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SmartBFA: A Passive Crowdsourcing System for Point-to-Point Barrier-Free Access

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***Abstract*—At the Bloomberg Live 'Sooner Than You Think' forum [1] held in Singapore in 2018, nearly 75% of delegates picked *inclusiveness* to be the key measure of success for a smart city. An inclusive smart city is a citizen-centered approach that extends the experiences provided by smart city solutions to all citizens, including seniors and persons with disabilities (PwDs).**

Despite existing regulations on barrier-free accessibility for buildings and public infrastructure, pedestrian infrastructure is generally still inaccessible to PwDs in many parts of the world. In this paper, we present SmartBFA (Smart Mobility and Accessibility for Barrier Free Access) - a publicly-funded initiative in Singapore that aims to design a scalable and sustainable system that can collect, classify and determine accessible point-to-point routes to address interconnection gaps in first and last mile BFA paths for persons requiring barrier-free access (such as wheelchair users and seniors with mobility aids).

In SmartBFA, point-to-point accessibility information is passively crowdsourced from IoT devices that are retrofitted on the wheelchairs of participants, as they go about their daily commute. We share preliminary findings from data acquired from 68 wheelchair participants between May 2018 to Mar 2019, spanning across 23,000 hrs and 40,000 km of traveled paths. We compare travel patterns of participants with varying wheelchair types, as well as demonstrate the feasibility and scalability of such a crowdsourced approach for acquiring accessibility data.

I. Introduction

In Singapore, there is a palpable government-led movement towards *inclusiveness* for the less-privileged, seniors and less-abled in our midst. While the narrative has been particularly strong for seniors, more can still be done to allow Persons-with-Disabilities (PwDs) and other Barrier-Free Access (BFA) users - such as seniors with mobility aids and parents with push prams - to live, work and play in Singapore, in an increasingly-fair, inclusive and dignified manner.

According to a study by the National Council of Social Services (NCSS), 7 out of 10 PwDs desire greater levels of independence [2]. In addition, choices and experiences at work or school are influenced by the availability of accessible and affordable transportation [3]. The accessibility and inclusiveness of public spaces are therefore pertinent in empowering the independence of PwDs and their participation levels in social, community, family and economic activities.

Despite existing regulations on barrier-free accessibility for buildings and public infrastructure [4][5], pedestrian infrastructure is generally still inaccessible to wheelchair users in many parts of the world [6][7]. In particular, barrier-free inaccessibility is exacerbated at interconnections between establishments (such as buildings or transport hubs), due to the lack of clear division of responsibilities in implementing accessibility provisions by different public and private entities. For instance, a wheelchair user in Singapore may take up to 30 minutes for a last mile journey from an underground train station to a building above-ground, in contrast to an able-bodied person who may require only 2 minutes [8].

In the literature, there are several attempts to map accessibility information for the public good. AllGoEasy [9], AXS Map [10], Google Maps [11], Wheelmap [12] and Wheelroute [13] rely primarily on actively crowdsourced user annotations to identify accessible points of interests. SPACES [14] and Project Sidewalk [15] solicit active contributions from online users who *virtually* walk through Google Street View to perform remote accessibility audits by identifying street-level accessibility issues such as curbs, ramps, obstacles and surface problems. However, these active crowdsourcing approaches generally suffer from data sparsity and user fatigue. While efforts such as [16] and mPass [17] leverage sensors that are installed on wheelchairs to passively crowdsource accessibility data, and are most similar to our work, these are often controlled experiments that demonstrate proof-of-concept rather than deployment at scale.

In this paper, we introduce **SmartBFA** (Smart Mobility and Accessibility for Barrier-Free Access), which aims to design a scalable and sustainable system that can collect, classify and determine accessible point-to-point routes. SmartBFA specifically addresses interconnection gaps in first and last mile BFA paths, including building-to-building, building-to-transportation hub and hub-to-hub routes. The system relies primarily on data acquired from Internet of Things (IoT) devices that are retrofitted on the wheelchairs of participants, as they go about their daily commute. The passive crowdsourcing approach adopted in SmartBFA overcomes the issue of user fatigue while maintaining contextual authenticity, and sets SmartBFA apart from existing efforts that depend primarily on active user contributions.

The contributions of this work are as follows:

- SmartBFA is a scalable and large-scale system that enables the collection of point-to-point barrier-free access routes through passive crowdsourcing. This *ongoing* initiative has collected data from more than 68 wheelchair participants since May 2018, spanning across more than 23,000 hrs and 40,000 km of traveled paths.

