MobiPrint: A Mobile 3D Printer for Environment-Scale Design and Fabrication

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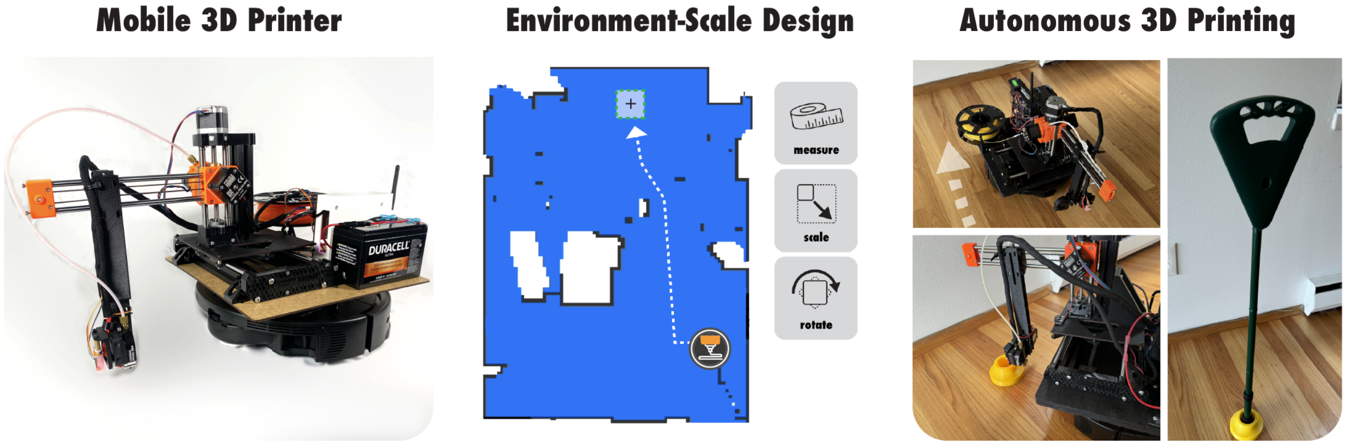
Mobile 3D Printer

Environment-Scale Design

Autonomous 3D Printing

Figure 1: *MobiPrint* is a custom-built robotic 3D printer that autonomously maps, navigates, and prints 3D objects directly in indoor environments. MobiPrint provides a multi-stage fabrication pipeline: (1) the robotic 3D printer maps an indoor space using LiDAR scanning and obstacle detection; (2) a custom design tool converts the map into an interactive CAD canvas for editing and placing models in the physical world; (3) the MobiPrint robot prints the object directly on the ground at the defined location, as demonstrated in the far-right figure showing a cane holder printed on the floor to prevent it from falling over.

ABSTRACT

3D printing is transforming how we customize and create physical objects in engineering, accessibility, and art. However, this technology is still primarily limited to confined working areas and dedicated print beds, thereby detaching design and fabrication from real-world environments and making measuring and scaling objects tedious and labor-intensive. In this paper, we present *MobiPrint*, a prototype mobile fabrication system that combines elements from robotics, architecture, and Human-Computer Interaction (HCI) to enable environment-scale design and fabrication in ad-hoc indoor environments. MobiPrint provides a multi-stage fabrication pipeline: first, the robotic 3D printer automatically scans and maps an indoor space; second, a custom design tool converts the map into an interactive CAD canvas for editing and placing models in the physical world; finally, the MobiPrint robot prints the object directly on the ground at the defined location. Through a "proof-by-demonstration" validation, we highlight our system's potential across different applications, including accessibility, home furnishing, floor signage, and art. We also conduct a technical evaluation to assess MobiPrint's localization accuracy, ground surface adhesion, payload capacity, and mapping speed. We close with a discussion of open challenges and opportunities for the future of contextualized mobile fabrication.

KEYWORDS

Mobile Fabrication, Environment-Scale Fabrication, 3D Printing

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1 INTRODUCTION

3D printing is progressively reshaping numerous fields, including design, engineering, and accessibility, by enabling users to customize, adapt, and augment objects. [16, 32, 40]. Extending the benefits and capabilities of 3D printing beyond individual objects

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and into larger real-world spaces allows for personalized and dynamic ways of navigating, decorating, and instrumenting the built environment. 3D printing at the scale of the built environment, however, remains a challenge because 3D printers have a limited working volume, require a dedicated print bed, and remain fixed at one working location [58]. The separation between the machine and the real-world context makes transporting, evaluating, and adjusting prints to fit the environment monotonous, time-consuming, and error-prone. In turn, this can lead to more design iterations and result in sub-optimal designs [35]. Perhaps even more importantly, this separation limits the very design space of what is possible to create and print.

Recently, mobile fabrication has emerged as a viable alternative to address these limitations with machines that have larger working volumes, enable on-the-go making, and integrate objects directly into the environment [47, 53]. Researchers have proposed handheld [63], portable [44], and wearable machines [22] that are easier to transport and set up in different places to make objects on-the-fly. However, handheld systems lack the precision, accuracy, and efficiency associated with digital fabrication; portable machines have smaller working areas; and wearable printers can be a significant burden for users to carry. Instead, we propose a new approach that leverages advancements in mobile robotics to make a mobile 3D printer that converts the ad-hoc indoor environment into a canvas and print bed for users to augment and customize with new objects.

