Travelogue: Representing Indoor Trajectories as Informative Art

Yunzhi Li
Carnegie Mellon University
Pittsburgh, USA
yunzhil@cs.cmu.edu

Tingyu Cheng
Georgia Institute of Technology
Atlanta, USA
tcheng32@gatech.edu

Ashutosh Dhekne
Georgia Institute of Technology
Atlanta, USA
dhekne@gatech.edu

ABSTRACT

In this work, we explore if informative art can represent a user's indoor trajectory and promote user's self-reflection, creating a new type of interactive space. 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 in a device free manner. 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 preliminary user study with 12 participants shows most users found Travelogue intuitive, unobtrusive, and aesthetically pleasing, as well as a desired tool for self-reflection on indoor activity.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

KEYWORDS

wireless sensing, informative art, personal informatics

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1 INTRODUCTION

A vast majority of our time is spent indoors [29]. Remaining active indoors, which includes short walks around the house, and taking frequent breaks from TV and computer screens, is important for our health [4, 42]. Individuals show varying levels of enthusiasm in indoor activities, and this motivation also varies over time. Irrespective of an individual's motivation level, an ability to self-reflect over one's activities, observe healthy habits forming over time and unhealthy ones fade away, could make indoor spaces a rich avenue for personal informatics. However, providing such a tracking ability is technically challenging : (1) GPS does not work indoors making it very difficult to map movements in indoor spaces [1]. (2) Many people typically do not wear activity trackers indoors, making it difficult to directly track or infer activity. Therefore traditional personal informatics tools such as FitBit, Apple Watch, etc. are of limited value indoors. Furthermore, the indoor space is relatively static, meaning, there is nothing new to look at, lowering the need and motivation to go on short indoor walks. In this work, we ask the question: *is it possible to monitor human activity in an indoor space without requiring any wearable gadgets and present it in a manner that inherently motivates people to move around?*

Enabling wearable-free monitoring is possible by capturing the disturbances to radio frequency signals caused by human presence (we call it wireless sensing). In indoor spaces, analyzing these disturbances can help *locate and track* occupants, thereby overcoming the challenges of mapping without wearable devices and without GPS. Wireless signals penetrate through walls and other indoor obstructions [14], thus covering large spaces, and evade privacy concerns that prevent the use of cameras in private spaces. Therefore, wireless sensing is an appropriate modality for tracking people's whereabouts indoors [34]. However, motivating people to be active in an indoor space still remains a challenge. Most activity trackers today present information visually through appealing graphs. Though sometimes effective, many researchers have pointed out that traditional visualization techniques cannot be directly adopted to non-work environments due to their complexity [36, 41]. We plan to address this challenge from a completely different perspective—motivating through informative art. The movements of the user will lead to the dynamic creation of digital art. If the user is not active, the digital art will be dull and uninteresting, while the user's movements will spruce up the digital art. In some sense, the user's movements are the brush that paints the art, thus creating an intrinsic motivation for users to move around. The generated graphics changes over time based on the movements and trajectories of the user, thereby constantly creating something new, introducing an element of curiosity and change, in the otherwise static indoor space. Combining both the wireless sensing and the digital art display into a single device deployed in the indoor space leads to our digital picture frame system called Travelogue, illustrated in Fig. 1(a).

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. Our contributions are:

(1) A new form of ambient personal informatics tool that captures indoor movement information, without requiring the user to wear any device.
(2) A new interface to convert wireless signatures of a space, its disturbances due to human presence, and the user's location, into informative art.
(3) An interview study with 12 participants revealing the novel utility and validating the user experiences made possible by our system.

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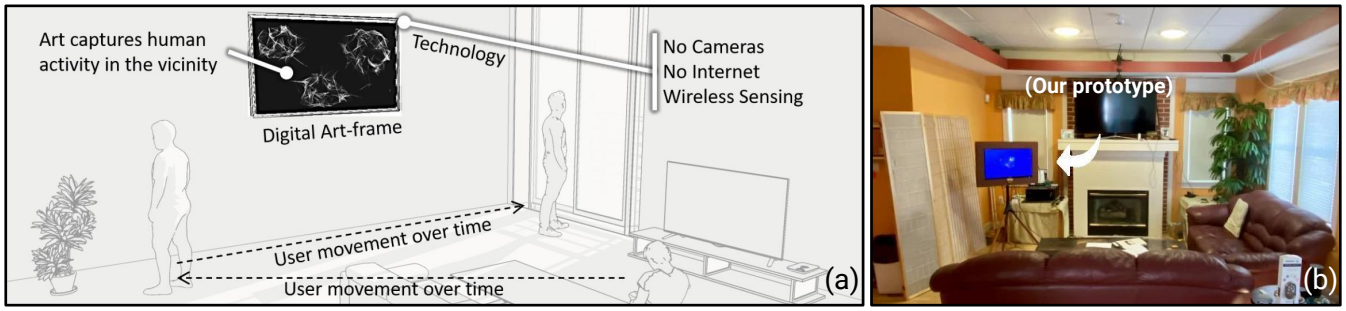

