measurements. The outer jaw is particularly useful for measuring dimensions of objects that

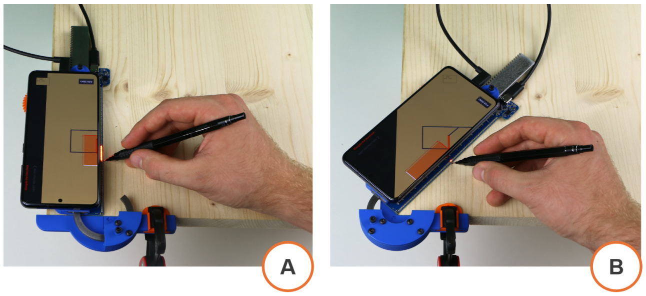


Figure 10: Comparison of plotting approaches: (a) Cartesian coordinates where the positioning of StoryStick++ is defined by orthogonal x-y axes, and (b) polar coordinates, where the positioning is defined by radius and angle relative to an origin point.

cannot be easily aligned with a straight edge—for instance, when the object's shape prevents flush alignment with a ruler.

6 StoryStick++ Measurement Interaction Styles

Building on the measurement device and spatial interaction metaphors described in the previous section, StoryStick++ supports several interaction styles that allow for precise, fast, and convenient dimensional measurements.

6.1 Coordinate Systems

StoryStick++ supports dimensional measurements in both Cartesian (x,y) and polar (r,θ) coordinate systems, allowing users to work in the representation that best fits the task or geometry. Figure 10a illustrates how points can be plotted on a workpiece using Cartesian coordinates. In this workflow, StoryStick++ must be repositioned along both the x and y axes, typically requiring the consecutive use of both the corner and edge mounts for accurate alignment. In contrast, StoryStick++'s built-in displacement and orientation tracking often makes polar coordinates more convenient. From a fixed reference point—such as the corner of the workpiece—users can adjust the angle and radial distance to plot several points without repositioning the device (Figure 10b).

Although polar coordinates may be less familiar to some users, StoryStick++'s unit-less interaction model removes the need to interpret numerical angles or distances. Instead, users interact directly with the spatial layout, making polar measurements as accessible and intuitive as Cartesian measurements. Both coordinate systems are available within StoryStick++, and users can choose the most appropriate system for each task. Moreover, the system supports automatic conversion between Cartesian and polar representations, allowing geometry defined in one system to be seamlessly used in the other.

6.2 Sub-Millimeter Measuring and Marking

While the edge LEDs on the StoryStick++ core unit are spaced at 1 mm (approx. 0.04 in) intervals, dimensions plotted with the edge LEDs can achieve sub-millimeter accuracy, up to the thickness of a single LED (0.5 mm, 0.02 in), when used in combination with the guiding rail. The process works as follows: the closest edge LED illuminates when the device is positioned near a target location on the physical workspace. To achieve sub-millimeter precision, StoryStick++ provides a visual alignment aid: a pair of alignment stripes appears on the smartphone display and is deliberately scaled up to support precise alignment beyond millimeter resolution. Users adjust the position of the core unit along the guiding rail with the thumb roller until the two stripes align (Figure 11a). This precision visualization uses a control–display (C–D) ratio of 25:1, allowing for very fine-grained alignment and thus marking.

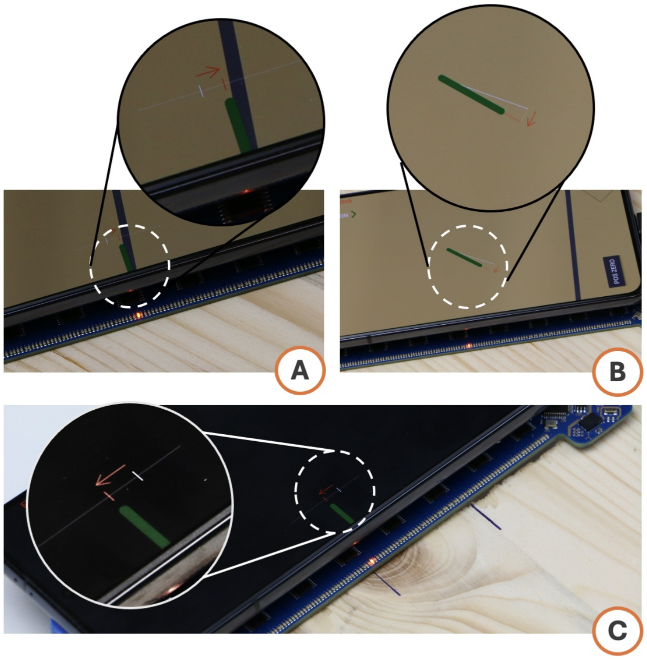


Figure 11: Marking with sub-millimeter precision: (a) the edge LED illuminates when StoryStick++ is positioned near a digital mark, sub-millimeter accuracy is achieved by aligning the two marks by sliding StoryStick++ over the guiding rail. (b) Similar guidance is provided for orientational alignment with 0.1 degree precision. (c) Existing marks on a workpiece can also be measured/digitized with sub-millimeter precision.

The same degree of precision is supported when measuring geometries (transferring geometries from physical to the digital space). As illustrated in Figure 11c, the position of a mark on a workpiece is measured by mounting StoryStick++ in the corner. The user now aligns the StoryStick++ core next to the mark. When the user taps the smartphone display, the nearest LED illuminates. For coarse positioning, the user may slide their finger up or down on the touchscreen, which cycles through adjacent LEDs at millimeter resolution. For sub-millimeter accuracy, the StoryStick++ core is shifted along the guiding rail until the illuminated LED precisely aligns with the mark on the workpiece. When tapping the screen again, the precise location of the illuminated LED is measured and recorded relative to the corner of the workpiece.

To enable even higher precision, StoryStick++ includes an alignment hole (Figure 14d) that can be positioned over existing marks or used with a pencil to create new ones. Because this alignment hole operates independently of the edge LEDs, its accuracy is not constrained by their size or spacing. Instead, its precise location is determined by StoryStick++'s position along the guiding rail, which is tracked with an accuracy of 0.02 mm (approximately 0.0008 in), exceeding the precision of a thousandth of an inch. When using the alignment hole for marking, the same precision visualizations are displayed as in Figure 11a–b.

