Drill Sergeant: Supporting Physical Construction Projects through an Ecosystem of Augmented Tools

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Abstract
Mapping techniques from software tutorials onto physical craft processes can assist novices in building multi-material assemblies. By providing in-situ step instructions and progress tracking, generating dynamic feedback on technique, and adapting tutorial content to a user's specific context and preferences, an ecosystem of smart tools can guide users through complete project tutorials. We demonstrate how such techniques can be enabled by augmenting common workshop tools (drill/driver, saw, router) with measurement, state sensing and interactive feedback; and by sequencing instructions across multiple tools. We validate the benefits of a smart tool ecosystem through reflections on a series of author-created design examples and informal feedback from four fab lab users.

Author Keywords
Smart Tools; Multi-Machine Ecosystems; Learning Instructional Systems; DIY

ACM Classification Keywords
H.5.m. [Information Interfaces and Presentation (e.g. HCI)]: Miscellaneous

Introduction
Builders—home improvement enthusiasts, woodworkers, and DIYers—rely on multiple materials (lumber in different

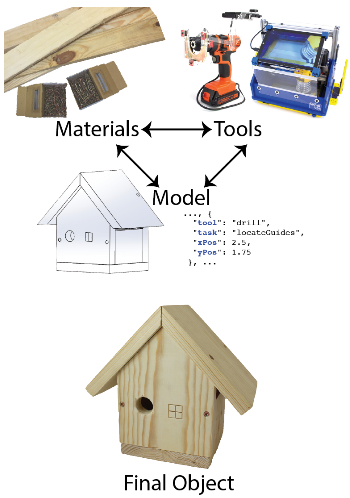

Figure 1: Drill Sergeant allows tools, materials, and model specifications to inform and define each other as a user works to create a final object.

dimensions, composites, fasteners, etc.) and an ecosystem of tools to craft physical artifacts. Novices become proficient in working with these different tools and materials through tutorials published in books, e.g. [10, 15], and online, e.g. [2]. These tutorials today are *static, pre-recorded media*, leaving builders with a non-trivial translation of written steps into corresponding actions [17]. Inspired by the techniques of *interactive* software tutorials, we seek to augment physical DIY projects by providing in-situ step instructions and progress tracking [3]; generate dynamic feedback on technique [9]; and adapt tutorial content to a user's specific context and preferences [4] (see Figure 1). We aim to achieve these goals by augmenting a set of power tools with sensing, communication, and local user interfaces for continuous task feedback. We develop a novel instruction format describing how tools should be used to fabricate a model out of raw materials and a framework to delegate instructions to appropriate tools in sequence.

Our current collection of smart tools includes a pose-sensing drill with projected feedback, a compound miter saw with tablet-based feedback, an off-the-shelf digital distance measurement tool, and a tabletop CNC router with added tablet input. We have performed a preliminary validation of Drill Sergeant through building example objects and user feedback from 4 experts.

Related Work

Drill Sergeant builds on prior work in three primary areas: tutorials, smart tools, and modeling.

Tutorials and Instructions

Tutorials researchers have previously investigated how to add instructions to physical task domains. In a related area, cooking, projects deliver instructions by augmenting a delimited *space* in which users work, e.g. through ceiling-mounted projectors [7] and sensors [14]. Drill Sergeant does not constrain users to a fixed counter top workspace: the tools are portable and self-contained (an approach shared with French Kitchen [6]). Other systems aid in furniture [1] or block assemblies [5] by using a *known* set of building blocks or parts. In contrast, Drill Sergeant guides the user through subtractively fabricating parts from raw materials that are then assembled. AR systems can also allow experts to assist remote novices in assembly tasks [11].

Perhaps closest to our domain is Smart Makerspace, which adds sensing to tools placed on a tabletop display [8]. In contrast, Drill Sergeant explores realtime *in situ* feedback coupled with integrated high precision sensing of tools, which can be used in any environment.

Smart tools

Zoran, et al., describe the space of smart tools, focusing on *individual* physical tools that can help users fabricate digital models [22]. A handheld tool can *correct* a user's toolpath to follow the model [13], or *guide* the user to sculpt a model from a block of material [12, 23]. In contrast to prior work, Drill Sergeant permits a full *ecosystem* of tools to work in concert to process and create assemblies.

Modeling in Physical Contexts

We take inspiration from prior work exploring CAD modeling *in context*—defining and modifying models through actions in physical space rather than manipulation on a screen. This context can come from bringing physical objects into an AR modeling booth [19], from measurement tools with a bidirectional link to a digital model [18], or from recording user tool motions [21]. Drill Sergeant object dimensions come from users physically cutting boards or using digital measurement tape.