- We compare travel patterns of participants with varying wheelchair types (manual vs motorized), as well as demonstrate the feasibility and scalability of such a crowdsourced approach for acquiring accessibility data.
- Through validations along our test route in downtown Singapore, we show that our system can differentiate between varying pedestrian path surface conditions - such as smooth or cobbled pathways and steep descents.

The rest of this paper is organized as follows: Section II describes similar initiatives on crowdsourced barrier-free route accessibility for wheelchair users. We present the study methodology and system design of SmartBFA in Section III. Preliminary findings from our pilot deployment with 68 wheelchair participants are detailed in Section IV. Challenges and limitations of SmartBFA from both operational and technical perspectives are discussed in Section V. We conclude with directions for future work in Section VI.

II. Related Work

In recent years, there have been laudable public and private efforts towards building *inclusive* societies. The availability of point-to-point barrier-free access is critical in empowering PwDs with independence, and improving quality of life. However, incumbent mapping tools such as Google Maps and Waze have limited provisions for barrier-free access. While there are government-led initiatives to map out BFA paths, these are often manpower-intensive, costly, as well as lack data recency and contextual authenticity. As such, *crowdsourcing* - whereby the public can contribute information relevant to a given cause - has emerged as a popular approach to determine barrier-free accessibility.

A. Active Crowdsourcing

Active crowdsourcing initiatives such as AllGoEasy [9], AXS Map [10], Wheelmap [12] and Wheelroute [13] rely primarily on user annotations on amenities (such as elevators, entrances, parking lots and restrooms) to identify accessible points of interests (PoIs). However, these initiatives are often unsustainable as they are susceptible to user fatigue and data sparsity [18], and may lack contextual authenticity if the annotations are contributed by able-bodied users. In addition, they focus on the accessibility of PoIs (such as shopping malls and establishments), and do not provide accessible navigation instructions. Although Google Maps [11] has started providing accessible routing, these are collaborative efforts with transit agencies and currently available in only six cities worldwide.

In contrast to the above-mentioned approaches that crowdsource annotations of location accessibility, SPACES [14] and Project Sidewalk [15] are active crowdsourcing initiatives that solicit contributions of virtual audits using streetside imagery. Users identify and label street-level accessibility issues such as curbs, ramps, obstacles and surface problems, as they *virtually* walk through Google Street View. While such approaches are more cost-effective and scalable, they are susceptible to issues such as poor data quality and data recency.

B. Passive Crowdsourcing

In passive crowdsourcing, users voluntarily contribute data without responding to explicit requests and may not be consciously aware that they are participating in a crowdsourced system [19]. Google Maps is a classical and successful exemplification of passive crowdsourcing, whereby real-time traffic conditions are derived from location data that is acquired from the large number of commuters who use the mobile-based Google Maps on a daily basis [20].

The use of sensors to passively crowdsource data is known as *participatory sensing* and is well-studied in the literature for several applications. In Pothole Patrol [21], a small number of taxis are equipped with vibration and GPS sensors to identify potholes and other severe road surface conditions. BikeNet [22] provides quantitative guidance to cyclists on pollution levels and terrain conditions of bicycling routes, through multi-modal sensors that are installed on bicycles.

Prior participatory sensing initiatives to crowdsource accessibility information include [16] and mPass [17], which leverage sensors that are installed on wheelchairs for passive data acquisition. These sensors collect accelerometer readings that can estimate conditions/roughness of the ground surface and/or detect obstacles such as steps and slopes. However, these prior work are limited to small-scale experiments that demonstrate proof-of-concept rather than deployment at scale.

Briometrix [23] provides wheelchair accessibility information (such as surface conditions, gradients and kerb sides) using wheelchairs that are equipped with inertial navigation systems, cameras, Lidar and image recognition. Similarly, WheelieMap [24] instruments wheelchairs with devices that can capture both sensor readings and videos, in order to identify accessibility issues. However, users may have privacy concerns over the use of such image/video based sensors, which are often viewed to be intrusive.

Our proposed SmartBFA initiative adopts a similar participatory sensing approach to passively crowdsource accessibility information from wheelchair users, as they go about their daily commute. We aim to achieve nationwide coverage in point-to-point barrier-free accessibility mapping and navigation, through public-private-people partnerships. Furthermore, we place significant emphasis on the scalability, replicability and sustainability of the system, with the vision that SmartBFA can be used globally, to map and provide BFA paths.

