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Real-time crowd monitoring dashboard

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ABSTRACT

Crowd management measures have become more and more important not only to guarantee safety, but also to maintain good accessibility of public function, high throughput of pedestrian flows and high-quality public spaces, both during events and in daily operations. To support crowd management, information is necessary on the pedestrian traffic state for decision making on the operational level, and to support policy making regarding longer-term infrastructural changes. This paper introduces an innovative crowd monitoring system, which can be used in real-time, as well as for the analyses on historical data. The system consists of three components, namely data collection, traffic engineering functions and visualization. The core of the system consists of the traffic state estimation functions, using real-time data as input to calculate indicators, such as number of pedestrians present, speed, flow, travel time and route splits. The real-time data comes from counting systems, Wi-Fi sensors, and GPS trackers, but the system can easily be extended to include other types of sensors. Special attention has been paid to the visualization of the indicators, as it needs to be accurate, intuitive and flexible, to adjust to the user needs.

1. INTRODUCTION

Crowd management measures have become inevitable to guarantee event safety. Nowadays, these measures turn out to be necessary in daily operations as well, due to the crowdedness in the city. Here, crowd management is defined as the systematic preventive planning and steering of the orderly course of gatherings with large crowds.

In essence, a crowd monitoring dashboard is a monitoring system that makes use of real-time updates from sensor-systems in order to assess the current pedestrian traffic state. Only a small number of operational real-time crowd monitoring systems exist, most of which are either employed at large transfer hubs or large-scale events. For example, a range of technologies is used by (*1*,*2*), among other things Bluetooth, Wi-Fi, infra-red and public transit check-in information, to determine origin-destination patterns in and between train stations. Similarly, Wi-Fi and camera data (*3*-*5*) is used to estimate pedestrian flows and the level-of-service in train stations, another study (*6*) adopted several vehicle and pedestrian related data streams to determine the traffic state nearby a triple-event location in the Netherlands.

Next to these integrated monitoring systems, which make use of multiple different types of sensor systems, earlier works have studied the application of one single technology to derive features from the crowd. Rudimentary techniques, based on CCTV footage were used by multiple researchers to detect anomalies in traffic flows in metro stations (*7*,*8*). Other computer vision techniques were used by (*9*-*11*) to determine crowd movements at train stations and the Hajj. Xi et al. (*12*) used the signal information of a camera to count the crowd and Nielsen et al. (*13*) made use of temperature sensors to determine how many people were present at a certain location. The sensing of GSM signals was used to analyze crowd travel behavior (*14*-*17*), while social media outlets such as Twitter and Instagram have been used to identify mobility patterns (*18*,*19*).

Up to this moment in time, most of the analysis and monitoring systems presented above have worked from the technology to the application. Yet, the authors are of the opinion that the starting point for the development of a real-time crowd monitoring system is an overview of the required information. Based on the information need one can work backwards and adopt the technologies that best serve the needs identified by the organization. A discussion with the crowd managers and a study of the crowd management plan showed that most of the triggers to deploy the measures are related to the basic traffic state characteristics, i.e. density, flow and speed. In addition, route splits and travel times are identified as valuable input.

This paper introduces an innovative (real-time) crowd monitoring system that incorporates multiple distinct sensor types to identify crowd movements. This monitoring system will be used as input for crowd managers and will also provide information to traffic and city operators for long term design and safety applications. Based on the functional requirements introduced in the introduction, the system design should be able to deal with a number of technical challenges to make the system work in real-time. First of all, the sensors are only temporal, which implies that ad hoc facilities need to be installed, such as electricity and (fast) internet connections. Secondly, the system can only be calibrated when all the sensors are installed and connected to the crowd monitoring system. This implies a short period available for calibration. Moreover, the system should work real-time, and deliver reliable and accurate information on large pedestrian flows. This means that most existent techniques (both sensor and traffic state estimation techniques) do not suffice. We have therefore developed a system from scratch, using those techniques that together covered our set of requirements.