Figure 1: (a) Travelogue is a digital-art picture frame that generates modern-art images based on human activity in its vicinity. We explore if Travelogue can replace personal informatics tools in indoor environments providing freedom from having to wear or carry a device. (b) Our finished prototype in a real home-like environment. (Our evaluation is based on users watching videos of an earlier prototype due to COVID-19 restrictions)

Travelogue currently renders four kinds of informative art utilizing the primitives available from wireless sensing. This includes depicting the user's distance or location with respect to the digital art frame, and depicting the room's overall wireless signature in different ways. This demonstrates the flexibility of our software interface. The 4 rendered art forms were used as probes for exploring how people perceive our system and might reflect on their own indoor movement. Our user study with 12 interview participants shows that people are interested in their indoor movement data as a source for self-reflection and Travelogue was deemed an unobtrusive, non-distracting, and aesthetically pleasing tool to inform users of their indoor traits.

We now briefly describe the related work, followed by a description of Travelogue's wireless sensing system. Then we describe in detail the design strategy, implementation details, and the findings from our user study. We end with discussing the limitations and future works.

2 RELATED WORKS

2.1 Visualization for Personal Informatics

Personal Informatics (PI) is a class of applications that collects personally relevant physical, psychological, and behavioral data to help people reflect on their behavior and habits, or track their health [31]. Main stream data visualization for PI tools is accomplished through a combination of traditional charts, maps and dashboards (e.g. Fitbit, Basis, Jawbone Up). Apart from that, several other feedback schemes have also been explored by previous works. For example, avatar-based feedback employs a virtual object to represent user's personal information, such as *Fish'n'Steps* [33] using a virtual fish to reflect step counts and *UbiFit Garden* [11] represents fitness activity as a digital garden. Tangible representations such as 3D printed materials [26] or foods [25, 27] have also been proposed and evaluated by researchers. Other than that, a few previous studies demonstrated that informative art can be another appropriate way of visualizing personal information. *Informative Art* [5, 40] refers to a way of visualizing dynamically updated information in artistic styles that does not provide exact information, but only a sense of perception. Rodgers et al. [41] utilized different artistic visualization to inform users on their energy usage. Probably closest to Travelogue is *Spark* [16], which uses abstract geometric art to visualize people's steps collected from Fitbit. However, Travelogue is different from previous systems in the following ways: (1) Travelogue is an integrated data capture and visualization platform that does not depend on external data collection; (2) to the best of our knowledge, Travelogue is the first system that combines informative art with human indoor trajectories.

2.2 Radio Frequency Based Device-Free Localization

Recently, there is growing interest in exploring radio frequency (RF) for device-free localization. Compared with camera, infrared-based [35, 47, 48] and acoustic-based solutions [8, 19], 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 [43, 44, 46, 49]. 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 by a number of systems using dedicated specialized equipment for device-free localization, such as Wi-Vi [3], WiDeo [24], Witrack [2], and Marko [20]. However, susceptibility to multi-path fading and low temporal resolution make it hard to develop accurate Wi-Fi based tracking system. Ultra-wideband radios (UWB) are a promising technology for device-free localization due to its wide bandwidth and superior time resolution. Most of the prior work on UWB is either device oriented [6, 7, 14, 15, 17], or the device-free localization is based on commercial-grade custom-built radar hardware [18, 21, 32, 50]. In contrast we adopt simple architectural modifications and a recently published CIR filtering algorithm [30] to achieve device-free localization using off-the-shelf components.

3 TRAVELOGUE'S SENSING CAPABILITIES

Travelogue employs wireless ultra-wideband signals to observe the environment and exposes its inferences through a software interface. These technical capabilities form Travelogue's sensing aspects, which in turn make the presentation through digital art possible.

