Capturing crowd dynamics at large scale events using participatory GPS-localization

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***Abstract*—Large-scale festivals with a multitude of stages, food stands, and attractions require a complex perimeter design and program planning in order to manage the mobility of crowds as a controlled process. Errors in the planning phase can cause unexpected crowd dynamics and lead to stampedes with lethal consequences. We deployed an official app for Züri Fäscht 2013 – the largest Swiss event – over a period of three days. The app offered information about the festival and featured a background localization allowing us to collect continuously the visitor position. With 56.000 app downloads and 28.000 user contributing 25M location updates in total, we obtained a large scale dataset. By aggregation of location points it captures complex crowd dynamics during the entire festival. In this paper we present the data collection for Züri Fäscht 2013 and best practises to acquire as many contributing users as possible for such an event. We show the potential of aggregating individual location data and visualising relevant parameters that can serve as tool for analysis and planning of program and perimeter design.**

I. Introduction

Large scale events with tens of thousands or millions of visitors contain an immanent risk for stampedes as they occurred, for instance, at the Love Parade in Duisburg in 2010 or at the Hindu-Fest Maha Kumbh Mela in India in 2013. A constrained space and the movement of the crowd can develop critical dynamics leading to such incidents. A careful design of the event area and planning of the event schedule are crucial factors to influence the crowd dynamics in order to minimise this risk. For example, after ending an event with a large attendance the crowd should dissolve slowly, supported by a ”smooth” schedule-ending and by sufficient and well located exit points on the area. Agent-based simulation tools support the planning but are rarely data-driven and are not able to compare simulation results with actual crowd behaviour in a posthoc analysis. The posthoc analysis however is a critical step of organisation an event and can reveal critical factors that may be addressed in future events. Although a great deal of data is available for the analysis, event organisers and crowd managers are forced to scan manually through video material, reports from forces in the field, or statements from individual visitors. Combining such heterogeneous sources is a tedious and error prone task preventing to obtain a situational awareness picture.

In this work we focus on capturing crowd dynamics important for analysing the entire process of an event with respect to the impact of event locations and schedule on the dynamics of the crowd. This has at least two major advantages for the practise of organizing large scale events. First, the event organizer can extract business intelligence to understand the effect of certain attractions and if necessary changes these in terms of place, time or act. Second, he can refine the schedule to minimize the risk of sudden crowd movement by arranging program items for future events. To this end, our goal is to capture relevant data. We adopt a participatory concept based on a mobile phone application similar to [11]. By locating a subsample of visitors (app users), we estimate multiple parameters that reflect the crowd dynamics important for event analysis.

Fig. 1. Official festival area and perimeter (red) with stage layout. The main train transportation hubs are indicated by green dots.

The contribution of this work targets several aspects of capturing the behaviour of crowds on large scale events: First, since our work is based on participatory sensing and requires the user's cooperation, we provide best practises on marketing the app and providing incentivising elements that increase participation to the best possible. Second, we contribute to our knowledge the largest mobility dataset collected for large scale events. 28.000 users contributed 25 million GPS data points over a course of 3 consecutive days. Third, we present visualisation techniques based on the aggregation of individual visitor localisation data using mobility mining techniques. Thereby, we are able to reflect the impact of perimeter design and the event schedule on the crowd dynamics.

First, we outline related work on the topic of crowd monitoring. In Section III we describe the festival for our data collection with the system outlined in Section IV. Section V describes the obtained dataset. Based on the collected data, we visualize crowd mobility parameters relevant to event analysis and planning (Section VI) and discuss lessons learned for this large scale experiment (Section VII). Finally, we conclude our work in Section VIII.

