Travelogue: Representing Indoor Trajectories as Informative Art

ANONYMOUS AUTHOR(S)

In this work, we explore if informative art can represent a user's indoor trajectory and further promote user's self-reflection as a new type of personal informatics tool. Under the assumption that the simplicity of a digital picture frame can be an appealing way to represent indoor activities and further create a dyadic relationship between users and the space they occupy, we present Travelogue, a picture-frame like self-contained system which can sense human movement using wireless signal reflections. Breaking away from traditional dashboard-based visualization techniques, Travelogue only renders the high-level extent and location of users' activities in different informative arts. Our user study with 91 participants shows most users found Travelogue an intuitive, unobtrusive, and aesthetically pleasing tool. By interacting with Travelogue, users were able to relate with their surroundings more, giving them a better sense of self-reflection than mere numbers or graphs shown by today's personal informatics tools.

ACM Reference Format:
Anonymous Author(s). 2021. Travelogue: Representing Indoor Trajectories as Informative Art. 1, 1 (May 2021), 19 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Personal informatics (PI) tools are a class of applications that help people collect and reflect on personally relevant information [48]. Today's PI tools can enable users to self-reflect on their moods, relationships, activities, and numerous other life factors by logging their physical and psychological data [18, 19]. This work focuses on one such aspect of the user's life—their indoor trajectory. Just like a person's heart rate and step count can reflect the intensity of their physical activity, a person's indoor trajectory contains details about the person's whereabouts, leading to inferences ranging from lifestyle to mental state. For example, by observing their own indoor trajectories, users may understand how they spend their time in different parts of their home, potentially what their daily routines look like, and how they interact with each other, and their surroundings. Besides, a personal indoor trajectory can contain subtle clues about the user's mental state, such as pacing back-and-forth may represent an anxious mood [15], and can also be a sign of several mental diseases such as psychomotor agitation [24] and autism [4]. This piques interest in such technology from healthcare providers [36], rehabilitation centers, old-age homes etc. Although indoor localization is quite a mature field, to the best of our knowledge, there is no existing research on designing and studying the potentials of a PI tool that collects and visualizes fine-grained indoor trajectory.

How would one create an intuitive and impressionable visualization for indoor trajectory? This is an important problem; visualizations affect the acceptance and continued usage of PI tools [48, 62], and in some sense differentiate utility from nuisance. In this paper, we take an exploratory approach, both in terms of how to collect data about a person's indoor whereabouts, as well as how to present this information in a calm and unobtrusive manner. Most PI tools available today rely on wearables and use graphs-based visualizations that allow in-depth analysis of one's activities. We attempt to break away from these shackles and contend that an approach which does not need wearing a device, and a glanceable design that integrates cohesively with home environments is more desirable [62]. Instead of additional cognitive load of detailed displays, we desire to create a pleasant and calming experience—one that relies less on exactness and more on the fuzzy notions of satisfaction. We recognize that such lofty goals must still be achieved through baby steps and

2021. Manuscript submitted to ACM

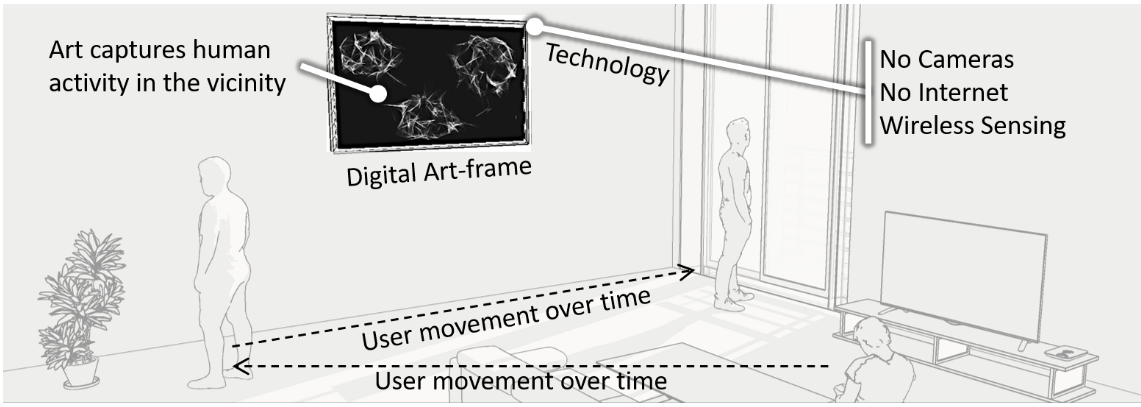

Fig. 1. Travelogue is a digital-art picture frame that generates modern-art images based on human activity in its vicinity. We explore if Travelogue can replace personal informatics tools in indoor environments providing freedom from having to wear or carry a device.

therefore explore our vision through creation of an ambient display that creates artistic visualizations mimicking a person's indoor trajectory, providing a more engaging, intuitive, and unobtrusive user experience [26, 57, 62, 63].

With this motivation, we present Travelogue, a system that passively captures a user's indoor movements and renders it as an ever-changing informative art in a digital picture frame. Instead of numbers or graphs, this digital frame, draws its abstract art, based on the physical activity around it. In a fuzzy manner, the informative art *remembers* activities in its vicinity and etches an abstract representation of those activities into a constantly changing picture. These changes in the art are slow transitions, and purposefully non-attention grabbing, so that the user can continue their activities without being distracted by the system. Figure 1 shows an artist's rendition of this vision. While obtaining precise information from this art will be difficult, simply a glance is sufficient to infer activity level[1].

Since Travelogue should respect user's privacy in their homes, it is based on wireless sensing; the digital picture frame houses a set of ultra-wideband (UWB) radio frequency (RF) devices. One of these RF devices is a transmitter: it sends out wireless signals, which spread out in all directions, bounce off different objects, walls, ceiling, etc. as well as the user's body, and *return back* to the Travelogue apparatus. Other RF receivers inside the picture frame capture these reflections. Careful analysis of the reflections allows Travelogue to distinguish between the user's reflections, and those from static objects. All reflections are available as inputs in rendering of the art. Data analysis occurs locally on the digital picture-frame, without connecting to the Internet. Furthermore, Travelogue functions without cameras (alleviating privacy concerns), and without the user wearing or carrying any device (alleviating abandonment concerns).

As examples of Travelogue's capabilities, we generate 4 kinds of informative art, primarily depicting the user's distance or location from the picture frame in different ways. More generally, we have created a system that can easily render an artist's imagination representing user trajectories. Among our 4 examples, the first two forms show the distance in form of strings and waves respectively and over time render new strings or waves on a linear time axis (see Figure 5(a), Figure 5(b)). These art-forms are closest to today's graphs-based representations on personal informatics systems. The third art-form renders time on a circular axis, much like the arms of a clock, while instantaneous distance and environmental reflections are shown radially outwards, creating a ring showing past behavior as time proceeds (see Figure 5(c)). The fourth art-form is the most abstract. It depicts the surrounding 2-dimensional space on the canvas with line strokes appearing at the user's location (see Figure 5(d)). Extensive user study[2] with 79 anonymous users and

[1]Privacy concerns are addressed in the discussion section at the end of this paper.
[2]IRB approved. Details withheld for anonymity.