Mobile robots can perceive the environment and autonomously navigate around obstacles in ad-hoc environments [48]. A report by *National Institute of Standards and Technology* (NIST) affirmed the potential of mobile robots to be transformational for manufacturing by having the flexibility to adapt to dynamic work environments and relieving people from doing tedious labor tasks [50]. Accordingly, mobile robots are increasingly used for daily tasks like cleaning [38], pedestrian and customer guidance [37], and accessibility assistance [43]. We extend this approach to 3D printing and help alleviate the repetitive measuring, installing, and adjusting tasks associated with fabricating and integrating objects in an environment. We also highlight how robotic 3D printing opens new possibilities for digital fabrication not previously possible, such as a dynamically printed 3D mural that is updated each day (*e.g.*, with the weather, stock prices, or simply abstract art).

In this paper, we introduce *MobiPrint*, a mobile 3D printer to support fabrication at an environment-scale by printing objects directly onto ground surfaces in ad-hoc environments. MobiPrint includes both a custom, cantilevered 3D printer with a robotic base which maps and navigates un-instrumented indoor environments as well as a custom web-based interactive design tool that converts the robot-generated map to a canvas for users to arrange, measure, scale, and rotate 3D models in-context. Once the placement, size, and orientation of the models are finalized, MobiPrint autonomously navigates to the desired location and 3D prints.

MobiPrint scales to large working areas, adapts to changing environments, and supports evolving or dynamic printing sequences. Our pipeline enables distance and reference measurements from a single interface and eliminates the wait and interruption of having to manually transport, adjust, and adhere to objects from a stationary 3D printer. Consequently, MobiPrint can scale to large environments and repetitive print jobs. Further, our approach makes it easy to design for and adapt to changing environments like conference venues or building atriums. For example, MobiPrint can scan and map changes for different events at a conference venue to print day-specific tactile surface indicators or floor signage that help attendees navigate to events. Relatedly, the design tool keeps a history of previous prints and relationships between objects for users to identify emergent and design print sequences that evolve over time.

To highlight applicable use cases and examine MobiPrint's performance, we created a series of "proof-by-demonstration" scenarios in accessibility, home furnishing, pedestrian guidance, and art. We also evaluated the localization accuracy, adhesion strength, mapping speed, and payload capacity which shows that our system can precisely reach a target location, adhere prints onto common floor surfaces, quickly map multiple room layouts, and carry large material loads. Our prototype is a step toward fabrication machines that are not confined to makerspaces or labs but instead can change, adapt, and augment the physical world with custom and personalized items.

In summary, this paper contributes:

- A novel mobile 3D printer that can navigate indoors and print directly onto various indoor surfaces.
- A design tool that supports measuring, scaling, and rotating objects in-context for environment-scale fabrication.
- A set of scenarios and objects that demonstrate how our system can serve different environments and needs.
- A set of design considerations for future mobile fabrication systems, including: integrating environmental context into the design process, supporting a spectrum of automation and interactive workflows, exploring more printing surfaces, and anticipating the life-cycle of printed objects.

2 RELATED WORK

Our work builds on a cross-disciplinary body of research in mobile fabrication systems, environment-scale fabrication, and in-context design tools.

2.1 Mobile Fabrication

While the concept of *mobile fabrication* has been explored across several disciplines, including architecture [18, 34], robotics [52, 53, 56], and HCI [47], there is no shared definition of the term, leading to its association with a range of differing approaches.

One approach involves making 3D printing machines smaller and portable. Roumen *et al.* envisioned a future of mobile fabrication where users could carry 3D printers and 3D printing pens to make objects on-the-go when needed [47]. Indeed, there has been a rise in the number of miniature [2, 8, 12], handheld [13], and wearable 3D printers [23, 31]. Handheld tools like *3Doodler* [13] allow for free-form designs and a theoretically unlimited print area but are imprecise, inconsistent, and inefficient for repetitive tasks over large areas like infills or shells [47, 55]. *PopFab* is a portable 3D printer and CNC mill that fits in a suitcase to make it easier to transport; however, it still requires a wired power connection and is restricted to the print area in the suitcase, which greatly limits where it can be deployed and the type of objects it can make [44]. Wearable printers and plotters also retain the precision and consistency that is a strength of digital fabrication and can print on unusual surfaces like skin [22, 25]. However, portable and wearable 3D printers have limited working areas and material capacity, only support a single substrate material, and can be cumbersome to carry and set up.