This paper starts with a description of the functional specifications and the system design. Then, the real-time data collection techniques have been elaborated upon, taking the event SAIL 2015 as an example. In chapter 5, the different state estimation techniques are shortly introduced, followed by a short overview of the current visualization, based on the application for the Amsterdam Red Light District. Then, lessons learnt are shown from a number of applications of the crowd monitoring dashboard. We end with conclusions and recommendations for future work.

2. FUNCTIONAL AND TECHNICAL REQUIREMENTS

Most crowd management systems cover a (hierarchical) set of goals, namely to avoid and to control unsafe situations (safety), provide high pedestrian accessibility of public functions and high throughput of traffic in a larger area around crowded location (accessibility and flow) and provide high-quality public spaces, in which pedestrians feel welcome, safe and comfortable (quality and comfort).

The first goal (avoid unsafe situations) needs to be met at all times in order to ensure the safety of everyone involved in an event, and is as such essential for events to take place and pedestrian infrastructure to remain accessible. In contrast, the second and third goals are convenient, but not indispensable.

A round-the-robin between universities, event organizers, transfer hub managers and municipalities uncovers that a crowd monitoring system should support crowd management as well as crowd control. This leads to the following requirements:

1. A well-functioning monitoring system that can be operational 24/7.
2. A well-functioning analysis system, supporting the decision making to guarantee public order and safety.
3. A system that can be embedded in the current organization, in order to fit in the operational processes within the municipality and the distribution of tasks and authorities of the users.
4. A scalable application, which makes its extension simple and cost-efficient.

Recent experiences with crowd monitoring systems show that the functioning of a crowd monitoring system is very dependent on the manner in which the system is embedded in the organization. That is, if organizations have a need for quantitative (real-time) insights into the pedestrian traffic state that is covered by the system, it is apparent to invest in the further development and polishing of such a system. Therefore, the third functional requirement should be broken down further to provide more comprehensive insights into the manner in which a crowd monitoring system can be embedded in the current organization. In general, this third requirement covers three levels of embedding, being

1. Operational use, covering among other things the control of pedestrian flows in the city, communication with police and other first response services and identification of pedestrian flow bottlenecks or crowdedness in the city.
2. Tactical use, to derive scenarios and threshold values for traffic state indicators, and the corresponding measures.
3. Strategic use, to analyze historical data to support policy making in traffic and the design of public space as well as for mobility and safety applications.

The three levels of embedding encompass the information need of very diverse organizations, such as the municipality (different departments with different roles related to traffic management, public space and the regulation of large-scale events), the police, security organizations and event organizations. A well-embedded crowd monitoring system will ensure that insights regarding all three levels of embedding can be derived by means of the system. Note that, only for operational use real-time updates are an essential requirement.

In addition to these functional requirements, technical requirements should be met to provide a reliable monitoring dashboard which can be operational 24/7. This refers to the technical availability and functioning of the sensors (e.g. minimization of the maximum down time and understanding the reliability of the sensor measurements under normal and exceptional crowd and weather conditions), the database (e.g. ability to receive, store and look-up large quantities of timestamped data of numerical and string formats on the fly), the server (e.g. combination and analysis of time sensitive data) as well as the network reliability to send the information from the sensors to the database.

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3. SYSTEM DESIGN

The real-time crowd monitoring system consists of the data collection, data analysis and state estimation and the visualization. An overview of these elements and how these elements jointly form a real-time crowd monitoring system is shown in FIGURE 1.

