

Using Mobile Technology and a Participatory Sensing Approach for Crowd Monitoring and Management During Large-Scale Mass Gatherings

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1 Introduction

Understanding the behavior of pedestrian crowds in physical spaces is important in many areas ranging from urban planning, policy making at community and state level as well as design, and management of pedestrian facilities and transportation systems. Therefore, in the past few years, efforts have increased to study how human crowds form and how specific collective behavior patterns among the involved individuals emerge.

To do so, simulation tools have been used to study the self-organizing effects of large groups of pedestrians. Different models exist to simulate pedestrian dynamics. The most popular models include: Physical models that model pedestrians based on the analogy to gases or fluids; the social force model together with its extensions [1]; and cellular automata [2]. To perform a calibration of the model parameters, experiments under controlled conditions can be performed [3], [4] or video footage capturing pedestrian dynamics can be evaluated [5].

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Simulations can then be used to study the effect of architectural configurations on crowd dynamics, the emergence of collective behavior patterns in urban spaces, the influence of commuting patterns in a subway system, etc. and help to derive data-backed recommendations useful to advise policy makers and other stakeholders. One area where knowledge of crowd behaviour and pedestrian dynamics is of special importance is in the management and monitoring of large-scale mass events and city-wide festivals. Such mass events are popular gatherings and commonplace in human societies all over the world. They range from concerts with a few dozen attendees to events of massive scale like the Olympic Games with millions of spectators. It is a top priority for every organizer of such an event to be able to maintain a high standard of safety and to minimize the risk of incidents. Hence, establishing adequate safety measures is important. The knowledge of pedestrian and crowd dynamics together with simulation tools has enabled the identification of critical locations where dangerous crowd behaviors may emerge. This helps to design and proactively deploy crowd control mechanisms before an event to mitigate the risk of a fatal crowd incident. By generalizing the obtained findings, a set of safety regulations and procedures can be defined aiming to help optimally planning future events [6], [7].

However, deriving and deploying optimized emergency strategies based on simulations remains challenging due to many unpredictable factors inherent in the nature of such events. A key issue is that the actual number of attendees of such events may greatly deviate from estimations as it depends on factors like weather conditions, alternative events, and the program etc. Yet, the biggest challenge of all is that the behavior of the crowd during an event remains highly unpredictable. These challenges foster the need to detect critical crowd situations like overcrowding at an early stage in order to rapidly deploy adequate safety measures to mitigate the impact of a potentially dangerous situation. To do so, real-time information about the behavior of the crowd is required. At present, mostly video-based monitoring systems come into operation for this task. Recent research has focused on developing computer-based methods to automatically analyze the recorded scenes and to detect abnormal and potentially dangerous crowd situations [8], [9], [10], [11].

Vision-based approaches face several limitations: Cameras cannot capture elements outside their fields of view or occluded by other obstacles [10] and it is still difficult to fuse information from many cameras to obtain global situational awareness [12]. Another drawback is the need for good lighting conditions. Furthermore, as many events happen during the night, the application of a vision based approach is limited.

Some countries, such as the UK may also use helicopters to gain an overview either in daylight or at night with thermal imaging. The use of helicopters, however, is expensive and requires highly trained personnel; they are therefore usually only used for events, which are expected to be problematic.

As an alternative to traditional approaches, we see a big potential in monitoring crowd behaviors by tracking the locations of the attendees via their mobile phone. We believe that the high distribution of location-aware mobile phones in our

society and the acceptance to share personal context information enables such an approach. A big advantage of tracking users via their mobile phone is that it allows these users to obtain notifications directly from the event organizers and security personnel. This is of particular relevance during emergency situations as the provided information can be timely, highly targeted and personalized.

The aim of this Chapter is threefold: First, we discuss the technology for monitoring crowd behavior using mobile phones and present our framework, which allows us to collect real-time location data from event participants and to provide them with timely, targeted and personalized notifications in case of danger and emergency. Second, we identify crowd conditions hinting at critical situations and present a way to extract and visualize this information from the gathered data. In the third and final part, we present our findings obtained by deploying our system during two city-scale mass gatherings and by conducting interviews with the festival attendees using the app, the security personnel responsible for the safety of the event, as well as with policy makers responsible for contingency planning and implementation.