III. SmartBFA: Methodology and System Design

A. Project Objectives

The three high-level project objectives of SmartBFA are:

1) Establish a scalable, replicable, quantifiable and algorithmic methodology for long-term, sustainable data collection of barrier-free access (BFA) paths.
2) Construct an up-to-date route advisory and navigational platform for wheelchair-accessible paths (for first and last mile accessibility, to and from transportation hubs).
3) Gather and integrate public transport accessibility information into a one-stop-portal to complement barrier-free accessible paths.

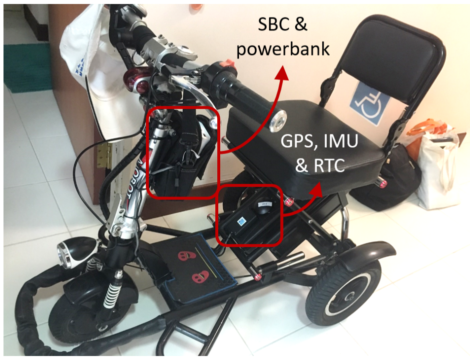


Fig. 1: The IoT device that is mounted on the motorized wheelchair of an actual participant. The device comprises GPS, IMU, RTC, single-board computer (SBC) and power bank.

To alleviate the issue of user fatigue that often plagues active crowdsourcing approaches, SmartBFA passively acquires barrier-free accessibility information through Internet-of-Things (IoT) devices that are retrofitted onto the wheelchairs of participants (see Figure 1).

B. Study Methodology

Participants are recruited through various mediums, such as the SmartBFA website at https://smartbfa.com, social media, word-of-mouth and social service organizations that are directly involved with disability groups. Based on the inclusion criteria, participants must be wheelchair users who can provide informed consent and make at least 3 out-of-home trips on their wheelchairs each week.

Most commuters (both able-bodied and PwDs) tend to have regular travel patterns, especially during weekdays (e.g., from home to office/school and vice versa). Hence, each participant remains in the study for one *run* - which is defined by a continuous period of 8 weeks. This allows for maximization of spatial data coverage through the reuse of IoT devices across participants of different runs, while maintaining sufficient levels of data fidelity.

The IoT device is mounted on a fixed location on the wheelchair that is non-obstructive for the participant; the mounting location may vary slightly depending on the wheelchair model. The device can be powered on for approximately 22 consecutive hours by a 20,000 mAh portable power bank. Participants are advised to: (i) power on the device using the power bank only when they are outdoors; and (ii) charge the power bank on a daily basis. As a token of appreciation, a small-value gift voucher of SGD10 ($\approx$ USD7.30) is provided to each participant for each week of data collection.

As the participant goes about his/her daily commute, time-and-location-tagged sensor data of the traversed paths are automatically acquired and cached in the IoT device, without the need for any user interaction. The sensor data, together with other system monitoring metadata, are seamlessly transmitted to the backend servers whenever pre-configured WiFi connectivity is detected by the IoT device - such as at home, school or office.

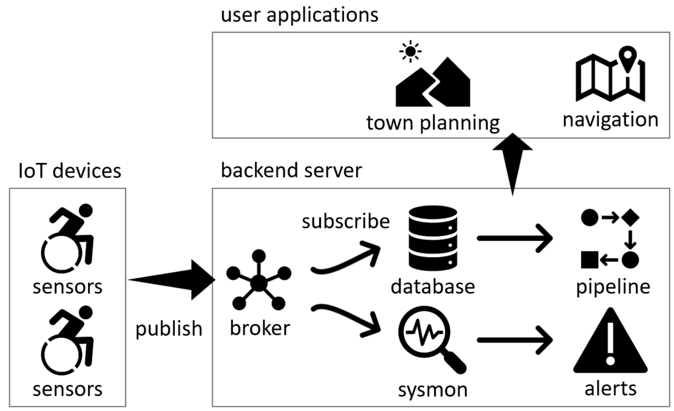


Fig. 2: Simplified SmartBFA system architecture

While the same IoT device can be installed on bicycles and personal mobility devices (PMDs), we focus on wheelchairs as able-bodied cyclists and PMD users are generally able to circumvent inaccessibility (e.g., steps, steep slopes and bumps) by dismounting to push their bicycles or PMDs as necessary - which will introduce noisy data into our system.

In addition to sensor data, surveys are conducted with the participants to gather demographic data, travel patterns, as well as self-reported ratings on participation levels and opportunities in different aspects of their lives. All study procedures and protocols are approved by SMU's Institutional Review Board IRB-17-176-A025.

