Post-Disaster Road Traversability Mapping Based on GPS Track Sharing and Map-Matching

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Abstract

The main motivation in undertaking this research was to address some of the practical issues that were widely reported during major disaster situations such as the 11 March, 2011 Tohoku earthquake in Japan. Apart from great loss of life and property in the near vicinity of the earthquake, metropolitan areas in Tokyo experienced disruption of train services, electrical outages and inaccessibility to Internet services leaving many commuters stranded. It is, therefore, necessary to develop a near real-time traversability mapping service that can be available during or soon after the disaster. In this research, we implemented a system that facilitates generation of updated road traversability map using aggregated GPS tracks. The post-processing consists of a line simplification based on Douglas-Peucker algorithm and map-matching with existing road network using Hausdorff distance algorithm. Line simplification was applied reduce the data in further processing and map-matching to remove outliers and generate a navigable traversability road network. Performance of map-matching algorithm, evaluated using data collected in two field campaigns in Yamate-cho, Suita City and Sumiyoshi-ward, Osaka City, Japan clearly demonstrates the efficacy of the proposed workflow.

1. Introduction

In recent years, with the development of mobile communication technology and Geographic Information System (GIS), Location Based Services have become indispensable for day-to-day life as well as in disaster management and mitigation endeavors. Location information based mapping tools are developing rapidly and can be used widely for emergency relief and rescue operations.

Due to its unique geographical location, natural disasters are inevitable in Japan. Recently, Great Hanshin-Awaji Earthquake Disaster in 1995 and The Tohoku Earthquake in 2011 caused huge damages (Ministry of Internal Affairs and Communications, Japan, 2011). The Cabinet Office of the Government of Japan has reported that the probability of occurrence of the Nankai Megathrust Earthquakes within the next 30 years reaches 70% (Disaster Management, Cabinet Office, 2016). Apart from great loss of life and property in the near vicinity of the earthquake and the subsequent tsunami event, metropolitan areas such as Tokyo experienced disruption of train services, electrical outages and inaccessibility to Internet services. As a result a vast number of commuters were stranded and compelled to proceed to their destinations using unfamiliar routes and transportation modes. Supporting stranded commuters during and soon after earthquake disasters or other emergency situations have been considered as one of the most important issues for ensuring safety of citizens. It is, therefore, necessary to develop a near real-time traversability mapping service that can be available during or soon after the disaster.

During The Tohoku Earthquake in 2011, an automobile manufacturing company demonstrated the use of near real-time Floating Cellular Data to provide usable routes and shared them to drivers (Honda Motor Co., Ltd., 2011). When road conditions are altered by natural disaster, distributing information of blocked road to emergency vehicle is very important. However, it is difficult to do so when communication networks are inaccessible or overloaded. It is, therefore, necessary to develop a real time information sharing system that can be widely used in off-line mode. The impact of the disaster can be significantly reduced if a post-disaster road traversability map is provided to the stranded commuters. With the aim to address some of the issues faced by stranded commuters not only in Japan but also in other parts of the world, we proposed a data processing workflow for road traversability mapping.

The workflow involves sharing of GPS tracks (Yu et al., 2013, 2015) over Mobile Ad-hoc Network (MANET) (IETF Datatracker, 2017) and Delay Tolerant Network (DTN) (National Aeronautics and Space Administration, 2017).

It is known that there are still some existing problems with GPS location data and navigation system, such as signal obstruction and sometimes-inadequate accuracy. In this research, to overcome this problem, GPS location information is filtered using Horizontal Dilution of Precision (HDOP) parameter. Further, data generalization using Douglas-Peucker (DP) algorithm to reduce the amount of location data is carried out. Similar filtering processes have been applied to improve collected GPS location data quality (Song et al., 2010) and deployed as web service (Yoshida et al., 2010). We match the stranded commuter's GPS tracks to the nearest street node while others are able to find the shortest and safest path to reach their destination using post-disaster road traversability map. The post-disaster road traversability map developed in this research does not include the data like road intersection and buildings. OpenStreetMap (OpenStreetMap Contributors, 2016) offline map has been used as background map to enhance the utility for navigation. Further, we evaluate performance of post-disaster road traversability mapping that originally proposed by this research. Study demonstrates the experiment results using mobile device (Nexus7). To evaluate map-matching effect, the field experiments were carried out in Yamate-cho, Suita City and Sumiyoshi-ward, Osaka City, Japan. The field experiment results are discussed and efficacy of proposed post-disaster road traversability mapping is evaluated.