2 Monitoring Crowds with Mobile Phones

To infer crowd conditions, we require location information of festival attendees. We use attendees' mobile phones to obtain their location as most of today's mobile phones are situation and location aware.

Methods to obtain location information include GPS positioning and WiFi/GSM-fingerprinting [13]. With these approaches a location accuracy of up to 5 m can be obtained for GPS and around 20 m for WiFi-based positioning, respectively [14], [15]. However, on-device positioning methods require users to install and run a dedicated application on their mobile phones to collect the location updates. At first sight, such an approach may appear undesirable, as it can be assumed that people are not willing to install such an application. In the case of a mass gathering, this may mean that only a fraction of all attendees would run such an application and many would opt for not having their location tracked for various reasons, including privacy concerns and energy (battery life) considerations. Nevertheless, we believe this approach is still viable and promising by following a participatory sensing approach where users are motivated to deliberately share their location information by offering them a set of attractive incentives. In a preceding study, we have verified that people are willing to share privacy-sensitive location information if they receive some benefits or if they realize that sharing such information is for their own good and safety [16]. By following such an approach, we offer users full control of the recordings and allow them to disable it at anytime.

A further advantage of an approach following the on-device localization principle is that we can uniquely identify the location of a device and communicate with users directly, while maintaining the anonymity of the user. Thus providing every user with personalized information based on the location of the device.

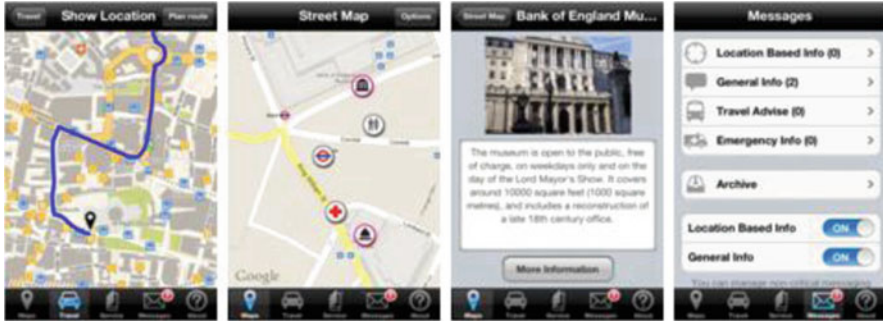


Fig. 1 Screenshots from the festival App

3 The S-App Framework

To collect location information of festival attendees, we developed a generic festival app for mobile devices which can be tailored to a specific event and provides the users with relevant, event-related information such as the festival program, a map indicating points of interest and background information (Fig. 1). These features are designed to be attractive and useful during the event to reach a large user base. Another incentive is provided through an intelligent notification system. Police forces and event organizers are able to send push notifications directly to the users' mobile phone and may inform them about critical crowd situations in certain areas and provide them with hints how any complications can be avoided e.g. by recommending alternative routes. Hereby, notifications can be targeted to people in a specific area so that only they receive the information, avoiding confusion among others, not affected users.

While a user is running the app, GPS location is regularly sampled with a frequency of 1Hz on the device and periodically sent to our servers running the CoenoSense¹ framework. CoenoSense acts as a centralized repository to store the location updates received from many mobile devices simultaneously and allows for real-time processing of the collected data. Figure 2 gives an overview of the platform's architecture. Our app offers users full control, at all times, over the sharing of data as data transmission can be disabled.