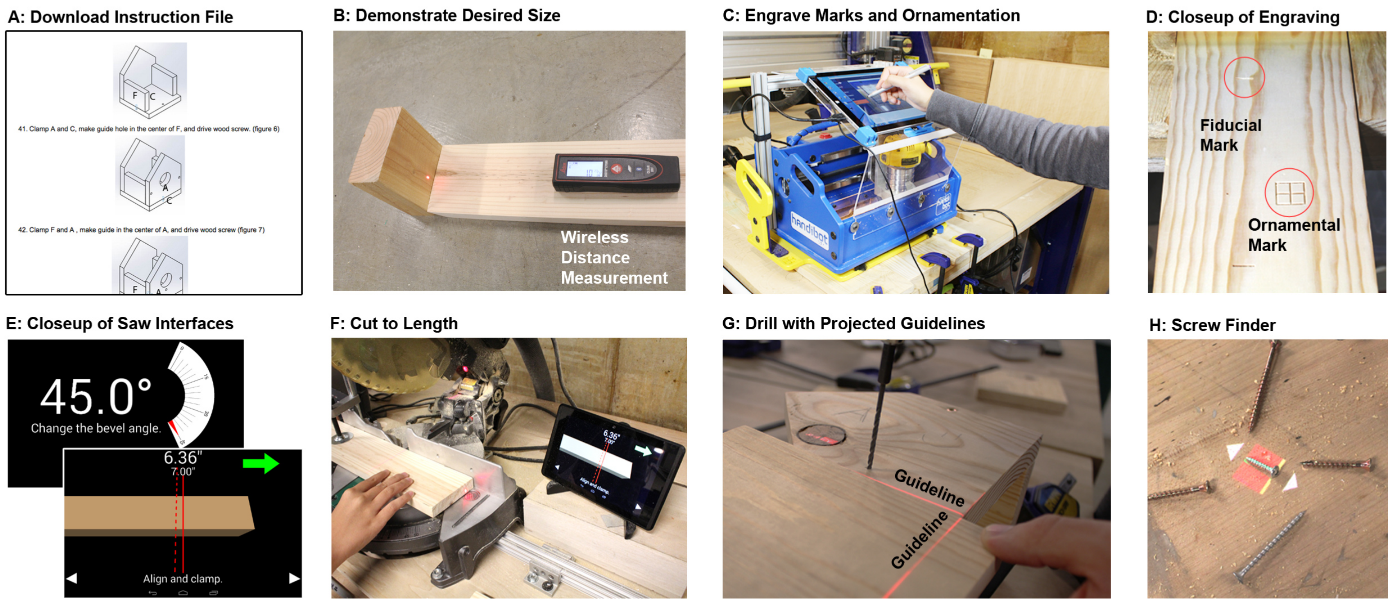

Figure 2: To complete a Drill Sergeant project, a user finds a model (a) and sizes it, measuring their desired final location (b). For this birdhouse, the user engraves a decorative pattern and fiducials (c, d), cuts boards to length (e, f), locates drill positions (g), and identifies the correct fasteners (h).

Using DRILL SERGEANT

We introduce a running scenario to demonstrate the different interactions enabled by Drill Sergeant's tools.

A builder finds a birdhouse project compatible with Drill Sergeant online (Figure 2A). The design can be built out of common 1x4 and 1x6 lumber boards[1]. The builder downloads the file into their Drill Sergeant environment.

Adapting to User Preferences: The system first prompts the user to measure the desired width, height, and depth of the birdhouse with a digital measuring tape on actual lumber (Figure 2B). These measurements are fed into the parametric model to calculate board lengths, cut positions, and fastener locations.

Cross-Tool Operations: The user then inserts a board into the CNC router (Figure 2C). The router engraves a decorative pattern onto a board, as well as fiducial markings to help the user align the a hole saw for the entryway in a subsequent step (Figure 2D).