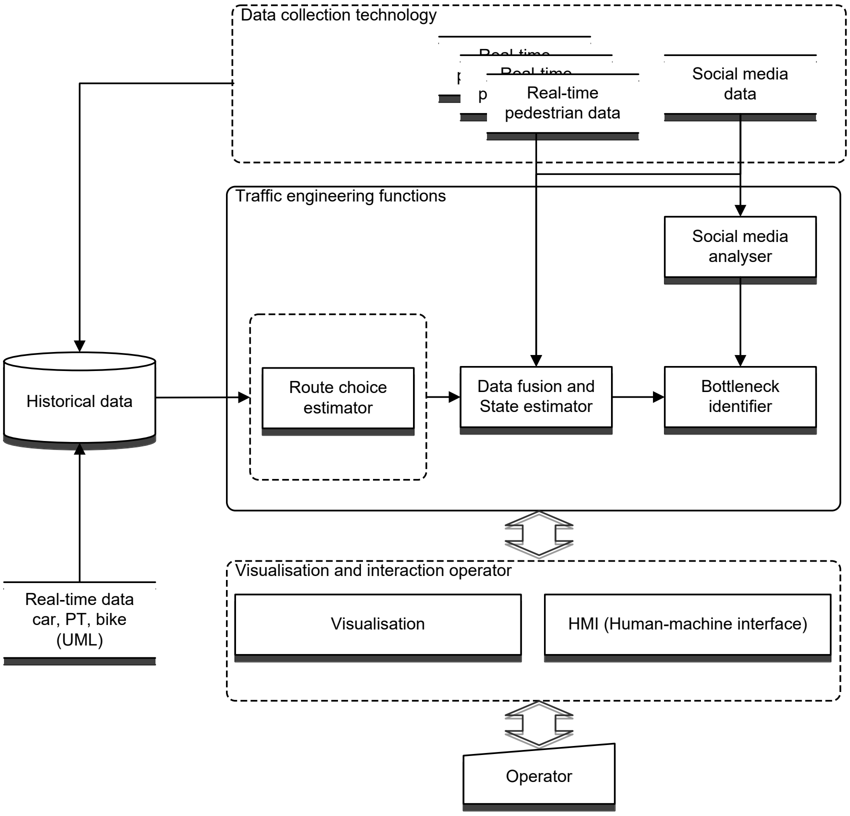

FIGURE 1 Functional architecture for a crowd monitoring system.

FIGURE 1 shows different data collection components, mostly to collect data on the pedestrian flows such as traffic count and number of pedestrians in an area, but also to collect social media data to describe the flow composition. Essential in this system is the data fusion, showing the importance of not only the quality of the individual data sources, but also the (different) semantic characteristics of the data sources (*20*,*21*). The historical data can be used to perform analyses before the event, but in case of a longer history, these data also support the state estimation.

The traffic engineering functions compose the heart of the crowd monitoring system, where the different data sources are fused and analyzed. Its main component is the state estimator, aiming to estimate density, speed and flow. The social media analyzer analyses social media data to generate insights into the crowd composition and the occurrence of bottlenecks in general. The route choice estimation aims to predict how crowdedness will move through the network. It uses route splits based on historical data and intends to identify origin-destination relations. The bottleneck identifier determines based on the actual and expected traffic state (where the output of the route choice estimator gives insight into the flow dynamics in the network), combined with event information and possible information from social media data, whether a bottleneck may occur as well as its cause. Knowing this cause is essential to identify efficient crowd management measures.

Visualization of the traffic state is essential in the communication with the user. This implies the development of an accessible and intuitive interface, showing the information needed for crowd management. Not only the choice of the indicators is addressed, also the visualization (e.g. choice of thresholds and colors).

Let us give an example of this range of functions. We start with a data collection system counting the number of persons passing per minute at a given cross-section (data collection technology element). The state estimator translates this number in a flow (number of pedestrians per minute), while the bottleneck identifier compares this flow to the capacity of this cross-section. If the flow turns out to be near capacity, and the route choice estimator shows that another large pedestrian will arrive at this cross-section within a few moments, the bottleneck identifier identifies this cross-section as potential bottleneck (traffic engineering functions). In the visualization, this potential bottleneck is identified to the user, as input for further crowd management measures.

With respect to the technical design, we have created a database with an availability of 99.8%. This database consists of several timestamped tables, each containing information from a certain type of sensor for a specific event (dashboard). Depending on the sensor type, the sensors send their information to this database through a hardwired or wireless connections (Wi-Fi + GSM), in both cases with different GSM networks as backup systems. Sensors have local storage facilities and battery packs to overcome the temporary loss of connection and/or power failures. The moment the sensor is reconnected, the local information is sent to the database according to a first-in first-out principle in order to restore to most insightful information regarding the current traffic state first. The traffic engineering functions then make sure that the data is correctly processed and included in the estimation process. Within these functions filters are included to determine the reliability of the incoming data. Visualization is performed through a password-protected website (URL), accessible for a group of users that have been registered in advance by the administrator of the system.