II. Related work

Capturing crowd dynamics on large scale events with computational aid is an evolving topic in research and in the practise of crowd management. Using video footage, Helbing et al. presents an empirical study of proposed indicators such as crowd turbulence [1] as signs for dangerous crowd situations. Similarly, video analysis revealed in [2] that the transition from smooth crowd mobility into stop and go waves for conditions becoming congested. Based on such evidence in video material, computer vision approaches has been proposed to extract such parameters automatically from CCTV cameras [4]. While CCTV-based computer vision approaches indeed allow accurate crowd monitoring, deploying a temporary camera network is costly and inhibits scalability of such techniques for events that usually happen infrequently and often have different installation requirements.

The rise of the mobile phone industry led to powerful mobile phones that today are equipped with a multitude of sensors such as GPS localization or motion sensors and Bluetooth- and broadband-communication. Supported by a large market penetration they offer an excellent instrumentation for crowd monitoring. Researchers recently started to investigate the mobile phone for the purpose of crowd monitoring. Scanning of bluetooth devices has been studied for crowd mobility or identifying social groups. In [9] bluetooth scanners are installed at fixed locations. By scanning bluetooth enabled devices crowd parameters such as relative visitor densities or visitor flow between locations are captured. In [8] the authors deploy a mobile phone app that collects the location of the user and scans for bluetooth devices in the surrounding. As a result they estimate the density of the crowd. Focusing also on Bluetooth [7] extract visitor behaviour targeting characteristics such as the stay at an attraction, number of visits for an attraction or how people transit through the event area. While using a different technology, our work is in line with the goal of answering similar questions.

Also the user location obtained by GPS has been used for aggregation into crowd parameters or understanding events [3], [11], [5], [6]. Using app-based localization in [11], crowd density and critical parameters such as the turbulence are estimated near-to-realtime to crowd managers. We build on this work, but focus on visualizing changing crowd characteristics over time for the posthoc analysis. Our goal is to reveal the impact of attraction locations and schedules on the crowd mobility. To this end, we recorded a new dataset in close collaboration with the event organizers and the city police Zürich. To the best of our knowledge, it marks the largest dataset collected on large scale events, which goes far beyond previously acquired datasets in terms of size, duration, and complexity.

III. The Züri Fäscht Festival

The *Züri Fäscht* is a three day event comprising an extensive program with concerts, dance parties, and shows and occurs every three years. It is hosted in Zürich and marks the biggest festival in Switzerland. In 2013 the festival started friday July 5 at 2:00pm and ended on sunday Juli 7 2013 at 12:00am. The festival spans over $1.5km^2$ (excluding the historic center and the lake) along the northern shore of the Zürich lake and northbound along the Limmat river. The event zone is marked red in the official map in Fig 1. The festival area is characterised by a complex infrastructure: around the lake the area is elongated and narrow; the northern part is composed of small streets and bridges interconnecting different attraction locations. Within the entire area 60 music stages, 130 party locations, and 300 market and food stands are distributed. Stands are located along way paths, and music stages on larger plazas. Over the course of three days the program contains hourly attraction and shows, such as high diving, wakeboard competitions, or acrobatic performances.

2 million visitors have been estimated to attend the festival during the event time. 900.000 are estimated to attend on the first day (Fri),1 million on the second day (Sat) and 400.000 on the last day (Sun). During the period of the event, vehicles are prohibited within the the festival area. Three train station hubs connect the public to the festival area: station Enge on the west side, station Stadelhofen on the east side, and the main station Zürich HB in the north, all marked as green spots in Fig 1. It has been estimated beforehand that most pedestrian traffic will be coming in from the east side.

IV. Data collection system

Our goal is to obtain crowd dynamics by probing the location of an individual visitor. It is therefore crucial to acquire as many visitors as possible who participate in creating a representative sample of the crowd behavior in its entirety. With the advent of the smartphone including GPS-modules, processing power, and internet communication, we can instrument each user simply through a downloadable app. Thereby we can capture each participant location, aggregate and process them centrally on a server, and finally visualize crowd behavior. Assessing the location by GPS is highly power consuming and drains the battery in continuous mode within several hours. Thinking power consumption as "commodity", an incentive is required for compensation.

