Crowdsourced Fabrication

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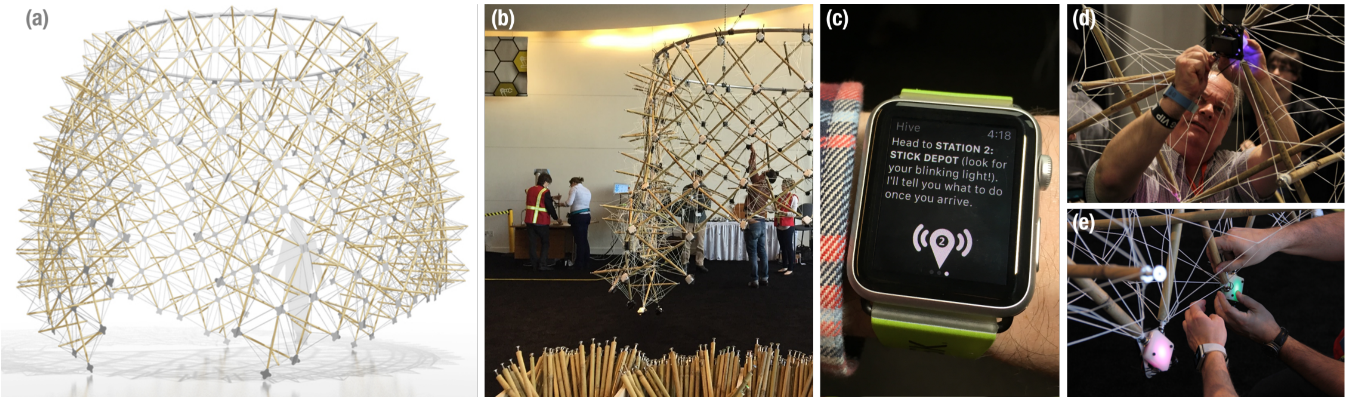

Head to STATION 2: STICK DEPOT (look for your blinking light!). I'll tell you what to do once you arrive.

Figure 1. We explore crowdsourced fabrication through the collaborative construction of a 12-foot tall bamboo pavilion (a). The pavilion was built with the assistance of more than one hundred untrained volunteers over a 3-day exhibition, enhanced and enabled by an intelligent construction space (b). Workers were guided by smartwatch devices (c), wireless LED modules embedded in building materials (d, e), and a backend engine that coordinated the overall build process.

ABSTRACT

In recent years, extensive research in the HCI literature has explored interactive techniques for digital fabrication. However, little attention in this body of work has examined how to involve and guide human workers in fabricating larger-scale structures. We propose a novel model of *crowdsourced fabrication*, in which a large number of workers and volunteers are guided through the process of building a pre-designed structure. The process is facilitated by an *intelligent construction space* capable of guiding individual workers and coordinating the overall build process. More specifically, we explore the use of smartwatches, indoor location sensing, and instrumented construction materials to provide real-time guidance to workers, coordinated by a *foreman engine* that manages the overall build process. We report on a three day deployment of our system to construct a 12'-tall bamboo pavilion with assistance from more than one hundred volunteer workers, and reflect on observations and feedback collected during the exhibit.

INTRODUCTION

Digital fabrication tools, including industrial robots, CNC machinery, laser cutters, and 3D printers, have had a transformative effect on the architecture and manufacturing industries, enabling them to move away from repetition and standardization, and toward customizable and unique design solutions [28]. However, the organization, development, and planning of these production processes, and the specialized knowledge and skill set necessary to use these tools, are logistical challenges that have kept them from being utilized to their fullest potential, particularly for large-scale fabrication.

Of potential promise is the extensive research undertaken by the HCI community in recent years to explore interactive techniques for digital fabrication. However, with few exceptions [1, 51], little work has examined how to involve and guide human workers in fabricating larger-scale structures. Building off of the emergence of *Industry 4.0* [28] – the possibility of augmenting physical construction practices with digital mechanisms and embedded sensors – there is the potential for a new type of production pipeline, in which human workers and digital fabrication systems complement one another according to their relative strengths.

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In this paper, we are interested in enabling digital fabrication at the architectural scale through a model of *crowdsourced fabrication*, where a large number of volunteers and workers contribute to build a structure, with assistance and enhancement by digital mechanisms. Specifically, we investigate the use of commodity wearable technologies, instrumented construction materials, and on-site hybrid fabrication systems to create an *intelligent construction space* capable of guiding workers and coordinating the build process.

We investigated these ideas through an interactive exhibit showcased at a large design conference. Over the three-day event, attendees could contribute ~20 minutes of their time to assist in the construction of a 12'-tall bamboo pavilion (Figure 1a). Volunteers received a smartwatch upon entering the exhibit, which would provide just-in-time contextual guidance on how to contribute to the build process. Additional visual guidance was provided by wireless LED nodes embedded within both the construction space and the building materials themselves. A central *foreman engine* coordinated the efforts of multiple workers in parallel to ensure an efficient build process.

Our work offers several contributions to the HCI literature. First, we propose a novel model of *crowdsourced fabrication*. Second, we present a set of design principles for developing crowdsourced fabrication systems. Third, we describe the system that we developed and deployed, and its implementation details. While many of the techniques and technologies used in the system are based on prior work, their synthesis into a coherent system for coordinating a large-scale fabrication process is a novel contribution. Finally, we contribute an evaluation of the worker experience of our deployment, and a discussion of the findings and design implications for future crowdsourced fabrication systems.

RELATED WORK

In this section we review existing research on digital fabrication, crowdsourcing, intelligent workspaces, and wearable guidance techniques.

Large-Scale Digital Fabrication

In the architecture community, digital fabrication techniques have been embraced in a range of ways for building at the architectural scale, typically through robotics and CNC machinery. For a detailed background, we direct the reader to existing reviews on the topic [12, 28, 40]. Examples include the development of techniques for 3D printing large-scale objects [51, 55, 56]; production systems that utilize sensing techniques to adapt a design in real-time during construction [28, 41]; and using in-situ robotic fabrication on construction sites to create structures that would be impossible to build using conventional methods [17, 18].

While large-scale digital fabrication remains an active research area in the architecture and robotics communities, there is comparatively little work in the HCI literature examining how to involve and guide human workers in fabricating large-scale structures. Recent work by Yoshida et al. [51] touched on this theme, presenting a handheld dispenser for additive printing of large-scale structures. Also related is Protopiper, a computer aided, hand-held fabrication device for sketching room-sized objects at actual scale [1]. We take inspiration from these projects, with greater focus on the guidance, training, and coordination requirements of human workers. For example, we explore the use of wearables to present context-specific instructions for more advanced physical and dexterous tasks (e.g., attaching a component to a structure in a specific position and orientation.)