C. Overview of System Architecture

The simplified SmartBFA system architecture is illustrated in Figure 2 and comprises three main subsystems:

- IoT frontend, whereby IoT devices that are retrofitted on wheelchairs collect timestamped sensor data;
- cloud-based backend server that hosts the web-based REST framework, persistent database storage, system monitoring (sysmon) tools and data pipeline process; and
- client-facing applications, such as interfaces for town planning and accessible navigation.

Each IoT device comprises a Raspberry Pi 3B+ as the single-board computer (SBC), GlobalSat BU-353S4 USB GPS receiver, Adafruit LSM9DS1 Inertial Measurement Unit (IMU), Adafruit DS3231 Real-Time Clock (RTC) and portable power bank. The IMU provides accelerometer and gyroscope readings, which are used to measure the angle and minute differences in vibrations that are experienced by the wheelchair as it traverses across pedestrian paths with varying surface conditions. The readings from the GPS and IMU are captured at frequencies of 1 Hz and 200 Hz respectively, and cached on the SBC. The cached data is opportunistically published to the backend server via MQTT [25] - a lightweight publish-subscribe messaging paradigm - whenever pre-configured WiFi connectivity is detected by the SBC.

A Django-based REST framework that resides on the cloud-based backend server provides unified Application Programming Interfaces (APIs) to the PostgreSQL database and various

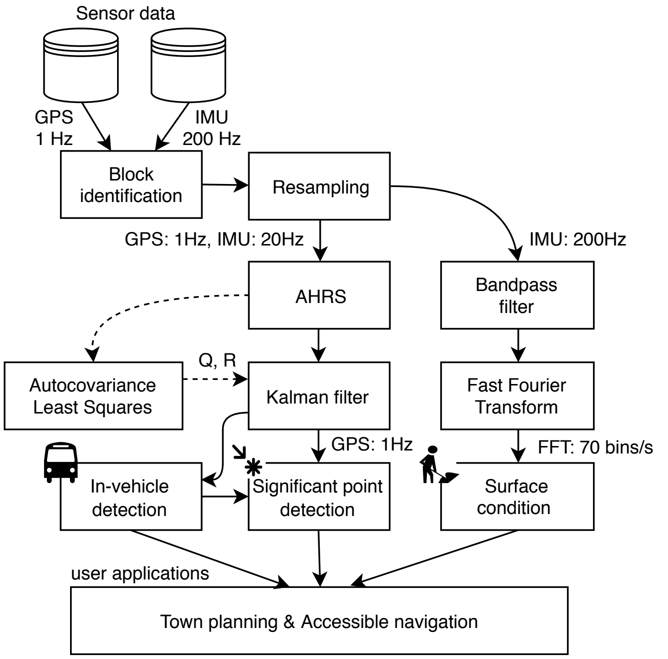


Fig. 3: Overall data pipeline process. AHRS is the acronym for Attitude and Heading Reference System.

client-facing user applications - such as that for town planning and accessible navigation.

Figure 3 provides an overview of the data pipeline process in SmartBFA. As first and last mile pedestrian paths typically comprise trips in continuous time blocks, the Block Identification module first consolidates the raw sensor data into contiguous data blocks based on timestamps, before they are resampled and synchronized.

As Singapore is a dense urban area with many sheltered walkways and high-rise buildings, the location accuracy of each GPS reading has to be improved through fusion with the IMU data. However, the heterogenity of participant wheelchair models makes it impractical to standardize the IMU mounting location and orientation. Hence, we leverage clever computation [26] to resolve IMU data into the reference north-east-down (NED) frame - which is also known as Attitude and Heading Reference System (AHRS). The NED-referenced IMU data, together with the GPS data, are parsed through the Autocovariance Least Squares (ALS) method [27] for Kalman filter [28] tuning, resulting in more accurate position and velocity data (that can be used for in-vehicle detection).