Robotics, instead, emphasizes autonomous navigation and locomotion where the machines travel to fabricate. Researchers have developed 3D printing systems that fly [33, 60, 61], drive [53, 56], and walk [39]. Drones have the largest possible working areas, but their flight dynamics can be unstable, and they cannot handle a heavy payload. Wheeled robots, though restricted to shorter working heights than drones, are simpler to control and can handle heavier payloads [30, 41, 52, 53, 59]. *FabRobotics* combines 3D printing with miniature wheeled robots that move around the printer bed for hybrid fabrication interactions [17]. However, they require orchestrated, pre-planned moves and are confined to the immediate vicinity around the printer. Robots using simultaneous localization and mapping (SLAM), on the other hand, can travel to target locations to print in unstructured, ad-hoc environments autonomously by using sensors like LiDAR to create a map "on-the-fly" [19]. For example, Zhang *et al.* use SLAM to have teams of mobile robots collaboratively print concrete structures in a factory setting [61].

Architecture has also explored mobile fabrication, primarily as a way for enhancing site-specific workflows that can integrate environmental, human, or ecological feedback into the construction processes [26, 28]. Mobile machines provide enhanced flexibility and dexterity and are also easier to deploy on-site [15]. For example, Sandy *et al.* developed a mobile robotic arm equipped with various vision and depth sensors to allow for in-situ construction of bricklayed walls [49]. Prior research has also explored how to automate other architectural building processes like laying down chalk lines for building layouts [10, 11] and human-machine interactions in the construction process like having the robot build a wall along a chalk line drawn by a person [30].

These differing notions inform our vision for standalone, easy-to-deploy machines that can autonomously map and navigate their surroundings to facilitate site-specific design and fabrication over large working areas.

2.2 Environment-Scale Fabrication

Environment-scale fabrication refers to machines and systems that can print on or operate across large surfaces and areas that are typically beyond the scope of digital fabrication [58]. Architecture has pursued environment-scale fabrication to build structures on-site instead of pre-fabricating components remotely and transporting them to the final location with benefits, including the safety, speed, and quality of new constructions, as well as a reduction of financial and environmental costs [1, 18]. Keating *et al.*, for example, presented the *Digital Construction Platform*, which 3D printed a 14 meter wide and 3.7 meter tall structure in 13.5 hours [34]. Since then, the promise of environment-scale fabrication has been further evidenced by the numerous architecture startups like *SQ4D* [13] and *Apis Cor* [7] using large-scale 3D printers to build homes in situ with cement composite materials. Unlike standard 3d printers, these large, industrial machines and materials provide coarse details, focus on specialized work, and are unlikely to become widely adopted for personal use.

In HCI and digital fabrication, researchers have explored ways of using smaller machines to produce or recreate large-scale objects and surfaces [46]. For example, *TrussFab* makes large-scale structures by combining 3D printed components with plastic bottles to produce trusses that can support a human [36]. *Protopiper* allows users to "sketch" room-scale objects using a handheld tube former [14]. These systems, though, lack the precision and consistency associated with 3D printing and depend on external materials to build scale. Conversely, *Creality's CR-30* 3D Printer uses a belt instead of a build plate to provide an "endless" print surface, but it requires a large CNC gantry and can only operate over the single belt surface [6]. Whiting *et al.* achieved environment-scale fabrication with 3D printing by scanning a rock climbing surface and selectively printing the spots where climbers placed their hands [58]; however, this required manual scanning of the surface by taking hundreds of photos of the climbing route. Closer to our work are compact, wheeled robots that can fabricate objects directly on the floor. Xu *et al.* [59] projected visual landmarks onto the floor to guide mobile robots to target locations and track the printing movements. The Goliath CNC is a wheeled robot with an endmill that can cut objects out of a large substrate material [4]. Marques *et al.* [41, 62] used robots that could work collaboratively to 3D print objects and tracked the robot position by using optical flow sensors and grid lines on the floor. All of these systems, however, require manual instrumentation or preconfiguration of the environment. In comparison, MobiPrint is a standalone system that can map, navigate, and locate objects in larger, ad-hoc environments that are un-instrumented or preconfigured.

2.3 Design Tools for Contextual Fabrication

MobiPrint also introduces a web-based design tool that transforms the map generated by the robotic 3D printer into an interactive canvas to let the users select, arrange, and edit 3D printable objects within the spatial context in which they will be used. Researchers have explored various ways of incorporating real-world objects [21], surfaces [29], and environments [58] into the design process for fabrication. For example, *CopyCAD* was an early work that allowed users to copy the geometry of real-world objects in its fabrication environment but was limited to small objects that could fit into the camera/projector workspace [24]. *Reprise* is a design tool for 3D printing adaptations to a library of real-world objects but requires having 3D models of each object preloaded or a coarse hand-measurement process to make adaptations [21]. Weichel *et al.*, instead, developed physical measuring tools, like calipers and protractors, that uploaded the measurements directly into a computer-aided design (CAD) program. We aim to extend this work and integrate the robot's mapping and localization capabilities into the design process by converting the scanned LiDAR map into a canvas to yield objects that can blend into the environment or serve site-specific purposes.