4 Crowd Conditions Hinting at Potentially Critical Situations

To improve pedestrians' safety, much research has been devoted to understanding crowd behaviors and to identify critical crowd conditions by conducting lab experiments and evaluating empirical data from real mass gatherings. An obvious,

¹ www.conosense.com

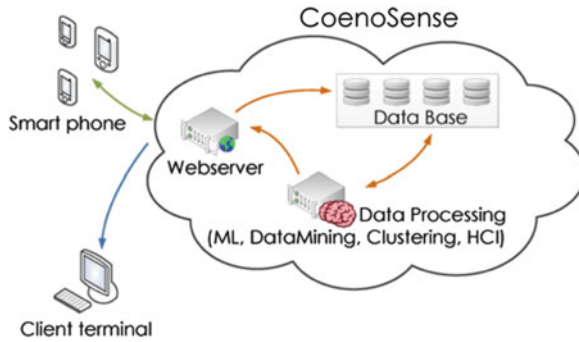


Fig. 2 Overview of the CoenoSense sensor data collection platform. Location updates are collected on mobile phones and periodically sent to a centralized server infrastructure where they are being stored in a data base. The collected data can be aggregated and processed in real-time to infer crowd characteristics. A terminal client can access this information via the web server

yet important crowd characteristic to assess the criticality of a situation is the density of a crowd. For example, most stampedes occurred in high-density crowds [3]. Different methods to measure crowd density and to identify dangerous overcrowding have been proposed [11]. The density, however, is not the only relevant characteristic. Also the movement velocity and the flow direction of a crowd have been identified as important indicators of critical situations [5], [17]. Methods for automatically measuring these conditions from location traces have been proposed in [4]. Johansson et al. identified a relation between flow and density of a crowd as they analyzed pedestrian dynamics of pilgrims visiting Makkah in Saudi-Arabia [5]. They measured a critical crowd density as soon as a breakdown of the flow occurred. They also identified crowd turbulence (irregular flows characterized by random displacement into all possible directions) occurring in high density crowds as especially dangerous, since the involved individuals are unable to self-control their motions and are pushed forwards and backwards by others [18]. In general, Helbing and Johansson [18], [5] suggest quantifying the hazard to the crowd (and with this the criticality of a situations in the crowd) by a measure they call *crowd pressure*, defined as the local pedestrian density multiplied by the variance of the local velocity of the crowd.

We have interviewed officers from the City of London Police Emergency Planning team to learn which crowd characteristics may be monitored during mass gatherings and which may give an early indication of crowd control issues. The City of London Police has a long history of policing and considerable experience in managing large scale events, often attended by thousands of people, within the City of London.

The interviewees reported that the main methods of gathering this information is through the monitoring of CCTV footage by Control Room staff and reports received from strategically deployed personnel on the ground. These methods cannot necessarily provide an overview of a large crowd that covers a widespread area as the section of the crowd that is monitored is limited to that which can be

seen by the CCTV operator and/or the person(s) deployed and can be quite resource intensive. Crowd density information can be an important parameter when assessing the potential seriousness of an incident and can be relatively easily inferred by observation. Other information of use in a crowd control situation or emergency is the crowd's movement velocity and its direction which can assist in determining where resources could be deployed. Crowd turbulence can be useful as an early indicator of potential crowd control situations, but can be hard to infer from observation. In the case of an actual crowd control situation or emergency, information about jammed exits or passageways is crucial to the deployment of appropriate countermeasures. As stated by the interviewees, the ability to identify potential crowd management issues from CCTV footage requires that the CCTV operator is able to recognise the possible indicators of these issues and has a high level of concentration during the event.

5 Information Mining and Decision Making

In the previous section we discussed measurable crowd characteristics important to assess the criticality of a situation. We want to provide emergency response personnel means to instantaneously assess the current crowd situation during mass gatherings. Displaying information as an overlay over a map is a common approach to present spatial information and allows for a quick assessment of the situation. In this section we will briefly discuss methods to obtain these measures from the collected GPS location updates and the obtained information can be visualized in an intuitive way to easily and quickly grasp the important information.

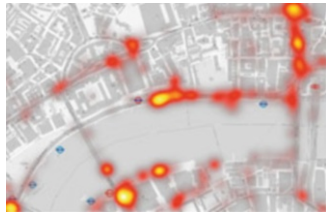
We chose heat map visualizations to convey crowd condition information. A heat map is a graphical representation of spatial data where regions are colored according to measurement values found at the specific location. Heat map visualizations have been used in different applications to convey various types of spatial information.