First, in order to maximise the chance to instrument as many visitors as possible, we collaborated with the organizers to be able to offer a single and official event app. Second, implementing standard functionality such as having access to the program or a map of the festival, we added additional features of which the user would benefit from a continuous location tracking. In the following we describe the employed app with these features. Then we describe the localization management for the GPS tracking and the backend for data collection, which has been similarly implemented in [10].

A. App user interface

We developed the official app for the Züri Fäscht festival for the two platforms Apple iOS and Android. See Fig 2 for a selection of screenshots of the iOS app. When starting the app, the user is asked to allow the usage of the location services. A short explanation is provided for the features using the location service and instructions are given how to opt-out. The main user functionality consists of the official program that has been included as mobile website into the app. A map with points of interests has been integrated for orientation on the event area. Since our goal is to capture the location of the user continuously, we added additional functionality that has equal requirements but benefits the user directly: *a friend finder*[1],

[1] Similar to Glympse™ for iOS and Android

Fig. 2. Screenshots of the official app with overview (top left), trophy viewer (top right), program (bottom left), and map (bottom right).

Fig. 3. Shared trophy collection on facebook from within the app.

Fig. 4. GeoFence zone (left). Zone for activating GPS tracking (right).

and a *trophy collector*. Users were able to share their location continuously to facebook friends who had the app as well. The trophy collector would automatically unlock a trophy when the user achieves a goal, such as *attending the first day*, *walking on the festival area for* $2km$, or *visiting the festival for more than 8 hours*. Each trophy has been attached to a score that is summed up to a total score. The user had the possibility to share his current achievements as image status on his facebook wall with a predefined message *"My trophies and already 177 points! Where are yours?"* (See Fig 3). With this suggestive formulation we aimed to stimulate a viral distribution of the app within the user's circle.

In total we created 21 trophies of different categories (e.g. duration, event attendance, distance, or coverage) and varying level of difficulty and evaluated the rule for unlocking using location and time continuously in the background. In the trophy view the user can view his achievements including the progress on individual trophies. As soon as a trophy has been achieved a pop up would notify the user.

B. Localization Management

GPS data has been acquired at $1Hz$ and stored temporarily on the device. Every $2min$ a packet is sent to the server. To automatically check if the visitor enters or exits the festival area, we made use of iOS geo-fencing. Most prominently it is used for location-based reminders on the iPhone. The geo-fencing is based on cell tower localization and therefore allows power efficient (but coarse) localization. The accuracy strongly depends on the infrastructure of mobile cellphone cells. We experimentally tested the accuracy for several locations. We obtained 150-500m accuracy. We created three circular geo-fences around the festival area, see Fig 4 (left). If the visitor passes the geo-fence by entering, the app wakes up and GPS-localization is enabled. The major advantage is that the user does not have to start the app manually, but the app can start autonomously, start the localization and execute other program logic. Then, the GPS localization is used to determine if the user in the more accurate zone, we wish to observe, see Fig 4 (right). If the user enters the green area, tracking (i.e. transmission of the user location) is activated. If the user exits the area the tracking is disabled, respectively if the user passes the geo-fence by exiting, the app turns off GPS localization and returns back to sleep. To ensure that the mobile does not miss to start the GPS localization, when entering the festival area, we enlarged the perimeter accordingly with respect to our obtained accuracy (150-500m).

At mass events the 3G-network can be heavily congested in peak times. We specifically handled failed (timed out) transmissions in order to avoid data loss for a later offline analysis. To this end, we recursively rescheduled the failed transmission thread to be sent $60min$ later. Thereby we would

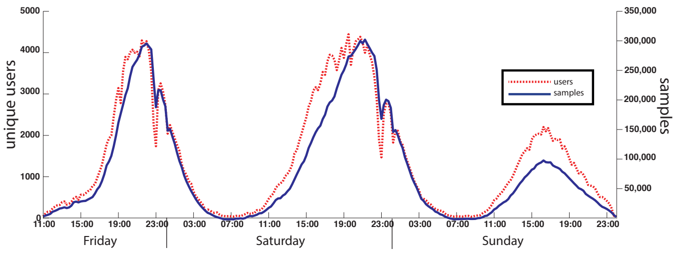

Fig. 5. Users and samples collected for 15 minute windows.

prevent further load on the network but still obtain data.