3 MOBIPRINT

MobiPrint is a mobile 3D printer that can autonomously map, navigate, and print in ad-hoc environments. Unlike other systems, MobiPrint does not require instrumenting the environment (*i.e.,* using projectors or grid marks [41, 59]) to locate and run print

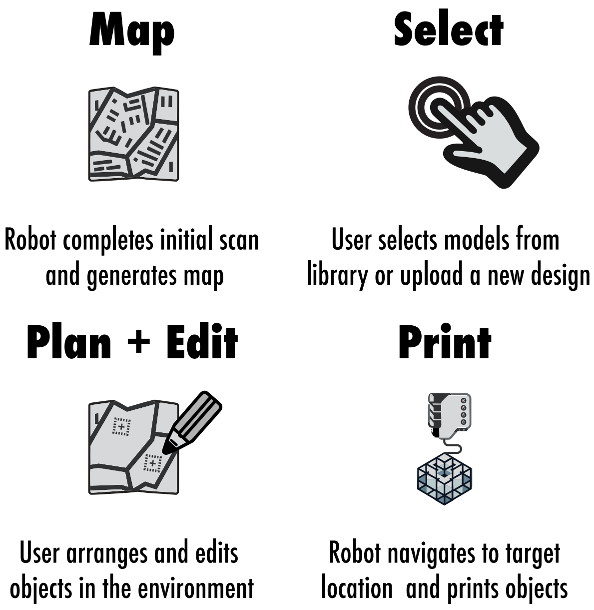

Figure 2: The workflow for environment-scale design and fabrication using our mobile 3D printer includes: (1) mapping a space; (2) selecting objects from a library or uploading files to print; (3) planning and editing objects using the map as an interactive CAD canvas; (4) and lastly, instructing the robot to go and print the objects.

jobs. Our system is untethered, allowing for navigation around large indoor environments like conference halls and multi-room apartments. Our accompanying design tool renders the map of the environment as a canvas for users to arrange, measure, scale, and rotate the desired 3D-printed objects. Once the user has finalized the models and desired print locations, MobiPrint will autonomously travel to the specified locations and print the objects in place.

Our mobile fabrication workflow (Figure 2) involves four main steps: (i) mapping an ad-hoc environment, (ii) selecting the desired objects to print, (iii) arranging and editing the models in-context, and (iv) printing the objects on the ground surface of the mapped environment. We describe each phase below. Please also see our accompanying video figure in the supplementary materials.

Map. The first step is to scan the environment and generate a map of the space. We limit our system to indoor environments because they typically have more landmarks (*i.e.,* walls) to facilitate the mapping process. Also, indoor floors are more amenable to 3D printing than outdoor surfaces. The robot can be placed in an arbitrary location and it will autonomously seek out and follow boundary walls until it generates an enclosed map. The system uses built-in sensors to detect and avoid obstacles and can segment the map into different rooms and areas. Once the mapping is complete, the generated map is stored locally on the robot and can be accessed via a web API.

Select. MobiPrint includes a database of 3D printable objects, including accessibility aids, pedestrian guidance, and small household items, to simplify on-the-go printing without having to model and slice objects. The library files were pre-sliced using a custom machine profile to match MobiPrint's hardware configuration, and we also embedded custom G-code to process rotation and scaling edits (detailed in section 3.1.2). Additionally, users can slice their own models and upload the G-code files to MobiPrint to print in their environment.

Plan + Edit. We convert the generated map into an interactive canvas for users to perform in-context design operations on their selected/uploaded 3D models like measuring, moving, scaling, and rotating. Users can use the map to measure real-world distances between objects and use the measuring lines as reference points to arrange their desired prints. Once the objects are placed on the map, users can move them to other desired locations (*i.e.,* a specific room in an apartment or the entrance to a building) as well as rescale and re-orient the prints using graphical widgets.

Print. Lastly, when the layout, size, and orientation of the objects are finalized, MobiPrint automatically generates a path to reach the target location and print the object. When the printer has reached the destination, the 3D printer will probe the print area to calibrate the floor and compensate for uneven surfaces.

3.1 Design and Implementation

MobiPrint is composed of two main parts: (1) a custom mobile 3D printer which is comprised of a robotic moving base and a fused deposition modeling (FDM) 3D printer and (2) a custom web-based design tool that allows users to select, arrange, move, and edit objects on a rendered map of the environment[1]. We built MobiPrint iteratively over an 18-month design and implementation cycle, including an earlier hardware prototype called *sPrintr* [20].

3.1.1 Hardware. The hardware (Figure 3) merges robotics and 3D printing to make a new system that can independently navigate various environments and print directly on the ground surface. Toward this goal, we needed a robotic platform that could safely and autonomously map a space and reliably travel to specified location points. While there are advanced mobile platforms used in warehouse and fulfillment centers [9], they are costly and inaccessible to most people. Vacuum robots, on the other hand, have been widely adopted by consumers and researchers [42, 54] to safely and efficiently traverse home environments and handle repetitive cleaning tasks. Modern cleaning robots also have sophisticated sensors like LiDAR scanners, cameras, and infrared light sensors to help detect and avoid obstacles.