Accurate angular orientation is equally critical when working in polar coordinates or angles. StoryStick++ provides a visual alignment tool consisting of two intersecting lines on the display. As shown in Figure 11b, users rotate the device until the lines overlap and turn green, indicating that the orientation is within a tolerance of 0.1 degrees with respect to an angular digital specification. In the angular alignment visualization, a C-D ratio of 40:1 is used to allow for precise input.

6.3 Segment Measurement and Marking

One of the most direct parallels between StoryStick++ and traditional story sticks lies in the ability to mark segments— regions that represent features such as gaps, joints, slots, or cutouts (Figure 2). These segments may appear individually or in repeating patterns and are commonly found in woodworking and construction tasks where precise spacing and alignment are critical.

StoryStick++ accommodates marking and measuring of segments using the edge LEDs that can illuminate regions and offer contextual understanding through on-screen visualisations (Figure 12).

Combined with the guide rail, even long segments are marked with precision, ease, and speed. When marking segments onto a workpiece, a digital representation is first defined or loaded into StoryStick++. Then StoryStick++ requires rotational alignment with the segments. This alignment often involves multiple steps for which the polar coordinate system is most suitable. For instance, StoryStick++ automatically calculates the intersection point of the direction of the line segment with an edge of the workpiece. As shown in Figure 12a users are guided to mark this location using the corner mount. Next, the edge mount is positioned at that location, and the clamp is attached to prevent further accidental shifts of the mount (Figure 12b). Visual instructions guide the user to set the correct orientation of StoryStick++. Fixating the set screw at the edge mount holds the StoryStick++ in the proper orientation during further interactions. Visual instructions now guide the user to displace StoryStick++ along the rail. When approaching the segments, they are precisely visualized via the edge LEDs and can be transferred with sub-millimeter precision onto the workpiece (Figure 12c).

In addition to marking segments onto a workpiece, StoryStick++ also supports digitizing existing regions present in a physical workpiece. This process parallels the point sampling described in Section 6.2. To define a region, the user touches the screen and first aligns the illuminated LED with the start point of the segment. Upon release, this start location is recorded. The same process is followed for recording the endpoint of the segment as shown in Figure 13a. When all segments are recorded, they can be digitally processed further or directly copied onto another workpiece as shown in Figure 13b.

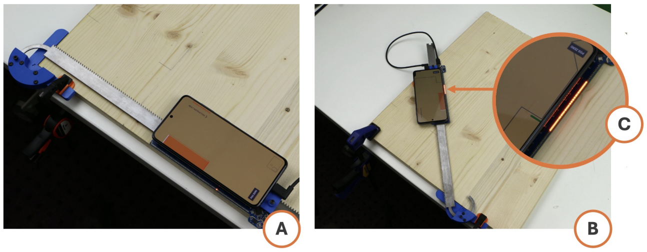


Figure 12: Segment Marking: (a) precisely marking the point along the edge where the segment intersects the work piece, (b) positioning StoryStick++ at this mark and aligning the orientation of the guiding rail and displacement along the rail (C) StoryStick++ lights up the line segment.

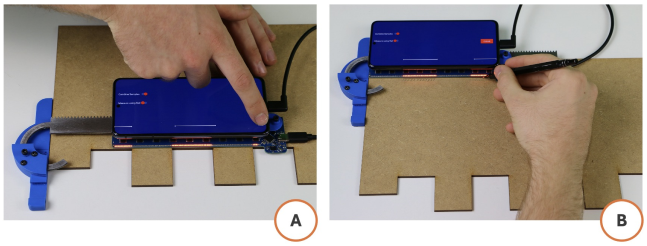


Figure 13: (a) Segment measurement and (b) immediate transfer of the same segment to another region.

6.4 Shape Inference from Point Sampling

StoryStick++ supports the inference of geometric shapes by sampling a minimal number of points on the physical workpiece using the alignment hole on the StoryStick++ core (Figure 14e). The technique enables users to quickly and precisely measure characteristics of intricate shapes, such as lines, angles, curves, and polygonal shapes. Point sampling can be performed in Cartesian coordinate systems. However, for most spatial layouts, polar sampling is more efficient, as it allows the user to remain anchored at a single reference position, typically using the corner mount, and measure multiple points by simply adjusting the orientation and displacement of the StoryStick++ device.

This interaction style supports a wide range of shape inference tasks. For example, the angle between two lines can be inferred by sampling two points along each line, as shown in Figure 14a. Circular features or arcs can be reconstructed by sampling three arbitrary points along their perimeter (Figure 14b,d). Polygons, such as triangles or star shapes, can be digitized by sampling their corners (Figure 14c). Once sampled, StoryStick++ can compute key geometric properties, such as the center point of an arc, and guide the user to mark it precisely on the workpiece. These geometric inferences are traditionally difficult and time-consuming using conventional tools. For example, accurately determining the center point of an existing arc or circle typically requires a combination of plotting construction lines, auxiliary measurements, and geometric

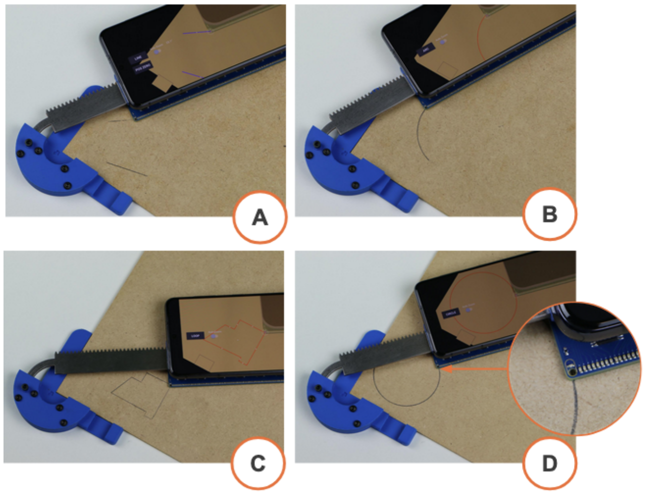


Figure 14: Shape inference by sampling points of (a) lines, (b) arcs, (c) polygons, (d) circles using the alignment hole of StoryStick++.

reasoning. Future versions of StoryStick++ could compute more advanced properties of captured geometries, such as generating offset or scaled variants to compensate for kerf and other effects in machining operations.