12 interview participants shows that the informative art was deemed unobtrusive and non-distracting. Participants found progressively abstract forms more intuitive and likable in a space. Finally a small-scale design workshop has spiked interest from designers and artists to create innovate visualizations using the Travelogue platform.

As far as we know, this is the first system that captures user's indoor location and movements using wireless sensing, and visualizes it in different informative arts. Overall, our contributions in this work are:

(1) A new form of personal informatics system is introduced that collects indoor movement information and displays it on an ambient dedicated display, without requiring the user to wear any device.
(2) A generic extensible platform is created which provides new creative opportunities; a set of four informative arts are designed as examples.
(3) An extensive user study comprising of an anonymous survey and a set of interviews reveal the novel utility and user experience introduced by our system, and open up new design opportunities for indoor spaces.

In the rest of this paper, we briefly describe related work, followed by a description of Travelogue's wireless sensing system. Then we describe in detail the design strategy, implementation details, and explore the findings from our user study. We end with an elaborate discussion section including insights from our small-scale design workshop.

2 RELATED WORKS

2.1 Personal Informatics Systems

Personal Informatics (PI) is a class of applications that collects personally relevant physical, psychological, and behavioral data to help people reflect on personal information [48]. Early examples of PI systems can be found in life logging research [17, 25, 30, 53] which usually contain digital records of an individual's experiences. Subsequently, many systems were designed to help users collect and visualize their personal information. In terms of the data collecting procedure, there are usually two main streams: self-reporting [14, 27, 29, 54] and automatic data collection by leveraging sensors and algorithms (e.g. SugarStats [10], Fitbit [5], and Jawbone Up [1]). Self-reporting is often argued to be biased and inaccurate because users are forgetful [56, 72] and reporting interferes with natural activities of the user [56, 70]. In sensor-based approaches, though the data collection process is simplified, users are burdened with the necessity of wearing the sensors. This results in adherence problems because people stop using the sensors over time [20, 28, 45, 47, 65]. In contrast, Travelogue collects data automatically without requiring users to wear a device. From the perspective of data visualization, a majority of PI systems still represent data with a combination of traditional charts, maps and dashboards (e.g. Fitbit, Basis, Jawbone Up). However, several other feedback schemes have also been explored. Avatar-based feedback employs a virtual object to represent user's personal information, such as *Fish'n'Steps* [50] using a virtual fish to reflect step counts and *UbiFit Garden* [22] represents fitness activity as a digital garden. Tangible representations such as 3D printed materials [42] or foods [41, 43] have also been proposed and evaluated by researchers. Probably closest to Travelogue is *Spark* [26], which uses abstract geometric art to visualize people's steps collected from Fitbit. In contrast, Travelogue is an integrated data capture and visualization platform that does not depend on external data collection.

2.2 Radio Frequency Device-Free Localization

Recently, there is growing interest in exploring radio frequency (RF) for device-free localization. Compared with other camera, infrared-based [51, 77, 78] and acoustic-based solutions [16, 35], RF-based solutions work in low-lighting conditions, have wide coverage distance, and good penetration across physical barriers. Wi-Fi as a commonly used RF technology has been employed by many previous works to realize device-free localization. Many systems utilized the received signal strength (RSS) to localize a target [68, 69, 75, 80]. However, due to inherent unreliability of received signal strength, it is difficult to achieve high localization accuracy in most home/office environments. More recently channel state information (CSI) has been employed where systems localize a target by analyzing the measured CSI information [76, 79]. Technologies that use dedicated specialized equipment can perform device-free localization—Wi-Vi [12], WiDeo [40], Witrack [11], and Marko [36] are good examples. However, susceptibility to multi-path fading and low temporal resolution make it hard to develop Wi-Fi only accurate tracking system. Ultra-wide-band (UWB) is a promising technology for device-free localization due to its wide bandwidth and superior time resolution. Most of the prior work on UWB-based device-free localization is based on commercial-grade custom-built radar hardware [33, 37, 49, 81]. In contrast to employing such purpose-built devices, we adopt simple architectural modifications and a recently published CIR filtering algorithm [46] to achieve device-free localization using off-the-shelf UWB devices.

2.3 Ambient Media and Informative Art

Ambient media refers to applications that do not render on the screen of a conventional computing device, but in the environment or periphery of the user. This notion of distributing information displays in daily environment spun from *Ubiquitous Computing* [73], which led to coining of the term *Calm Technology* [74] describing an encalming technology that reduces user's information overload. A typical example of calm technology is the *dangling string* [74], an art installation where a piece of cable hanging from the ceiling is affected by the amount of traffic in the local Ethernet. Similarly, there are previous works which use decorative or everyday objects in general to deliver digital information in a calming and aesthetically pleasing manner, such as the *ambientROOM* [38], the *Information Percolator* [34], and the *Calm Station* [44]. In addition to using physical objects, using art to represent digital information has also been studied by many researchers. *Informative Art* [13, 61], adopt different kinds of artistic styles to visualize dynamically updated information. Besides, an informative art application usually does not provide exact information, but only a sense of perception. For example, *InfoCanvas* [55] paints meaningful scenes based on online data such as unread emails, stock markets and weather. *WaveWatch* [64] visualizes web traffic by representing the underlying dynamics with different levels of ocean wave activity. Tobias et al. [66] designed and evaluated an ambient information visualization of bus departure times in abstract geometric forms. It is worth noting that previous informative art related works mainly focus on visualizing data from available sources such as online resources or commercial wearable devices. In our work, we build and evaluate a standalone end-to-end prototype which has the ability to both sense and visualize. To the best of our knowledge, Travelogue is the first system that visualizes human indoor trajectories in the form of art.

3 TRAVELOGUE'S LOCALIZATION MECHANISM

Travelogue is envisioned to work in people's homes and passively track the user's movements inside a home environment. Since Travelogue will be used in a private space, we shun the use of cameras and instead rely purely on wireless reflections alone to estimate a person's location in the indoor space. This approach allows Travelogue to remain a self-contained system that passively collects users' trajectory in indoor settings without even connecting to the Internet. Travelogue continuously transmits RF signals and analyzes its reflection to estimate the user's distance to receivers. Further, by estimating the user-receiver distance from two different spatially separated receivers, the user's 2D location is estimated. Next, we briefly describe the techniques used for localizing the user's position using wireless reflections.

3.1 Interpreting distances from received wireless signals

The core idea in Travelogue is to transmit wireless signals from a transmitter, let them bounce off various objects in the environment and then capture reflections at a receiver. The returning signals arrive at different times (in the order of nanoseconds) based on the distance they travel from the transmitter to the physical object they reflected from. Figure 2 shows an example of how signals arriving at different times can be observed in the channel's impulse response (CIR).

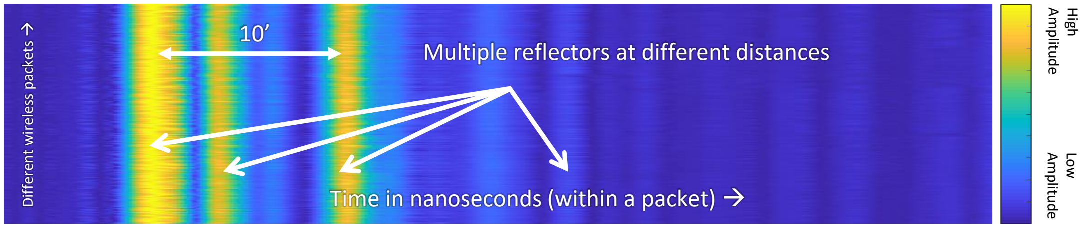

Fig. 2. A channel impulse response can capture the reflections from multiple reflectors, and estimate the distance between reflectors.