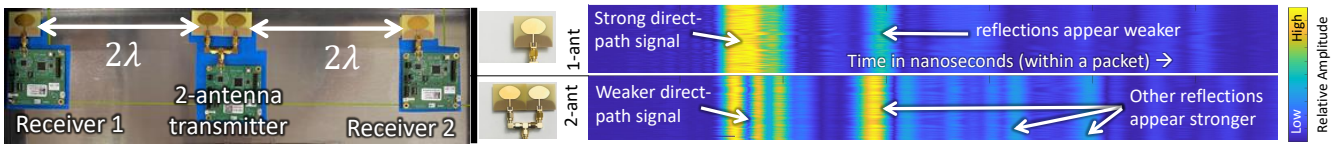

Figure 2: (a) Travelogue uses a 2-antenna transmitter with two single-antenna receivers in a straight line. (b) This setup attenuates the transmitter's direct signal while amplifying environmental reflections.

3.1 Wireless Sensing Mechanism

At its core, Travelogue creates a small-scale wireless radar system with a transmitter sending out ultra-wideband (UWB) wireless signals in the environment and two receivers capturing reflections of this signal from slightly different locations. By comparing the reflections obtained by the two receivers and using the observation that static objects produce stable reflections while humans produce quivering reflections, Travelogue deduces the user's location. We make special modifications to the transmitter, using a two-antenna setup, to severely reduce the power of the direct transmitter-receiver signal. Fig. 2 (a) shows our hardware setup which is stationed within Travelogue's enclosure. The comparison between the received reflection patterns using a single antenna transmitter and a two-antenna transmitter is shown in Fig. 2 (b). The reflection pattern is known as the channel impulse response (CIR).

Travelogue performs on-device computation of the CIR and separates the room's response from the effect of human movements. Inferences from this system are made available through Travelogue's software interface, which we describe next.

3.2 Software Interface

Travelogue's software interface provides a unified platform that aggregates the inferences made by the wireless sensing mechanism. This includes the current and historic reflections obtained from the environment, the user's estimated location and distance from the digital frame. We expect art designers to be able to use this interface to produce innovative art designs, which will feed into a generic rendering engine based on the Processing visual art framework [39]. Finally, the rendered image is presented on Travelogue's integrated display. As a demonstration for the capabilities of this software interface, and to evaluate the overall effectiveness of Travelogue platform, we have designed several art forms.

Figure 3: The software interface exposed by Travelogue provides a unified framework for a designer's art module to create custom visualizations.

4 TRAVELOGUE'S PRESENTATION SYSTEM

Travelogue is created with indoor spaces in mind. The visualizations take a dual role as a personal informatics tool and a visual motivator. Based on these goals we now discuss the design considerations informing our sample art forms. We conducted an informal discussion workshop with design students where more art ideas were envisioned. We expect to open up Travelogue's interface allowing users to download creative artists' ideas in the future.

4.1 Travelogue's Overall Design Considerations

We follow four design strategies for self-reflection and behavior change proposed by previous work [23], which are suitable for Travelogue.

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 and instead only presents the most pertinent information through geometric shapes, different colors, or spatial relationships of visual elements. Displayed graphics can persist for a significant time building up history which facilitates personal reflection.

Public. By the very nature of converting a person's indoor activities into art, we are making public some information about the user. Our design should present personal data in a manner that the user is comfortable sharing. Since we use geometric abstract art forms to visualize personal data captured without using cameras, the art-form masks direct interpretations for a stranger.

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 addition, all displayed abstract art forms are designed to change subtly through time, as described with more details in the following section.

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. The visual design of the different abstract art forms of our system have been aesthetically appreciated by most participants of our user study.

4.2 Demonstrative Art Designs

We now discuss the four art forms that we have designed as probes for our preliminary user study. Each art form embodies a slightly different design or visual aspect from the design dimensions we discussed above. 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.