6.5 Plotting Circles and Arcs

The alignment hole introduced in the previous section, used for sampling points, also accommodates the tip of a pencil. This feature is particularly useful when plotting circles or smooth arcs. While the corner and edge mounts can be used to plot circular features whose center lies exactly at the corner or edge of the workpiece, the compass attachment offers a more flexible and universal approach. It can be positioned anywhere on the surface. As shown in the Walkthrough (Figure 4b-c), to plot a circle or arc, the visor of the compass attachment is first placed at the desired center. The StoryStick++ core unit is then precisely displaced along the guiding rail so that the alignment hole reaches the desired radius. Once aligned, the position is locked using the set screw. A pencil is inserted into the alignment hole, and the user traces the circular arc by sweeping the device around the fixed pivot point. Throughout this process, StoryStick++ provides step-by-step guidance to precisely locate the center point using the corner or edge guides and adjust displacement using the guiding rail as presented in the interaction styles discussed above.

Plotting arcs requires precise control over both the start and end points. To support this, StoryStick++ first guides users to draw a line through the arc's center point, allowing the compass attachment to be properly oriented relative to the workpiece. Once this reference line is marked, the system instructs users to align the device with it to stabilize IMU-based orientation tracking and avoid drift. The user is then guided to rotate the device to the correct starting angle, aided by an on-screen visualization (Figure 4c), before sweeping the arc to the end position.

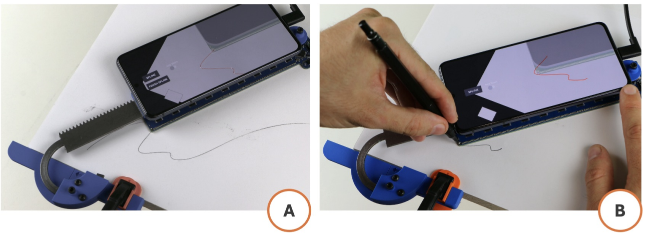


Figure 15: Freehand (a) capturing and (b) sketching of the rough outline intricate geometries.

In addition to plotting angles and arcs, StoryStick++ can also measure circles and arcs as we discussed in Section 6.4.

6.6 Freehand Sketching and Capturing Geometries

Although StoryStick++ supports the precise measurement and plotting of various geometric entities, such as circles, arcs, lines, and points, using the interaction styles described above, these methods typically require each geometry element to be sampled or plotted individually. For more complex geometries involving multiple connected or curved segments, this can become time-consuming. To accelerate such workflows, StoryStick++ supports interaction styles for freehand sketching and capturing, enabling faster layout and digitization of shapes.

This interaction style also makes use of the alignment hole on the StoryStick++ core. The core unit remains attached to the corner mount via the guiding rail, but with the set screws released, it is free to move across the workpiece surface. The system continues to track the position and orientation of the device relative to the corner of the workpiece and plots the alignment hole as a crosshair on the smartphone display.

When sketching a shape from a digital plan onto the physical workpiece, the user inserts a pencil into the alignment hole and moves the tool along the digital contour shown on the screen, thus transferring the shape in real-time (Figure 15a). Conversely, to capture an existing physical geometry, the alignment hole is simply moved along the contour of the shape. StoryStick++ continuously records the movements, resulting in a freehand digital trace of the geometry (Figure 15b).

Unlike other interaction styles where movement is tightly constrained for precision, this mode prioritizes speed and flexibility over accuracy. The ability to quickly sketch or trace even rough outlines is valuable in practical scenarios such as defining glue regions, placement zones, or masking areas. In future versions, StoryStick++ may apply computational techniques such as curve smoothing or error correction to refine freehand input and improve its geometric accuracy.

6.7 Caliper-Style Measurements

When the jaw attachment is connected to StoryStick++, the device functions as a digital caliper. The jaw acts as an outer measuring jaw, enabling users to measure dimensions of objects placed between the jaw and the edge of the PCB (Figure 16). By sliding the jaw along the guiding rail, the tool achieves sub-millimeter accuracy.

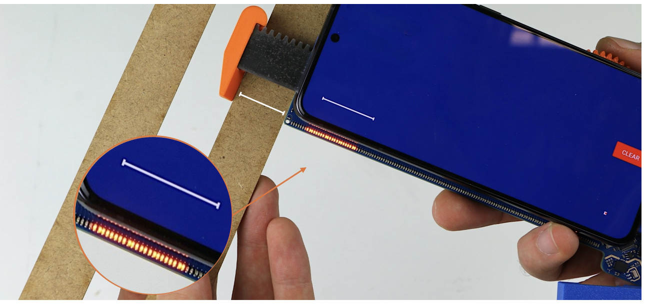
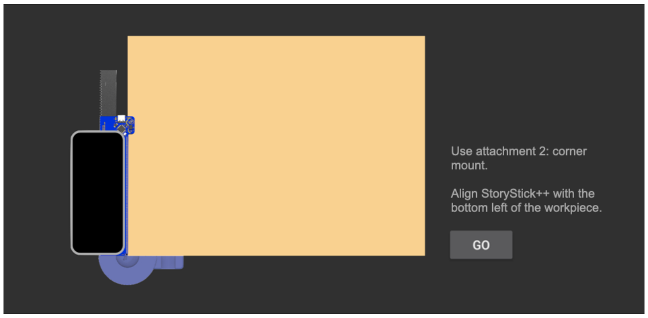


Figure 16: Caliper-style measurement with StoryStick++ using the jaw attachment.



Use attachment 2: corner mount.

Align StoryStick++ with the bottom left of the workpiece.

Figure 17: StoryStick++ provides step-by-step guidance. For example, to align the corner mount with the workpiece.

7 Supported Workflows and Interactive Guidance

As presented in Section 6, StoryStick++ supports a variety of interaction styles, each offering specific benefits for different measurement and marking tasks. Interaction styles also come with different steps to correctly set up StoryStick++, including mounting the appropriate attachment, aligning StoryStick++ with the workpiece, orienting it correctly, and securing its position using set screws. Some procedures may also require drawing auxiliary points or lines to support the measurement process (see Section 6.3 and 6.5). To facilitate accurate execution, StoryStick++ provides step-by-step instructions for each interaction style. For example, Figure 17 shows on-screen instructions for attaching the corner mount and positioning it in the corner of the workpiece.