The most essential functional requirements on the Crowd Monitoring Dashboard are related to the protection of privacy, of which the most important ones are mentioned below. First and foremost, all data that is deemed privacy sensitive at the moment of detection by the sensors (e.g. MAC-addresses or video feeds), is hashed at the source or stripped of privacy sensitive features before it is transmitted to the database. The connection between the database and the sensors is secured via a HTTPS protocol. At data-ingestion, hashed MAC-addresses are rehashed in order to deprivitize them even further. The running memory of the system retains a temporary image of the ingested information, next to that, the completely privacy insensitive information (e.g. counts, trends, route splits) is stored in the database for long-term research.

4. DATA COLLECTION

Input for the real-time crowd monitoring system is real-time data describing the pedestrian flows in the area. The necessary sensors should on the one hand observe accurately, while on the other hand sending the collected data to a central database with an as short as possible delay. Moreover, the information needs require different types of measurement. Local measurements cover traffic dynamics at specific locations in the network (e.g. an entrance), while global measurements refer to the traffic flows in the network. Both types can be further divided into measurements with a microscopic perspective that relate to movements of individual persons, while macroscopic measurements deal with movements of traffic flows (*22*). To gather both local and global measurements, in previous crowd monitoring dashboards we have used counting systems, Wi-Fi sensors and GPS trackers in the crowd monitoring dashboard (*20*). In addition, social media data have been collected (*23*); we are currently investigating how to include these analyses in a crowd monitoring system.

Counting systems count the number of pedestrians passing a cross section in each direction. The aggregation period of the counts is 60 seconds, which has shown to be sufficiently accurate to give an accurate overview of both the current situation and the recent trend. The counting system used consists of a high density video camera equipped with counting software (*24*,*25*). This way, the video footage is analyzed at the source and not stored (privacy reasons). Only the aggregate counts per minute are sent through either a hardwired network connection or a GSM connection to the central database. The average counting accuracy is 95% (*25*), though it decreases for increasing density.

Wi-Fi sensors are passive scanners, recognizing the MAC-address of a mobile device with an active Wi-Fi connection (such as smartphones, tablets and smartwatches) within approximately 25 meters of the location of the Wi-Fi sensor. The exact configuration of the Wi-Fi sensors is dependent on the placement location and the company that installs the sensors. As such, even though the setup of the Wi-Fi sensor is important when configuring and using the CMD, general statements about the technical details of the Wi-Fi sensors are difficult to present, given that they vary quite heavily between the use-cases. It pseudonymizes this information before sending it to the server (so-called hashing). We have developed a filter to identify hashed MAC addresses of Wi-Fi enabled devices that move between two sensors to derive routes, route splits and travel times between sensors. Moreover, Wi-Fi counts can be obtained at each sensor. However, static devices and other noise need to be filtered to get accurate results, see (*26*).

GPS trackers record their location each 10-20 seconds. We used dedicated GPS trackers, sending their position through the GSM network to a central server (*27*). The quality is dependent on the environment: high-rise buildings and water are known to cause reflections, and thus a lower accuracy (e.g. pedestrian might be located at the other side of the canal).

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The location of the sensors to collect real-time data depends on the application. As an example, we use SAIL Amsterdam to indicate the sensor locations (*28*). SAIL Amsterdam is the largest free nautical event in Europe. During this five-yearly event, in 2015 taking place between August, 19 and August, 23, more than 600 tall ships moor in and around the IJ-port in Amsterdam. More than 2 million visitors have enjoyed the events during SAIL Amsterdam, most of them in the city center of Amsterdam. Data have been collected in the so-called orange ocean, a walking route round the IJ-port with a length of 5 km. To this end, 8 counting systems, 20 Wi-Fi sensors and 100 GPS trackers (collecting in total 324 GPS tracks) have been used, see FIGURE 2.