For example Paulos et al. use heat maps to illustrate carbon monoxide concentration distributions in urban spaces [19]. Spakov and Miniotas perform eye gaze analysis and use heat maps to understand which part of a website is looked at for the longest period [20].

5.1 Crowd Density

To visualize density information, we calculate a density estimation by applying a Kernel Density Estimation (KDE) [21] from the active users' location updates at a given time. KDE is a non-parametric way of creating a smooth map of density values in which the density at each location reflects the concentration of sample points. Hereby, each sample point contributes to the density estimation based on the

Fig. 3 Heat map
visualization of crowd
conditions: Crowd density



distance from it. By using a Gaussian kernel K , the density estimation \hat{d} at each location X_i at time t is given by

$$\hat{d}(X, t) = \frac{1}{h \cdot N} \sum_{i=1}^N K\left(\frac{X - X_{i,t}}{h}\right) \quad (1)$$

with h the Bandwidth (an application dependent smoothing parameter), and $X_{1,t} \dots X_{N,t}$ the users' current location. The Gaussian kernel function K is given by

$$K(u) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}u^2\right). \quad (2)$$

By determining the density values $\hat{d}(X, t)$ for each location and mapping each density value to a color using a color gradient, a heat map representing the participant density estimation is obtained. Figure 3 shows an example of such a heat map. The visualization can be read in the following way: The warmer the color, the higher the crowd density at that location. The previously introduced approach is suitable to visualize the concentration of data samples as a density representation.

It is in the nature of our data that we have areas with many active app users and by contrast, areas with very few; also large parts with no users. We are only able to infer crowd conditions in areas where location updates have been recorded. By calculating crowd conditions in an area, the amount of active users (and hence available location updates) is relevant: Information from areas where many location updates were recorded might be more important as this region seems to be more popular than in regions with only a few individuals. To visualize the crowd conditions and to also include the importance, we adjust the heat map generation method in the following way: We use a color gradient to indicate the crowd conditions at a location with a varying opacity level that corresponds to density at the location.

The calculation of the density is identical to the approach presented previously by performing a KDE using Eq. 1. The obtained density estimation for a location is then directly mapped to the opacity value of the point. A very low density value will result in an almost transparent point, while a high density value will result in a fully opaque point. Hence, the more users are situated around a location, the more intense

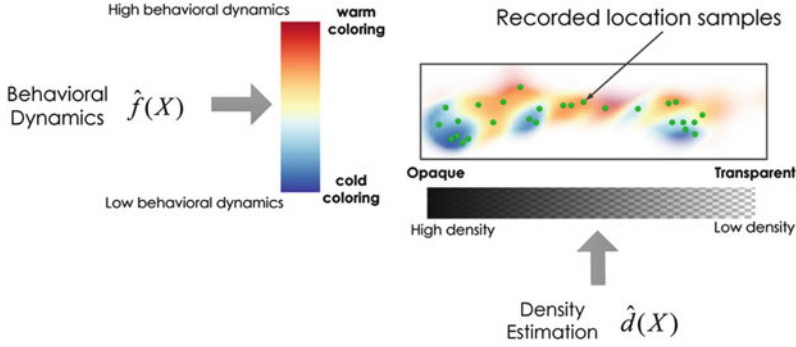


Fig. 4 Heat map of the crowd characteristics are generated by considering the density distribution of the recorded samples as an opacity value. The more users are situated around a location, the more intense the location color. Regions where no data is available remain transparent. The coloring is then determined by calculating the crowd conditions at the specific location and mapping this value to a color value using a color gradient

the location color. Regions where no data is available remain transparent. The coloring is then determined by calculating the crowd conditions at the specific location and mapping this value to a color value using a color gradient.

With this, for each point in space, we obtain an opacity value representing the density together with a color value for the crowd condition at that location. Figure 4 illustrates this process.

Next, we introduce the methodology to calculate the three remaining crowd conditions.