Fixed objects have a static reflection which remains unaltered over time, whereas reflections from humans change or quiver because of the person's movements. This allows differentiating reflections into static or human reflections.

Capturing wireless reflections is not simple due to a phenomenon called self-interference. Simply put, the power of the transmitted signal is so immense compared with the feeble reflections that it "drowns" the reflections. We create a special 2-antenna transmitter to overcome this issue—signals from the two antenna cancel each other at specific spots where receivers are placed as shown in Figure 6(a). This allows Travelogue to observe reflections well. Figure 2 shows bands of reflections arriving from different static objects in an indoor room. When the transmitter-receiver distance is known, the weak direct path (first yellow band in Figure 2) can be used as a reference to calculate the overall signal traveling distance. Next we discuss identifying a user's location from among the various reflections.

3.2 Filtering the channel impulse response to estimate user distance

A reflector's relative distance from the transmitter can be estimated by analyzing the delays experienced by various returning signals. Among these various reflections seen in a CIR, *which reflections are from a human being?* A key component in distinguishing human reflections is the realization that humans are not rigid objects and therefore constantly move ever so slightly (even when appearing to be stationary). When the user moves, signals that reflect from the person change in amplitude and time delay. Further, such movements cause a cascading effect on subsequent reflections (second order, third order reflections, etc.) These expected distortions in the CIR provide us a signature—aligning and comparing multiple CIRs looking for this signature can reveal the user's distance. We adopted a recently proposed approach [46] for an efficient and lightweight configuration; the high-level idea is presented below.

Our ultra-wideband hardware provides a CIR time resolution of 1 *nanosecond*, however, the internal clock has a resolution of $\frac{1}{64}$ *ns*. The leading edge of arriving signal provide a good reference which allows us to shift all CIRs to align with this fine-grained timestamp. Figure 3 shows 30 overlapping CIRs captured 50ms apart (20Hz) with individual CIRs shown with matching gray dots (of varying darkness and size). An arbitrary CIR is highlighted in red dots to show how every sample from a particular CIR is still equispaced 1 *ns* apart. CIRs in figure 3 have been captured in an indoor setting without humans present in the vicinity. Observe how all of the CIRs appear consistent and together produce a CIR similar to what would have been obtained through super-interpolation.

In contrast, figure 4 has been captured in the same environment but with a person walking at a certain distance from the frame. The beginning of "Region A" denotes the minimum distance between the walking person and the picture frame. We observe a sharp increase in the CIR's variations introduced by the user's movements. These increased CIR variations match the human-detection signature and triggers the distance estimation module. The CIR tap where variations exceed a threshold, subtracted from the CIR tap of the direct arriving signal from the transmitter (denoted as 0) gives the round trip distance of the user from the picture frame (after compensating for transmitter-receiver distance). Finally, we employ two receivers inside the picture frame to measure the user's distance from two vantage points

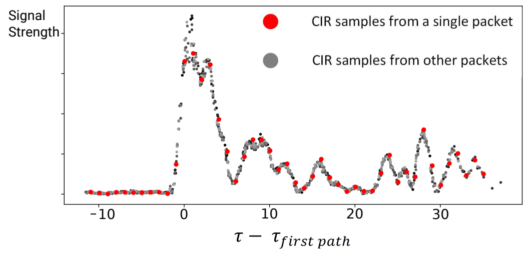

Fig. 3. Overlapping channel impulse responses for a static environment. All CIRs are consistent.

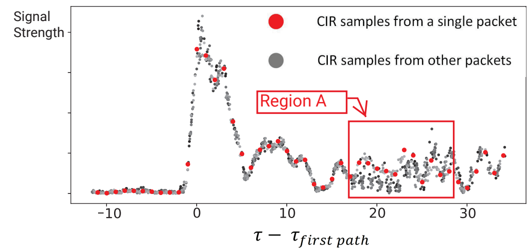

Fig. 4. Overlapping channel impulse responses with a person moving in the area denoted as Region A.

(similar to human binocular vision), thereby resolving the user's location. The disturbances in the CIR, the distance estimates, and the location estimates are all available as *information sources* to design art, which we discuss next.

4 TRAVELOGUE'S INFORMATIVE ART DESIGN

The information sources described above provide vital inputs to Travelogue, becoming the foundation for designing a data visualization system. This section presents the deliberations over Travelogue's distance/location data presentation.

4.1 Design Guideline

Travelogue follows the four design strategies for self-reflection and behavior change technologies proposed by *Breakaway* [39]. In addition, we list 3 Travelogue specific strategies.

4.1.1 Abstract & Reflective. User reflection is encouraged through the use of data abstraction rather than just displaying collected raw sensor data to present information. Travelogue abstracts out the raw wireless signals received by our sensors and instead only presents the most pertinent information through geometric shapes. More specifically, user activity is encoded into different colors, geometric shapes, or spatial relationships of visual elements. Further, information shown in our art persists for a significant time as it builds up history. This allows personal reflection by observing the art form, much like watching oneself in the mirror.

4.1.2 Public. By the very nature of converting a person's indoor activities into art, we are making some information about this person public. Our data visualization design should present personal data in a manner that the user is comfortable with even in the event that others may see the art. Since we use geometric abstract art forms to visualize personal data, and we do not use cameras to capture it, the art-form masks direct interpretations for a stranger.

4.1.3 Unobtrusive. It has been suggested that data should be collected and presented in an unobtrusive manner without interrupting or calling unnecessary attention to itself. Travelogue uses passive RF sensing techniques to sense user location/activity without requiring the user to actively log or wear any devices. In terms of the visualization, all displayed abstract art forms are designed to change subtly through time. More details about how the art forms will be generated are provided in the following sections.

4.1.4 Aesthetic. The physical and visual aspects of the prototype should be comfortable and pleasing to the user. Our prototype is in the form factor of a picture frame, which is naturally pleasing in terms of its physical appearance, since picture frame is a commonly used daily object for decoration. Also, the visual design of the different abstract art forms of our system have been aesthetically appreciated by most participants of our user study.

4.1.5 Temporality. Two aspects of user's movement over time are important: 1) *Immediate Information*, which depicts the current location of the user, and 2) *Historical Information*, which provides an aggregated view of the user's location in a certain period of time in the past. Both information are useful as immediate information could provide time-sensitive information about the user's current status and historical information could help the user better understand and reflect on their behavior patterns [21]. In Travelogue, we used an "additive" strategy to visualize both type of information at the same time. More specifically, basic visual elements that represent immediate information will be periodically painted onto the canvas in a period of time to form a historical view of the user's movement. The time interval between two immediate information can be adjusted to support custom needs. For example, the user can get a more fine-grained movement representation by setting the time interval to be short, or get a more coarse representation of their movement in a longer period by extending the time interval.