We used a *Roborock S5* vacuum robot [5], removed the cleaning components (*i.e.,* brushes, water reservoir), and added additional support wheels to stabilize the added weight of a 3D printer. We rooted the custom firmware [27] on the robot and added an open-source cloud replacement service for vacuums, *Valetudo* [57]. Critically, this gave us access to the map generated by the robot's LiDAR scanner, the robot state (*e.g.,* moving or stationary), and manual controls for operation. Additionally, we could programmatically set a target destination for the robot to reach while avoiding obstacles.

Next, we needed a 3D printer capable of printing objects on arbitrary indoor floor surfaces without additional post-processing. This ruled out printers that use liquid resin-like stereolithography (SLA) and digital light (DLP) because these require UV-blocking

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[1] Design files, slicer settings, hardware list, and code can all be found at https://github.com/makeabilitylab/MobiPrint

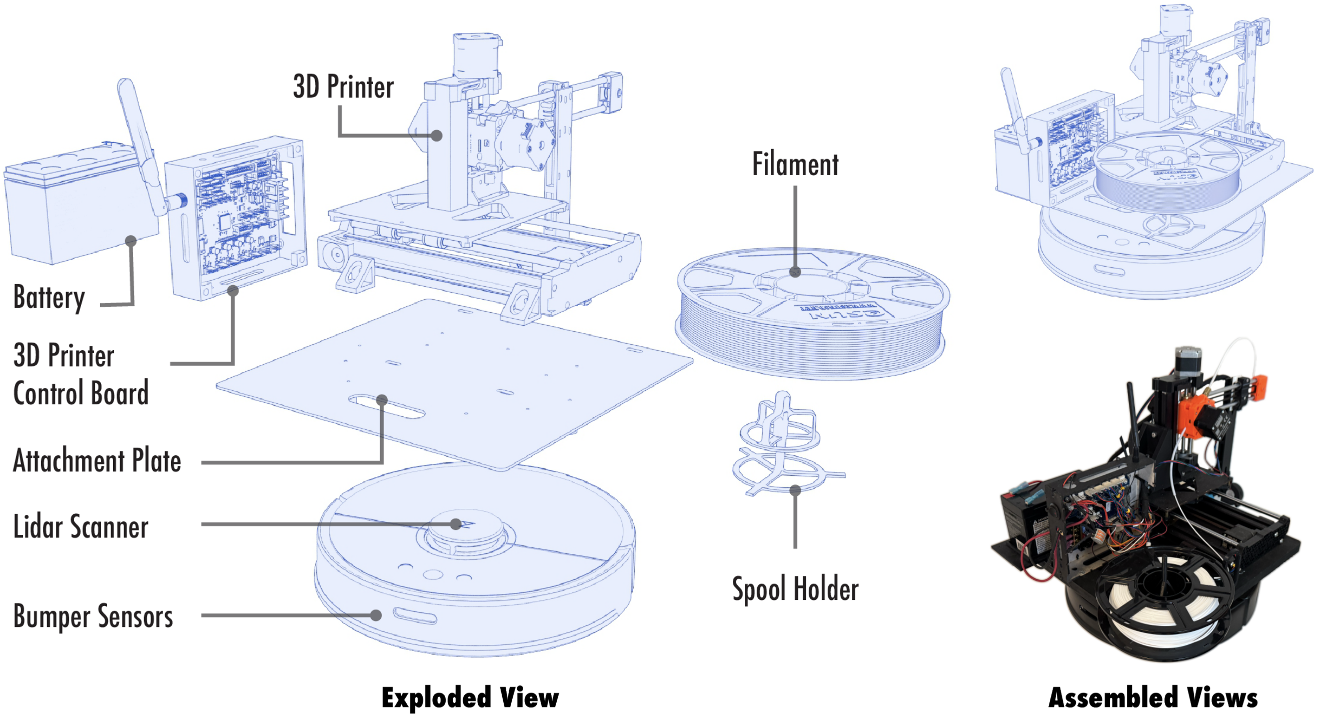

Figure 3: An explosion diagram and assembled views of the MobiPrint hardware, which consists of a modified Roborock S5 vacuum robot with built-in LiDAR and obstacle sensors, a Prusa Mini+ FDM 3D printer, a WiFi-enabled 3D printer control board (Duet3 Mini5+) using RepRap firmware, a 12V 7Ah rechargable battery (allowing 3-4 hrs of untethered operation per charge), and custom 3D-printed and laser-cut assemblies for the cantilever arm and attachments.

enclosures and a cleaning bath for the prints. FDM printing was the logical choice because of the simple control mechanics and the ability to print in various environmental conditions (*i.e.,* without a heated bed or reservoir tank). We also distributed the weight of the printer, battery, and filament to center the mass over the robot and minimize the weight at the nozzle.

We chose a cantilevered FDM 3D printer (*Prusa Mini+*) and modified the mechanical structure to extend away from the robot and reach the floor (Figure 3). We also replaced the control unit with a WiFi-enabled 3D printer control board (*Duet3 Mini5+*) using *RepRap* firmware that can run on battery power. We used a Bowden-tube extruder with *Polylactic Acid* (PLA) filament and a *BlTouch Z* probe at the nozzle. The touch probe is used to calibrate the printing area and compensate for irregularities and unevenness of the floor. MobiPrint has a printing area of 180 mm × 180 mm × 65 mm and runs off a 12V 7 Ah rechargeable battery which supports the printer to run for approximately 3-4 hours at a time.