The in-vehicle detection module leverages velocity data to identify first and last mile segments. These are then spatially compressed by the significant point detection module for path creation and map update [29]. The surface condition analysis module attempts to detect and classify inaccessible features on pedestrian infrastructure. While uneven paths (e.g., cobbled streets, tactile paving, road bumps, steps and ramps) may pose little or no hindrance for able-bodied people, they can cause discomfort and even exacerbate spinal injury to wheelchair users over time. Hence, wheelchair users should be routed on

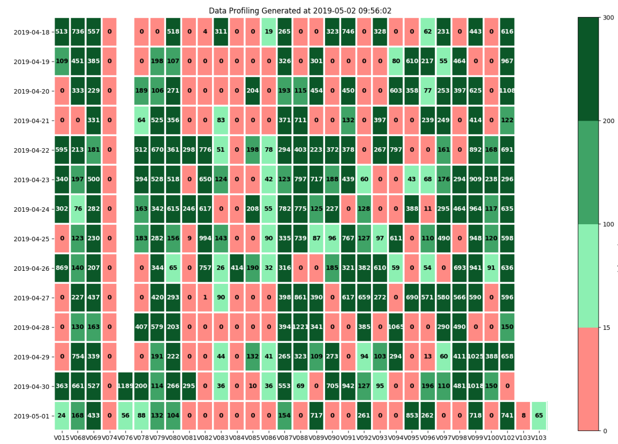


Fig. 4: A daily Slack [30] report shows the amount of data (in minutes) contributed by each participant for the last 14 days.

more *accessible* paths, akin to motorists being guided to less congested roads and motorways.

D. Robust Data Collection through System Monitoring

Unlike other pilot initiatives that conduct controlled experiments, the IoT devices in SmartBFA are deployed with actual wheelchair participants across a period of 8 weeks per run. As such, it is critical that a system monitoring (sysmon) framework is established, to ensure that the IoT devices are operating robustly and reliably. This translates to the following two requirements:

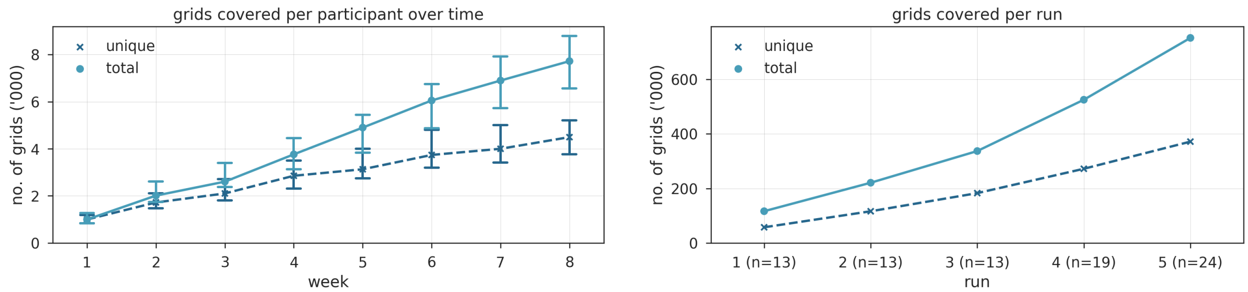
R1 Each sensor data tuple must be timestamped, as well as contain both location and IMU data.

R2 Missing data must be reported as soon as possible, so that device failures can be quickly rectified to maximize the amount of data collected from each participant.

A monitoring script is thus incorporated into the IoT device, such that an alert is triggered to the research team whenever any *partially* missing data (e.g., missing GPS or IMU data) is detected at the device level. Another monitoring script is scheduled in the backend server on a daily basis to: (i) compute the amount of data (in minutes) that has been contributed by each participant in the last 14 days; and (ii) generate a visual report in Slack [30], as illustrated in Figure 4.

Here, it should be noted that: (i) wheelchair participants are expected to power on the IoT device only when they make out-of-home trips; and (ii) no sensor/sysmon data will be received by the backend server if the IoT device is powered off. It is therefore not possible to remotely diagnose the main cause of any prolonged periods of 'missing data', as this may be attributed to any of the following factors:

- device is not powered on because the participant did not make any out-of-home trips for one or more days;
- participant has incorrectly powered on the device, forgotten to power on the device, or decided not to power on the device, when making an out-of-home trip; or
- there is a device failure that requires rectifications.



(a) Cumulative no. of grids covered per participant over 8 weeks.

(b) Cumulative no. of grids covered across runs.

Fig. 5: Density coverage in terms of grids covered. Each grid size is 20m $\times$ 20m.

TABLE I: Demographic statistics of the 68 unique wheelchair participants in the study between May 2018 to Mar 2019.