C. Backend

To be able to collect data at a large scale and process the data near real time, we adopted a configuration similar to [10] and extended its scalability. We used 6 Amazon AWS EC2 instances each offering 4 cores and 8GB of memory. One instance ran the data receiver, a second instance aggregated individual locations into a crowd density map, and the remaining 4 instances ran a sharded MongoDB database. The data receiver is based on a load-balanced tornado web service that connects to a sharded mongoDB database. This configuration allows processing thousands of mobile devices simultaneously. The data has been processed at an interval of $2min$ and a heatmap visualizing the crowd density is rendered at a resolution of 4000x4000px covering the festival area. We used location data not older than $15min$ for the live view. While the live view is not the topic of this paper, we visualized the crowd density during the entire event in the command and control center of the police.

V. Dataset

The localization has been activated from friday July 5 2013 from 11am till sunday July 7 2013, 11:59. During these days the tracking has been limited to the area of the festival (see Fig 4 (left)). To capture incoming and leaving visitors, the tracking area included the main transportation hubs Zürich HB (main station), station Enge (west) and Stadelhofen. (east). For each user we collected amongst other parameters a generated unique identifier, longitude and latitude with localization accuracy, speed and direction, time of location acquisition, time of data upload, and the battery level. Overall the app has been downloaded about 56.000 times in total for Android (29%) and iPhone (71%). We received location updates from 29.000 users. Over the course of three days 25M GPS data points have been collected. Figure 5 shows the distribution of location updates sent by users over the period of three days.

A. Survey

In addition to the GPS data collection we conducted a survey that has been dispatched through the app. Besides demographic data we were interested in several categories: user satisfaction, data protection, safety, app distribution. In total we asked 36 multiple-choice or likert-scale questions.

Getting visitors aware in time of the existence of the app was crucial. Therefore, we highlight in this work questions regarding the distribution of the app: *How did you get aware of the app? (Facebook page of the festival, friends, press, app store, google)*, and word of mouth propagation: *Did you tell your friends about the app?*, *Which are the features you mentioned to your friends?*. We included the survey as part of the trophy collection game. That is, when answering the survey a trophy can be unlocked. To further increase the potential of a user answering we attached high score value compared to other trophies. As a result we received a total of 3.162 filled out surveys.

Fig. 6. Density for multiple attractions at different times and locations.

VI. Results

We extracted multiple crowd characteristics that provide actionable information for crowd managers and event organizers. We present multiple visualization techniques that allow data exploration and show the potential of GPS data for fine-grained capturing of crowd dynamics on large scale events. In this section we focus on data from the first of all three days to keep readability.

A. Crowd density

We adopted the algorithm of [11] to visualise crowd densities. Figure 6 shows a heat map of the visitor density. It can be clearly seen an increase of the crowd during ongoing attractions. While this visualization can be shown in real time it is limited to a snapshot of the current crowd status only and does not capture the crowd flow.

B. Crowd flow

To visualize the crowd flow we simply color-coded the walking speed (Fig 7) and direction (Fig 8). Both figures visualize the crowd flow *before*, *during*, and *after* the fireworks attraction at the lake. Before starting the fireworks, one can see in the walking speed that people start gathering and standing at the shore, while behind the spectator crowd, pedestrian are still walking. In the walking direction it can be seen that a significant amount of visitors are moving southwards to the lake (red) before the event. During the fireworks the mobility of the crowd at the lake's shore and viewpoints Quaibridge and Münsterbridge comes to a minimum. After the fireworks, the crowd moves back to the northern festival area (green). Interestingly, one can also clearly see that pedestrians form a right hand traffic. This organized crowd flow allows quick mobility and dissolving. However, since the observation is local in time and space, it does not allow for understanding the mobility of the pedestrian between specific locations.