5.2 Crowd Velocity

The local crowd velocity can be seen as the weighted average velocity of each user at a given location by weighting the speed values of each user depending on the distance to that location with a Gaussian weighting scheme. With this, the formula to calculate the crowd movement velocity estimation $\hat{v}(X, t)$ at location X and time t is given by:

$$\hat{v}(X, t) = \frac{\sum_{i=1}^N v_{i,t} K\left(\frac{X-X_{i,t}}{h}\right)}{\sum_{i=1}^N K\left(\frac{X-X_{i,t}}{h}\right)} \quad (3)$$

where K is the Gaussian kernel according to Eq. 2 to determine the weight for each speed value $v_{i,t}$ and $X_{1,t} \dots X_{N,t}$ the locations of the active users.

For the heat map generation, the user density value is considered as the opacity and the crowd movement velocity estimation is mapped to a color gradient. Figure 5

Fig. 5 Heat map
visualization of crowd
conditions: Crowd velocity

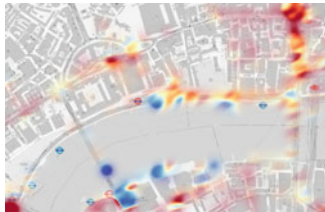
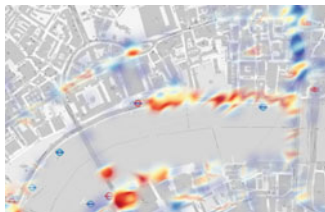


Fig. 6 Heat map
visualization of crowd
conditions: Crowd turbulence



shows an example of such a heat map. This heat map now conveys the following information: the warmer the color, the higher the movement dynamics and the more intense the color, the more users are to be found in this region.

5.3 Crowd Turbulence

To determine the crowd turbulence $\hat{c}(X, t)$ at location X and time t , we calculate the variance of the heading direction of the users at that location. We use the heading direction θ of each user to calculate the weighted circular variance introduced by Brundson et al. in [22] which is given as

$$\hat{c}(X, t) = 1 - \left| \frac{\sum_{i=1}^N K\left(\frac{X-X_{i,t}}{h}\right) z_{i,t}}{\sum_{i=1}^N K\left(\frac{X-X_{i,t}}{h}\right)} \right| \quad (4)$$

where $z_{i,t} = e^{i\theta_{i,t}}$, and $\theta_{i,t}$ is the heading angle of subject i at location X_i at time t . K is the Gaussian kernel according to Eq. 2 to determine the weight for each sample.

A heat map representation is now generated in the same way as previously by mapping the crowd turbulence values to colors using a color gradient and considering the user density values as opacity values. Figure 6 shows an example of such a heat map. The hotter the color, the larger the heading direction variance at this location, and thus the higher the turbulence. The more intense the color is, the higher the density of users in that spot.

Fig. 7 Heat map
visualization of crowd
conditions: Crowd pressure



5.4 Crowd Pressure

According to [18], the crowd pressure is given as

$$p(X, t) = d(X, t) \cdot Var_{X,t}(v) \quad (5)$$

where $d(X, t)$ is the local pedestrian density and $Var_{X,t}(v)$ the local velocity variance. In our case, we can obtain a density measure using Eq. 1 and can calculate the velocity variance as

$$Var_{X,t}(v) = \frac{\sum_{i=1}^N |v_{X_i,t} - \hat{v}(X, t)|^2 \cdot K\left(\frac{X-X_{i,t}}{h}\right)}{\sum_{i=1}^N K\left(\frac{X-X_{i,t}}{h}\right)} \quad (6)$$

where K is the Gaussian kernel according to Eq. 2 to determine the weight $X_{1,t} \dots X_{N,t}$ the locations of the active users. With this, the formula to calculate the crowd pressure estimation $\hat{p}(X, t)$ at the location X at time t is given by:

$$\hat{p}(X, t) = \hat{d}(X, t) \cdot Var_{X,t}(v) \quad (7)$$

The heat map is generated analogously to the other crowd conditions by mapping the crowd pressure to a color and combining it with the opacity obtained from the crowd density. Figure 7 shows an example of such a heat map.