The counting systems appeared to be very reliable and sufficiently accurate. The Wi-Fi sensors measure around 30% of the counts from counting systems, while only 50% of these Wi-Fi counts match unique devices (including noise, consisting of among other things electronic devices with Wi-Fi connections). As the Wi-Fi sensors are passive for privacy reasons, the matching rate between two adjacent Wi- Fi sensors is only 3~4 %. GPS trackers provided detailed but not continuous information on individual route choice behavior, and the sample size is rather small compared to the Wi-Fi data. More details on the information of these sensors can be found in (*20*).

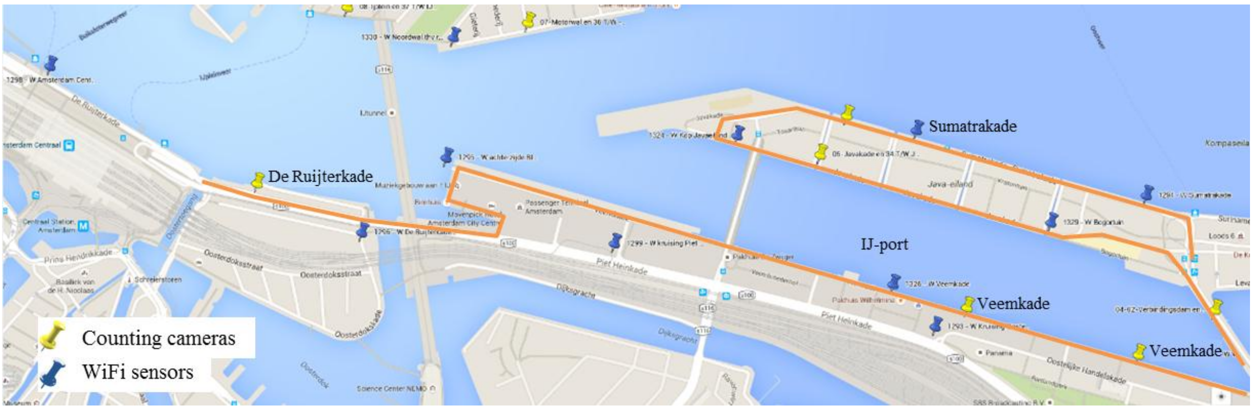

FIGURE 2 Overview of the data collection locations in the orange ocean, consisting of the orange line indicating the walking route along the tall ships. Yellow pushpins indicate combined counting systems and Wi-Fi sensors; blue pushpins indicate Wi-Fi sensors. GPS trackers have been distributed at the Amsterdam Central railway station (on the left of this figure).

5. TRAFFIC STATE ESTIMATION

We developed/adopted/adapted several traffic state algorithms in order to function during large-scale outdoor events. To derive the traffic states (and more specifically, to calculate travel time (speed), density and flow) from the collected data, three state estimation methods have been developed (*21*):

- Travel time estimation method based on the Buckley method (*29*).
- NWi-Fi method, using Wi-Fi counts to determine number of pedestrians.
- Flow estimation using the BPR method (*30*).

The corresponding formulas, as well as the relation to the collected data, are shown in TABLE 1. More details on the state estimation methods can be found in (*21*), while a comparison of the information derived with these formulas is shown in (*20*). All data sources provide necessary (and reasonable) input for the estimation methods. Given the large visitor flows during SAIL 2015, the Wi-Fi dataset was sufficiently large to get information on routes and travel times (speeds). However, an accurate estimation of the penetration rate (ratio between total flow and share of detected mobile devices) is essential to calculate a correct traffic state, see also (*26*). Though the sample size of GPS tracks was too small for the SAIL event, the GPS data (e.g., from mobile crowd sensing networks with a higher penetration) may serve as a promising data source for the estimation algorithms.

TABLE 1 Relation between Traffic State Estimation Methods and Data Sources, based on (*21*). The Numbering (I – IV) shows the Order in which the Indicators are estimated.