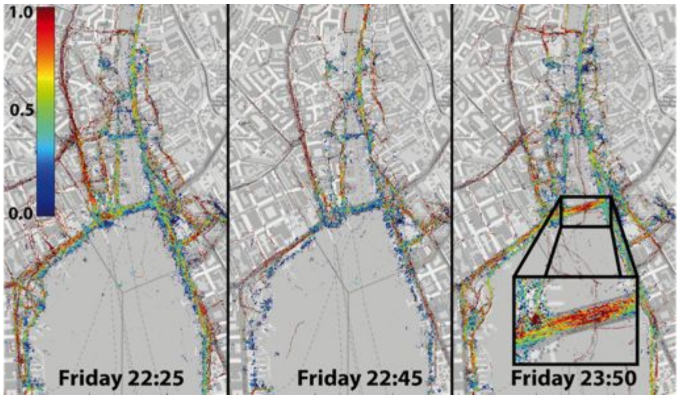

Fig. 7. Color-coded pedestrian speed (left) before (middle) during and after (right) the fireworks attraction.

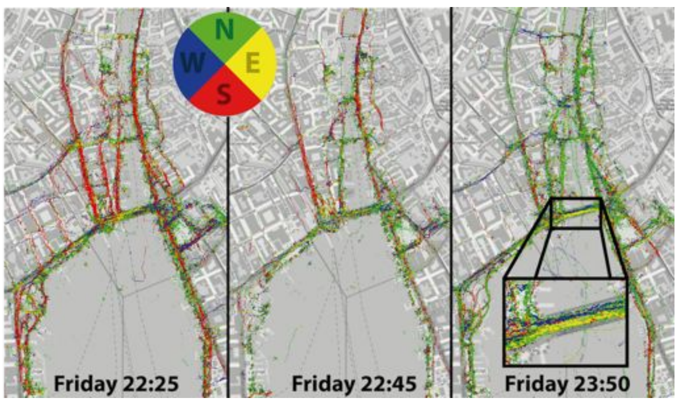

Fig. 8. Color-coded pedestrian direction (left) before (middle) during and after (right) the fireworks attraction.

C. Mobility graph

To understand the mobility of the user across the festival area, we created a mobility graph. To this end, we selected main locations spread over the event area (see Fig 9). The edges have been calculated by counting the frequency of users transiting from one location (or node) to another. Similarly the circle size has been calculated by the frequency of pedestrians observed in one location. It can be seen that the user's mobility clusters into two regions (1) *limmat, Muensterbruecke, and muensterhof* and (2) *Buerkliplatz, Quaibruecke, North-utoquai, South-utoquai*. This has two reasons. First, the festival area splits towards the lake, allowing pedestrians to move either west or east of the Limmat river. Second, while more food stands are located at the Limmat with attractions focused on daytime, the southern part is more popular at night time attracting different types of visitors.

D. Relative density timeseries

To see the effect of the schedule on the visitor mobility, we plotted for main locations and attraction items the relative densities of visitors (respectively app users). One can observe visitor behavior for different event times. For instance, at the beginning and at the end of the festival the train station Stadelhofen shows an increase in visitor ratio. During the "Flugprogramm" many visitors gather at the Quaibridge near the lake to follow the airplane show. Shortly after the Wakeboard-Show starts near Muensterbridge (15:30), which causes visitors to move there. Worth to mention is the steep drop after the fireworks ending (23:00). With visitor numbers peaking at that time (Fig. 5), such sudden attraction endings can cause a sudden mobility of the crowd. As a result critical situations can emerge. The event organizers leverage this information and plan for combined attractions that reduce (large) crowd movement for future events.