2. Framework for Road Traversability Map

The system framework of the proposed traversability mapping and data processing workflow are depicted in Figure 1 and Figure 2 respectively. The workflow consists of three main steps, namely, GPS tracks sharing, data pre-processing and map-matching. The traversability mapping workflow is basically designed to perform GPS location data collection and sharing between nearby devices when Internet connectivity is unavailable. MANET and DTN were investigated using Android application developed for sharing GPS tracks.

In the next step, pre-processing of GPS tracks collected by individual devices was considered, in order to minimize volume of data transfer over Ad-hoc networks where bandwidth is limited. GPS filtering was implemented based on standard parameters such as number of GPS satellites used for positioning, GPS accuracy and HDOP to eliminate low accuracy GPS data. The application also allows for uploading the aggregated data to the server for further processing when the Internet connection becomes available.

A post-processing workflow was implemented for generating updated road traversability map using the aggregated GPS tracks. The post-processing consists of a line simplification based on Douglas-Peucker algorithm and map-matching with existing road network using the Hausdorff distance algorithm. Line simplification was applied reduce the data in further processing and map-matching to remove outliers and generate a navigable traversability road network. Performance of map-matching algorithm was evaluated using data collected in two field campaigns in Yamate-cho, Suita City and Sumiyoshi-ward, Osaka City, Japan.

Combined use of line simplification and map-matching algorithm was found to provide desired results to achieve the final objective. Subsequently, as and when new GPS tracks are loaded to the server, the traversability maps are automatically updated by running the post-processing program on the server. The updated road traversability maps are published as Web Map Service (WMS) using GeoServer and available as a raster layer on any mobile device or computer that is connected to Internet. The traversability road network is stored in a PostgreSQL/PostGIS spatial database. As new data is uploaded to the database, updated the road traversabilty map are automatically generated.

3. Data Processing for Road Traversability Map

This section describes methodology and data processing workflow for sharing GPS tracks data and filtering parameters used to eliminate low accuracy GPS data. GPS filtering was implemented based on standard parameters such as number of GPS satellites used for positioning, GPS accuracy and HDOP to eliminate low accuracy GPS data. Further, GPS track data is uploaded to the server and data generalization using Douglas-Peucker algorithm was carried out to reduce the amount of location data and speed up processing. The system match the stranded commuter's GPS track data to the nearest street node and users are able to find the traversability path to reach their destination using post-disaster road traversability map.

3.1 Acquiring and Sharing Location Data using Android Application

A Java based Android application has been developed to facilitate acquisition and sharing of GPS data between mobile devices. Data includes position, speed and time.