At smaller scales, hybrid fabrication systems that combine digital and analog fabrication techniques with human involvement have seen more exploration [53, 54]. Taken to an extreme, Devendorf and Ryokai explored a hybrid fabrication system that guides users in building 3D models by following instructions typically given to 3D printers, with the human "being the machine" [7]. We build on the above work, applying a hybrid fabrication approach to mobilizing crowds of workers with varying degrees of skill and training to build at the architectural scale.

Crowdsourcing Physical Tasks

Research on crowdsourcing and human computation has explored a range of ways that human workers can enhance digital systems (e.g., [23, 25, 35, 38]), but this work has mainly focused on harnessing the unique creative and cognitive abilities of human workers, with less work on harnessing their unique *physical* skills and abilities.

In Haptic Turk, a player of a virtual-reality game is physically supported by a small group of volunteer "actuators" who manually lift, tilt, and push the player's limbs or torso based on timed motion instructions, simulating haptic feedback in the game [4]. More recently, the TurkDeck system has extended this idea to simulate large virtual words in a finite space [5]. These projects share with ours the idea of volunteers following prompts to perform physical tasks, including some element of building in the case of TurkDeck. We build on this idea to support the coordination and guidance of workers in performing more advanced physical tasks, such as constructing an architectural-scale structure.

Some preliminary work has also investigated using crowdsourcing for tasks where workers must collaborate and synchronize in both time and physical space. Sadilek et al. proposed a "crowd-powered delivery service" in which people carry packages and hand them off to other volunteers until the packages can be delivered to a destination [39]. However, the contribution of this work was a computational simulation of the viability of such a system, and not the design or user experience of workers.

Intelligent Workspaces

A number of projects have explored the idea of creating intelligent workspaces capable of providing contextually-relevant guidance for physical tasks. Knibbe et al. developed a Smart Makerspace, consisting of an instrumented workbench, toolbox, and tools, designed to provide contextually-relevant assistance to novice makers [24]. Instrumented workspaces have also been developed for kitchen environments [32] and lab benches for molecular biologists [44].

Our system applies similar guidance techniques to those used above (e.g., using lights in the environment to guide a user's attention), but differs in that it was designed explicitly to support a large scale, collaborative construction task.

Wearable Guidance for Physical Tasks

Several projects have investigated the potential for wearable devices to provide guidance for physical tasks. The main focus of this work has been on wearable computers with head-mounted displays (HMDs) that either provide supplementary information in the field of view, or create augmented reality (AR) experiences, overlaying digital information over physical objects in the user's vision. AR systems have been investigated for a range of physical tasks, including aircraft inspection [30], assembly tasks [45, 50], construction [37], machine maintenance [19, 20, 52], and locating and selecting items [48]. Recent work has looked at how AR, as well as Virtual Reality (VR) and Mediated Reality (MR) systems can be used to enable remote experts to guide a local user through performing complex tasks [15, 31, 43, 46]. We see these techniques as complementary to the ideas explored in this paper, although head-mounted systems may not be practical for active construction workers in some situations.

In contrast to work using VR and AR, there has been much less research investigating the potential of non-HMD wearables, such as smartwatches, for guiding users in physical tasks. Existing work on smartwatch guidance has focused on providing navigational assistance [26, 49], and we are unaware of any work on using smartwatches to guide assembly or construction tasks.

DESIGN PRINCIPLES

To guide the development of a crowdsourced fabrication system, we propose a set of five design principles. These encapsulate the overall objective of supporting an efficient build process, but also consider logistical aspects and constraints, such as working with untrained crowdsourced workers and maintaining worker safety.

D1. Just-in-Time Learning and Guidance. Our first goal was to provide interactive guidance and support for just-in-time learning, to enable workers to start the task immediately, regardless of their level of skill related to the task. Prior research has argued for the benefits of contextual assistance [2], and shown that providing clear goals and immediate feedback can be effective for learning [22], and also create a highly engaging experience [11]. Moreover, the software learning literature has repeatedly demonstrated the effectiveness of just-in-time learning techniques [6, 13, 27, 33].

D2. Unobtrusive Technology. The technology used for guidance should not get in the way of the task. In particular, the worker's hands must remain available for performing the physical actions required for the construction task. Handheld devices, such as tablets, should thus be avoided, with preference given to wearable devices [19] or non-intrusive environmental displays, such as external projectors [51].

D3. Worker Safety. Safety is an important consideration in any work environment, but is particularly important when working with untrained volunteers. Thus, the site should be developed to minimize risks, and workers should be proactively notified of potential safety issues. Past work was demonstrated how intelligent workspace environments can provide new opportunities for relaying safety information and enforcing safe practices [24].

D4. Increasing Coordination and Efficiency. Utilizing a large number of workers, especially those of varying levels of skill, adds complexity to the build process. It is thus important to improve efficiency by combining the collective efforts of the crowd with carefully designed digital coordination mechanisms. In this, our approach was informed by existing work on crowdsourcing techniques [9, 25, 38].

D5. Active Analytics. A final design goal was to enable monitoring and data gathering during the build. This can to help satisfy other design goals, such as increasing efficiency and ensuring safety, but also creates opportunities for applying advanced analytics to the build process, or visualizing the build process in real time to motivate volunteer crowd workers and allow remote monitoring [16].

SYSTEM DESIGN AND IMPLEMENTATION

Guided by the principles above, we developed an *intelligent construction space* to fabricate an indoor pavilion over the three days of a conference, with participation by a mix of volunteer conference attendees and project staff. The inclusion of both volunteers and staff enabled us to explore the effectiveness of our system for workers with varying levels of task knowledge.

Structure Design and Materials

The pavilion structure was designed to be built out of 224 *tensegrity modules* [21], each consisting of three bamboo sticks held together by the tension of thread (Figure 2 left).

Figure 2. An individual tensegrity module (left), and a connector node (right).

The modules were designed such that they could be attached to one-another using *connector nodes* consisting of a steel plate and a wireless RGB LED (Figure 2 right). An endcap bolt, affixed to each bamboo tip, fit into the steel plate and was held in place with two zip ties. The structure consisted of eight rows of modules, with 28 modules on each row. The top row of modules was designed to be attached to a 10 ft.

diameter steel ring suspended from the ceiling, with each subsequent row attached to the row above.

The global design of the structure consisted of two doubly-curved surfaces separated by seams forming a front and back doorway (Figure 1a). The two sides of the structure were symmetric, but each constituent module had a unique geometry, defined by the angle between its sticks. As a result, the design required each individual module to be added to the structure in a particular location and orientation.