6 System Trial and Interviews

To understand the usefulness of a real-time visualization of crowd conditions during mass gatherings, we deployed the system during various city-wide mass gatherings. Namely during the Notte Bianca Festival 2011 in Valletta, Malta, and the Lord Mayor's Show in London on 12th November 2011.

Fig. 8 A police officer in the control room is consulting the heat map visualization to assess the current crowd conditions



6.1 Lord Mayor's Show 2011 in London, UK

The Lord Mayor's Show is a street parade in the City of London, the historic core of London and the present financial centre. A new Lord Mayor of the City of London, is appointed every year and this public parade is organized to celebrate his inauguration. The day after being sworn in, the Lord Mayor and several others participate in a procession from the City of London to the Royal Courts of Justice in the City of Westminster, where the Lord Mayor swears his allegiance to the Crown. As in the Middle Ages, he is accompanied by military displays, marching bands, acrobats, dancers, displays of pomp and charity and symbols of London's ancient strength and resolve. The annual one-day event attracts about half a million spectators each year and is one of the City's longest established and best known annual events dating back to 1535.

The event starts at 11:00am and the processional route goes from the Mansion House via Bank, St. Paul's Cathedral and Fleet Street to the Aldwych; the tail of the procession will reach the Royal Courts at about 12.15pm. There is a short break during the ceremony, then the whole procession sets off again at 1pm to take the new Lord Mayor back to Mansion House. The procession finally ends at about 2.30pm when the last floats reach the City.

In collaboration with the event organizers, we tailored our festival app to the event and distributed it for free as the festival's official app. It was advertised on the Lord Mayor's Show website and available through Apple's iTunes app store.

Data collection was active between 00:01am and 11:59pm on November 12, but only if the user was in a specific geographical area around the festival venue. Over the whole day, we collected a total of 3'903'425 location updates from 827 different users. During the parade, location updates from a maximum of 244 users at any one time, were received simultaneously.

Security aspects of the Lord Mayor's Show 2011 were managed by the City of London Police. Together with the event organizers, they operated out of a Control Centre to monitor the event, from where they had access to the CCTV camera network and could communicate with strategically deployed personnel on the ground. Additionally, we provided access to a web interface displaying the heat map visualization of the density information. The photograph in Fig. 8 shows a police officer consulting the visualization to gain an overview of the current situation.

In the following we will report on feedback received from the City of London Police Emergency Planning team after the event, on the advantages and limitations of our system.

By asking the interviewees to compare our system to existing approaches, they reported that currently, mostly visually obtained information gathered from CCTV cameras and officers on the ground is used for crowd monitoring and management. Additionally, experience gained from policing the same event over several years, leads to a buildup of knowledge of where crowds gather, which routes are often jammed, etc. Such information is used to optimally distribute policing resources and event stewards over the event footprint. Additional crowd information could be obtained, if required, from the deployment of a police helicopter, which has equipment that can give an overview of the crowd from a higher vantage point during both day and night time. The use of a helicopter, however, is very expensive and resource intensive, and would not normally be used during events which are usually peaceful. All these methods can be used in conjunction to obtain an overall picture of the situation. A minimum of one person is required to monitor the CCTV footage in the Control Room and several people are needed on the ground especially in areas not covered by CCTV or at night when CCTV systems without infrared capability may be ineffective. The time required to detect a crowd problem (e.g. critical density, clogging of narrow pathways, etc.) is less when CCTV is available, but it is still difficult to build an overall picture of the whole situation.

Those viewing the heat map visualization during the Lord Mayor's Show 2011 found its interpretation was intuitive, with little explanation required. The heat map was seen as very helpful in obtaining an overview of the current crowd conditions at a glance. The police reported that the heat map provided an easier method of gaining an overview of crowds than from purely manual observation and/or CCTV system monitoring. The spatial resolution provided, was perceived to be sufficient for the nature of city streets. While more precise location information would be useful, it was stated that it was possible to get a sufficient overview of what was happening during the Show based on the visualization.