Depending on the desired workflow and skill level of users, StoryStick++ offers support during individual tasks or provides end-to-end guidance for more complex marking tasks. In flexible, ad-hoc workflows and situated design or fabrication scenarios—where users respond directly to the current state of the workpiece, users can rely on the Quick Measure and Quick Draw modes, which are available for each interaction style. For example, *Quick Measure* can be launched to measure distances, angles, intervals, center points, areas, arcs, circles, or sampling points. Similarly, *Quick Draw* allows users to plot specific distances, angles, intervals, arcs, or circles after entering the required parameters for these geometries. These modes let users rapidly measure, sample, or mark features without substantial up-front design work or committing to StoryStick++ for an entire workflow. In such cases, guidance is provided only for the individual measurement or marking actions.

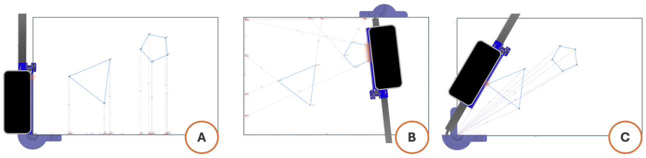


Figure 18: StoryStick++ computes several different solutions for plotting geometries: (a) plotting points using the Cartesian coordinate system, (b) plotting line segments using the polar coordinate system, (c) plotting only the start and end points of each segment using the polar coordinate system.

For more complex marking tasks or when more guidance is desired, StoryStick++ supports guidance throughout an entire marking workflow at the expense of more up-front design. Users can import an SVG file containing multiple geometry elements, such as line segments, angles, circles, or paths. Once loaded, the system automatically extracts key parameters for each entity, such as start and end points, orientation, displacement, and generates step-by-step instructions for transferring them to the physical workpiece. During this process, StoryStick++'s interactive software optimizes the order of operations to minimize the number of times the device needs to be repositioned or attachments swapped. Figure 18 visualizes the different steps that StoryStick++'s interactive software computes when plotting (a) points using the Cartesian coordinate system, (b) the line segments using the polar coordinate system, (c) only the start and end points of each segment using the polar coordinate system.

8 Implementation and Engineering

The implementation of StoryStick++ consists of several components: StoryStick++'s mechanical design, the electronic hardware, the on-board firmware, and the interactive guidance software.

8.1 Mechanical Design

The current prototype of StoryStick++ is fabricated using a combination of 3D printing, CNC milling, and waterjet cutting. These fabrication methods were selected based on the required precision and functional role of each component. Parts demanding high accuracy and smooth mechanical operation were CNC milled or waterjet cut, while less critical components were 3D printed using carbon-filled FDM filament, enabling rapid iteration during design refinement. For future iterations, we envision transitioning to a fully CNC-milled version to enhance durability, accuracy, and ensure consistent mechanical performance suitable for long-term use.

8.1.1 StoryStick++ Core Unit: From a mechanical perspective, the core unit houses the StoryStick++ PCB, the smartphone, rail slots for mounting onto the guiding rail, a thumb roller for fine-grained displacement control, and a set screw for temporarily locking the device in place on the guiding rail. All custom parts of the core unit are 3D printed. A key design objective of the core unit is to position the edge LEDs on the PCB as close as possible to the

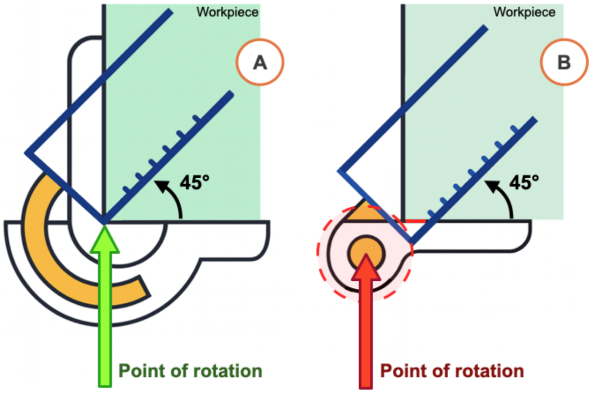


Figure 19: (a) StoryStick++'s concealed hinge design vs (b) traditional hinge design.

workpiece, in order to minimize parallax errors during alignment and marking. To achieve this, the PCB is designed to slide directly over the workpiece, while the guiding rail is positioned above it (figure 15).

The rail slots for attaching the guiding rail are engineered to ensure that the rail remains at a fixed distance from the onboard sensors for measuring the displacement (see Section 8.2). V-grooves are embedded in the slots to fit ball bearings for smooth displacement along the guiding rail.

While primarily electronic, the PCB also incorporates a mechanical feature: a notch to ensure its alignment with the workpiece when positioned near the edge as shown in Figure 20. Additionally, precisely dimensioned slots in the PCB allow it to press-fit onto the bottom of the rail slots.

8.1.2 *Attachment Designs:*

The guiding rail is made of 2 mm steel and features an integrated tooth rack that enables micro-adjustments via the thumb roller on the StoryStick++ core. The end of the rail is curled to interface with the hinge embedded in the corner and edge mounts. The rail is waterjet-cut with high precision to ensure both the stiffness and straightness needed for longer lengths, as well as the tight tolerances required for smooth hinge operation.

In contrast to the guiding rail, all other attachments, including the corner mount, edge mount, jaw, and compass, are 3D printed using FDM carbon-filled filament. The compass attachment also integrates a bearing to ensure smooth rotational movement. Due to the bearing's diameter, the minimum radius for plotting circles or arcs is 29 mm (approx. 1.14 in).

8.1.3 *Concealed Hinge Design:*

The corner and edge mount each embed a hinge of respectively 90 and 180 degrees to reach any position on a workpiece with StoryStick++. Both hinges have a concealed design, which, in contrast to conventional hinge designs (Figure 19b), ensures StoryStick++ pivots exactly in the corner of the workpiece rather than around a displaced axis (Figure 19a). This design is crucial to ensure interaction simplicity and a consistent reference geometry. The hinge embeds a set screw to temporarily lock the orientation of StoryStick++.