The architectural design of the pavilion was chosen to be a visually compelling final artifact, and provide a reasonable level of complexity for workers in terms of the construction process and timeline of the exhibit.

Construction Space

The structure was built within a 30'×30' construction space, with the pavilion at the center (Figure 3). At each corner there was a robot station with a 6-axis robot arm used for on-site fabrication. There were also two material stations for retrieving the required bamboo sticks and connector nodes.

At any given time, four workers could be working in parallel within the exhibit. Workers all followed the same series of steps to gather materials, assemble them into a part with the aid of one of the robotic fabrication stations, and attach the part to the pavilion in a specific location.

Figure 3. The construction space consisted of a number of stations surrounding the structure being constructed.

During the exhibit, each worker had a member of the research staff shadow them while they went through the build process. Research staff members observed the workers behaviors and only provided assistance if needed.

System Implementation

Next, we describe the five core components of our system, which together create an *intelligent construction space*. We highlight how each component relates to our design principles for crowdsourced fabrication.

1. *Wearable Guidance System*

To enable workers to receive real-time guidance and feedback (D1) in an unobtrusive manner (D2), we instrumented each worker with a wearable guidance system. Upon entering the exhibit, workers received an Apple Watch (42mm Sport model) running a custom iOS app driven by an iPhone 5c located in the worker's tool belt. Each watch had a color-coded band, which was used as part of the environmental guidance provided in the exhibit, prompting users to follow lights matching the color of their watch band. Smartwatches have limited display space, but they are a compelling mode for delivering guidance due to their low obtrusiveness and hands-free nature.

The app provided just-in-time, illustrated instructions throughout the build process (Figure 4). Workers navigated between screens by swiping left and right. In some cases, new pages were triggered automatically, based on the location of the worker, or an external event occurring (such as a robot completing the winding procedure). When a new page was triggered automatically, a tactile and audio notification was provided. All illustrations could be viewed in full-screen (312px × 390px) by tapping on them.

4:23
Lets try it now! Go to
STATION 1: TRAINING
(look for the **PINK**
light)

4:23
Next, tie off the thread
to the bottom tip with
a double knot.

Figure 4. Example guidance screens from the smartwatch app.

2. *Location Tracking*

To enable contextual guidance (D1) and to optimize operations for efficiency (D4), the spatial locations of workers were tracked during the build process. Location updates were used to trigger contextual actions and maintain an accurate model of the ongoing build process in real-time (D5). Tracking was enabled using nine Kontakt.io iBeacons distributed throughout the construction space. Signals from the beacons were received by the iPhone in each worker's tool belt, and processed using a heuristic based on a low-pass filtered Received Signal Strength Indication to determine when the worker moved between stations in the construction space.

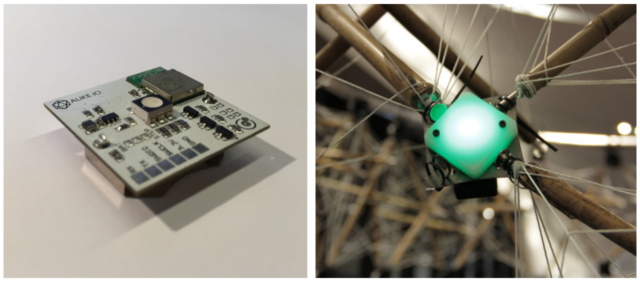


Figure 5. The wireless RGB LED control board (left), and an assembled connector node (right).

3. *Instrumented Environment*

To enable additional guidance (D1), the construction space was instrumented with 298 individually addressable Alike wireless RGB LED boards [57] (Figure 5), running our own custom firmware. These wireless LEDs served three purposes. First, they were located at each station in the workspace, to guide users to that location. Second, a wireless LED on each robot station was used to guide users in how to load bamboo sticks onto the robot arm. Third, LEDs were embedded in the connector nodes, to direct workers to the exact nodes they needed collect, and the exact location to attach their completed module to the pavilion structure. When activated, the LED slowly pulsed at the specified color.

4. Hybrid Fabrication and Assembly

Assembly of bamboo sticks into completed tensegrity modules was performed on a UR-10 robotic arm [58] (Figure 6). A custom end effector was designed to hold three bamboo sticks using a clamping mechanism. The angle between sticks was adjustable to accommodate the required geometry of each individual module.

Modules were assembled through a filament winding procedure [8, 34, 36] in which a waxed thread was wound around the three sticks with a controlled tension during winding. The stations also included a lightbox and webcam, which was used to scan each of the three sticks before winding began. The scanning process calculated the exact position of each bamboo tip in 3D, allowing the robotic motion paths for winding to be dynamically recalculated in response to material variation and human error during stick loading. Additional details of the robotic measurement and winding procedures are beyond the scope of this paper, and are described separately [47].

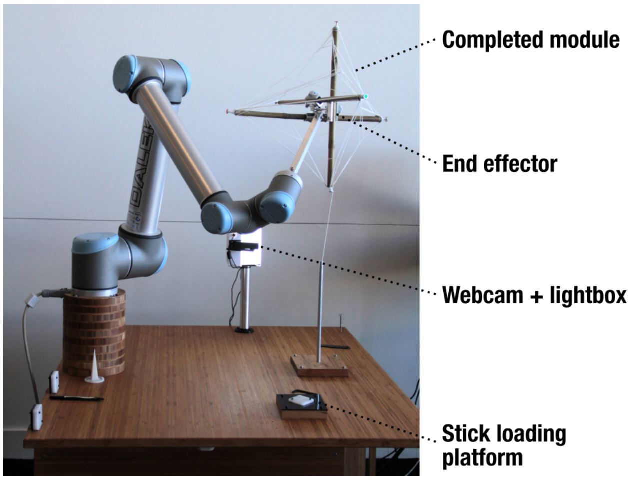


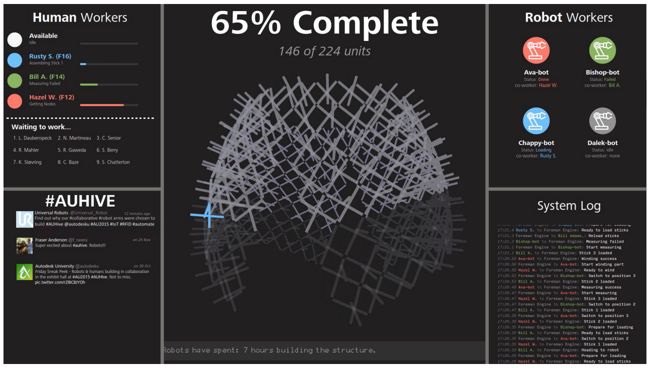
Figure 6. Individual Hive components are made up of three bamboo sticks, with a thread winding holding the module together. The winding is performed by a 6-axis robotic arm.