	Raw data	Travel time TT	Speed $\boldsymbol{v}$	Number of pedestrians $\boldsymbol{k}$	Flow $\boldsymbol{q}$
Travel time estimation based on Buckley method (M1)	Wi-Fi travel time samples	Buckley Method - Composite TT model $^{\text{I}}$	$v = \frac{L}{TT}$ $^{\text{II}}$	$k = FD(v)$ $^{\text{III}}$	$q = k \cdot v$ $^{\text{IV}}$
NWi-Fi method to estimate density (M2)	Counts and Wi-Fi matches	$TT = \frac{L}{v}$ $^{\text{III}}$	$v = FD(k)$ $^{\text{II}}$	$k = \frac{NWi\text{-}Fi}{P \cdot A}$ $^{\text{I}}$	$q = k \cdot v$ $^{\text{III}}$
BPR-based method and flow estimation (M3)	Counts and Wi-Fi matches	$TT = BPR(q)$ $^{\text{II}}$	$v = \frac{L}{TT}$ $^{\text{II}}$	$k = \frac{q}{v}$ $^{\text{IV}}$	$q = \bar{q}$ $^{\text{I}}$

The comparison in (*21*) has shown that all proposed estimation algorithms can provide reasonable results at selected spots (e.g., closed-off sections). However, it is clear that the methods based directly on the data provide best results. This implies that for real-time application a combination of methods is recommended: travel time estimation based on the Buckley method, NWi-Fi method for density estimation, and the BPR-based method for flow estimation. Though each method in itself will provide the most accurate estimation, the drawback is that the traffic state estimates may not be consistent, as they are based on different data sources with different accuracy and assumptions. More insights into these potential inconsistencies and further development of the robustness of the traffic state estimation methods are ongoing research. Here, inconsistencies of the density and the flow, especially when resulting in underestimation, are most important to be solved.

As the crowd monitoring dashboard is a real-time dashboard, the calculations should be as efficient as possible. This implies that the abovementioned algorithms for data fusion and traffic state estimation are relatively simple. At the moment, the algorithms have been implemented in Matlab and run on a generic desktop computer (Intel Xeon 3.20 GHz with Windows 7(x64).

6. VISUALIZATION

The visualization depends highly on the needs and desires of the users. In the introduction, the users of the crowd monitoring dashboard are diverse. A brainstorm with these users resulted for each crowd management goal in a set of user requirements and the presentation thereof, as shown in TABLE 2.

TABLE 2 User Requirements for the Crowd Monitoring System, adapted from (*31*). Underlined the primary Requirements, in Italics the secondary Requirements and in normal Font the Nice-to-haves

	User requirements	**Presentation**
Safety	Occupancy (count of persons per square meter)	Signal values using colors
Accessibility and throughput	Direction (inflow and outflow) at a cross-section Route (through an area) Speed (in a corridor) *Movement (derived from direction and route)* Location of fences and other materials for crowd management measures	Signal values using colors *Generic information on the situation and events (time line, agenda, routes, historical data)*
Quality and comfort	Occupancy (count of persons per square meter) Crowd composition Perception of the situation/event	Signal values using colors

TABLE 2 shows that the required information consists of four indicators, namely density, speed, throughput and direction of the movement (route splits). This information should be provided using a good, intuitive and user-friendly presentation of the (processed) data. In further discussions with the users of the crowd monitoring platform we found out that the alerts depend on the situation, e.g. during rain the threshold value for occupancy is lower than in sunny conditions. As the decision to initiate a crowd management measure is taken by the crowd managers, not by the monitoring dashboard, we have chosen to use a color code to indicate the different conditions, thus showing the (objective) traffic state.

The dashboard is accessible through a website, and is platform independent. The user can personalize its dashboard, and through cookies these settings are stored in order to be kept the next time the dashboard is accessed.