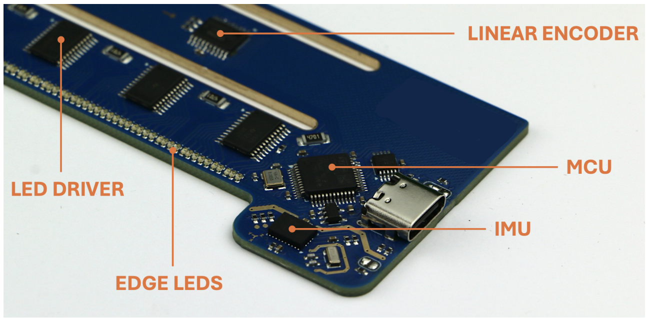


Figure 20: Overview of the StoryStick++ custom PCB embedding, among others, LED-drivers, edge-LEDs, an IMU, MCU, and a linear encoder.

8.2 Electronic Design

The electronics of StoryStick++ consists of a custom-designed PCB that integrates four tightly coupled subsystems: output, sensing, control, and power.

8.2.1 *Output.*

The PCB includes 140 edge LEDs driven by a daisy chain of TLC5926 constant-current shift registers, allowing full control via just three microcontroller pins (data, latch, clock). Each LED can be individually addressed. Orange LEDs were chosen for their high visibility, low visual fatigue, and lower forward voltage ($\sim 2.0V$ vs. $\sim 3.0V$ for green/blue), improving energy efficiency.

8.2.2 *Sensing.*

The PCB senses both linear displacement and angular orientation of the StoryStick++ core unit. For linear tracking, a 2+2 mm pole-pair magnetic strip is mounted beneath the guiding rail (Figure 9a). An AS5304B Hall-effect magnetic encoder on the PCB reads the strip's sinusoidal magnetic field and interpolates it into 256 steps per pole pair. With ×4 quadrature decoding, this yields up to 1024 counts per 4 mm (approx. 0.16 in), corresponding to a nominal resolution of ~ 3.9 µm (approx. 0.00015 in) per step. In practice, the system operates at an effective ~ 25 µm (approx. 0.0008 in) resolution for robust, low-noise measurements.

For orientation tracking, the PCB integrates a Bosch BNO055, a 9-axis absolute orientation sensor. Unlike standalone IMUs, the BNO055 includes on-chip sensor fusion via a dedicated Cortex-M0 core, outputting stabilized orientation data. Although smartphones contain built-in IMUs, their performance and drift characteristics vary widely across models. By embedding a dedicated IMU, StoryStick++ ensures a consistent performance across smartphones.

8.2.3 *Control and power.*

A built-in STM32F1 microcontroller coordinates the system's operation: maintaining a low-latency bidirectional data transfer with the smartphone over USB-C, sampling and preprocessing sensor data in real time, and controlling the edge LEDs. Communication is managed via a CH340 USB–UART converter, which translates between the microcontroller's serial interface and the smartphone's USB protocol. Power regulation is handled onboard via a 5V-to-3.3V low-dropout (LDO) regulator, which supplies a stable 3.3 V for the microcontroller. The sensors draw directly from the 5 V USB line. In standby mode, the system consumes approximately 40 mA, increasing to 250 mA during normal use, and peaking at 700 mA when all LEDs are illuminated at full brightness simultaneously.

8.3 Onboard Firmware

StoryStick++ communicates via a custom protocol that handles measurement guidance, LED control, and calibration. At fixed intervals, the firmware samples the magnetic encoder and converts its readings into millimeter values, which are transmitted along with IMU orientation data over USB-C. The firmware also supports external sensor control, for instance, the smartphone can reset the orientation reference for recalibration during use.

The edge LEDs support static and dynamic control modes. In static mode, specific LEDs are illuminated based on their fixed position on the PCB. In dynamic mode, LEDs are addressed relative to their position along the guiding rail—for example, lighting the LED currently aligned with the 5–6 cm region on the workpiece. As the device moves, the active LED updates accordingly or turns off if misaligned. This enables real-time, responsive feedback, automatically compensating for small displacements during marking or measurement.

8.4 Interactive Guidance Software

The interactive software is implemented as a Java-based Android application. It supports features such as peephole visualizations, off-screen navigation arrows, sub-millimeter alignment tools, step-by-step instruction rendering, and communication with the StoryStick++ PCB.

To generate step-by-step instructions, the application takes SVG vector graphics as input and converts them into instructions based on the supported interaction styles. It automatically computes auxiliary points and lines when needed—for example, determining the intersection between a segment and the workpiece edge to guide alignment (Section 6.3). When multiple geometry elements are present, the software optimizes the operation order to reduce repositioning and attachment changes (Figure 18), considering dependencies between steps.

9 Technical Evaluation

To assess the accuracy and cognitive demands of StoryStick++, we conducted two benchmarks comparing it against traditional measurement instruments: one focused on measuring, the other on plotting. Within each benchmark, we included multiple geometric tasks of varying complexity. As StoryStick++ integrates the capabilities of several traditional tools, we selected a baseline condition (referred to as *traditional condition*) that used a triangular protractor and compass—a common and reliable combination for accurate manual measurement and layout.

To ensure consistency between the StoryStick++ and baseline conditions, all tasks were carried out by one of the authors using standardized procedures. As this is a technical benchmark, the focus was on comparing system capabilities rather than evaluating usability, user preferences, or user behavior.

For each task in both conditions (StoryStick++ and baseline), we considered four metrics:

(1) Accuracy: The precision of the resulting measurement or plot, evaluated against a digital ground truth — a high-fidelity digital model of the task geometry created using CAD software.
(2) Number of precision steps: The total number of steps in a task where precision is critical, such as alignment, scale reading, or marking. For instance, plotting a perpendicular line using the triangular protractor requires one accuracy step (aligning the tool). However, plotting a perpendicular line of exactly 5 cm involves two: alignment and length marking.
(3) Number of numerical handling steps: This metric counts the total number of numerical values users must handle during a task—including reading, retaining, transferring, or comparing values. As discussed earlier in this paper, such steps are especially prone to user error. For example, calculating the perimeter of a triangle involves four numerical reasoning steps: one per side, and one for the total sum.
(4) Number of calculations: The total number of explicit mathematical operations (e.g., additions, divisions) required during a task. These operations typically impose greater cognitive load than simple number handling (metric 3). Continuing the example above, computing the triangle's perimeter involves two calculations (two additions) in addition to the four numerical handling steps.