During the build process, workers loaded sticks onto the robot's end effector and initiated the assembly process, with the worker's watch acting as the main interface to the robot. Before each action by the robot, the watch would display a warning screen and instruct the worker to stand back and confirm that they were ready. These features were designed to enable safe interaction with the robot arm (D3).

5. Coordination Engine

Finally, all activities in the construction space were coordinated by a central *foreman engine* that communicated with the watches, wireless LED nodes, and robot stations. The foreman engine determined which unique module each worker should build; assigned each worker to a robot station; provided the associated fabrication instructions to the robot stations; and coordinated multiple participants working simultaneously. Through these roles, the foreman engine orchestrated a build process that minimized situations where one worker's efforts would be blocked or slowed down by another worker, increasing overall efficiency (D4).

In addition to coordinating activities in the construction space, the foreman engine monitored the build process (D5) and displayed the current status on a large dashboard display at the entrance to the exhibit (Figure 7).



Human Workers

Available
Idle

Rusty S. (F16)
Assembling Stick 1

Bill A. (F14)
Measuring Failed

Hazel W. (F12)
Getting Nodes

Waiting to work...

1. L. Daubenspeck
2. N. Martineau
3. C. Senior
4. R. Mahler
5. R. Gaweda
6. S. Berry
7. K. Støvring
8. C. Baze
9. S. Chatterton

#AUHIVE

Universal Robots @Universal_Robot 12 minutes ago
Find out why our #collaborative #robot arms were chosen to build #AUHive @autodesku #AU2015 #IoT #RFID #automate

Fraser Anderson @f_rasera on 25 Nov
Super excited about #auhive. Robots!!!

Autodesk University @autodesku on 30 Oct
Friday Sneak Peek - Robots & humans building in collaboration in the exhibit hall at #AU2015 #AUHive. Not to miss. pic.twitter.com/r2l8C8JYOh

65% Complete

146 of 224 units

Robots have spent: 7 hours building the structure.

Robot Workers

Ava-bot
Status: Done
co-worker: Hazel W.

Bishop-bot
Status: Failed
co-worker: Bill A.

Chappy-bot
Status: Loading
co-worker: Rusty S.

Dalek-bot
Status: idle
co-worker: none

System Log

```
17:21.4 Rusty S. to Foreman Engine: Ready to load sticks
17:21.3 Foreman Engine to Bill Adams.: Reload sticks
17:21.3 Bishop-bot to Foreman Engine: Measuring failed
17:21.1 Foreman Engine to Bishop-bot: Start measuring
17:21.1 Bill A. to Foreman Engine: Stick 3 loaded
17:20.58 Ava-bot to Foreman Engine: Winding success
17:20.56 Foreman Engine to Ava-bot: Start winding part
17:20.56 Hazel W. to Foreman Engine: Ready to wind
17:20.53 Foreman Engine to Bishop-bot: Switch to position 3
17:20.53 Bill A. to Foreman Engine: Stick 2 loaded
17:20.49 Ava-bot to Foreman Engine: Measuring success
17:20.47 Foreman Engine to Ava-bot: Start measuring
17:20.47 Hazel W. to Foreman Engine: Stick 3 loaded
17:20.47 Foreman Engine to Bishop-bot: Switch to position 2
17:20.47 Bill A. to Foreman Engine: Stick 1 loaded
17:20.39 Foreman Engine to Ava-bot: Switch to position 3
17:20.39 Hazel W. to Foreman Engine: Stick 2 loaded
17:20.35 Foreman Engine to Bishop-bot: Prepare for loading
17:20.35 Bill A. to Foreman Engine: Ready to load sticks
17:20.35 Foreman Engine to Ava-bot: Switch to position 2
17:20.35 Hazel W. to Foreman Engine: Stick 1 loaded
17:20.33 Bill A. to Foreman Engine: Heading to robot
17:20.29 Foreman Engine to Ava-bot: Prepare for loading
17:20.29 Hazel W. to Foreman Engine: Ready to load sticks
```

Figure 7. The foreman engine dashboard, displayed at the entrance to the exhibit.

System Architecture and Communication

The overall system architecture is illustrated in Figure 8. The foreman engine was at the core of the system, communicating as necessary with all other components. The foreman engine was developed as a Node.js application backed by a PostgreSQL database. WebSockets (using the socket.io module) were used for communication with the smartwatches and robot stations. Communication with the robot stations was through Ethernet, but all other communication was achieved using wireless technologies, including Wi-Fi, Bluetooth, and the 2.4Ghz ISM band.

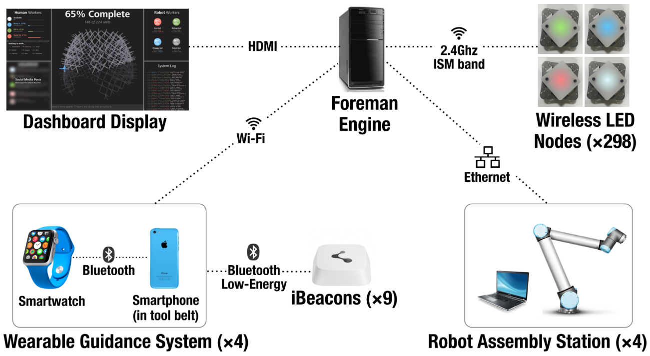


Figure 8. The system architecture.

PARTICIPANT EXPERIENCE

This section walks through the participant experience from the perspective of an individual worker. The process of building and adding a module to the structure took approximately 20 minutes for a volunteer to complete.

Check-In. Workers start by checking in at a staffed registration desk, and putting on the smartwatch and tool belt. From this point forward, the watch provides instructions to guide the participant through the build process.

Location guidance training. After checking in, the watch welcomes the participant and instructs them to proceed to a training station in the exhibit area (Figure 4a). A wireless LED module at the training station activates and blinks the same color as the band of the participant's watch. When the volunteer arrives at the training station, the next set of instructions is automatically triggered and the participants' watch vibrates to indicate that new instructions are available. This step establishes a pattern for how navigation guidance is provided throughout the rest of the build process.

Stick gathering. Following training, the participant is guided to the "Stick Depot" station, and instructed to collect a set of three bamboo sticks with color-coded endcaps.

Preloading. The user is then guided to the next available robot station. As the user approaches the station, the robot arm moves into position for the first stick to be loaded. The participant is instructed to loosen a bolt on the end effector (Figure 9a), and adjust the channel of the clamp so that it is perpendicular to the ground plane (Figure 9b). This adjustment orients the channels for the remaining two sticks as well, to match the required geometry for the part being built.