Precision Measurements: Next, the tablet instructs our

[1] The actual dimensions of these boards are 0.75"×3.5" and 0.75"×5.5"

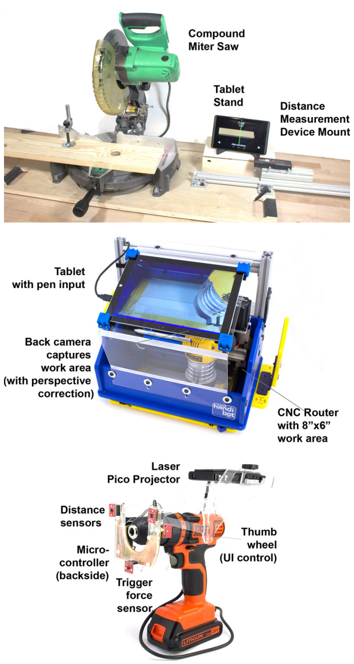

Figure 3: Augmented miter saw (top), augmented CNC router (middle), augmented drill (bottom).

builder to insert a board into their compound miter saw. The tablet display then helps them align the board to cut to the correct length, displaying a live correction interface (Figure 2E, F). For subsequent cuts, they adjust miter and bevel angles of the saw as indicated on the tablet UI, e.g., to cut the sharp peak for the roof.

Real-Time Operation Feedback: The drill leads our builder to the proper drilling points, projecting guidelines which align with material edges and fiducial markers engraved by the router (Figure 2G). The drill also shows an indicator of drill angle and depth feedback to ensure the pilot holes are drilled appropriately for the screws (Figure 5).

Finding Parts: The builder is guided to collect several correctly-sized screws—the smart drill projects a perspective- and size-corrected image of the desired screw size, giving the builder a visual template to identify correct parts (Figure 2H). With all parts prepared, the builder's tablet leads them through assembly steps including clamping and driving screws. The birdhouse completed, our builder proudly hangs it outside.

Implementation

Smart tools in Drill Sergeant gather and process data from onboard sensors to show high-level feedback in their user interfaces. Tool actions are coordinated by a central server that maintains the project model, tracks its current assembly status, and receives and updates measurements of model parameters (e.g., width, height, depth) for the project.

Instruction File Format

We model step-by-step instructions for woodworking assemblies in a JSON file format. Each assembly file consists of an ordered list of steps containing recording `tool` and `task`, for all steps, alongside task-specific parameters (see Figure 4). Task parameters may also be

```
{
 "tool": "miterSaw",
 "task": "distoMeasure",
 "measurementName": "chair_height"
},
{
 "dynamic_params": ["targetMeasurement"],
 "tool": "miterSaw",
 "task": "cutToLength",
 "targetMeasurement":
    "chair_height + seatback_height"
},
```

```
{
 "tool": "drill",
 "task": "locateGuides",
 "xPos": 2.5,
 "yPos": 1.75
},
{
 "dynamic_params": ["depth"],
 "tool": "drill",
 "task": "drillToDepth",
 "depth": "screw_depth"
},
```

Figure 4: Our JSON-based language has dynamic and static parameters for instructions; formulas are evaluated in Python. This language captures all tasks, from measuring a dimension and cutting to length on a saw (left) to locating and drilling in the correct location (right).

represented as parametric constraints with our model, i.e. `TargetMeasurement: seatZ + matlThickness`. To properly order fabrication steps, we rely on a precedence model: router engraving, miter saw cuts, drilling, and driving. We manually generate files for our prototype.

Server/Proxy

The server provides three major functions: (1) maintaining assembly progress and parameters, (2) forwarding current step information to the proper tools, and (3) modifying the assembly from user input. Tools poll the server at regular intervals to retrieve information. Once a tool reports the completion of a step, actual measurements are recorded and the server updates all subsequent steps which depend on that measurement.

Tools

The essence of each augmented power tool is a commodity tool augmented with sensors and/or a display. We focus on tasks that require precision and may be hard to judge by eye or measure with conventional tools, e.g., ensuring a drill is exactly perpendicular to a workpiece.

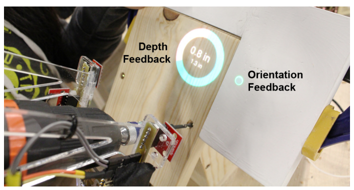

Figure 5: Users are given perpendicularity (right) and depth (left) feedback while drilling. The drill's rangefinder array ensures that the UI maintains a constant size and aspect ratio.

Drill

Our drill is a Black and Decker LDX120C cordless drill fitted with a force-sensing resistor (FSR) on its trigger to determine input pressure, a photocell on its status LED to determine spin state, and three time-of-flight rangefinders to reveal the drill's relative plane with respect to the workpiece. A top mounted laser pico projector displays UIs and measurement guides. Projected images are corrected for size and perspective distortion using camera parameter backsolving [20], based on the drill's orientation inferred from the rangefinder array. The current prototype requires a tether to a laptop to generate graphics, though an on-board computer could remove this restriction.

Distance Measurement

We use an off-the-shelf Leica Disto E7100i laser distance finder, which streams continuous distance measurements over Bluetooth Low Energy at 3Hz. These are forwarded to our server via a tablet. This device can be used for free-hand measurements as well as mounted onto tools in to aid with measurement tasks.