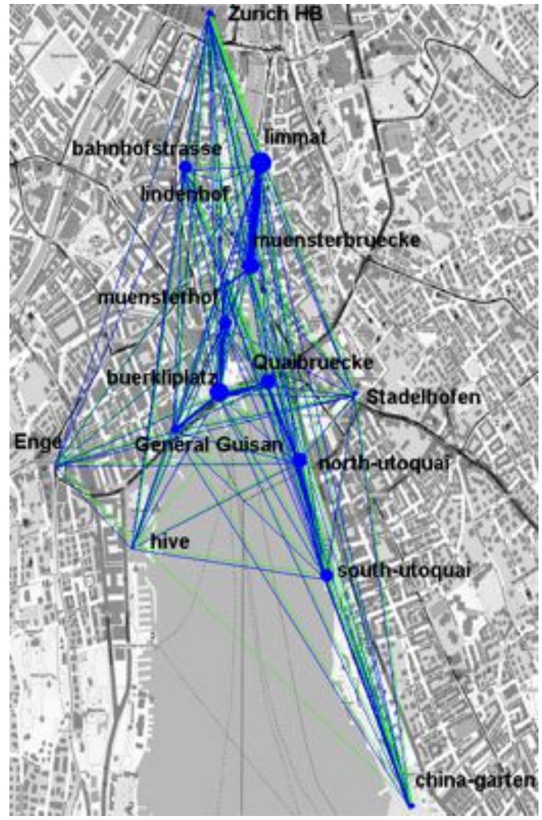

Fig. 9. Graph connecting most key locations on the festival area. Circle sizes visualise observed pedestrians, the edge weight the number of transiting pedestrians between locations. (friday 17:00 – saturday 2:00)

E. Survey

Since our approach is based on a participatory concept, marketing the app is a critical step to acquire as many users as possible. To this end, the app has been announced at the festival's press conference three weeks ahead of the event. As a result multiple local media outlets covered our experiment and the official app we provided. Also the organizers advertised the app on his channels such as the event website as well as, the facebook page. Consequently, we were interested which channels do reach the user the best and included this topic into our survey. 42% of the users got aware by the press, 33% by friends, while only 15% through the festival's website, respectively 9.8% through the festival facebook page (with 10K followers). Surprisingly, 10.7% of the users got aware through the Appstore. We believe that many visitors do not inform themselves specifically on the website. Through media coverage however, we obtained a high visibility and raised attention explicitly. This has been also observed in the download number that peaked on press releases.