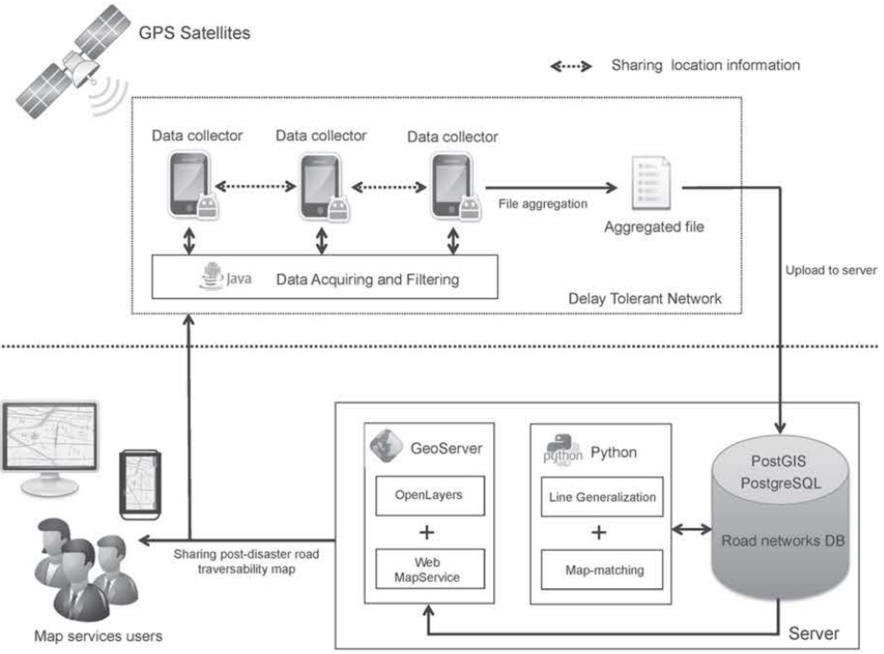

Figure 1: The framework of post-disaster road traversability mapping system

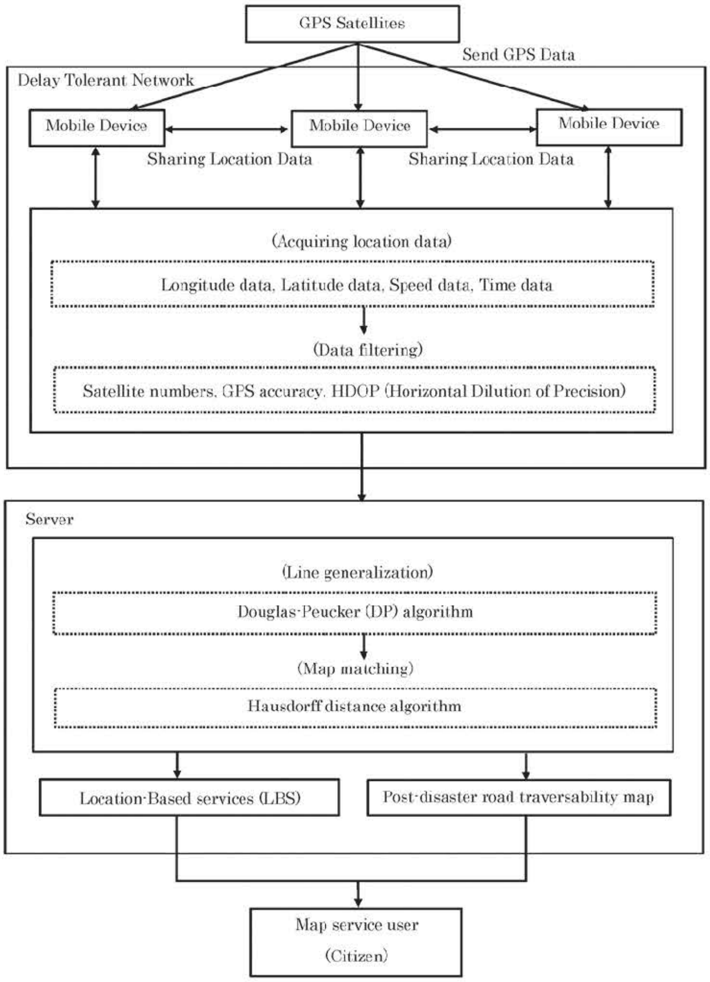

Figure 2: Post-disaster road traversability workflow

The accuracy of GPS location information is impacted by several factors such as sky visibility to the GPS receiver, atmosphere multi-path reflection and receiver quality. In an area with wide-open sky, the location data are expected to be of higher precision, however, in area with high-rise buildings, view angle of sky is narrow and GPS accuracy decreases. To overcome this problem, filtering of GPS data is carried out.

3.1.1 Filtering location information

Collected GPS location information is filtered using parameters such as satellite numbers, GPS accuracy and HDOP parameters. The horizontal location can be determined when minimum of three satellites are available. In practice, a minimum of four satellites is needed to estimate altitude. Therefore, we filter location data, acquired from more than four satellites. Secondly, GPS accuracy is set to according to the size of the roads in the study area. In this study, 24m is assigned as the maximum road size, defined in Japan's Road Traffic Act (Ministry of Justice, Japan, 1960). The GPS accuracy of the location data is estimated by using Android function *location.getAccuracy*( ) (Android Developers, 2017). HDOP is a key parameter in determining the relative accuracy of a horizontal position. The position with a lower HDOP value means a potentially high positioning accuracy. Therefore, one can expect a low position accuracy if the HDOP value is higher. However, HDOP can be effectively used to remove deviant position points from the GPS location data using information provided in NMEA $GPGGA sentence.

3.1.2 Sharing location information

In this research, Android application shares GPS location data between nearby devices that are connected through MANET and DTN. The mobile devices automatically recognize and connect to each other when they are within communication range. Not only the Android application shares data between closely surrounding devices but also data transfer to other devices using MANET through surrounding devices. More devices in the MANET, the greater will be the communication range. Finally, the system allows the Android application to upload collected location data to server using relative path. A PHP script is executed on the server to receive location data and transfer the location data to PostgreSQL/PostGIS database.

3.2 Line Generalization and Map-Matching

As depicted the flowchart (Figure 2), when the Internet is restored, the system allows the mobile device client to update the GPS location data to Web server. In addition, by combining location data from each device, post-disaster road traversability map can be generated. The post-disaster road traversability mapping created does not include data like road intersection and buildings etc. OpenStreetMap (OSM) offline road map will be use as background map to enhance the utility for navigation. Further, in order to prevent system load and data size of communication, data line generalization using Douglas-Peucker (DP) algorithm to reduce the amount of GPS location data. This reduces the amount of GPS location data to minimize system load and data communication overheads.