6.2 Lord Mayor's Show Survey and Telephone Interviews

The app users to the Lord Mayor's Show were asked to complete a short questionnaire and to participate in a short and anonymous telephone interview. The sample was small, and the findings are shown only as indicators, not as a statistically robust sample.

Seventy Percent of responders indicated that they would consult their iPhone app for advice during an emergency. They were then asked whether they would still consult their mobile phone if they were running for their lives; they answered that they would, but it depended on (a) the type of emergency and (b) whether official personnel were present and 30 % specified that they would prefer to follow instructions from figures of authority who were present, rather than from a mobile

phone. If such a figure of authority was not present, then they would take the advice given through the smart phone if (c) it came from an authoritative source they could trust (e.g. the police or emergency services); (d) the information was reliable and consistent with what they were experiencing locally; and (e) the technology was robust.

Asked how they would communicate the information to others, without the app, they responded that they would talk face to face with those in the vicinity; and would also use twitter and other social media to communicate with others further afield.

Although the app showed overcrowding during exit periods, such as after the fireworks; the overcrowding combined with some physical barriers, which restricted exit, led to crowd frustration and a potentially risky situation. One insight from the interviews was that the visualisation was not enough to establish the position of barriers for future events, but that additional information in terms of context and understanding of crowd behaviour, was also needed.

The experiment showed that the app was found to be very useful during the event, both for users and organisers, but for a deeper understanding of crowd behaviour during such events and for future planning, short surveys and interviews provide a deeper context, not available through the technology on its own.

6.3 Notte Bianca 2011 in Valletta, Malta

The Notte Bianca is an annual event held in Valletta, Capital City of Malta, aiming to promote culture through arts. The event runs from around 7.30pm until the early hours of the morning with an estimated 40,000–70,000 people flocking into the city, visiting the numerous shows, activities, and exhibitions running throughout the night at various locations across the city. Although, the city is closed to traffic during the event, there are still problems related to traffic and parking as a considerable number of people, park their cars in the car parks available or in the surrounding nearby towns. During the evening, various museums, and other historical places, including the Parliament and the Prime Minister's offices are open to the general public with free access, thus generating a relatively large crowd and queues waiting at the doors.

The Civil Protection Department of Malta (CPD) is one of the officially appointed teams of emergency first responders that are on location throughout the night, in the event of any emergency. Other agencies, including the Malta Red Cross, are also on location, ready to help in the case of any emergency.

Although there is direct communication amongst the various emergency services throughout the event, it is not always easy to reach the responders spread across the city by radio contact. Communication between the Notte Bianca organisers and the CPD is also difficult to control and manage, and is subject to a number of challenges that are often difficult to overcome. In addition, the Notte Bianca organisers have very limited information and feedback from the people attending the event, in terms

of the venues and activity which attract the largest number of people, or those which generate the greatest amount of congestion in the crowd movement.

Although the city is closed to the traffic for the evening and throughout the night, there are areas, in which there is a considerable increase in crowd density, thus causing some turbulence in the flow of people as they move towards different venues and activities. During these periods, an emergency is quite likely to occur, as people may be subject to medically-related failures and would thus be in need of immediate medical attention. When the CPD and the Ministry of Home Affairs officials were first contacted, with a description of the possible services that might be offered by the SOCIONICAL app, the potential which such an app holds for the protection of the individual, was immediately recognised and all the possible support was thus given to be able to pilot this app for the event. The most important features, which this app holds for an emergency rescue team, include amongst others the real time crowd density information, which would be important to identify areas in which an emergency would be most likely to occur. The more information which is gathered from the people attending the event, through their movement, direction and speed of travel – all gathered from the app running on their smart phone, the easier it would be for any emergency service to provide in-time rescue and first-response service. Moreover the possibility of relaying back important information to users and providing them with alternative route directions, especially in areas of heavy congestion in crowd movement, would also help in easing inconvenience as well as possibly preventing any incidents which might occur. The Notte Bianca organisers, as well as the Mayor of the city of Valletta, were also very helpful and supportive in setting up the pilot for the app. Since this was a pilot to test the technology, statistical information was not available for analysis. The potential, however, is recognized; as such information might lead to the improvement of this annual event for the people who attend both in terms of the individual's safety and protection, as well as in the entertainment value, that such an event promises for attendees.