Across both conditions, multiple valid strategies sometimes exist to complete the same task. For fairness, we consistently selected the approach that minimized the number of precision steps (metric 2) in each case. This allowed for a balanced comparison between StoryStick++ and the baseline tools, independent of user familiarity or tool bias.

9.1 Measurement Benchmark

The measurement benchmark consists of seven tasks with varying levels of geometric complexity. Each task involved a predefined geometry and required measuring specific features, such as positions, angles, lengths, or perimeters. The task geometries were lightly engraved onto MDF sheets using a Trotec Speedy 100R laser cutter. Laser engraving was chosen over ink-based printing to guarantee high geometric precision; the laser cutter offers an accuracy of 0.015 mm (0.0006in). Although each task was conducted on a separate MDF sheet, Figure 21 shows a compiled view of all seven task geometries. A detailed description of the measurement approaches taken for each task in each condition is provided in Appendix A. To evaluate measurement accuracy, results from both the StoryStick++ and baseline conditions were compared to a digital ground truth—the original high-fidelity model used for laser cutting. Some tasks required drawing of auxiliary construction lines on the MDF sheet to complete the measurement task. In both conditions, we tried to be as accurate as possible.

9.2 Plotting Benchmark

The plotting benchmark consists of three tasks featuring geometries of varying complexity. Fewer tasks were included in this benchmark, as each plot combines multiple types of dimensional information—both angular and linear measurements—within a single task. Each task involved plotting a predefined geometry, with dimensions and specifications provided via a technical drawing. Figure 22 shows

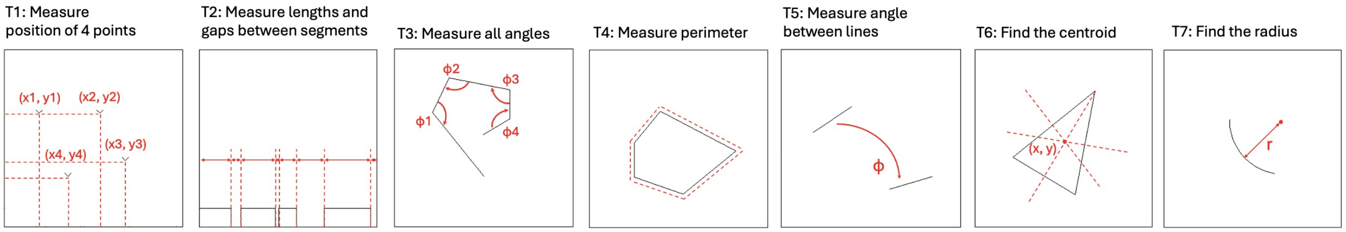


Figure 21: Reference drawing of Measurement Benchmark: the geometries to be measured are shown in black, the requested dimensions are shown in red.

Table 1: Results of the measurement benchmark.

Task	(1) Acc.	(2) Prec.	(3) Num.	(4) Calc.
T1 Traditional	$\overline{\Delta l} = 0.138$ mm	8	8	0
T1 StoryStick++	$\overline{\Delta l} = 0.44$ mm	4	0	0
T2 Traditional	$\overline{\Delta l} = 0.50$ mm	16	8	0
T2 StoryStick++	$\overline{\Delta l} = 0.59$ mm	8	0	0
T3 Traditional	$\overline{\Delta \theta} = 0.20°$	10	5	0
T3 StoryStick++	$\overline{\Delta \theta} = 0.6275°$	7	0	0
T4 Traditional	$\Delta c = 1.8$ mm	5	5	4
T4 StoryStick++	$\Delta c = 0.64$ mm	6	0	0
T5 Traditional	$\Delta \varphi = 0.3°$	4	4	0
T5 StoryStick++	$\Delta \varphi = 0.0°$	4	0	0
T6 Traditional	$\Delta p = 1.0$ mm	6	6	2
T6 StoryStick++	$\Delta p = 0.8$ mm	3	0	0
T7 Traditional	$\Delta r = 2.0$ mm	4	3	2
T7 StoryStick++	$\Delta r = 0.5$ mm	3	0	0

Table 2: Results of the plotting benchmark.

Task	(1) Acc.	(2) Prec.	(3) Num.	(4) Calc.
T1 Traditional	$\overline{\Delta l} = 0.27$ mm	25	7	0
T1 StoryStick++	$\overline{\Delta l} = 0.73$ mm	13	0	0
T2 Traditional	$\overline{\Delta l} = 0.19$ mm	9	4	0
T2 StoryStick++	$\overline{\Delta l} = 0.21$ mm	7	0	0
T3 Traditional	$\overline{\Delta l} = 1.93$ mm	46	13	0
T3 StoryStick++	$\overline{\Delta l} = 1.29$ mm	36	0	0

the technical drawings for all tasks. A detailed description of the procedures used in each condition is provided in Appendix 4. To evaluate plotting accuracy, a high-precision caliper was used to measure the x and y coordinates of all points of interest with respect to the corner of the drawing, and these were compared to the ground-truth — the technical drawing. For line segments, these points of interest included the start and end points. For the arc (Task 2), this included the start and end points of the arc as well as the centroid. The deviations of every task are reported as a mean error.

9.3 Measurement and Marking Benchmark Results

Table 1 and Table 2 present the results for the measuring and plotting tasks across both conditions. Despite StoryStick++ still being in a prototyping phase, the system demonstrates high accuracy, with average errors consistently well below 1 mm (0.04 in) and 0.6 degrees. Remarkably, these results are comparable to—and in some cases slightly better than—those obtained using traditional measurement instruments. This strong performance is particularly encouraging given that the current prototype relies on rapid fabrication techniques and integrates both hardware and software components, including IMU-based sensing, which have not yet been fully optimized. Future hardware iterations may further improve accuracy through refinements such as replacing the IMU with high-resolution rotational encoders.