3.2.1 Line generalization using douglas-peucker algorithm

Filtering location information data on mobile devices can reduce the number of GPS track points. However, some queries extract a large volume of data and need a bit of time to display the result, in addition, processing gets slow if the extracted data is large. In order to reduce the amount of GPS track points, a line generalization function was implemented using the Douglas-Peucker algorithm. The algorithm could produce the closest approximating results by simplifying a line. It recursively splits the approximating poly-line at the vertex of furthest distance, keeping those vertices under a given error bound or tolerance. The application of the Douglas-Peucker algorithm for line generalization is effective and efficient in eliminating redundant points. Additionally, the algorithm also eliminates extraneous position points and can speed up the performance at the next processing stage.

3.2.2 Map-matching using hausdorff distance

Common problem observed in traversibility mapping is spatial misalignment of GPS location information with road network data due to the low GPS horizontal accuracy. In order to overcome this problem, map-matching is carried out by using Hausdorff distance algorithm.

The length-weighed Hausdorff distance is applied to calculate the similarity between the GPS tracks and candidate roads, and select the roads with a short distance to the candidate road of matching. Given two finite point sets $T = \{t_1, t_2, \ldots, t_m\}$ (representing a GPS track in the database) and $R = \{r_1, r_2, \ldots, r_n\}$ (representing a road from road networks), the length-weighed Hausdorff distance from T to R, $H(T, R)$, is approximately calculated as follows:

$$H(T,R) = max\,(h\,(T_i,R_j), h\,(R_j,T_i)), \qquad i = 1,2,\dots,m-1 \quad j = 1,2,\dots,n-1$$

Equation 1

Where:

$$h\,(T,R) \; = \max_{t_i \in T} \min_{r_j \in R} || \, t_i - r_j \, ||, \qquad i = 1,2,\dots,m-1 \quad j = 1,2,\dots,n-1$$

Equation 2

The $|| \, t_i - r_j \, ||$ is the shortest distance on the points of T and R. The function $h\,(T,R)$ is called the directed Hausdorff distance from T to R. It identifies the point $t_i \in T$ that is the farthest from any point of R and measures the distance from t_i to its nearest neighbor in R. The Hausdorff distance $H\,(T,R)$ is the maximum of $h\,(T_i,R_j)$ and $h\,(R_j,T_i)$. Thus, it measures the degree of mismatch between two sets by measuring the distance of the point of T that is farthest from any point of R and vice versa.

The steps involved in the map-matching process are as follows:

Step 1) Selecting candidate roads from road networks: GPS tracking buffer roads are generated by applying a threshold buffer size assigned as 24m, which is almost half of the minimum distance between roads in study area. In order to reduce the map-matching time, overlapping GPS track buffer roads are used as candidate roads.

Step 2) Finding the counterpart of the candidate road on the GPS track: By computing the shortest distance from the candidate road to the GPS track, the counterparts on the GPS track are found. A correspondence line is determined accordingly for the GPS track segment being matched to the candidate road.

Step 3) Computing the length-weighed Hausdorff distance: Calculating the length-weighed Hausdorff distances from the candidates to their counterpart GPS track segments.

Step 4) Determining map-matched roads: Selecting the map-matched roads using a distance less than a specific threshold. The threshold is determined by considering the positioning accuracy and the road width form the field experiment.

4. Application Examples and Results

In this section, we evaluate performance of traversability mapping proposed in this research. Study demonstrates the experimental result using mobile device (Nexus7). In order to demonstrate the effectiveness of the proposed map-matching method, we performed field evaluation.

4.1 Environment of Field Experiment

In order to evaluate performance of the proposed post-disaster road traversability mapping, two field experiments were carried out in Yamate-cho, Suita City and Sumiyoshi-ward, Osaka City, Japan. Study area shown in Figure 3(a), geographically stretches from latitude 34°46′01″N to 34°46′57″N and longitude 135°30′02″E to 135°31′23″E covers about 2km x 1.5km area.

The second study area shown in Figure 3(b), geographically stretches from latitude 34°35′06″N to 34°36′02″N and longitude 135°29′40″E to 135°31′01″E covers about 2km x 1.5km area. In this field experiment six mobile devices were used to collect GPS track points from both study areas Figure 3(a) and Figure 3(b). Characteristics of parameters used for field experiment are shown in Table 1. GPS tracks were collected using mobile devices in field experiments are shown in Figure 4(a) and Figure 4(b). More than 20,000 position points with GPS tracks in each area were collected.