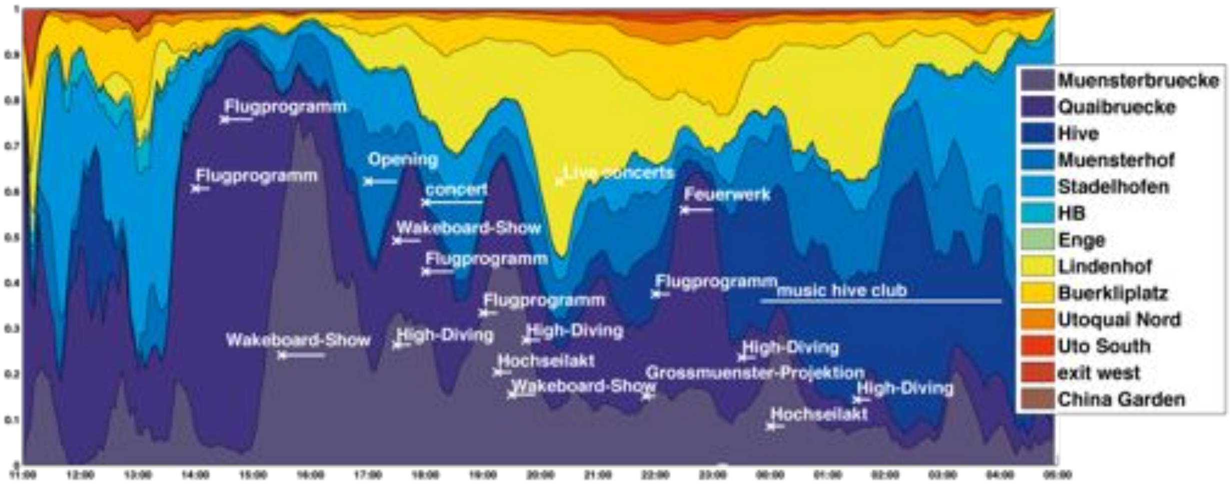

Fig. 10. Relative visitor ratio between main locations at the festival. Selected annotations for attractions are given by the white cross (start time) and duration (white line) and attached to the locations of happening.

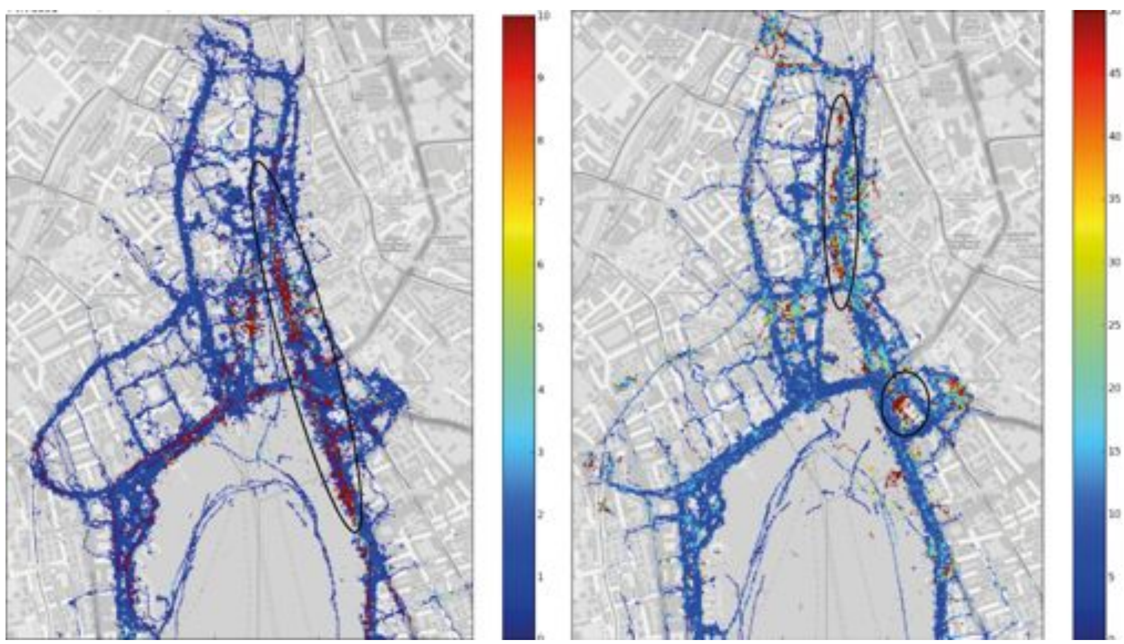

Fig. 11. Delay of transmission of location packets (left). GPS-accuracy obtained from the location manager (right).

Another important channel for distribution was word to mouth advertisement by the users. 88% of users told their friends about the app. More specifically 64% mentioned a festival map and program, 45% mentioned the festival game, while only 24% mentioned the friend finder and 15% the safety concept. These results show that features specifically designed for the festival are more likely to be mentioned to others and probably play a key role for raising awareness virally. The friend finder as a more generic feature can be found in existing apps already (whatsapp, glympse). Therefore it tends to be less interesting. While [12] shows that users accept apps for emergency usage, it shows here that it does not play a predominant role. The safety concept — i.e. the actual purpose of our study — is mentioned least often. We believe that apps for safety seems too abstract for users to grasp, since there is no direct benefit for the user. Instead the trophy collector, yet simple, attracted user interest. As soon as the first trophy would be activated users wished to collect more. One test user, though skeptical beforehand, mentioned "Oh, I already achieved a trophy? I want more now.". Therefore, we provided a trophy that users would achieve by just using the app for a minute after downloading. That way users experience early the achievement of a trophy and are engaged to achieve more trophies, hence allowing the location tracking during the festival. Most users answered with 3 on a likert scale from 1 to 3, if they enjoy collecting trophies. Interestingly, most users answered with 1 if collecting trophies would have an effect on their behavior. That is, while enjoying the collection passively, willingness to put effort in the collection is not given. This has two major advantages, (1) the user benefits from this feature and rates it positively, and (2) it does not influence his behaviour, which is what we try to avoid.