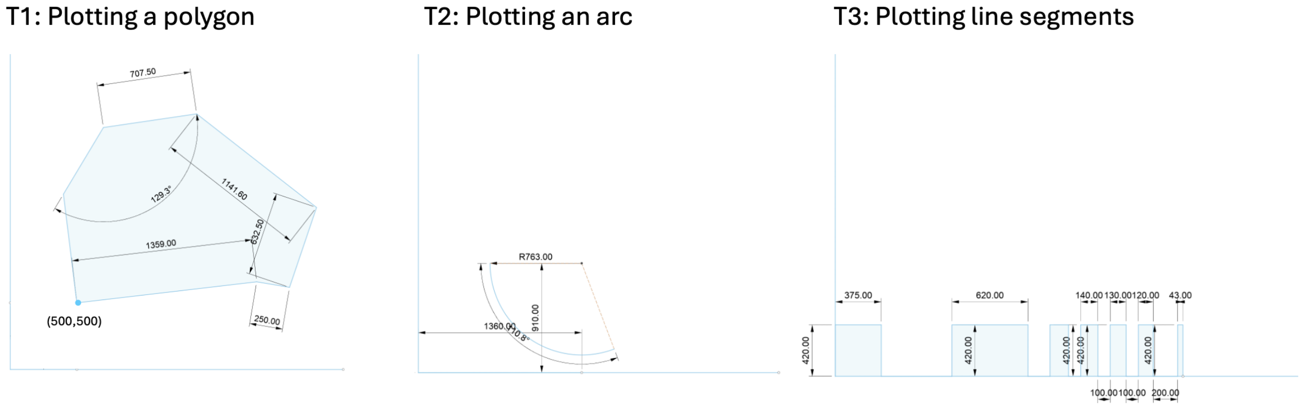
It is important to highlight, however, that StoryStick++ was not designed to outperform traditional tools in terms of pure metrological precision. Instead, StoryStick++ introduces significant usability benefits through its unit-less, guided interaction approach. These benefits are evident in the three other benchmark metrics: across nearly all tasks, the number of required precision steps is lower when using StoryStick++. More importantly, StoryStick++ eliminates the need for any numerical value handling or manual calculations. This stands in contrast to traditional tools, which require users to interpret, retain, and operate on numerical values—a process that is prone to mistakes and imposes considerable cognitive load [18].

10 Discussion and Future Work

StoryStick++ opens up new opportunities for precise, unit-less measurement and marking. Building on our current prototype and findings, we highlight several directions for extending this approach and exploring its broader implications for future research:

Although the examples and interaction styles presented throughout this paper illustrate the versatility and ease of use of StoryStick++,

The evaluation in this paper primarily benchmarks technical aspects compared to traditional instruments. Although the reported differences on the number of required of precision steps, numerical


T1: Plotting a polygon

T2: Plotting an arc

T3: Plotting line segments

Figure 22: Reference drawings of Plotting Benchmark.

handling steps, and calculations required per task, offer a first indication on potential differences in cognitive load of StoryStick++ compared to traditional measurement instruments, formal user studies are needed in the future that systematically assess usability aspects. These studies should be situated in realistic workflows across architecture, construction, engineering, and maker practices to understand how StoryStick++ performs in different domains and for different levels of expertise. Equally important is understanding the fundamental impact of our unit-less approach on measurement activities. Handling an individual measurement in isolation typically imposes little cognitive load, yet prior work indicates that errors frequently arise in basic interpretation or arithmetic once measurements are embedded in more complex engineering tasks, performed under time pressure, or require multi-step calculations (Section 3). To assess whether unit-less workflows mitigate these problems, future studies will need to simulate realistic scenarios with sufficient complexity. One avenue is a longitudinal comparison in which participants design and build artifacts using traditional measurement instruments versus StoryStick++. Another is to focus on tightly scoped measurement or marking tasks that incorporate distractor tasks or interruptions to emulate real-world cognitive demands. Taking a broader perspective, this line of work also points to an opportunity for more standardized procedures to evaluate the user aspects of measurement instruments, analogous to evaluation frameworks for toolkits proposed by Ledo et al. [21] and FEDT [37]. In the longer term, we envision usability heuristics [30] tailored to measurement instruments to evaluate novel and existing measurement instruments and guide their design, similar to platform-specific heuristics in user interface design [26].

While this paper advocates for unit-less measurement approaches and demonstrates the practical feasibility of such an approach with StoryStick++, numeric readouts and standard units remain deeply established and valuable, especially for communication and standardization. Unless all tools become seamlessly interconnected and blend the physical and digital world, as we showed with StoryStick++, numeric measurements and standard units will continue to be essential for communicating dimensions to collaborators, checking compliance with building codes, and transferring measurements to other equipment such as CNC machines. Although the current version of StoryStick++ deliberately limits users' direct exposure to numeric readouts, this information is available within the system and can be surfaced when needed to facilitate interoperability with tools that do not integrate directly. We therefore do not propose to eliminate numbers altogether; rather, we argue that measurement instruments can expose far fewer numeric values by more seamlessly integrating the physical and digital worlds, thereby offering the best of both worlds: direct, situated manipulation where possible, and conventional numeric representations where necessary.

In line with this view, future research can further explore how to embed StoryStick++ into both existing and emerging workflows. Many of the current interaction styles work best when StoryStick++ is supported by planar surfaces. Future versions could support full 3D spatial tracking or introduce new attachments that enable use on irregular or organically shaped objects, for instance, by guiding users in defining custom reference frames or temporary corners. StoryStick++'s caliper interaction style is already designed to be used without a supporting surface and can be extended with additional features, such as inner jaws, to further support such workflows. The current prototype supports *quick measure-and-draw* features for ad-hoc tasks as well as end-to-end guidance for more advanced marking tasks. In the future, this end-to-end support can be extended to complex measurement procedures that require many auxiliary steps. To support this, higher-level procedural knowledge about measurement problems should be embedded in the device. This would allow users to specify a measurement goal, such as "Guide me through the process of measuring this laptop for making a stand", and receive contextual, step-by-step instructions on how to approach and complete the task with StoryStick++ [9].