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

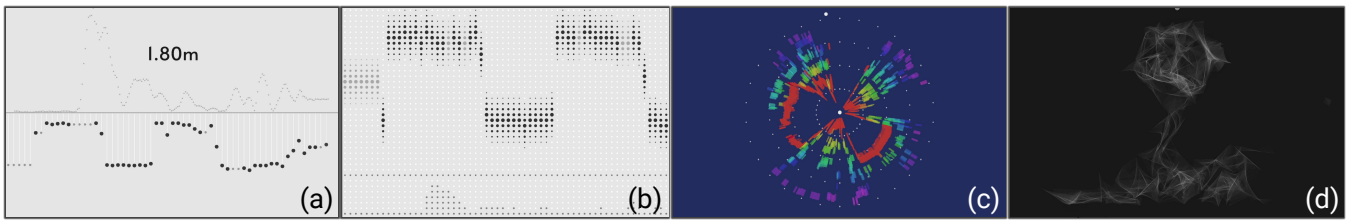

Figure 4: (a) User's distance from the picture frame is captured by the length of the hanging strings. (b) Waves depict the user's distance. (c) Circular sweep depicts time, while radial distance captures the user's distance. (d) Line-art continuously generates showing the user's location in 2-dimensions.

motivation behind the "Strings" art-form (see Fig. 4(a)). The visualization is divided into two parts. The top part is influenced by the reflections from the environment, 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. A numerical value showing the user's distance in meters maps this visualization to familiar aspects of current personal informatics tools. Over time, new hanging strings fade-in (no sudden changes) filling up the bottom part of the visualization from left to right, cycling back to the left side every 5 minutes.

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 [28] has inspired the "waves" art-form shown in Fig. 4(b). The top area captures the user's distance from the picture-frame shown by a wave of dark dots. The wave travels from left to right and then cycles back and its peak indicates the user's distance from the frame, without a direct numerical representation. Below the center-line is a rendition of the environmental reflections.

4.2.3 Ringbow. Rotational motion is a classic epitome of passage of time, and orbits in such circular motion embody distance. This is the inspiration for the "Ringbow" art-form in Fig. 4(c). The user and other reflectors in the environment form rings of colored patterns which sweep around the frame's center over time. 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.

4.2.4 Blooming. Inspired by Casey Reas's generative art work *Process 6* [38], we designed "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 Fig. 4(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 are painted over old ones and the canvas is not flushed, and therefore the density of geometric lines will help the user reflect on their time in this space.

4.3 Beyond our Designs for Informative Art

To further explore the opportunity of using *indoor* trajectory data as a novel design material, we conducted a informal design workshop with seven graduate students with design background. During the 2-hour long workshop, 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. For example, a virtual pac-man idea was 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 futuristic idea of a virtual "mirror" also 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. These ideas demonstrate that a rich design space around a person's indoor trajectory including gamification and interpersonal relationships is possible.

5 IMPLEMENTATION AND TECHNICAL PERFORMANCE

5.1 Proof-of-concept Implementation

Our Travelogue proof-of-concept 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. An aluminum sheet makes the picture-frame's back-cover and all devices were mounted onto the aluminum sheet; Fig. 5(a) shows the internal layout. We use three off-the-shelf Decawave TREK1000 UWB radio modules [12] in our prototype. Central module with two parallel antennas serves as the transmitter (half-wavelength apart for destructive interference) and the other two single-antenna UWB devices serve as the receivers, all using UWB signals at 4 GHz center frequency. A Raspberry Pi 3B+ single-board computer (1.4 GHz Cortex-A53 with 1 GB RAM), running Raspbian OS, is used 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 [37, 39]. The resulting art-forms are shown on the central $10.1''$ 1280×800 TFT display.

Figure 5: (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.

5.2 Distance Estimation and Localization Accuracy

Fig. 5(c) shows our testbed used for evaluating Travelogue's distance and location measurement accuracy. For ground truth, markers were placed 1 meter apart in a $5 \times 3\ m$ room, creating a grid. The picture frame hangs at a height of $1.3\ m$. Ground truth distances are measured using a laser ranger (with $1\ mm$ precision). 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 $20\ Hz$. We obtain the distance and location estimates; median errors of 0.07m and 0.9m respectively (see Fig. 5(d)).

6 USER STUDY

To help us better understand Travelogue's overall user experience, as well as how users might utilize and reflect on their indoor trajectory, we conducted a preliminary user study with 12 participants (6 males and 6 females, aged between 18 and 39) using semi-structured interviews (online via Bluejeans). Participants were recruited via digital flyers and word of mouth. The study lasted approximately one hour and the participants were paid $10. The entire recruitment and study procedure was approved by Georgia Tech's institutional review board (IRB). More specifically, the participants were first shown a short introduction video describing Travelogue. Then, a video recording of a person walking around different parts of a room, juxtaposed with real-time renderings of different informative arts, was played. Only one informative art was shown at a time with the order being randomized to avoid order-bias [13]. 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; Fig. 6 shows stills from the videos. After all videos are shown, we conducted a semi-structured interview with each participant around the usefulness, unobtrusiveness, intuitiveness, and aesthetics of our system. All interview recordings were transcribed and analyzed around the above design considerations.