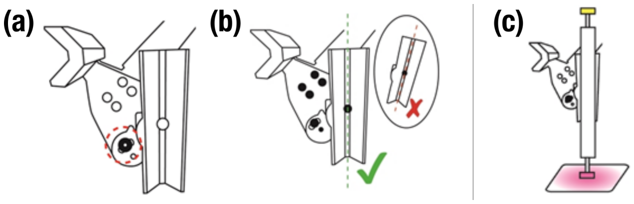


Figure 9. Instruction provided for loading the bamboo sticks. The user loosened a bolt (a) and then adjusted the angle of a clamp (b). (c) An LED on the loading platform indicates which stick to insert and the proper orientation.

Loading. Next, the participant is instructed to place a stick into the clamp in a vertical orientation. To indicate which stick to insert and the correct orientation to insert it, an LED module on the platform activates in a color matching the end cap of one of the sticks gathered earlier (Figure 9c). Once the stick has been secured, the participant is instructed to confirm that they are a safe distance from the robot. The robot then moves into the loading position for the next stick, and the procedure is repeated until all three sticks are loaded.

Stick measuring. Once the sticks have been secured, the robot measures each of the sticks by moving each of the six bamboo tips into the lightbox (Figure 6).

Thread winding. When all sticks have been measured, the participant is instructed to pull a length of thread from a dispenser on the robot station, and tie it to the end cap of one of the sticks. The participant is then instructed to step back, and the robot begins the winding process.

Node gathering. During winding, the participant is directed to a "Node Depot" station to collect connector nodes that will be attached to the completed module once it is secured to the pavilion. When the participant arrives at the station, the specific nodes they need to retrieve pulse in the color matching the participant's watch band. The number of nodes gathered by a participant in this step varied based on the state of the structure – some participants gathered two nodes, some gathered one, and some were not directed to perform this step at all because the required connector nodes were already on parts attached to the pavilion structure.

Unloading. Once the winding is complete, the user is instructed to tie off the end of the thread (Figure 4b), release the clamps and remove the completed module from the robot.

Adding the part to the structure. Finally, the user is directed to the pavilion to attach their completed module. To indicate where the module should be attached, connector nodes already on the pavilion structure blink in the color of the worker's watch band. Once the participant confirms that they have located the correct spot, these nodes change color to indicate the proper orientation to attach the part (a). As described earlier, the part is attached by inserting its endcaps into notches in the nodes on the pavilion, then tightening plastic zip ties (Figure 2 right). Finally, if the worker gathered additional nodes during the Node Gathering step, these nodes begin pulsing, and the worker is directed to attach them following a similar procedure (b).

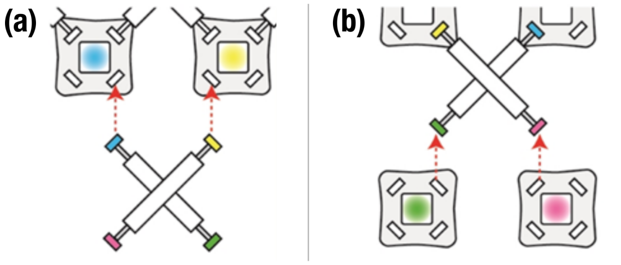


Figure 10. (a) Connector nodes on the structure pulse in colors that indicate the location and orientation to attach a part. (b) The worker's connector nodes pulse in colors that indicate the end caps they should be attached to.

RESULTS AND FEEDBACK

Our system was deployed and the structure was successfully built over the three day exhibition, with participation from 108 volunteer workers (Figure 11). To understand participants' reactions to the experience, and to gain insight into the concepts of intelligent construction spaces and crowdsourced fabrication more generally, we gathered a set of observations and data. We followed a mixed-methods approach, consisting of an email survey of participants, short in-person interviews, and an analysis of log data gathered during the exhibit. We begin by presenting log data and our high level observations from the exhibit.

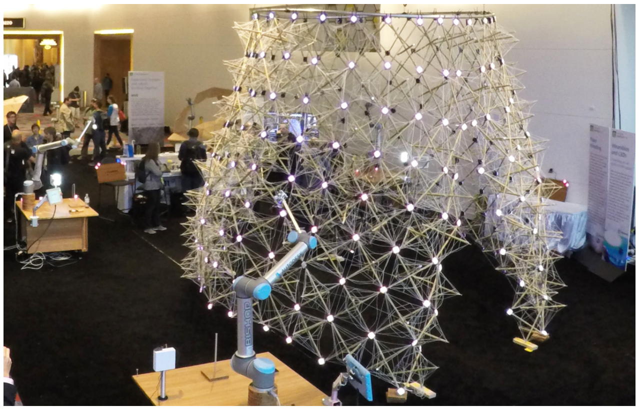


Figure 11. The completed pavilion on Day 3.

Observations and Log Data

Build Progress

Figure 12 shows progress on building the pavilion over the three days of the conference. The part numbers for Day 1 start at 33 because we constructed the first 32 modules during setup and testing before the conference began, without the use of the foreman engine and guidance system.

On the second day of the conference, there are two gaps in the build progress. First, around noon, we had to shut down the exhibit for 90 minutes while we replaced a number of modules that were built incorrectly. An integer truncation error in the communication between the foreman engine and robot stations caused 15 modules to be fabricated with incorrect geometry. These modules were refabricated by staff and replaced in the structure. Second, around 6:00pm we had concerns about the structural integrity of the pavilion, which prompted us to shut down the exhibit for an assessment.

To ensure the structure was stable, team members resumed building in the evening, after the exhibit was closed, completing the sixth ring just before midnight. On the third day, the exhibit was only partially open to the public as a safety precaution. Members of the project team built the majority of the remaining modules, with conference attendees invited to follow them through the process and participate in some of the steps. At around 2:00pm on the third day, the final ring of the pavilion was completed.

Disruptions

Aside from the two disruptions described above, other minor technical and logistical issues occurred throughout the three day build. These ranged from robotic winding failures, to network communication problems. In most cases, these issues would only cause a single robot to be taken offline, and the build would continue with the remaining stations. The foreman engine was set up to automatically detect if robots were offline, and assign workers to alternate stations, which minimized the effect of these disruptions.