Technical refinements could further improve both the precision and usability of StoryStick++. Currently, angular sensing is handled by an IMU embedded in the custom PCB. Although our interaction styles mitigate drift, for example, by re-zeroing the orientation before each angular alignment, some drift remains. In future versions, the IMU-based sensing can be replaced with a rotational encoder integrated directly into the hinge mechanism of the corner and edge mounts. At present, all attachments are passive, but power and communication could be routed from the core unit through the guiding rail, or alternatively via wireless communication (e.g., Bluetooth), which would also eliminate the USB cable used in our current prototype. Regarding marking precision, StoryStick++ includes a small alignment hole that only accommodates a sharp pencil when held perpendicular to the surface. Our benchmark shows that this enables accuracies comparable to traditional tools, yet pencil lead still has a finite thickness. Future versions could incorporate a sharp scribing tip to achieve even higher accuracy. In addition, potential parallax at the edge LEDs could be further reduced by fabricating their carrier on thinner PCBs [19]. Finally, StoryStick++ currently features fixed clips for a Samsung Galaxy S21; this should be extended with adjustable clips to support smartphones of different sizes. A lightweight calibration procedure could then be used to align on-screen visual guides and technical drawings with the edge LEDs. While this can be supported in future versions, the exact alignment of the smartphone relative to StoryStick++ will not affect the system's precision. The precision of our approach is defined by relative location of the edge LEDs and alignment hole with respect to the ruler and attachment, which is not impacted by the attached smartphone. Precise smartphone placement primarily enhances the realism of the peephole display and the clarity of off-screen content navigation aids.

Beyond these immediate design implications, our work also speaks to a broader opportunity in HCI and digital fabrication. StoryStick++ illustrates how computational capabilities can be layered onto tools and workflows that have been refined in crafts over generations, rather than replacing them outright. Traditional tools such as story sticks, marking gauges, and templates embody effective practices. By augmenting them with sensing, visualization, and guidance, we can preserve their strengths while extending what they can do. In the future, we hope to see more of such *computationally augmented craft tools* that embed computation into existing tools and familiar practices rather than forcing a shift to new smart tools and abstract CAD-centric approaches.

11 Conclusion

StoryStick++ reimagines measurement as an interactive process by drawing on the unit-less, align-and-mark principles of traditional story sticks, while addressing their limitations through digital augmentation. By combining sensing, visualization, and procedural guidance into a smartphone-based device, StoryStick++ enables a wide range of measurement and marking tasks with sub-millimeter precision without relying on standard units or numerical interpretation. Our system introduces new interaction styles, guides users through complex layouts, and supports both precise and ad-hoc workflows. With StoryStick++, we argue for rethinking measurement not merely as a technical challenge, but as a core HCI problem, prioritizing convenience and ease-of-use.

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A Measurement Benchmark Tasks

Table 3: Measurement benchmark tasks with traditional and StoryStick++ conditions.

Task	Description	Traditional Condition - Approach	StoryStick++ Condition - Approach
1	Measure the position of four points relative to the bottom-left corner.	Use the triangular protractor to measure the x and y coordinates of each point.	Align using the corner mount and sample each point via the alignment hole; positions are recorded automatically.
2	Measure the lengths of, and distances between, multiple aligned line segments.	Align the triangular protractor with each segment’s start and end position to read individual lengths and distances. Keeping the protractor fixed is not preferred as it requires subtracting offsets between many odd numbers.	Align StoryStick++ with the segments using the edge mount and guiding rail, then slide the device along the segments to measure all lengths and distances (Section 6.3).
3	Measure all angles of a polygon.	Measure each individual angle using a triangular protractor.	Align using the corner mount and sample each point via the alignment hole; angles of the polygon are calculated and recorded automatically.
4	Measure the perimeter of all line segments of a polygon.	Measure each individual line segment using the triangular protractor and sum.	Align using the corner mount and sample each point via the alignment hole; the perimeter of the polygon is calculated and recorded automatically.
5	Measure the angle between two disconnected lines.	Extend one line, draw a perpendicular to intersect the second, then use the triangular protractor to measure the bisecting angle and subtract 90 degrees.	Align using the corner mount and sample two points arbitrarily on both lines using the alignment hole; angles between the two lines are calculated and recorded automatically.
6	Measure the coordinates of the centroid of the triangle.	Use the triangular protractor to draw perpendicular bisectors on two sides of the triangle. Their intersection is the centroid, whose coordinates can then be measured.	Align using the corner mount and sample each corner via the alignment hole; the centroid of the triangle is automatically calculated and recorded.
7	Measure the radius of the arc.	Use a triangular protractor to plot two chords that intersect the arc at the same point. Draw the perpendicular bisectors of both chords. Their intersection marks the arc’s center. Measure the distance from this center to the arc.	Sample three points arbitrarily on both lines using the alignment hole; the arc is digitized, and its centroid and radius is automatically calculated and recorded.

Table 4: Plotting benchmark tasks with traditional and StoryStick++ conditions.

Task	Description	Traditional Condition - Approach	StoryStick++ Condition - Approach
1	Plot four points given their coordinates	Use the triangular protractor to plot the x and y coordinates of each point.	Align the corner mount, for every point: align the orientation and displacement according to the on-screen instructions, mark the points (Section 6.2)
2	Plot 5 aligned line segments at the given intervals.	Draw a construction line using the triangular protractor at the height of the segments, mark the start and end points of the segments on the construction line using the triangular protractor	Use the corner mount to plot the height of the segments, align the edge mount at this location and transfer the start and end points of all segments which are highlighted by the edge LEDs (Section 6.3).
3	Plot a polygon from a start point using edge lengths and internal angles.	Plot the start location using the triangular protractor, subsequently plot all edges using the lengths and angles in the technical drawing.	Align the corner mount, for every corner of the polygon: align the orientation and displacement according to the on-screen instructions, mark the points.
4	Plot an arc given its centroid, radius, and arc length.	Plot the horizontal radius and centroid using the triangular protractor, align the triangular protractor with that radius and mark the arc length, set the compass to the radius and plot the arc.	Align the corner mount, plot the centroid and horizontal radius according to the on-screen instructions, align the compass in the centroid and follow the on-screen instructions to plot the arc from start to end point.