FIGURE 3 shows some examples of the visualization in the crowd monitoring dashboard. As the visualization has developed since our first application during SAIL 2015, we show its latest version, applied in the Amsterdam Red Light District. Here, instead of monitoring an event, we monitor the daily operations, as the local inhabitants perceive crowdedness due to the presence of visitors and commuters. A more detailed description is given of the elements in FIGURE 3a, as these seem to be the most common visualizations. The caption of FIGURE 3b gives details on the additional types of information. On the left hand side of the figure, the counts of the previous minute are indicated at the locations of the counting systems. The arrows indicate the flow direction, the numbers next to the arrows show the corresponding amount of pedestrians that has passed during the previous minute and the color indicates the ‘severeness’ of the numbers. On the top right of the figure, the trend of the observed amount of pedestrians per quarter during the day is visualized. This trend can be compared to a historical trend (in the figure the line indicates the numbers of the day before). The two figures on the lower right hand side of the figure show the results from the Wi-Fi sensors and the route splits respectively. The circles indicates the location of the Wi-Fi sensors on the map, while the number next to each circle indicates the amount of devices observed by the Wi-Fi sensor. The route splits are calculated between multiple Wi-Fi sensors. The sensor in the middle left is most relevant, as it indicates the distributions from the center of the district into the narrow roads (right) or through the area along the canal (top and bottom sensors).

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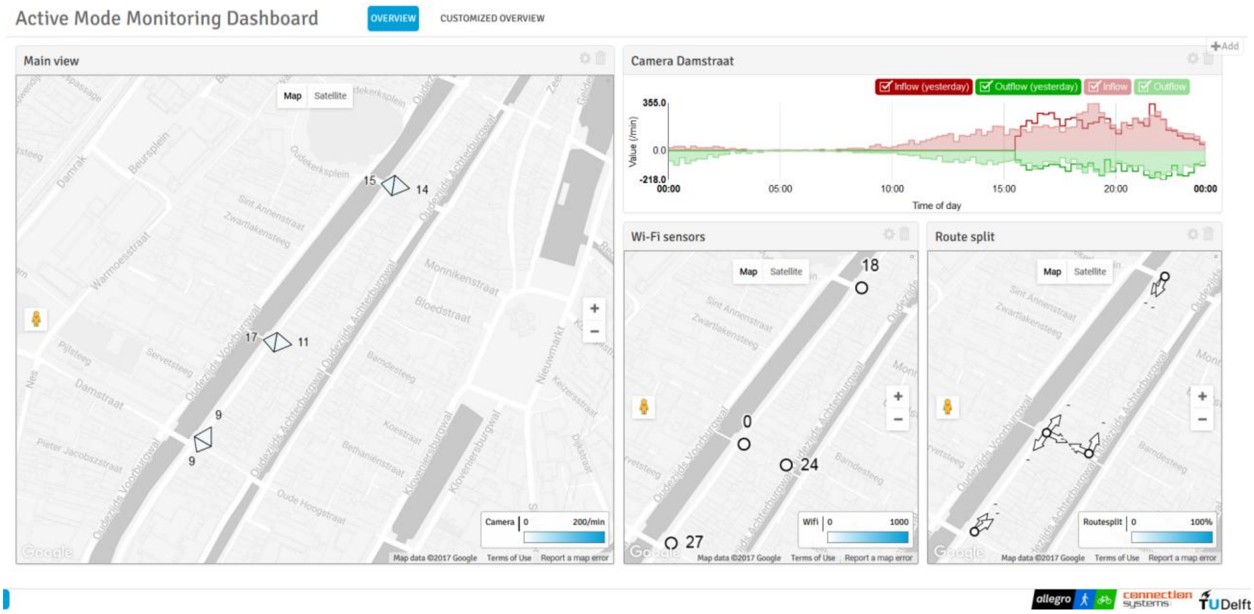

a. On the left hand side counts are shown of the previous minute, where the arrows indicate the walking direction. On the top right inflow and outflow are visualized per minute (same numbers as in figure on the left) over time, with a comparison between today (solid boxes) and another day (yesterday in this case, solid line). In the middle of the bottom row counts are shown from Wi-Fi sensors for a period of 5 minutes, covering small areas and on the bottom right route splits, that is, percentages of flows in the different directions on an intersection of two or more streets.

b. On the left hand side counts of the counting system and Wi-Fi sensors have been combined in one figure, together with the GPS positions of a sample of pedestrians equipped with a dedicated GPS tracker. In the middle of the top row counts are shown for areas, while the area takes the corresponding color (to be set by the user). At the top right direct video footage is visible (e.g. to identify abnormal situations), while in the middle of the bottom row a so-called heatmap is visualized. This heatmap is based on GPS positions, and shows where most pedestrians have been during the last fifteen minutes (time period can be set by the user).