Module Completion Time

The average completion time of each worker was calculated as time between starting the training process and confirming the part was successfully added. We removed six outlier data points with build times <5 minutes or >40 minutes, which can be attributed to testing or builds interrupted by technical difficulties. Across all workers, the average completion time was 18m 37s. The involvement of the researchers during the build process also allowed us to compare the performance of volunteers, coming into the exhibit without any prior knowledge, to more experienced staff members with a familiarity with the overall process. Volunteers took an average of

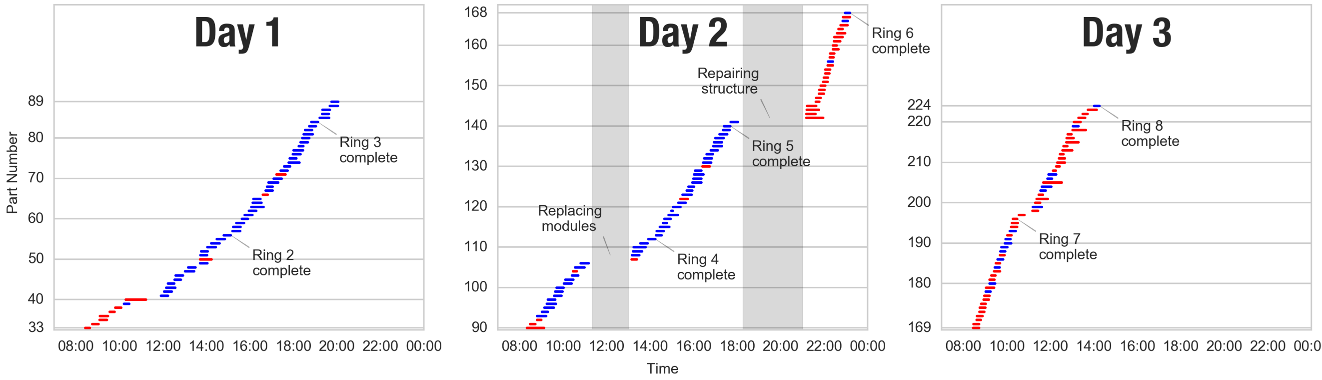


Figure 12. Build progress on the pavilion over the three days of the exhibit. Each line represents the start and end time for one part. Blue lines represent parts built by volunteer participants, while red lines indicate parts built by staff.

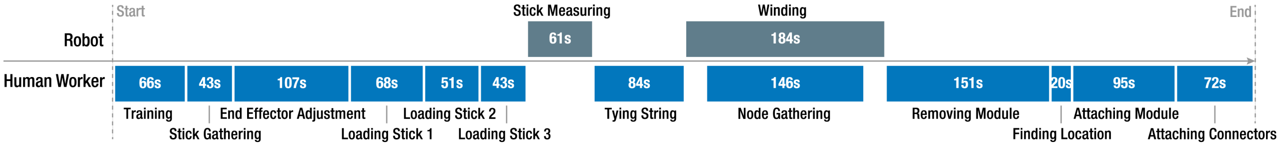


Figure 13. Median times for individual steps in the build process (volunteer participants).

20m 4s, compared to 16m 37s for the project staff. A t-test showed that this difference was significant ($t_{188} = 4.55$, $p < .01$). Overall this suggests there are opportunities to further close the gap between expert and novice performance.

Sub-Task Analysis

To get a sense of how much time volunteer participants spent on each step of the build process, we examined the log data for 98 of the 108 participant runs in which a module was logged as being successfully added to the pavilion (Figure 13). This omits 10 runs in which technical issues prevented the task from being successfully completed or logged. The median time spent by participants on most tasks is between one and two minutes. We also notice some learning effects for tasks with repetition – in particular, the median times for loading the three sticks was 68s, 51s, and 43s respectively.

Survey Method and Participants

Following the conference, an email survey was sent out to the 108 participants to understand both who they were, and to gather their feedback on the exhibit experience. To incentivize participants to respond to the survey, we randomly selected five participants to receive a $25 Amazon.com gift card. In all, we received 61 responses (56% response rate).

Participant Demographics

Of the participants who responded to the survey, 49 were male, 11 female, and one preferred not to say. Participants' mean age was 37 years (SD 9, min 23, max 61). Participants self-reported a mean of 10 years of experience in their industry (SD 7). In terms of individual industries, participants reported being in Construction (15 participants), Architecture (13), Engineering (8), AEC (*Architecture, Engineering, and Construction*) (5), Software (5), Manufacturing (3), Education (2), and a range of other related industries reported by one participant each.

In addition to the email survey, we conducted short in-person interviews with participants on-site after they had taken part in the exhibit. In all, we interviewed ten participants (7 male, 3 female). We report the combined findings from the email survey and the in-person interviews.

Survey and Interview Results

When asked to rate the overall experience of participating in the exhibit, most participants (43/61) rated it Very Positive, with no participants rating it negatively (Figure 14).

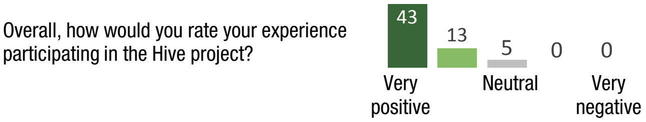


Figure 14. Overall ratings of the building experience.

Participants provided a range of rationales for their ratings, but a common theme was that they enjoyed working with the novel technologies used in the exhibit. The integration between technologies was mentioned by a number of participants, as in the following quote:

> *The technology was incredible. The networking between the robots and the app to guide the user in the workspace was amazing. – P11*

To understand how individual steps of the build process were perceived, we asked participants to rate each step on a five-point scale from Very Straightforward to Very Challenging (Figure 15). Participants tended to be positive in their ratings, with all steps rated as more straightforward than challenging. Comparing the ratings for individual steps, *Loading sticks into the robot* and *Attaching the part to the pavilion* had the highest number of Challenging or Very Challenging ratings, which makes sense because these steps involved the most complicated physical manipulations.

We also asked participants to rate the usefulness of individual components of the exhibit, including the smartwatch app, LED modules, location tracking system, foreman engine, and dashboard display. The results of the usefulness ratings are shown in Figure 16. Ratings were generally positive, with all components receiving ratings on the high end of the scale. In particular, the wireless LED modules were highly rated for indicating the position and orientation to insert a completed part, as suggested by the following quote:

> *I was surprised by the seeming intelligence of the [exhibit] in guiding me to install the component I helped build into the structure by color-coded lights at the intersecting joints. – P28*

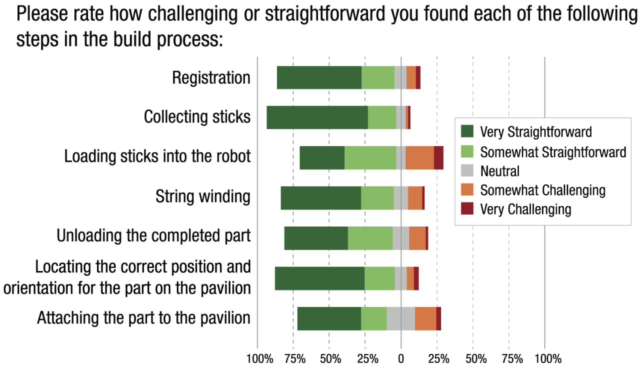


Figure 15. Ratings of individual steps in the build process.