4.1.6 Location or just Distance? Travelogue estimates the user's distance to the frame from two vantage points providing the user's location. While 2D location is precise, the 1D distance is more straightforward and intuitive in some cases to depict spatial relationship. We have designed different art forms that encode user movement data at both these levels.

4.1.7 Environmental Reflection. Besides capturing the signal reflections from human body, our localization algorithm can also capture the reflections from static objects (e.g. furniture, wall, ceiling, etc.). Environmental reflections add another aspect to the art-form, making it unique across different indoor spaces. We visualize these reflections in some of the designed art forms, to add uniqueness and beauty.

4.2 Art Designs

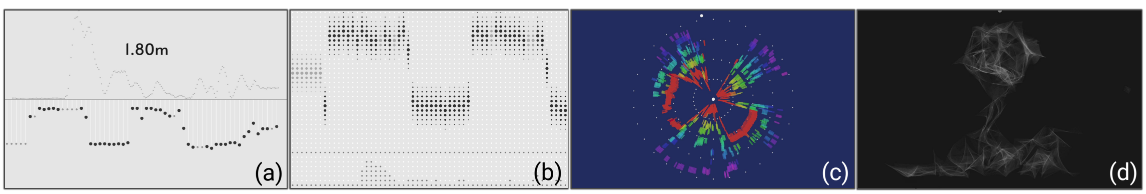

Fig. 5. (a) User's distance from the picture frame is captured by the length of the hanging strings. (b) Waves depict the user's distance from the picture frame. Top is near, bottom is far. (c) Circular sweep depicts time, while radial distance captures the user's distance from the frame. (d) Line-art continuously generates showing the user's location in 2-dimensions.

In this section, we discuss the four art forms that we have designed and evaluated. Each of the art form embodies a slightly different design or visual aspect and our aim was more to create categories of art instead of specific images. These categories progressively depart from traditional "charts and numbers" and enter into more abstract. We start with *Strings* that displays a numerical value indicating the user's distance from the frame. *Waves* indicates user distance in the form of a group of fading dots and shuns the use of the numerical distance value. *Ringbow* draws a radial visualization with both the user distance and the environment rendered in vibrant colors. Finally, *Blooming* draws a line-art that slowly expands and becomes brighter as the user spends more time in a particular location. This art-form is the most abstract while also capturing 2D user locations. These given names will not be stylized beyond this section.

4.2.1 Strings. Imagine the user is tethered to the digital picture-frame using a string, and as the user moves around, the picture-frame expands or contracts the length of this string. This is the motivation behind the "Strings" art-form. Figure 5(a) shows an example image that has captured a user's movements over about 5 minutes duration. We have refrained from labeling the various visual elements in the figure in the spirit of truthfully capturing only what the user will see in this image. The "Strings" visualization is divided horizontally into two parts. The top part is influenced by the reflections from the surroundings, while the lower part is influenced by the user's movements. The user's distance is indicated by a black bead hanging from a string attached to the center-line in the visualization. A numerical value showing the user's distance in meters connects this visualization to familiar aspects of current personal informatics tools. Over time, new hanging strings appear filling up the bottom part of the visualization from left to right[3] and cycling back to the left side. Tunable parameters include the duration of one cycle, update rate for the environmental reflections portion, location of the "center-line". If no human is detected, the end of the string remains a dull gray, but persists the most recent string-length. New strings fade-in, avoiding any sudden changes in the image.

4.2.2 Waves. Ocean waves imbibe a feeling of changing distances, which is similar to what we expect from user activities. This natural metaphor together with a dot-based generative art designed by Nakauchi Kiyoshi [6] has inspired the "waves" art-form shown in Figure 5(b) . Similar to "Strings" the visualization is divided into two parts. The top area captures the user's distance from the picture-frame captured by a wave of progressively larger and then smaller dark dots. The peak of this wave indicates the user's distance from the frame. The wave travels from left to right and then cycles back. Below the center-line is a rendition of the environmental reflections. Thus, the overall visualization is a function of the space and the activities that occur in this space over time. No numerical value of the user's location is presented, keeping this a purely abstract art-form. The update speed is a tunable parameter, allowing capturing the dynamic nature of the space. The visualization has 60 steps, each faded-in, before cycling back from the left.

4.2.3 Ringbow. Rotational motion is a classic epitome of passage of time—the earth rotating around the sun, for example. Orbits in such circular motion embody distance. This is the inspiration for the "Ringbow" art-form in Figure 5(c) . The user and other reflectors in the environment form rings of colored patterns in Ringbow which sweep around the frame's center as time passes. Red streaks drawn radially indicate the user's distance from the picture-frame, while streaks of other colors denote various other important reflectors in the environment. A user's movements causes many reflections to change, which creates a burst of color at that time. The visualization sweeps through the entire 360 degrees and repeats over again. Sweep-rate can be tuned to suite the ambiance and the indoor space. Amongst all art forms, the Ringbow has the largest possibility of distraction due to its vibrant colors and sudden changes to the picture.

4.2.4 Blooming. How would a space express its happiness that we are a part of it at this moment? Inspired by Casey Reas's generative art work *Process 6* [59], we designed an art form called "Blooming". The user's presence is celebrated by this art through a geometric line based art-form that progressively develops to depict the user's location and duration of presence (see Figure 5(d)). The art's canvas is the two-dimensional space around the picture frame (position of the picture frame on the canvas is indicated by a small gray dot in the center of the top border). When the user is static at a place, the line-art intensifies in that location as if a white flower was blooming in the darkness. New lines fade-in giving the art a calming effect. New lines are painted over old ones and the canvas is not flushed, but the option to do so will be presented to the user. The density of geometric lines will help the user reflect on their time in this space.

5 IMPLEMENTATION AND TECHNICAL PERFORMANCE

Fig. 6. (a) The internal components include UWB devices, single-board computer, and TFT display. (b) External appearance with live visualization on the digital picture frame. (c) Evaluation space. (d) The blue line shows the absolute distance estimation error and the orange line shows the absolute location estimation error.

[3] A maximum of 60 strings can appear on the visualization.

5.1 Proof-of-concept Implementation

Our proof-of-concept implementation of Travelogue (Figure 6(a)) consists of five components: (1) an external picture frame, (2) an aluminum backing sheet, (3) UWB devices (1 transmitter, 2 receivers), (4) a TFT display, and (5) a single board computer (Raspberry Pi). We use an off-the-shelf wooden picture-frame ($24'' \times 18'' \times 1.7''$) as the housing for all the electronic components (see Figure 6(a)). An aluminum sheet with the thickness of $0.019''$ makes the picture-frame's back-cover and all devices were mounted onto the aluminum sheet, as shown in Figure 6(a). The aluminum backing prevents signals from leaking behind the picture frame. We used three off-the-shelf Decawave TREK1000 UWB radio modules [3] in our prototype. Figure 6(a) shows the internal layout. Central module with two parallel antennas serves as the transmitter and the other two single-antenna UWB devices (25 cm from the transmitter) serve as the receivers, all running at a center frequency of 4 GHz. For destructive interference at the Rx antennas, the half-wavelength distance between the two transmitter antennas is 3.75 cm. We use a Raspberry Pi 3B+ single-board computer (1.4 GHz Cortex-A53 with 1 GB RAM), running Raspbian OS, for all compute tasks. This includes processing CIR packets, running distance estimation and localization algorithms, and generating the art forms in Python using Processing 3 software [2, 60]. The resulting art-forms are shown on the central $10.1''$ 1280×800 TFT display.