Table 1: Parameters in filed experiments

Study area	Yamate-cho, Suita City	Sumiyoshi-ward, Osaka City
The model of devices	Nexus7	Nexus7
The number of devices	6	6
Area covered	2.5 x 2 km	2.5 x 2 km
Experiment time	1 hour	1 hour

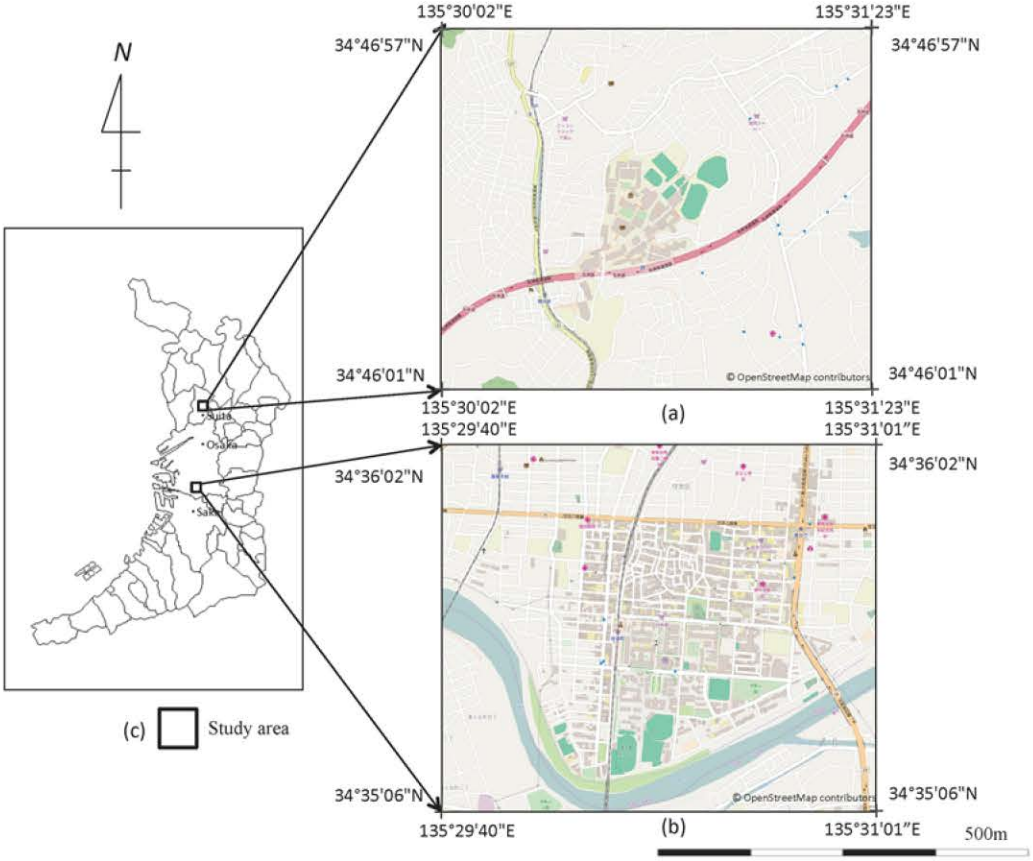

Figure 3: Study area (a) Yamate-cho, Suita City and (b) Sumiyoshi-ward, Osaka City, (c) Osaka Prefecture, Japan