3.1.2 Software. Our design tool transforms the map of the environment into an interactive CAD canvas for users to arrange, edit, and plan prints for MobiPrint to complete. Informed by previous work on mobile fabrication [47], our design tool supports desktop and mobile devices to offer on-the-go control of the system. Additionally, the design tool provides real-world information that can help the design process, for example, by providing dimensions and allowing users to measure how far to place the prints from objects in the environment.

We built the front end using *React* and the backend server that handles scaling and rotation edits with Python. The tool communicates with the robot, the printer, and a server that stores the printing files and processes edits made to the objects. The design tool allows users to start a new scanning and mapping pass and provides real-time visualization of the process, showing the robot location and mapped regions. Once the space has been mapped, users can select models from a pre-loaded library of objects or upload new G-code files using our custom machine profile for *PrusaSlicer* [45].

Most of the operations are done on the *planning and editing* page where users can plan their prints and edit the models using the map. Currently, we support four operations: measuring, arranging, scaling, and rotating. Users can draw lines and check the distances between objects on the map and use the measure tool to place the objects. Users can drag the prints, which are rendered as a bounding box, and preview the results of rotation and scaling operations. The robot then receives the target destination and navigates to the location. If the objects are scaled or rotated, the system processes the G-code file on a backend server that applies a coordinate transformation, scales the G-code commands, and wirelessly sends a new version of the file to the printer. After it reaches the destination, the printing operation starts, and the robot remains stationary throughout the printing process.

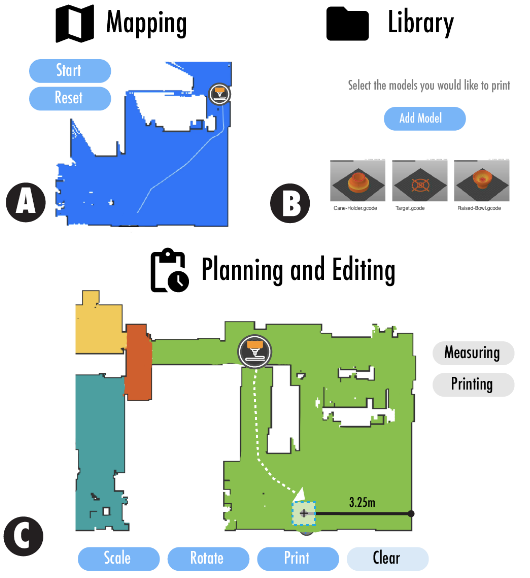

Figure 4: Our design tool has three main pages: (A) a *mapping* page to generate and reset maps; (B) a *library* with a repository of 3D printable objects; and (C) a *planning and editing* page where users can measure, move, scale and rotate chosen print files. The latter page also lets users command the robot to certain locations on the map.

4 APPLICATION SCENARIOS

To showcase MobiPrint and how it enables *in situ* mobile fabrication, we developed six "proof-by-demonstration" examples ranging from adding functional components in the home and accessibility adaptations like tactile surface indicators to decorative art and informational graphics as floor signage. See also the video figure.

Accessibility. MobiPrint can augment the physical environment to make it more accessible for people with disabilities (Figure 5B). For example, tactile surface indicators serve as navigation aids for people who are blind and low-vision and warn them of hazards like stairs. The typical fabrication and installation process is laborious and costly because they are usually embedded into cement or cast in place. MobiPrint, instead, can integrate on-demand tactile navigation aids in a single step. The design tool allows users to place the surface indicators at critical parts on the map to signal entranceways or provide directional guidance.

Home Furnishing. 3D printing is often used to make personalized or custom objects for use in the home, such as an ergonomic foot rest, a pet feeding bowl, and a cane holder. With MobiPrint , users can tailor objects for their specific home needs and locations. For example, an ergonomic footstool can be printed under the work desk with a proper height to hold the feet or scaling a raised feeding bowl for the pet as it grows (Figure 5A). The mapping feature allows users to measure and place objects where they will be most useful, such as an umbrella holder and cane holder by the door.

Art. In addition to functional objects, MobiPrint can also be used to create floor art and decorative elements. For example, we created a floral motif mural on a 5 m × 2.5 m area (Figure 5D). The mural consists of various botanical designs printed with different colored filaments to add aesthetic variety. These tactile murals can be used to enhance playpens or decorate rooms with custom graphics.

Pedestrian Flow and Queuing. Lastly, by converting the ground and surface into a canvas, users add informational graphics on the ground that could be used to guide pedestrian traffic (Figure 5C). We create sample floor signage to show how MobiPrint that could be used at a conference to help with directional guidance for attendees by adding graphical elements to the environment

5 EVALUATION

In addition to the application scenarios above, we also validated MobiPrint through a series of controlled studies to examine: mapping speed, localization accuracy, floor adhesion, and payload capacity.