5.2 Distance Estimation and Localization Accuracy

Before the art-forms can be evaluated, it is important to ascertain that the distance measurements made by Travelogue are accurate, since it forms an input to the art generation modules. We measured a $5 \times 3\,m$ grid space where each marker is separated by 1 $meter$. The picture frame is placed on the wall at a height of 1.3 m with its center carefully aligned with one set of markers on the grid space, as shown in Figure 6(c). Then we used a laser ranger (with 1 mm precision) to measure the distance between each grid marker and the projected center of the frame as our ground-truth. One of the researchers walked in this space and stood on each grid point for ten seconds. The UWB modules inside our prototype transmitted and received CIR packets at the frequency of 20 Hz. Then, by processing the middle five seconds of each ten second interval (to remove pollution from movement between grid locations), we obtain the distance and location estimates; median errors of 0.07m and 0.9m respectively (see Figure 6(d)).

6 USER STUDY

Whereas the distance and location estimates described above serve as a prerequisite for generating art-forms, this work goes beyond being just a device-free localization system. An important part of this work is in assessing the opinions of real users through an extensive user study. To that end, we conduct a user study with 91 participants to evaluate Travelogue's usefulness, ease of use, and overall user experience. Our study has two sub-components: (1) an online survey which aims at evaluating our system with perspectives from a relatively large diverse population, to gain a broad understanding of user perception; and (2) an online focused interview study which aims at gaining in-depth understanding of opinions and experiences from a few users. The participant demographics is summarized in Figure 7. We now describe the procedures for the two studies and then discuss the specific questions we investigate.

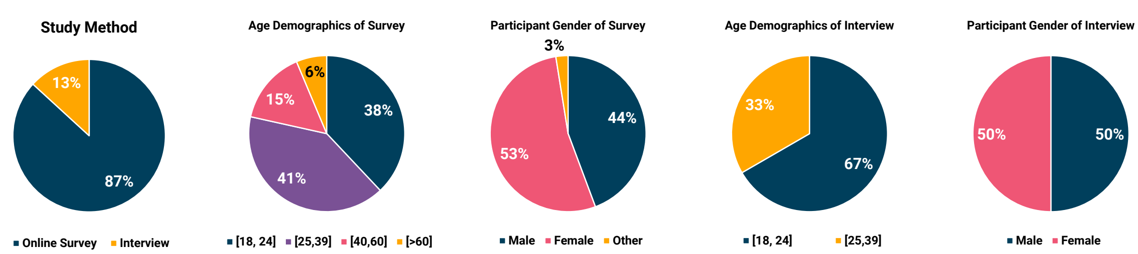

Fig. 7. Demographics of our online survey study and interview study.

6.1 Study Procedure

All participants were requested to read the IRB approved consent form before proceeding. For the anonymous online survey, *documentation* of consent was waived, but the system ensured that participants could not enter the next part unless they consented. We used our institution's site-wide license for Qualtrics Research Suite [8] to create the online survey, hosted through Prolific [7]. Given COVID-19 related constraints, where in-person interaction and deploying our prototype in participants' houses is challenging, we decided to show our participants videos of user movements and the corresponding changes to the art-form. The approach of showing videos for evaluation study is similar to other existing design-research evaluations [23, 58, 67]. The online participants were first shown a short introduction video describing Travelogue. Then, a video recording of a person naturally moving to different parts of a room, juxtaposed with real-time renderings of different informative arts, was played. The participants were shown only one informative art form at a time, and the order of different arts was randomized to avoid order-bias [9]. The videos, shot by a steady wide-angle camera that covered the entire room, aid understanding the spatial context: the locations of human activities vs. the picture frame's location, and the resulting rendering progress of the art-form; Figure 8 shows stills from the videos. At the end of every video, the participants were asked a set of questions about the appeal of that specific art-form (Table 1).

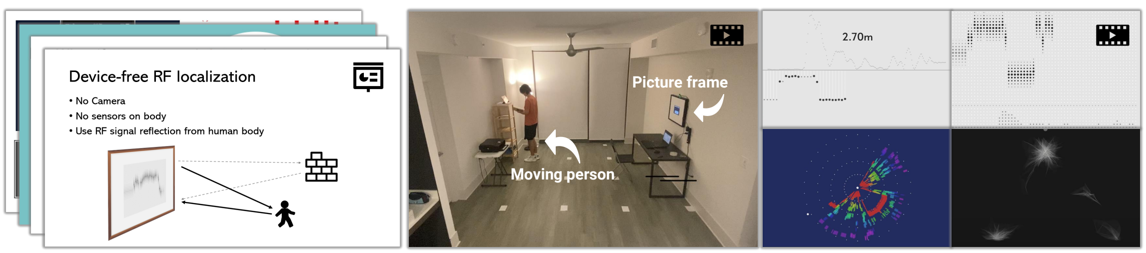

Fig. 8. Study procedure: the participant will be first shown with an introduction presentation, followed by a video of a person moving to different spots in a room, with the evolving informative arts rendered alongside.

To compare different art-forms produced by Travelogue, our survey questions are inspired by the eight heuristics of evaluating ambient display proposed by previous work [52] (heuristics are shown in Table 1's left column), modified for scenarios applicable to Travelogue; we omitted "Easy transition to more in-depth information" and "Visibility of state" since they do not apply. Participants were asked to rate their agreement or disagreement with the question's statements on a 7-point Likert Scale (1=*Strong Disagreement*, 7=*Strong Agreement*). Finally, we asked a few general questions about the idea of representing indoor motion in form of informative art (Figure 9), followed by a few open ended text questions. In-depth interviews were conducted for 12 participants, with documented consent. These interviews also started with the same survey videos and questions as the anonymous participants. At the end, however, the open ended questions were expanded on further, over a video interview. This gave us the opportunity to answer clarifying questions from the participants and get insights about their impressions. All participants were paid $10 for their time and effort.

6.2 Results

Figure 9 shows the Likert divergent graph for questions about the overall Travelogue idea. Figure 10 and Figure 11 summarize our findings in comparing the various art-forms. We analyze important aspects of these findings below.

6.2.1 Usefulness. Travelogue's utility ranges from use as a replacement to personal informatics tools, as a motivator, to even as an encalming device. We report our findings from these perspectives next. 87% (Likert mean: 5.67, std dev: 1.14) of the participants believe that Travelogue could give them the opportunity to reflect on **where they spend their**

Heuristics [52]	Survey Questions
Useful and relevant information The information should be useful and relevant to the users in the intended setting.	9. By observing the art, it is easy to get an approximate sense of the user's current (distance from the digital frame)/(location). 10. The generated art clearly shows the user's overall movement pattern. 11. The art clearly depicts how much time the user is spending in different locations.
"Peripherality" of the display The display should be unobtrusive and remain so unless it requires the user's attention. User should be able to easily monitor the display.	12. If this digital frame is hanging in my living space, it will constantly distract me.
Match between design of ambient display and environments One should notice an ambient display because of a change in the data it is presenting and not because its design clashes with its environment.	13. The transitions on the digital picture frame are subtle so that if I was not directly looking at it, I would not notice them.
Sufficient information design The display should be designed to convey "just enough" information. Too much information cramps the display, and too little makes the display less useful.	14. It displays too much information on the art form
Consistent and intuitive mapping Ambient displays should add minimal cognitive load. Cognitive load may be higher when users must remember what states or changes in the display mean. The display should be intuitive.	15. The design of the art form is intuitive.
Aesthetic and Pleasing Design The display should be pleasing when it is placed in the intended setting.	16. The art form is aesthetically pleasing.