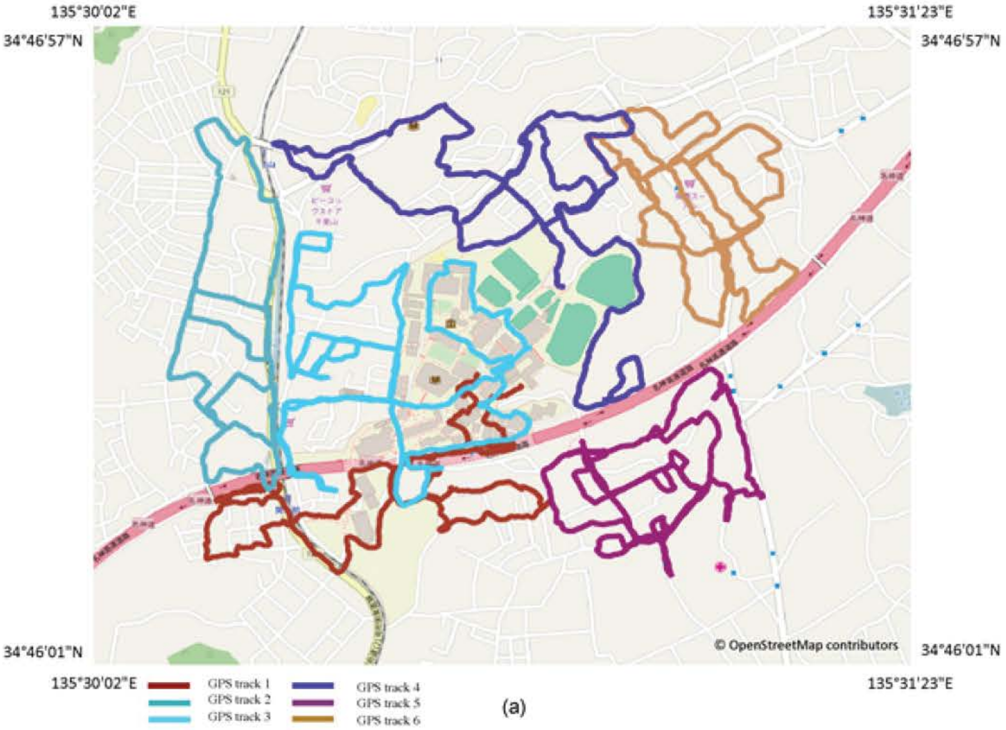

Figure 4(a): GPS tracks collected using six mobile devices in Yamate-cho area

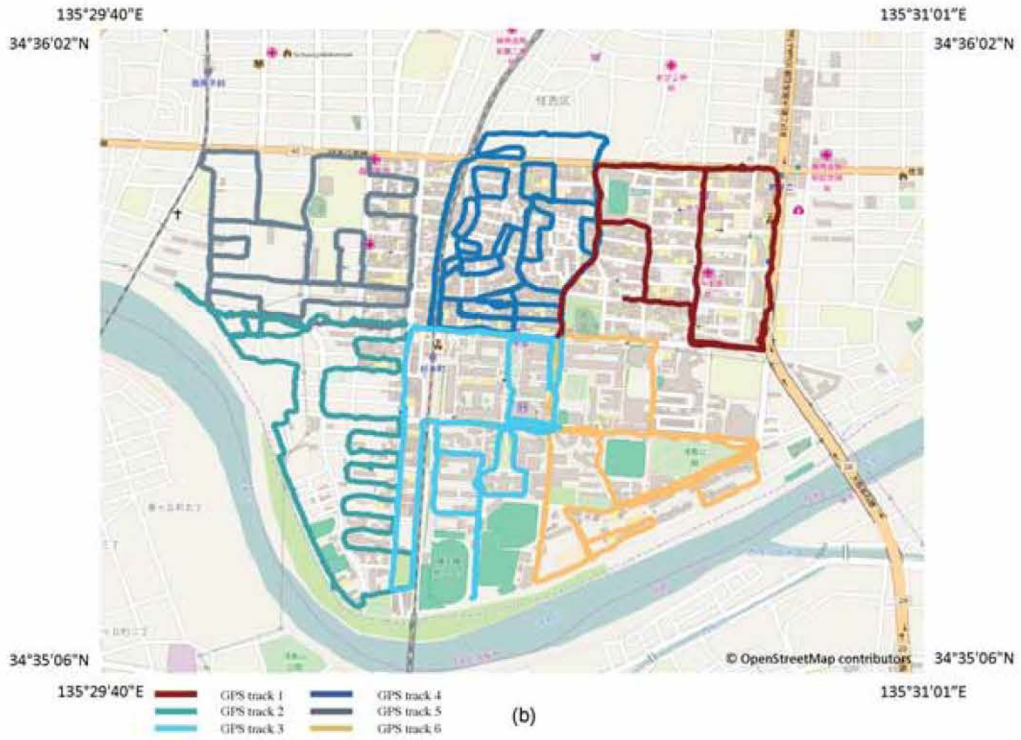

Figure 4(b): GPS tracks collected using six mobile devices in Sumiyoshi-ward

Table 2: Results of filed experiments

	Yamate-cho, Suita City				Sumiyoshi-ward, Osaka City			
Device number	**Number of points**	**Number of filtered points**	**Number of matched segments**	**Running time (s)**	**Number of points**	**Number of filtered points**	**Number of matched segments**	**Running time (s)**
Device1	3525	3363	238	1.125	4157	3208	180	2.273
Device2	3315	3179	197	0.983	3275	3057	153	0.868
Device3	3743	3620	248	1.332	2550	2335	156	0.989
Device4	3818	3099	161	2.743	4158	3975	219	1.703
Device5	3387	3008	201	1.135	2767	2419	188	0.634
Device6	3467	2857	144	1.628	3131	2288	157	1.212