Demographic characteristic	**Category**	**No. of respondents**	**Percentage (%)**
Age group	18-29	8	11.8
	30-49	14	20.6
	50-69	26	38.2
	$\geq$ 70	20	29.4
Gender	Female	30	44.1
	Male	38	55.9
Employment status	Student	2	2.9
	Homemaker	1	1.5
	Working (part-time)	11	16.2
	Working (full-time)	10	14.7
	Seeking work	4	5.9
	Not seeking work	40	58.8
Wheelchair type	Manual	18	26.5
	Motorized	50	73.5

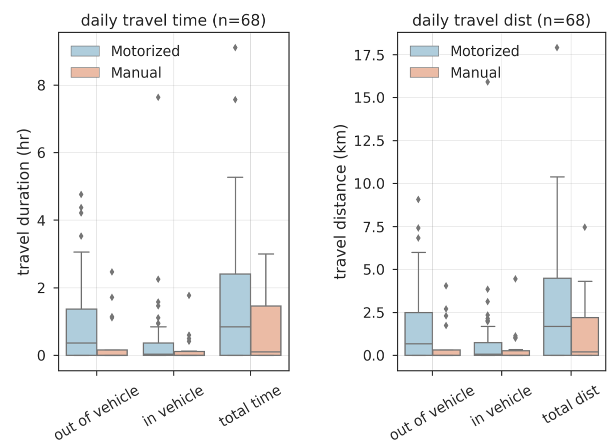
When no data has been received from an IoT device for 4 consecutive days (as indicated by 4 contiguous pink blocks in a column in Figure 4), the Slack report will contain additional alert messages. The research team will then contact the wheelchair participant to identify the likely cause of the missing data and schedule a maintenance visit if necessary.

IV. Evaluation

A. Participant Demographics

A total of 68 unique wheelchair participants are recruited between May 2018 to Mar 2019 across a total of 5 *runs*, with each run spanning 8 weeks. Table I summarizes the demographic statistics of the participants.

Survey results reveal that the top 3 obstacles that participants fear the most are uneven ground (52.9%), small steps (50.0%) and ramps/slopes (41.2%). 28% of participants with motorized wheelchairs indicate that they do not fear obstacles, as compared to only 5.6% for those with manual wheelchairs. This highlights that the former are more confident than the latter when traveling outdoors. In addition, participants rate themselves as doing fairly well in terms of levels of opportunity and participation in social and family life, but much less in economic and community life.



(a) Daily travel duration (hrs).

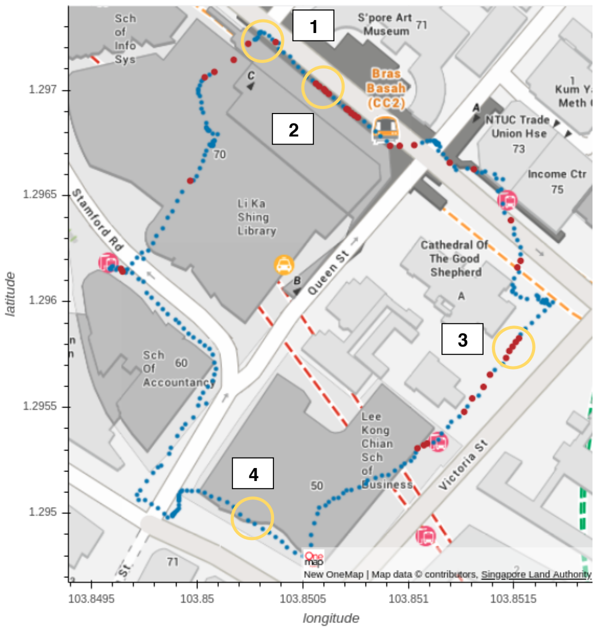
(b) Daily travel distance (km).

Fig. 6: Daily travel durations and distances by participants.

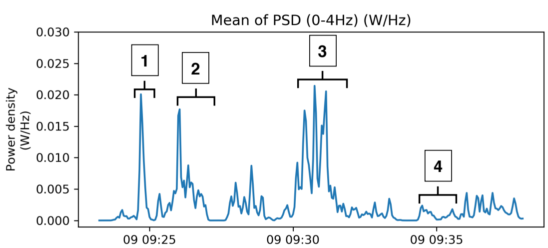
B. Travel Patterns

Based on Figure 5a, each participant traverses approximately 7,800 grids (each of size 20m $\times$ 20m) in each run, of which an average of 4,200 grids are uniquely traversed. The cumulative grids covered by all participants across each run is illustrated in Figure 5b. To put things in perspective, the traversable land area of Singapore spans across approximately 952k grids (excluding reserved land, nature reserves and reservoirs); hence, we have achieved $\approx 42\%$ coverage in 10 months, based on the number of uniquely traversed grids.