Table 1. Art-form specific survey questions asked after every video.

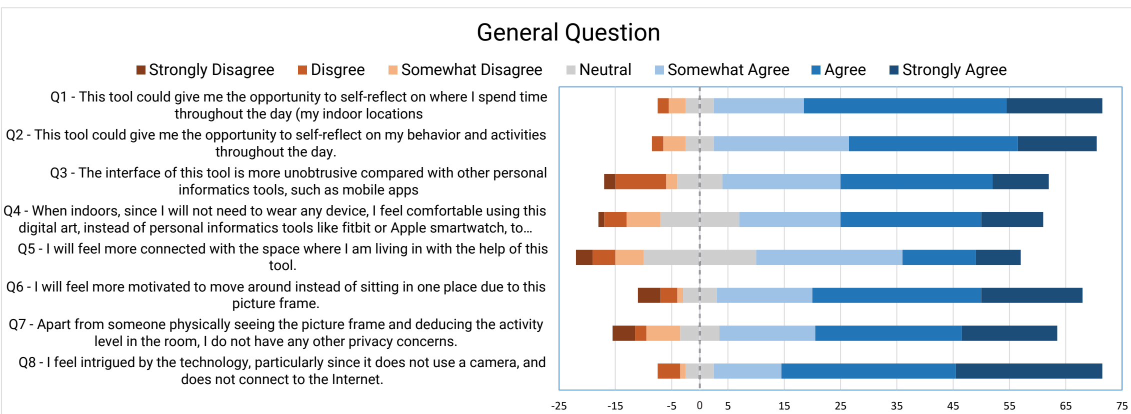

Fig. 9. The results of all general questions of our anonymous online survey (total 79 participants).

time throughout the day, while 86% (mean: 5.49, std dev: 1.16) believe it could give them the opportunity to reflect on **their behavior and activities**. While 82% of the participants agreed that this tool could make them **feel more motivated to move around** instead of being sedentary, only 59% felt Travelogue enabled establishing **a connection with their living space**. The in-person interviews and open ended questions revealed more details. Overall, 11 out of 12 participants believe our system is useful other than providing aesthetic experiences. For example, P1 thinks our system could help him better organize his life, since *"It (our system) has a more direct reflection of my daily activities compared with other (personal informatics) tools"*. Eight out of twelve participants believe Travelogue is good for their health; e.g., P3 mentioned *"Especially during this pandemic, people are working from home and tend to stay at one place for a long time. It will remind me to move around and it is good for my health."*, and P4 mentioned that *"I might put it near my PlayStation. So if I see I am close to this frame for a long period of time, I will realize that I might keep playing games for too long, which is not good."* Nine out of twelve participants also believes that Travelogue can help them better reflect on their living habits. According to P2: *"I think it will help me know my personal habit that I have not noticed before. I guess I*

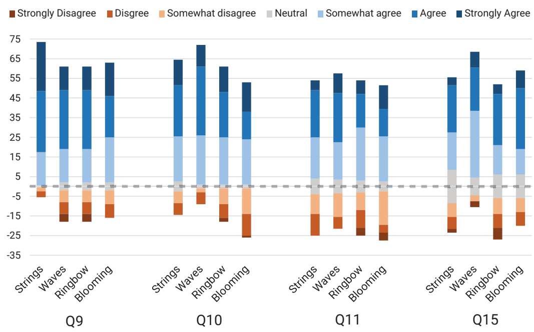

Fig. 10. Results of survey question: Q9, Q10, Q11 and Q15.

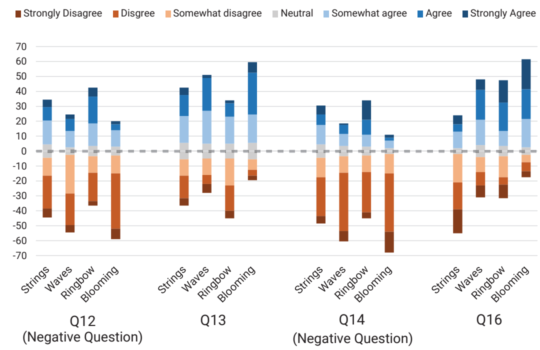

Fig. 11. Results of survey question: Q12, Q13, Q14 and Q16.

might find some locations in my room where I will stay longer but I didn't realize before." P10 also mentioned that he might be able to identify some bad habits by reflecting on his trajectories. P7 also compared our system with her Apple smartwatch, and said, *"If I only use my watch, I will not know where I spend most of my time."*, referring to the added advantage of location and context provided by Travelogue. Even though a sense of connection with our living space is a new concept, P4 mentioned that *"I somehow feel this environment is more interactive than before."* P5 felt a link between herself and her living space through Travelogue and she mentioned, *"My moving path will be kind of interacting with my furniture and my room."* P7 feels being visualized within the context of her environment creates the connection.

In terms of the effectiveness of different art forms (Q9, Q10, Q11), all four art forms were perceived to depict the user's movement well, evident from Figure 10. Inter-art-form comparison is done using one-way ANOVA and if significant difference is noticed, then we will perform a post-hoc pair-wise t-test with Bonferroni correction to understand which pairs are significantly different from others. By performing the above test process on Q9, we found that Strings and Waves are significantly better than Ringbow in providing immediate spatial information about the user's distance/location ($p < 0.0009$, and $p < 0.004$ respectively). This is probably caused by the circular shape and the interference of other colorful representations of environmental reflection shown in Ringbow, as revealed by our interview session. For Q10, participants regarded Waves as significantly better than Blooming on providing historical information about how the user moved over time ($p < 0.002$). And for Q11, we didn't find any significant difference among four designs on depicting the time distribution of user's activity. During the interviews, participants correctly pointed out that Blooming does not have an explicit timeline (hence the lower scores on these dimensions). But some participants do associate Blooming with duration of time spent at a location, like P6 says, *"The aggregation of the line on canvas clearly shows the time (duration) you spend in one location."*

6.2.2 Unobtrusiveness. One of the important requirements of Travelogue is to blend into the environment. 77% (mean: 5.27, std dev: 1.41) of the participants agreed that our system is **more unobtrusive compared with other personal informatics tools, such as mobile apps.** And 87% (mean: 5.81, std dev: 1.27) felt intrigued by Travelogue since it doesn't need any on-body devices and cameras to track the user. During the interviews, P1 thought our system is unobtrusive since it can be integrated into the environment very well, but for mobile apps one would have to check them explicitly. P4 thinks that information is delivered in a smooth and unobtrusive way by integrating information in abstract art forms and it is very comfortable to use. P5 mentioned that this visualization format (abstract art) could make her better accept this kind of technology and give her more sense of beauty. Moreover, all interview participants agree that **being device-free contributes to the sense of unobtrusiveness and is beneficial.** P3, P7 and P11 explicitly mentioned that keep wearing devices like smart watch will make them feel uncomfortable. For example, P7 talked about her experience of wearing a smart watch: *"During the pandemic, I am at my home everyday. Sometimes, I feel it's like an extra work to put on my watch. And also it is not that comfortable wearing it all the time."*