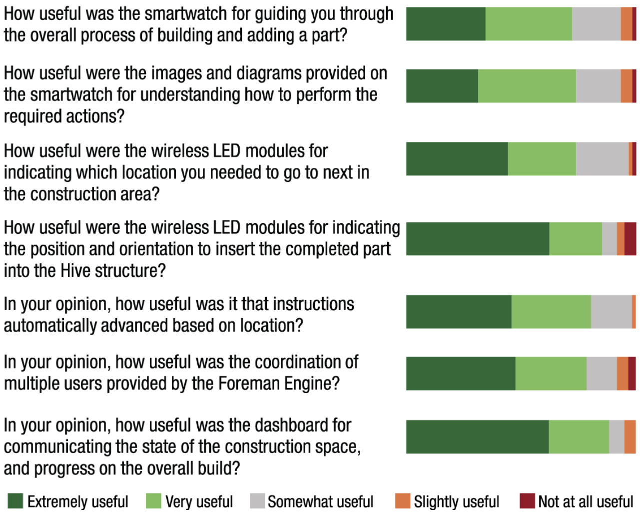


Figure 16. Ratings of individual guidance mechanisms.

In contrast, the LED modules received lower ratings for indicating locations in the construction space. Participants suggested a number of reasons for this, including occlusion, and distractions from other signage and lights:

There were too many other bright colors on the posters etc. in the area, and the [pavilion] was too big to see the blinking LEDs on the other side. – P18

The dashboard, foreman engine, and location tracking also received favorable ratings, with the majority of ratings in the Extremely Useful category. The smartwatch application, and the images and diagrams that it provided also received generally positive ratings, though comparatively lower than the other guidance mechanisms.

To further understand reactions to the smartwatch guidance, we included two additional survey questions – one about how comfortable participants found the watch to use, and another that asked participants to compare the smartwatch with a hypothetical smartphone, tablet, or printed instructional manual. Participants were also asked to provide a rationale for their ratings. A summary of ratings is shown in Figure 17. Again, responses generally favored the smartwatch, but participant comments gave a more detailed picture.

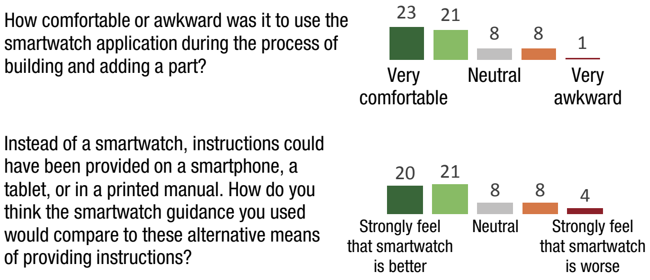


Figure 17. Additional survey questions about the smartwatch.

In their rationales for the above ratings, the hands-free nature of the smartwatch was cited as a key advantage, while the small size of the screen was often cited as a disadvantage.

The nice thing about the watch is that it didn't get in the way. I feel like a phone or tablet or manual would have been more cumbersome, bulky, and awkward. The only downside to the watch is that the screen was small, so the diagrams had limited usefulness. – P3

I was able to keep my hands free to do other tasks, also the vibrating feedback the watch gave when it needed me to do something was just enough to grab my attention, having it on any other device would not have been as effective. – P17

Finally, we asked participants to report how confident they felt that they could have completed the entire task without assistance from their researcher guide, assuming that no errors with the technology occurred (Figure 18). The majority of responding participants (53/61) reported that they were somewhat or very confident that they could have completed the task without staff assistance.

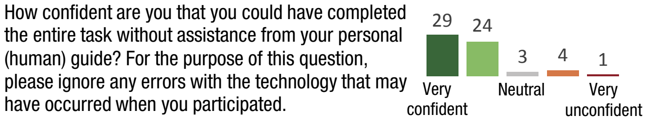


Figure 18. Self-rated confidence that participants could complete the task without assistance.

Potential Applications

In addition to receiving feedback on our specific instantiation of a crowdsourced fabrication system, we wanted to gain broader feedback on the general principles which our exhibited demonstrated. Because many of our participants work in industries involved in design and construction, we asked participants whether they felt that these concepts could be applied to their own fields.

In their responses, participants cited a number of specific aspects of the project that they could see applied to their own areas. The most frequently cited themes were coordination of work, receiving real-time guidance, and tracking work to improve awareness, either in real-time or for later analysis. These themes have a strong overlap with our design goals D1, D4, and D5. The following quotes reflect a number of these themes:

In construction, I can see extreme potential for both tracking progress of tasks, accounting for labor, directing workers to daily tasks, and making installation of pre-manufactured components easier to understand. – P31

My industry, in particular, is Fire Sprinkler systems, a subset of the MEP trades in building construction. I could imagine a system of IoT sensors linked with QR scanners, smart devices, and location sensors giving guidance to the installers of a sprinkler system. Our materials are pre-fabricated and delivered to job sites. Part of the process is distributing the materials to the correct portion of the site and coordinating the installation phases with other installers as well as other tradesmen. – P28

Participants also suggested the potential for supplementing skilled labor, or enabling construction in scenarios where skilled labor is not available:

This could be used in remote locations to enable unskilled workers to construct dwellings etc. without the need for a team of specialized trained workers. – P26

Other participants commented that these technologies could create opportunities for people who are not classically trained in an area, or make the average worker more versatile. One participant suggested a connection to how amateurs and hobbyists learn skills from their peers over the Internet:

The skilled workforce of the past is fading away and we have to create a new modern way to guide the workforce of the future which may be less disciplined in learning a specific expertise and more accustomed to receiving instructions in this fashion when they build stuff outside the workplace. For example... I am not a mechanic but I recently repaired my car. I studied the repair guides as best I could, but it is YouTube that helped me the most. If I had to choose learning from other amateur mechanics on YouTube vs. experts in a book... I am going with amateurs on YouTube because I can more completely understand the task I am taking on. – P34

These comments suggest three very different possibilities for crowd construction – it could stand-in for skilled work in scenarios where skilled workers are not available; it could supplement the skills of existing workers; and it could be part of a broader democratization of abilities to anyone willing to teach themselves. We discuss some of these possibilities in greater detail in the sections that follow.

LIMITATIONS

Our findings demonstrate both the feasibility and promise of utilizing crowdsourced fabrication for large-scale construction tasks. However, we also observed first-hand the complexity of coordinating a large numbers of workers, especially those with a range of skill levels. In this section, we discuss some challenges and limitations of the exhibit, and their implications for future work.