Figure 6 compares the differences in travel duration and distance covered by participants who are on different wheelchair types (manual vs motorized). The detection of in-vehicle versus out-of-vehicle is determined by the speed of travel. Our survey findings that participants on motorized wheelchairs are more confident when traversing outdoors than those on manual wheelchairs corroborate with the observation that the former make median trip lengths that are 2.2 times longer and further than the latter. The higher level of confidence among motorized wheelchair users also manifests in a significantly higher proportion of travel time out-of-vehicle compared to in-vehicle. In contrast, manual wheelchair users, who are less confident, do not travel much more out-of-vehicle compared to

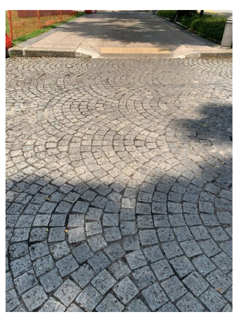


(a) Map showing locations of selected path surfaces.



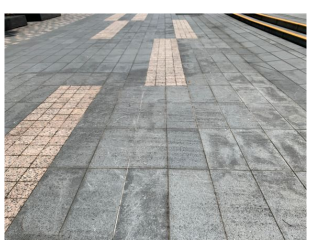
(b) Mean of power spectral density components up to 4 Hz.

(c) 1 Steep descent at pedestrian crossing.



(d) 2 Cobbled pathway.

(e) 3 Cobbled pathway.



(f) 4 Smooth pathway.

Fig. 7: A route taken by a participant in downtown Singapore with different pathway sections. (c) to (e) show pathways which hinder wheelchair users, while (f) shows a smooth pathway.

in-vehicle. This highlights that ease and convenience of travel (for instance, motorized wheelchairs and accessible locations) play significant roles in determining the level of (outdoor) activities that participants partake in.

C. Surface Condition Analysis

A Discrete-time Fourier Transform (DTFT) with a moving window size of 300 IMU data points is used to detect different pedestrian path surfaces. The mean of components that are less than 4 Hz is computed and used as an *inaccessibility index*, based on the assumption that the energy contained within deep, uncomfortable bumps fall within the first 4 Hz.

The algorithm is applied to a test route taken by a participant around a university campus in downtown Singapore. The inaccessibility indices that correspond to the yellow regions (labeled 1 to 4 in Figure 7a) are plotted in Figure 7b; regions 1 to 3 have high inaccessibility indices while region 4 has low inaccessibility index.

We validate the inaccessibility indices computed by our algorithm by ground truth inspection of the actual pathways. Figures 7c to 7e reveal that the regions 1-3 are indeed inaccessible, and characterized by steep descent or cobbled pathways. In contrast, Figure 7f shows that region 4 (which has low inaccessibility index) has a smooth pathway.

The above illustrates that while every effort has been made to make pathways inclusive, there are still some which may be a hindrance or cause discomfort to wheelchair users. These locations are generally at pedestrian crossings where the pedestrian pathway interfaces with roadways (via a ramp) or cobbled pathways (which are generally uneven).

V. Discussions and Lessons Learned

In the following, we discuss some of the challenges and lessons learned in our ongoing work on SmartBFA.

A. Spatial Coverage

A key limitation associated with the crowdsourcing approach in SmartBFA is that data is captured only along paths that participants have traveled. There are thus two possible inferences that can be made about areas without spatial coverage: (i) they are inaccessible; or (ii) they are accessible, but no wheelchair participant has visited the areas yet.

Based on the data collected over a period of 10 months from our 68 wheelchair participants, approximately 42% of Singapore has been covered. For areas that lack coverage, we can: (i) incentivize participants to provide data on that area through gamification; (ii) extend partnerships to social service and grassroots organizations to target more participants in those areas; and/or (iii) augment our data set with additional data sources, such as sensor data from able-bodied pedestrians [31] and virtual audits [15].

B. Data Utility

The utility of accessibility information in SmartBFA depends on both location accuracy and algorithmic accuracy of the path surface condition analysis. It is well-known that GPS location is likely to be less accurate in dense urban areas; however, this can be alleviated through the use of better GPS chips and improved software algorithms. On the other hand, the accuracy of pedestrian path surface condition analysis is highly dependent on a multitude of factors - such as the wheelchair type (manual or motorized), wheelchair speed, weight of participant and device placement on the wheelchair.