Statistically, our participants found that Blooming is significantly less distracting than Strings and Ringbow ($p < 0.007$ and $p < 0.0001$, respectively). Also, Waves is considered as significantly less distracting than Ringbow ($p < 0.0075$). Blooming is considered significantly more subtle than Strings and Ringbow ($p < 0.002$ and $p < 0.0001$ respectively). Through in-depth interviews, we learned that Strings and Ringbow were considered to be less subtle and more distracting since one has an explicitly changing number and the other one is painted with more bright colors. Four out of twelve interview participants suggested us to get rid of the explicit number on Strings. For example, P7 mentioned that *"Strings seems to be too scientific. I don't like it because it shows the exact meters I am away from the tracker (frame). I will feel a little pressured if I see that I am too far way from it, I will try to keep it (the number) within a certain range."* P5 also mentioned that *"I also think the number makes it distracting. Imagine you have a giant number on it, it will less subtle which is something I don't want to see."* For Ringbow, Six out of twelve participants think the bright colors makes it more distracting and less subtle.

6.2.3 Intuitiveness. All four designs are considered to be intuitive by the majority of the participants. More specifically, Waves scored the highest with 81% of the participants finding it intuitive, while Ringbow scored the lowest at only 58% participants finding it intuitive. Interviews revealed significant disagreement over intuitiveness, and we associate some of it to personal taste. Slightly different from the result of survey study, Blooming was agreed to be intuitive by all twelve participants, which is mainly because that it shows the user's current location in a 2D plane instead of just a relative distance (Strings, Waves, and Ringbow). For Ringbow, four out of twelve participants think it is less intuitive on showing the time information than Strings and Waves, because of its circular shape. However, another three participants (P3, P7 and P11) do like this circular shape more, as P7 mentioned that *"For me, it is more intuitive because I am already used to the clock (like) notion of time. It is also easier for me to tell how much potion (fraction) of time I spend in one location than using a single line."* For Strings, P6 mentioned that the explicit number makes it more intuitive on showing user's current location.

6.2.4 Aesthetic. We also asked the participants to rate how elegant they think the four art forms are. As expected, Strings got the lowest score with the mean of 3.19 (std dev: 1.84). Waves ranked third with the mean of 4.33 (std dev: 1.85), and Ringbow ranked second with the mean of 4.53 (std dev 1.99). Blooming got the highest score with the mean of 5.14 (std dev: 1.75). Here we believe the sense of aesthetic is really subjective and varies a lot among the population, which is also depicted by the high standard deviation of four scores. But we do noticed the trend showing in our survey results that **higher abstract level leaded to a higher aesthetic score.**

In interviews, nine out of twelve participants think Blooming is the most aesthetic pleasing art. For example, P4 mentioned *"I feel very comfortable with seeing this art. Just like its name, it is like blooming flowers."*. P7 said, *"It (Blooming) is very much like an art work."*, and P3 mentioned that *"I am also happy to have it even if it doesn't record my movement."* And similar to our survey results, Strings and Ringbow are considered as less aesthetic pleasing than the other two. More specifically, Strings received complains because it looks too scientific and looks more like traditional charts. Opinion is somewhat divided on the bright colors of Ringbow. Some participants think bright color looks beautiful to them and some participants think vivid colors are distracting. For example, P5 mentioned that *" Those bright colors are more distracting than those black, white and grey colors. Those (black, white, grey) colors make me chill and calm. But vivid colors don't look good to me."*

6.2.5 Miscellaneous. 86% of the participants felt our system is privacy preserving. P3 mentioned that *"I usually don't use any personal informatics tools partly due to privacy concerns. I don't know if they will upload my information or not and I feel unsafe about it. I don't have such concern here, since it doesn't have to be connected with internet."* P7 also believes that the inherent propriety of abstractness makes this tool more privacy-preserving, as she mentioned that *"If you don't explain it (to others), they probably will not understand what those patterns means. And people probably will not notice this to be a health tracker."*

In terms of the amount of information been displayed, 83% of the participants didn't think there was too much information been displayed on Blooming, while for Waves, Ringbow and Strings, 72%, 53%, and 55% respectively thought there was not too much information. Interviews revealed that nine out of twelve participants think the environmental reflection showing the the Strings and Waves are not useful and makes the art looks more distracting and confusing.

7 DISCUSSION, LIMITATIONS, AND FUTURE WORK

Here we will first discuss some insights gained through our study, and then discuss the limitations of our work and how we might solve them in future works.

7.1 What are the potential benefits of understanding indoor trajectories?

Promoting self-reflection is one key functionality of most PI tools. By providing users with different visual representations of their indoor trajectories, we are interested in studying how users perceive this new personal data and what would be the potential benefits. Through our user study with over ninety participants, we are happy to find that most of our participants indeed believe that knowing their indoor trajectories is helpful. More specifically, the utilities can be classified into three main categories: self-understanding, self-motivating, and free-exploration. **Self-understanding:** most participants appreciate that Travelogue can provide a new fine-grained information—trajectory—unavailable today, which may help them better understand their daily routines and living habits, and therefore help better arrange their daily lives. **Self-motivating:** many participants mentioned that by reflecting on their trajectories, they can understand whether they have remained in one spot for too long and therefore need some exercise to keep healthy. A lot of participants mentioned that this is especially useful considering that most people are working from home due to the pandemic. **Free-exploration:** some participants mentioned that their trajectories may help them better arrange their furniture and therefore use their indoor space more wisely. Some participants felt it might be useful to remain aware of the activities of their children and even pets.

7.2 Visualizing Indoor Trajectory

When designing the different informative arts, we had to decide how to represent three specific elements of the data captured: the temporal element, the location or distance element, and the element of environmental reflections. For the temporal element, while all four designs obey the additive strategy that provides both current-time information and historical information, we used different timeline representations: a horizontal timeline, a circular timeline, and no explicit timeline. Our user-survey revealed that the horizontal timeline is, by far, the most intuitive one since it is a common representation of time in everyday life. Several participants also favored Ringbow's circular design, since it moves like a clock arm and therefore is intuitive. The Blooming design's absence of explicit timeline made it the most difficult for users to reflect on the sequence of their activities.