6.1 Results

6.1.1 Usefulness. Based on the interviews, we learned that users perceive Travelogue's utility ranging from use as a replacement to personal informatics tools, as a motivator, to even as an encalming device. 8 out of 12 participants believe **Travelogue is good for their health as a motivator**; 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."* 9 out of 12 participants also believe 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 might find some locations in my room where I will stay longer but I didn't realize before."* P7 also compared our system with her Apple Watch, 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. Some participants felt that **Travelogue could help establishing a connection with their living space**. 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."*

6.1.2 Unobtrusiveness. Similar to many existing work on seamlessly augmenting sensing capabilities on everyday surfaces [9, 10], we believe one important requirement of Travelogue is to blend into the environment. All interview participants agree that **Travelogue is more unobtrusive compared with other personal informatics tools, such as mobile apps**. P1 thought our system is unobtrusive since it can be integrated into the environment very well, without needing to explicitly check it. P4 thinks that information is delivered in a smooth and unobtrusive way by integrating information in abstract art forms. 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 they feel uncomfortable with constantly wearing devices. 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."* Through interviews, we also 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

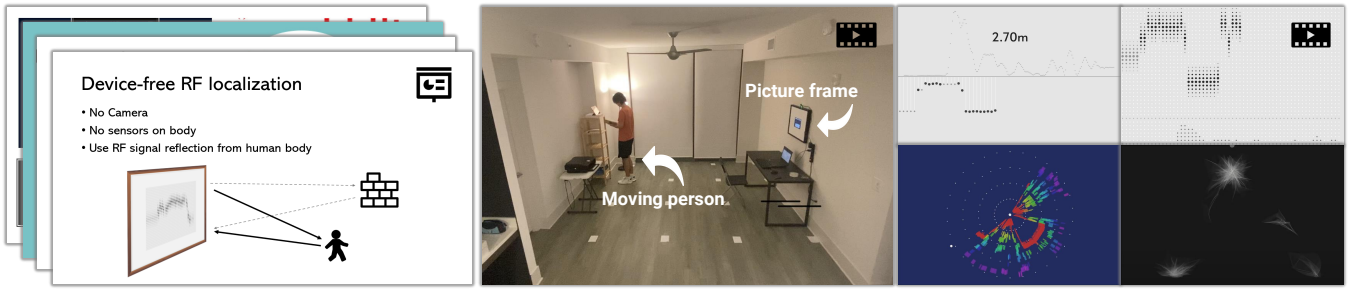

Figure 6: Study procedure: the participant are first shown an introduction presentation, followed by a video of a person moving to different spots in a room, with the evolving informative arts rendered alongside.

bright colors. 4 out of 12 interview participants suggested us to get rid of the explicit number on Strings. For example, P7 mentioned that *"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."*

6.1.3 Intuitiveness and Asethetics. In terms of intuitiveness, Blooming was agreed to be intuitive by all 12 participants, which is mainly because it shows the user's current 2D location instead of just a relative distance. For Ringbow, 4 out of 12 participants think it is less intuitive on showing the time information than Strings and Waves, because of its circular shape. However, another 3 participants (P3, P7 and P11) do like this circular shape more, since it can be related to circular clocks. 9 out of 12 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."* We also found that 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."*

6.1.4 Miscellaneous. Most of the participants agreed that 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."*

7 TRAVELOGUE'S CURRENT 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 [45, 50], 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 100 $feet$.

User Study. Ideally, an evaluation of such a system would require inferences from prolonged user experiences, and our evaluation lacks significantly in this aspect. However, we have enabled study participants through detailed explanations and videos of different actions and the corresponding changes to the informative art as it could provide a complete overview of all four demonstrative art designs and the physical actions that generate those arts. We are planning to ship our newer, larger prototype (as shown in Fig 1(b)) to people's home or host it in a home-like environment for a real-world user evaluation. And we expect new user experience and utilities to be discovered after the real-world deployment.

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 [22]. We expect art designers to build over our software interface creating more interesting art forms in the future.

8 CONCLUSION

Travelogue is a self-contained sensor and visualization system that track user's distance or location and visualizes 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 self-reflection, 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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