Compound Miter Saw

Our saw is a Hitachi C10FCH2 10-inch single bevel compound miter saw. To measure boards for cutting, the distance finder is mounted at a known distance from the blade and a tablet mounted is next to the body (see Figure 3, left). The distance finder points down the length of a board inserted for cutting, such that it can tell where the saw will cut the board. The mounted tablet display helps refine positioning before a cut. We do not currently track bevel or miter angle automatically—the user has to read these out manually on the saw.

CNC Router

Our CNC Router is a commercially-available Handibot with a 6"x8"x2" work area. We augmented it with a tablet on top, positioned so that the back camera images as much of the work area as possible (see Figure 3, center). The tablet display shows a perspective-corrected live video which allows users to preview where in the work area cuts or engravings will be made. The CNC router operates largely autonomously, requiring minimal user guidance aside from placement over a workpiece. Toolpath instructions are generated on the fly from a manually-generated vector drawing contained in the assembly. Once the toolpath is aligned, the user presses cut to begin the engraving.

Validation

In order to validate the utility, usability, and flexibility of Drill Sergeant, we created instruction files and built example objects with them. We also sought feedback on our interaction model from four users with shop experience.

Example Objects

A box (Figure 6) is made of six pieces of 1 by 4 lumber, with 45° beveled edges. Its width can be freely defined by users, but the depth is constrained to multiples of the board's width. In addition to the augmented miter saw and measurement device, the box uses the drill's projected alignment guides and orientation feedback for drilling and driving screws through the corners to secure the frame.

Our birdhouse is described in "Using Drill Sergeant". The CNC router is used to add decorative detail and cut fiducial marks for locating screws. The birdhouse uses 1x4s for the sides and 1x6s for the roof, front and back; and requires reinserting a single block into the miter saw multiple times. The front piece has two 45° cuts meeting at the roof peak in addition to the 90° sizing cut at the bottom. This points towards the possibility of creating more complex joinery that involves multiple cycles with our augmented tools.

Figure 6: We created example objects to test the utility of our tools: a box with beveled joinery (top) and a birdhouse with peaked roof (bottom).

Preliminary Exploration with Users

In order to gain insight into how Drill Sergeant may help users, we solicited informal feedback from 4 experienced shop users (2 male). We provided them with a partially-completed box (to reduce operation repetition, as all 4 sides are processed identically), and had each user perform several operations with each of our tools to complete the box. Sessions lasted less than one hour each.

All four users successfully completed their boxes. In addition to orientation feedback, users expressed a desire for seeing more data, such as the amount of force being applied, e.g., to suggest when to press harder. One user remarked that the type of display could depend on the expertise of the operator, e.g., focusing on safety and handling for novices. Some participants were concerned with the danger of focusing on the projected interfaces at the cost of considering their workpiece directly. Ergonomics were also an issue with the handheld drill: the physical shape of the mounting bracket prevented one user from bracing the drill with a second hand. Such issues could be remedied with an improved industrial design.

Conclusion and Future Work

Dynamic software tutorials have helped countless people bootstrap themselves into new skills and improve their grasp of existing ones. With Drill Sergeant, we extend the ideas of these tutorials into the DIY realm, leveraging an ecosystem of augmented tools that work together to track and give real-time feedback to a user completing a tutorial. One question is whether augmentations should always be present. We believe augmentations for tool-centric skills is scaffolding that could recede over time [16], so users become proficient even without augmentations; while project-specific assembly instructions and measurements change from project to project and should always be delivered through Drill Sergeant. In ongoing work, we seek to improve the following areas:

Interactions: We have only begun to explore the design space of teaching interactions enabled by our augmented tools. We would like to explore practice tasks and games (e.g., [9]) to build skills.

Authoring: Authors must currently write instruction files manually, which requires significant expertise. We would like to create an authoring tool that leverages physical demonstration to create tutorials.

Ergonomics: We seek to improve the ergonomics of our tools. E.g, orientation sensing on the drill depends on all three distance sensors hitting the same plane, sometimes requiring jigs to surround the workpiece at an even height. Miniaturizing the sensing PCB could address this.

Sensing: We would like to explore further instrumentation of our tools and other tools. E.g., sensing the the orientation of our miter saw would enable users to more easily create intricate and precise joinery. Drill guides are also currently limited by the size of the drill's projected image.

Evaluation: We seek to further evaluate the precision, capability, and usability of our system through a more comprehensive study with novice users.

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