In addition to the objective considerations mentioned above, it is important to contextualize the path surface condition based on subjective perceptions, such as how a specific wheelchair user 'feels' when going through that surface. Ultimately, the *inaccessibility* index derived to represent different path surface conditions needs to be contextualized when presented to each user - depending on his/her existing health condition.

Beyond the spatial relevance of accessibility data, the temporal relevance needs to be considered. For example, a path that is repeatedly used, either by one or multiple users, may lend confidence to its accessibility. On the other hand, more recently traversed paths that deviate from previous paths may indicate the presence of new obstacles due to construction or temporary maintenance activities, such as tree-pruning or servicing of underground infrastructure.

C. Point-to-Point Barrier-Free Accessibility

SmartBFA, through its data collection, is able to map out barrier-free accessibility for the first and last miles of the journey taken by a wheelchair user. However, as a one-stop portal for barrier-free access, SmartBFA requires cooperation from both public and private entities to achieve point-to-point accessibility. For example, information on building accessibility (e.g., lift landings, accessible toilets and entrance/exits) should be obtained from building owners (e.g., office buildings, schools, shopping malls etc), while transit station accessibility should be obtained from the transport authorities of each city.

D. Scalability and Sustainability

The success of the SmartBFA initiative hinges on the: (i) ability to recruit sufficient wheelchair participants who will consent to passive data collection; and (ii) demonstrable utility of the data. As this initiative is relatively new, monetary incentives (funded by a grant) are provided to the participants. Other key expense items are the custom hardware that are installed on wheelchairs, and in some cases, the provision for Internet connectivity for users without home or office access to WiFi (to disseminate the IoT data to the backend server). Although data collection is passive, participants have to recharge the portable power bank that powers the IoT device on a daily basis, which may give rise to fatigue.

As most participants remain in the study for only one run (8 weeks), the hardware can be reused and per-user incentives are finite. However, our current approach may not be sustainable when participation scales, both in terms of number of participants and duration.

1) From explicit to implicit incentives for participation: The Google Maps model, which is also based on passive crowdsourcing of data, is evidence that stickiness can be achieved without explicit monetary incentives. As Google Maps users gain awareness of real-time traffic conditions during route navigation (gaining utility), they also passively contribute data towards real-time traffic conditions that inherently benefit other users (performing common good). While this is conceptually applicable to SmartBFA, we currently may not have the requisite wheelchair participant numbers to achieve the same level of stickiness.

For wheelchair users who require incentivizations in order to participate in data collection, we may consider monetization through Data-as-a-Service to offset operating expenses, as wheelchair accessibility information may be useful for companies that provide services depending or relating to accessibility (such as the use of couriers on personal mobility devices), as well as to other mapping or geospatial services.

2) From explicit to implicit devices for participation: Instead of deploying custom hardware, participant smartphones may be used for data collection as they contain the necessary sensing and connectivity elements. However, the following factors will need to be considered:

- **Device heterogeneity:** Every smartphone model has sensing elements that may differ in terms of sensitivity and resolution; hence, the backend algorithms will need to account for such variability.
- **Device placement:** Participants may not want to affix their smartphones on the wheelchairs, as they may want to use them when traveling. Moreover, the improper placement of the phone on the wheelchair may obstruct the normal use of the wheelchair, and may even dislodge, resulting in damage or safety risks.
- **Consumption of battery life and data plan:** Participants may be concerned that passive data collection and dissemination will deplete the battery life and data plan of the smartphone more quickly, as compared to normal day-to-day usage.

VI. Conclusion

Many cities around the world are increasingly placing more emphasis on *inclusiveness* as a central theme in their planning for infrastructure and services. In this paper, we present SmartBFA - a scalable and sustainable system to provide point-to-point barrier-free accessibility information for PwDs.

SmartBFA adopts a passive participatory sensing approach, whereby IoT devices that are retrofitted on the wheelchairs of participants seamlessly collect data about path surface conditions. We demonstrate the feasibility and scalability of the system through our initial study involving 68 wheelchair participants across a period of 10 months. Preliminary evaluations highlight that concerns with out-of-vehicle accessibility affects the confidence of manual wheelchair users to travel on out-of-vehicle paths. In addition, SmartBFA is able to differentiate between different pedestrian infrastructure surface conditions when validated along our test route. As part of ongoing efforts, we intend to scale the participant numbers and spatial coverage in SmartBFA, as well as refine our algorithms for both surface condition detection and map construction.

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