VII. Discussion and Lessons Learned

Our initial visualizations show the potential using visitor GPS localization to capture complex crowd dynamics during an event. As expected the 3G network has been congested in areas with larger crowds. Fig 11 (left) shows the delay of transmitted packets. It can be seen that for popular areas (left shore of the Limmat river) and along the eastside of the lake pakets have been delayed 10 or more minutes. While not relevant for this work, it shows that for real time crowd monitoring a network offloading would be required to reduce the dependency and the load on the 3G-network and to acquire location data by the user in time. Regarding the GPS accuracy shown in Fig 11 (right), we obtained on average a good accuracy (below 5m), even in congested areas. However along the eastside of Limmat river and on near the Stadelhofen train-station, we constantly experienced a low accuracy. Buildings and trees (in the latter case) prevent to obtain a GPS signal of sufficient quality.

Note that our approach captures data from visitors with activated app-localization, which is a subsample of the festival visitors. We did not investigate the correlation between the real visitor number and the app users. In [11] a correlation coefficient of more than 0.8 has been shown for a radius of 55m (828 of total users at an event with 500k visitors). In our experiment, the number of contributing user is 30x more. Therefore, we assume a strong correlation here as well.

To ensure a high user participation, we observed that media coverage is the most important seed for awareness. An important aspect are features using continuous localisation from which the visitor can directly benefit. This led users to tell their friends. Besides, Apple developer guidelines require to include a direct user benefit from background localization. Arguing for a participatory crowd behaviour monitoring only is not sufficient. Interestingly, although covered in press releases, the safety aspect did not raise much attention by the user. While the majority of users may not be altruistically motivated to activate localisation, many users (>50%) that downloaded the app were willing to trade sharing data with features they benefit from. To summarise we can provide following recommendations based on the development of our app:

- A simple, yet engaging trophy collection game helps to engage the user by providing him a direct benefit.
- Automatically starting the app using geo-Fence capability reduces the dependency on user interaction. Once the user gave his consent and started the app once, no further action is required to start the data collection.
- Integrate experimental aspects into app logic. By providing a trophy for an answered survey we were able to collect more than 3000 answers.
- A quick initial app distribution with help of local media outlets helps to enter the top ten lists in Appstores, increasing the app visibility. Here more than 10% of the users downloaded the app by discovering it in the Appstore.
- Integration into social media using suggestive messaging "I already have trophies, what about you?" offers the user to *show of* his trophy status to his friends and can stimulate viral distribution.

VIII. Conclusion

In this paper we presented a large scale data collection experiment for capturing crowd dynamics at the Züri Fäscht 2013. We provided best practises for executing a large-scale experiment and to acquire as many users as possible. Preliminary visualisations to explore the data show the potential of this data for fine-grained understanding of crowd behavior in light of the event schedule and location of attractions. Event organizers can leverage this data-driven insights to understand the effect of the schedule and how design and schedule attractions to optimally influence the crowd mobility in order to avoid sudden crowd movements that could eventually lead to stampedes. In the future, we would like to investigate user group profiles and extend previous work of estimating current crowd densities towards predictive density estimation. Thereby, we hope to identify locations with rising or decreasing visitor numbers and provide early warning mechanisms for dangerous crowd situations.

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