Table 1: Mapping time in different environments

Environment	Area	Mapping Time
1 Bedroom Apartment	120 m^2	12 minutes
Makerspace	80 m^2	15 minutes
Computer Lab and Hallway	174 m^2	43 minutes

Mapping Speed. Mapping is the first step in our environment-scale fabrication process, so it is important to investigate how quickly and accurately new spaces can be mapped. Both speed and accuracy are influenced by many technological (*e.g.,* type of SLAM algorithm, sensor quality) and environmental factors (*e.g.,* scene layout, obstacles). Although a full analysis of how these factors influence mobile robots like ours is out of the scope of this paper, we measured the approximation for the duration MobiPrint would take to generate a complete map that users could use to design and print objects. We mapped three different indoor environments—an apartment, a makerspace, and a university hallway and classroom—each designed for distinct uses and thus with different layouts and varying sizes. We mapped each space three times (each trial had a different starting location) and averaged the mapping time. Our results (Table 1) indicate that MobiPrint can quickly generate maps for the apartment and makerspace but is much slower for hallways.

Localization Accuracy. To evaluate MobiPrint's localization accuracy (*i.e.,* how well it could reach a target location), we designed and constructed a 2 m × 2 m wooden box with 3D-printed corner brackets on a hardwood floor. The floor was annotated with grid lines spaced 50 cm apart using laser-level squares and range finders. We then mapped the arena with the robot and overlayed a grid on the design tool's canvas to match the floor's grid. We generated ten random test points in the arena and measured the distance between the target location in screen space and in the real world (measured from the top of the LiDar Scanner). The average error was 5.1cm (*SD*=3.4cm) or 4% (±2.4%).

Floor Surfaces Adhesion. Since MobiPrint prints directly on the ground, we performed an empirical evaluation to measure the adhesion strength on four common flooring materials—hardwood, ceramic tile, carpet, and vinyl. We printed hooks with a 50 mm circular base and used a force gauge to measure the force to laterally

Figure 5: *In situ* 3D-printed examples by MobiPrint, including: (A) functional domestic objects like an ergonomic footrest, a raised pet feeding bowl, and a floor holder for a cane to prevent it from tipping over; (B) tactile navigation aids for people who are blind and low vision; (C) informational floor signage and graphics; (D) and decorative floor art.

dislodge the print (Figure 7). We tested three trials on each floor material, varying the location for each print. The prints adhered best to the low-pile carpet, requiring over 50 N (the max on our scale) on average to remove, followed by vinyl (*avg*=37 N; *SD*=10.4 N) and Hardwood (*avg*=8.7 N; *SD*=3.2 N). Prints on the ceramic tile were unsuccessful, perhaps due to surface texture or temperature. Adhesion could be improved with the use of rafts and brims, which increase the contact area of the print.

Payload Capacity. MobiPrint must be able to carry the weight of the 3D printer, battery, and filament material to complete the mapping and printing sequences. The total weight of our components is approximately 8.5 kg (1 kg filament spool, 2.1 kg battery, and 5.4 kg 3D printer). Since vacuum robots are not designed for towing, we validated that the Roborock machine could adequately haul the additional weight by loading the robot with metal plates and manually moving forward, turning 180 degrees, and forward again. We could load up to 35kg weight on the robot—far more than the weight of our system. We note that the additional weight might decrease the robot's battery life, which is rated for three hours of continuous cleaning. However, we do not consider this a critical issue since MobiPrint does not require constant motion; instead, the robot remains stationary during the 3D printing process.

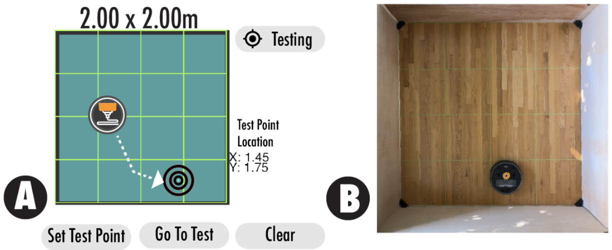

Figure 6: We tested the localization accuracy by setting up a 2 m × 2 m test area on the ground which the robot scanned. We overlayed the grid on the interface and placed random points for the robot to reach and measured the difference between the target location on the design tool and the final position in the test arena.

Figure 7: We tested the adhesion strength on four common flooring surfaces—carpet, hardwood, vinyl, and ceramic tile. We printed hooks with a circular base (A) and used a manual force gauge used to measure the force to laterally dislodge the print (B). The prints successfully adhered to all of the surfaces except for the tile.

6 DISCUSSION

MobiPrint marks a step toward our vision for interactive mobile fabrication that combines elements from robotics, architecture, and HCI to achieve fabrication at an environmental scale. Our system autonomously maps indoor areas and converts the map into a canvas for users to plan, edit, and print objects directly onto the ground. MobiPrint can automate the often tedious, time-consuming, and laborious process of measuring, editing, and integrating 3D-printed objects into the real world. Below, we enumerate the limitations of our current system and elaborate on design considerations for future improvements.