7 Conclusion

Understanding the behavior of pedestrian crowds in physical spaces in real-time is important for many fields of application. In this work, we introduce a framework to infer real-time crowd conditions by tracking people's movement traces via their mobile phone. By aggregating and visualizing this information as heat maps, we can offer an intuitive way to obtain a global view of the crowd situation and to assess different crowd conditions instantaneously. Our framework also allows direct interaction with each user individually. This can be used to directly communicate with the users and provide them with targeted and highly personalized information e.g. in the case of a critical situation. That each person can be notified individually has the advantage that different users may receive different information e.g. on how to behave and where to go during an evacuation. This can be used

to streamline the evacuation process by sending users not only to the nearest available exit but to also perform a load balancing by distributing them across all suitable exits. This is a great advantage over traditional systems like loudspeakers or information screens.

There are, however, some challenges inherent in this approach. Mainly, due to the participatory nature of our sensing approach, the system can only collect data from the users of the mobile phone app, which form only a subset of all attendees. Keeping this in mind, two aspects are crucial:

- **Ensuring a large user base:** Providing attractive incentives is important to reach a large user base. We reach this by offering festival attendees an enhanced experience by using our festival app. Hereby, a user study has revealed a set of attractive features and helped us to design the app accordingly [16]. Advertising the app in an appropriate way is key. Recently, big events started to offer their own app. Our tools can easily be integrated into their existing solution.
- **Seeing users as probes:** By designing robust crowd condition measures that are robust with respect to the ratio of the app users, it is possible to extract accurate crowd condition measures, even when not all attendees are being tracked. To do so, we have to consider the users as probes and conclude from their behavior the overall crowd situation. This can be achieved e.g. through calibration of the data. While the ratio of app users to festival attendees remains unknown, we assume that the spatio-temporal distribution of users reflects the distribution of attendees at any one time during the event. With this assumption in mind, an actual crowd density estimation can still be obtained by determining the ratio of mobile app users to festival users in a given area e.g. by inspecting CCTV recordings. This ratio has to be updated periodically throughout the event.

The framework can provide the following features of value to policy makers: (a) an overview, not available by the usual means of crowd monitoring including CCTV, as it can cover a larger area at any one time, for longer; (b) it is cheaper than a helicopter. Helicopters do have thermal imagery technology, but they are expensive and need highly trained personnel to fly them and on the ground; (c) especially valuable at night, (e.g. during the Fireworks display at the LMS), when CCTV cameras are not effective; (d) can be used to plan future events and to position barriers, ambulance stations, etc. more accurately; (e) using the heat map is intuitive and does not require any training, although it does need a trained officer to identify potential critical issues and take appropriate action. Overall the framework was found by the organisers and emergency services to be a valuable tool in taking appropriate action quickly to avoid a potential incident, thus increasing safety.

From a complexity theory perspective it shows evolving emergent crowd dynamics; it can be used to illustrate self-organising behavior of groups; and the messaging feature would contribute to active co-evolution between users and emergency personnel.

During the Lord Mayor's Show 2011, only the emergency response personnel and security personnel had access to the real-time visualization of the crowd conditions. It will be of further interest from a complexity science point of view

to investigate the dynamics evolving when festival attendees themselves are given access to such crowd information. It would then be of interest to study how the available information is considered in their decision making process and what kind of co-evolutionary dynamics will emerge. Ultimately, we would like to understand if such information can help to lower the number of overcrowded situations, while decreasing turbulence and crowd pressure.

So far, we used the location updates from the users to assess the current crowd state and visualized this information. The relevance has been evaluated in this work. However, we believe there is much that can be done with this data for mitigating the risk of crowd incidents. Of great interest would then be to evaluate if this data can be used to predict upcoming crowd situations. So to speak, the available locations information from the users can be used to predict the future behavior of the crowd and identify potentially dangerous situations that may happen in the near future. With this, counter measures can be employed at a very early stage in order to prevent any potentially fatal incident.

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