Most participants prefer to see their locations, instead of just distance. The additional information carried by the location is expected to aid in recalling their activity's context. One participant also explicitly mentioned that pure distance will not be very informative for room-scale space. However, pure distance is also helpful in a setting where the

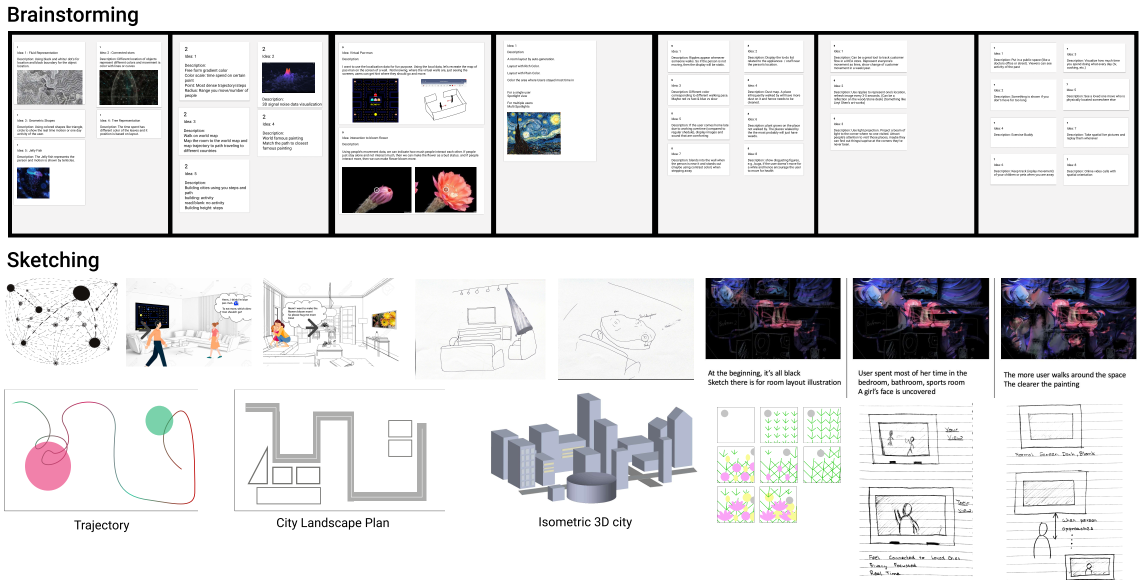

Fig. 12. Outcome of a 7-participant design workshop: new visualization ideas, event triggers, and display styles emerged.

picture frame is collocated with an object of interest. For example, P5 mentioned that he would like to place this frame next to his PlayStation to help him understand how much of his time is spent on gaming.

Lastly, the environmental reflection element adds uniqueness to pictures generated in a particular space. Though several participants mentioned that the decoration built upon it is beautiful (e.g. Ringbow design), most of the participants think adding raw environmental reflection pattern into the design is not useful and even confusing. P12 suggested that environmental reflections can only be useful to him if our system can extract higher level information (e.g. different activities) from them. Weaving environmental information subtly into the main image is left for future work.

7.3 Indoor Trajectory as Novel Design Material

Whereas previous research studying visualization of trajectories exists [31, 32], most of it focuses on large city-scale applications such as traffic intensity or places visited analytics etc. Through this work we have shown the opportunity of using *indoor* trajectory data as a novel design material and we expect its use to expand beyond just enabling self-reflection and calm experiences. To explore such possibilities, we conducted a design workshop[4] with seven students with design background. Our 2-hour long design workshop consisted of four sections: introduction, brainstorming, sketching, and free-discussion. During the brainstorming session, not only were many different visual representations or geometric metaphors for indoor trajectory proposed, but also several inspiring ideas emerged which show the potential of indoor trajectories as a novel design material (see Figure 12). For example, a virtual pac-man idea was proposed by one designer with background in architecture. She proposed that indoor trajectories be utilized to build a seamlessly interactive space by representing the user as a virtual pac-man and his/her living space into the playground. Another designer ideated around creating a 3D city-scape that expands as the user moves around more in the indoor space.

Another designer imagined a dark canvas (on our display) to begin with, and as a user moves around the indoor space, the corresponding parts of the canvas wipe out to reveal an underlying picture. In a similar vein, another designer visualized a farmland that progressively blooms at the spot that the user virtually moves to. Both these ideas essentially

[4] IRB approval details withheld for anonymity.

gamify the Travelogue idea to build a joyful interactive space. A new aspect that emerged from the workshop was to use Travelogue's ambient media for better interpersonal relationships. For example, one participant proposed a virtual flower idea which is built up on the assumption that users' trajectories can reveal their frequency of interaction. More specifically, a flower-bud will gradually blossom as users in the vicinity interact with each other. Some designers were fascinated by the possibility of tracking their children or pets can be a fascinating idea. A futuristic idea of a virtual "mirror" came forth where two picture frames, deployed by loved ones in each other's houses can show each other's indoor movements, thereby creating a feeling of closeness and connection.

Realizing that artists and designers can truly build on top of the basic primitives provided by Travelogue, we have decided to create an API that provides wireless signal information at various levels of abstraction, from raw signals, to distance estimates, to locations, to interactions. We plan to explore this enabling API approach in the future.

7.4 Limitations and Future Work

Possible Improvements to Localization. Travelogue uses only two UWB receivers for location estimation limiting our localization to a 2D space. However, by employing additional UWB receivers and by filtering the obtained CIRs [71, 81], it might be possible to track a target in 3D space, and track more people simultaneously. In Travelogue, localization precision is diluted by our constraint of keeping the UWB receivers inside the picture frame (just 0.5 m apart). We did not measure the monitoring range of our setup in large homes, though theoretically the range is about 200 $feet$.

User Study. Ideally, an evaluation of such a system must be through prolonged experiences of users. Our evaluation lacks significantly in this aspect. Yet, given the current restrictive environment due to COVID-19, where face-to-face meetings and physically deploying Travelogue devices is challenging, we have enabled study participants through detailed explanations and videos of different actions and the corresponding changes to the informative art.

Diverse Indoor Scenarios. Currently we have motivated Travelogue's use only in the home setting. However, Travelogue can also be deployed in more public indoor spaces, such as restaurants, offices, classroom, etc. where richer shared experiences can be enjoyed by people who happen to be in a shared space at a given time. Ironically, during the current COVID-19 pandemic, such an art could be a subtle indicator of how crowded a certain space is.

Privacy Concerns. We are acutely aware of how wireless sensing, with its power to sense beyond traditional privacy barriers such as walls, can be misused. At a minimum, Travelogue will include a "veil switch" that will conceal the informative art from guests or visitors. However, to truly restore privacy in the light of wireless sensing technology would require pervasive changes to barriers, such as by using active phased reflectors on walls or embedding wall with materials that block RF signals. While important, such investigations are beyond the scope of this work.

Ecosystem of digital-art with distance/location as an API. We see a clear opportunity of creating an "app-store" of informative arts which a user can download to their Travelogue digital frames and receive generative art from professional artists, creators, and hobbyists. The Travelogue will provide a simplistic API that includes estimated distance from moving objects in the environment, the interpreted environmental background, as well as the raw CIR for app-developers to create sophisticated algorithms over this platform.

8 CONCLUSION

Travelogue is a self-contained system that uses passive RF sensing to track user's distance or location and visualize their movements in abstract art forms. We showed through our user study that Travelogue can promote better self-awareness of user's indoor behavior, be a motivator, and a resource for further self-exploration, while remaining unobtrusive and privacy-preserving. Of course, considerable work remains to be done in this space, but we expect Travelogue to be an enabler in that direction; one that inspires creators to innovate further on this platform.

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