First, we encountered some structural integrity issues, mostly due to the novel computational design of the structure which was previously untested. However, this was also in part due to the zip ties on connector nodes not being adequately tightened by workers, which affected the rigidity of the overall structure. Untrained workers were not aware that this could be an issue, and even if they were, they may not have been able to recognize whether a zip tie was tight enough. This suggests a role for more sophisticated quality control and error checking within crowdsourced fabrication systems. For example, the system could ask workers to check one-another's work, building on patterns such as Find-Fix-Verify developed in the crowdsourcing literature [3].

Second, participants in our exhibit had an experienced staff member who shadowed them and provided supplemental assistance and error correction when required. While we envision future instantiations and real-world deployments having some level of experienced staff presence, it may not be available at such granularity. Building on the above discussion of quality control, we can imagine a system where volunteers perform a task initially as an *apprentice*, and then "graduate" to the role of a guide for one or more subsequent participants. This progression could be triggered automatically based on a worker's performance measurements. Alternately, techniques could be developed that enable experts to provide guidance remotely, drawing on work in the AR and VR literature [15, 31, 43, 46].

A related issue is that our pavilion was not built entirely by volunteers. Instead, volunteers contributed during some periods, with staff stepping in during disruptions. While it is encouraging that our system was able to serve workers with a wide range of skill levels, our experience suggests that crowdsourced fabrication systems will require at least some participants with greater task knowledge. This again points to the possibility of techniques that could enable a small number of experts to guide a large number of novices, an idea that has been explored in the education domain [14].

DISCUSSION AND FUTURE WORK

Despite the limitations discussed above, we believe that our work will be valuable for inspiring future research and development of crowdsourced fabrication systems. In particular, there is potential to adapt and extend this approach to a number of real-world scenarios where volunteer labor plays a strong role, such as community building or disaster recovery. We also see opportunities to integrate some of the concepts we have explored into traditional construction sites, particularly the coordination and tracking mechanisms. Finally, we see this work as opening up new research directions in the broader domain of crowdsourcing physical tasks. Below, we reflect on the key findings from this project, grounded by our initial design principles, and discuss additional future avenues of research.

D1. Just-in-Time Learning and Guidance: Overall, the guidance mechanisms used in our exhibit were well received. As well as providing positive ratings, we observed a sense of delight in workers when LEDs illuminated at the right moment, or the watch screens advanced automatically. However, there were also cases when the LEDs were difficult to see from a distance, and the small watch screen was limiting. Overall, we believe the use of visual guidance mechanisms is extremely important for this type of system, but it is worth exploring alternative mechanisms for providing this guidance, such as external projection [29, 42], or augmented reality techniques [20, 50].

It is also important to note the difference between learning and guidance. Our observations indicated that workers were not blindly following instructions, but were taking time to understand the intent of each step they performed. We believe that if workers repeated the task, they would show performance improvements, which would indicate some learning was occurring. It would be interesting to explore this effect in more detail in future implementations.

D2. Unobtrusive Technology: The technologies used for guidance and fabrication in our exhibit did not significantly intrude or hinder workers' tasks, and had clear benefits. The only minor inconvenience was interacting with the watch while both hands were occupied. This points to future research on operating smartwatch applications hands-free, using gaze [10] or other interaction modalities.

D3. Worker Safety: We used two strategies to ensure worker safety. First, we designed the building task to minimize risk (avoiding ladders, scaffolding). Second, we integrated warning prompts and confirmations into the smartwatch app for steps where the worker was interacting with the robot fabrication system. These measures were effective, but some additional safety concerns arose surrounding the structural integrity of the pavilion. This emphasizes the need for experienced on-site staff at any large-scale construction project.

D4. Increasing Coordination and Efficiency: We were pleased with the overall level of coordination that the foreman engine provided. In cases where technical problems occurred with a single robot station, the foreman engine automatically adapted and did not assign workers to that station. This points to a broader concept: in any complex environment, things can and will go wrong, and any backend system must to be able to adapt. This issue is particularly salient when untrained workers are involved. Our work could be extended further along these lines to dynamically assign roles in real time based on current needs of the build process, instead of having all workers complete the same task.

While we expected that the system would be useful for untrained workers, we also found it to be valuable for the expert staff – when the staff were building components on the third day of the exhibit, they chose to keep the foreman engine and guidance systems running to direct the construction, including using the smartwatches. Even for the skilled team, the feedback, guidance, and coordination provided by the intelligent constriction space was useful. This suggests that many of the concepts that we have demonstrated could be applied to scenarios where crowds of trained workers and professionals are coordinating on a large-scale construction task. Investigating approaches for integrating skilled workers into this type of system, and adapting existing crowdsourcing workflows that utilize skilled workers (e.g., [38]) to physical tasks are interesting areas for future work.

D5. Active Analytics: Finally, the status information generated by the exhibit was useful in several ways. First, this real-time data was necessary for the foreman engine to operate. Second, we received many positive comments about the dashboard display, which may suggest that it motivated conference attendees to take part in the exhibit. Finally, participants commented that status and analytics information could have immediate value in their own industries.

Crowdsourcing for Physical Tasks

From a crowdsourcing research perspective, the novel contribution of this project is in harnessing human workers' unique physical abilities to enhance a digital system. We see a rich area for future work that investigates key research questions from the crowdsourcing literature in this setting. For example, specialized techniques for soliciting workers for physical tasks could be investigated; techniques could be developed to utilize workers' creative and cognitive skills in concert with their physical abilities; and approaches could be investigated for adapting tasks to each individual worker's particular skills and limitations.

In addition, formal evaluations of the crowdsourced fabrication model should be conducted. We were limited because of the scale of the project and its public exhibition, but in future work the approach could be compared with alternative methods for building an equivalent structure (e.g., an experienced foreman coordinating a set of volunteers.)

Generalizability

Finally, an important area for future work is to investigate how generalizable techniques and tools can be developed for crowdsourced fabrication. Though many aspects of the system presented in this paper are specific to the pavilion that we built, we believe the overall approach followed by our system is generalizable and the design principles presented in this paper will be valuable to guide the development of intelligent workspaces for this purpose. Building on this, there are opportunities to develop new guidance mechanisms, materials, workflows, and design tools that could be applied to crowdsourced construction across a range of different structures.

CONCLUSIONS

In this paper, we have presented a model of *crowdsourced fabrication*, in which a large number of workers and volunteers are guided through the process of building a large-scale structure. Our specific deployment of this concept resulted in a 12'-tall pavilion being built with assistance from over one hundred volunteers across a three day event. The experience has provided us with a rich set of observations and feedback that we hope will inspire future efforts in this area.

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