4.2 Results of Field Experiment

The GPS track data were collected using mobile devices and buffered in order to overlay with road network data collected from OSM. The Figure 5(a) and Figure 5(b) demonstrate the overlay map of buffered GPS tracks and road network for both study areas. Different colors are used to distinguish the buffered GPS tracks collected from different mobile device and road network that overlaps with buffered GPS tracks. The GPS tracks were processed, and the roads that overlap the buffer area of the GPS tracks are preliminarily selected as candidates for matching. The results of matched segments and running time are described in Table 2. In study area Figure 3(a), an average of 3,543 track points was collected using six devices. Around 10% of low accuracy track points were removed by filtering and an approximately 3,187 track points were finally derived. Further, duration of average 1.491s was taken to run Hausdorff distance map-matching algorithm for 3,187 GPS track points. Around 198 candidate segments were overlapped with the area of GPS tracks. In study area Figure 3(b), an average of 3,340 track points was collected using six devices. From these, around 14% of low accuracy track points were removed by filtering that an average of 2,880 track points was derived. Further, an average of 1.279s was taken as time to run Hausdorff distance map-matching algorithm for a number of 3,340 GPS track points.

Figure 5: Road network and buffered GPS tracks before map-matching (a) Yamate-cho, and (b) Sumiyoshi-ward

Around 176 candidate segments were overlapped the with GPS tracks of the area. Also the detailed result of filtering for each device is shown in Table 2. In the field experiments it was found that using the Hausdorff distance algorithm, more than 2,000 segments were map-matched within 1 second. The length-weighed Hausdorff distances from candidate roads to the GPS tracks were computed. Finally, the roads with a distance less than a specific threshold value were chosen as matched roads. The result of road map-matching depends on the selection of threshold value. The threshold value is an experimental value related to the positional accuracy of GPS and the environment of data collecting.

In this research, it was set to 20m by comparing all the map-matching results. Map-matching with 20m Hausdorff distance threshold provides acceptable balance with real road network data. Map-matching with specific threshold was used to determine if the GPS tracks collected by using mobile devices had an adequate accuracy or not. Consequently, only GPS traces which lie inside road network buffers were used to create the road traversability map. The system evaluates the status of the road whether the road is usable for travel or not by using GPS tracks collected by stranded commuters. A road is considered usable for transportation, if one stranded commuter has already travelled through a particular road. Finally, the Hausdorff distance of the roads measured to be less than a specified threshold value, were chosen as traversability roads. Traversability maps based map-matching for two areas are shown in Figure 6(a) and Figure 6(b).