6.1 Printing Dynamics

Although MobiPrint can successfully navigate and print in ad-hoc indoor environments, our system has several limitations. First, MobiPrint does not involve the robotic base during the print itself—instead, it moves to a target location and prints a discrete object while stationary. In contrast, a continuous, free-form 3D printing robot would require higher-precision motors for the robot's wheels and a more sophisticated slicing algorithm to coordinate the robot and the 3D printer movements. Moreover, our system is prone to "ghosting" or artifacts on the prints resulting from vibrations during printing. This is a key trade-off between mobile and fixed systems. Stationary machines can be fastened or secured to provide an improved structural loop compared to mobile systems. However, the print quality of our mobile system could be improved with stiffer and stronger components (*i.e.,* metal dropdown bracket, adding a third guide rail to resist torsion) and a more accurate probe mechanism [3]. Currently, we only print with PLA because other materials, like ABS and TPU, require better control of the ambient and surface temperatures to print properly. This could potentially be addressed by adding a heating element under the robot to pre-heat the floor or shielding the printing process to allow for multi-material printing to make soft, grippy surfaces to improve traction (with TPU) or strong fixtures to serve as anchors to the floor (with ABS).

6.2 Design Tool

As MobiPrint supports environment-scale design in the real world, our design tool could be improved to provide richer environmental data, support multiple maps, and enable more CAD operations. The current tool presents users with a 2D representation of the map, but future iterations could convert it to a 3D map to provide more context while performing CAD operations on objects, *e.g.,* visualizing the new Z height. Richer environment data could also enable more complex model operations like boolean difference or union that involve multiple 3D models or add physics simulations to preview how objects would behave in the space. Additionally, MobiPrint currently needs to re-map when moved to a new space. Instead, future iterations could save, store, and share the map scans to form a "library" of maps, allowing for faster transitions between environments. Despite these limitations, we believe that MobiPrint points to new possibilities for digital fabrication to model and augment the physical world.

6.3 Design Considerations for Future Systems

How might mobile fabrication systems advance the future? Drawing on our experiences building and evaluating MobiPrint as well as synthesizing prior work [26, 30, 47], we offer the following design considerations and directions for future mobile 3D printing systems:

Environmental and Contextual Information. Our system can provide detailed maps of indoor environments that users can use to measure distances and edit existing 3D models. Mobile fabrication should strive to provide rich environment data to enhance the design process. For example, future systems could utilize collected spatial information for model editing in the environment, or provide augmented reality-based overlay to help users choose, edit, and place 3D objects in situ with more precision and real-time preview. Moreover, machine learning and computer vision techniques could be integrated to perceive the environment, identify objects, and suggest relevant designs, providing more data to suggest objects that relate to the context for fabrication, for example, detecting cracks on the surface or breaks in objects and then patching them.

Automation and Interactive Fabrication. We sought to explore how autonomous mapping and navigation could relieve the burden of having to transport, measure, and install objects into the world. However, there are many possibilities for introducing interactivity and collaboration into the process. For example, the robot could suggest adaptations or objects to the user based on the environment data. Future work should explore different collaborative patterns of Human-Robotic interaction and modes of autonomy (*e.g.,* user could draw a bounding box on the floor for the robot to print on). Additionally, the system could respond to environmental factors and wait for a chance to print, for example, when there are fewer obstacles to maneuver around.

Printable Areas. By converting the ground to a print bed, we begin to find new ways for 3D printing to augment our environment. We were able to add tactile navigation aids, ergonomic features to homes, and graphics to the physical world. However, future fabrication systems should explore additional degrees of freedom to print in various orientations and surfaces, such as vertical walls, ceilings, and even upside-down under other objects. For example, adding a rotation axis at the end-effector or using a 6-DOF robot arm with swappable end-effectors. With additional printing capabilities, it is possible to deploy fabrication systems in unreachable or hazardous areas (*e.g.,* small ducts, tunnels, disaster relief areas) for people to physically patch infrastructure or print building tools.

Permanence, Removal, and Recycle. Our system can autonomously print new objects, but removing the objects still needs to be done manually. Future systems could develop a print removal or material recycling capability to close the making/unmaking loop and prompt the sustainability of mobile fabrication. Recently, there has been a raised focus on design tools that consider the entire lifespan of the object and design for unmaking and decay [51]. Mobile fabrication could extend this line of work to consider how to support temporal or transient augmentations to the environment and remove and recycle materials and objects for future use.

7 CONCLUSION

MobiPrint introduces a novel approach to digital fabrication by merging the versatility of mobile robotics with 3D printing technology to transform ad-hoc indoor environments into dynamic fabrication spaces. This advancement enables environment-scale fabrication of objects that can be autonomously integrated into the physical world. Our system is composed of a mobile 3D printer that maps the indoor space and converts it into an interactive canvas in our accompanying design tool where users can select, move, plan, and edit 3D models in situ in the environment. Our system facilitates in-context operations such as measuring, scaling, and rotating objects in relation to real-world surroundings. Our contributions demonstrate the system's utility in a broad spectrum of scenarios and implications for future mobile fabrication systems to facilitate environment-scale fabrication.

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