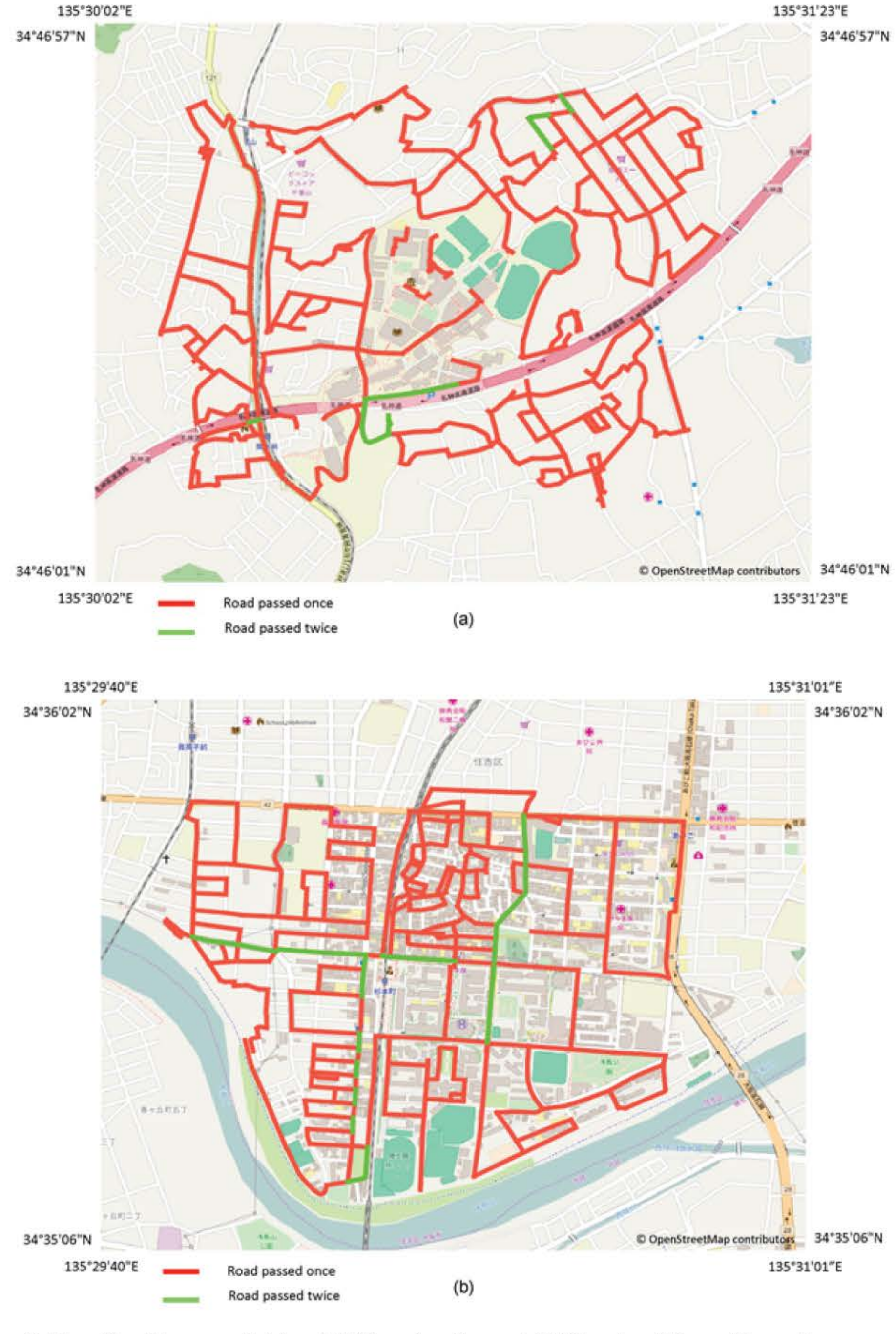

Figure 6: Results of map matching (a) Yamate-cho and (b) Sumiyoshi-ward based map-matching

Different colors are used to indicate the traversability of the road, which is determined by the pass frequency. Only two colors were used to differentiate traversability of the roads due to limitation in the number of mobile devices used for field experiments. The roads, which were traversed only once by the commuters are shown in red color, and roads, which were traversed twice or more are shown in green color in Figure 6. Future, with the increase in the numbers of the mobile devices, the color will be more intuitive.

5. Discussions and Conclusions

As discussed in earlier, stranded commuters require post-disaster road traversability mapping system. Post-disaster traversability mapping in near real-time scale is always been a challenging task especially due to the non-availability of Internet connection. Potential obstacles that can be occurring during disaster events include fire outbreaks, unexpected stoppages in public transportation, road damage, traffic signal damage and Internet disconnection. Hence, the traversability mapping system needs to consider these issues. The traversability mapping system developed as a part of the present research, is effective in addressing several of these issues and provides a workflow for generation a near real-time road traversability map even when no Internet connection is available. The data processing workflow implemented as a part of this research helps overcome several of the limitations of previous research. Some salient feature that distinguish this research from previous works are below:

a) Usability by stranded commuters using public transportation rather than private automobile. This is an important factor especially in urban areas in Japan where public transportation is more widely used than private automobile. Although a large automobile maker demonstrated the use of near real-time Floating Cellular Data to provide usable routes and shared them with drivers. It is difficult for stranded passengers using public transportation to utilize information provided for automobile users. This research described the workflow of post-disaster road traversability mapping system that can be used supporting stranded commuters during or soon after disasters in urban areas. The system is made available to mainly support standard commuters carrying mobile device.

b) Most of the functionality is available both in online as well as offline mode and the system is usable even when Internet connectivity is unavailable. In this study, acquired GPS location data from several devices were assimilated to create a post-disaster road traversability map. Even when Internet connection is unavailable, the proposed system can get GPS location data from nearby devices connected through created Ad-hoc networks.

c) The entire workflow is implemented using Open Source software and libraries and, therefore more amenable for future enhancements and customization. The source codes developed post-disaster road traversability mapping will be uploaded to GitHub repository. Therefore, the source code can be access by one who wishes to carry out further improvement in the developed system.

Based on the features described above, it can be concluded that the proposed framework and data processing workflow are effective in accomplishing the objectives envisaged for the current research. As a future work, it is necessary to consider ways and means to incorporate additional contextual information to the traversability maps to make them more intuitive. Another challenge would be to enhance the system functionality by considering realistic situations affecting crowd dynamics and behavioral patterns as regards mobility.

Additional field experiments or simulation with large number of field devices need to be undertaken to evaluate scalability and robustness of the proposed system. The present study focused on a small experiment area ($5km^2$) and only limited number of mobile devices used to evaluate the system. Moreover, further work is required to evaluate effectiveness of the proposed system in situations where civil infrastructure like bridges may have been rendered unusable. Therefore, in the future investigations will need to focus on experiments including scenarios of collapse of civic infrastructures and other disruptions that may occur in real disaster situations.

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