FIGURE 3 Visualizations in the crowd monitoring dashboard for the Red Light District in Amsterdam.

7. APPLICATIONS AND LESSONS LEARNT FROM THE CROWD MONITORING DASHBOARD

The crowd monitoring dashboard has been applied in five pilot projects in the municipality of Amsterdam, namely SAIL 2015, Kingsday 2016 (*32*), Europride 2016 (*33*), Kingsday 2017, and, the Red Light District 2017. In the following, we shortly introduce the first three of these applications, in order of complexity, and show the lessons learnt; more information can be found in (*31*). Before going into detail into each application, some generic lessons can be given. The first one is that the numbers given in the dashboard always have a context. In this respect, the numbers (and other information provided by the dashboard) serve to support the own experience and knowledge of the user; the information is not used independent from its context. Secondly, the numbers only give an indication; exact numbers only matter if the situation becomes critical or is going to be. Most crowd monitoring dashboards will therefore only be used as confirmation. We have been very careful in not giving inaccurate information as literature from other fields has shown the information needs to be reliable. If it is not, the information (and in this case the dashboard) will not be used, which will be a waste of money and resources. Finally, the crowd monitoring dashboard should not only show the normal or expected use of the infrastructure, but it should also cover the remaining part of the network. This makes it possible to e.g. see whether alternative routes are used after crowd management measures have been initiated.

The aim of the SAIL 2015 crowd monitoring dashboard was to get insight into large pedestrian flows along the shores of the IJ. More specifically, we aimed to answer two research questions:

1. Is it technically possible to develop a real-time crowd monitoring dashboard?
2. Is a real-time crowd monitoring dashboard an added value for the crowd managers of the municipality and the SAIL organization?

The crowd monitoring dashboard for SAIL 2015 has been developed within a period of only 3.5 months, which means that both the visualization and the traffic state estimators were relatively simple. Despite this short development period, the dashboard was active during SAIL. The data collection systems have provided real-time information, which was visualized in the monitoring dashboard. The dashboard made it possible to communicate directly with the crowd managers and the event organization and to provide them with real-time information. Both crowd managers and event organization used the information from the dashboard (either through the dashboard directly, through dedicated graphs (e.g. an overview of in- and outflow of the area) or through the camera feeds) in their (crowd) management of the event. In the end, both research questions have therefore been answered positively.

However, as neither the developers nor the crowd managers and the event organization had previous experiences with a similar system, no specific requirements have been set to the visualization. Though the dashboard functioned well, especially the lack of requirements made it difficult to integrate it fully in the organization. Additionally, we found that the information did not give a sufficiently specific overview of the pedestrian flows. The reason is that a large area (a route of more than 5 km) was monitored through a limited number of sensors, see FIGURE 2. Also, the Wi-Fi sensors appeared to reach a much lower quality than expected (*20*), which is compensated for by the large pedestrian flows. In future applications, the data (and visualization) requirements therefore need to be specified beforehand. This way, the sensor plan (describing number of sensors and corresponding locations) can be optimized for a specific event.

In the second application during Kingsday 2016 we explicitly formulated a number of research questions, mostly related to counts and flows at certain locations. Moreover, the sensor density was higher, leading to more accurate observations. Only information which reliability could be guaranteed was provided on the dashboard, which made the dashboard simpler, but also more intuitive.

During the Europride 2016, the crowd monitoring dashboard has been applied as the festival terrain was rather limited, given the large amounts of visitors that were expected to attend. To this end, the dashboard has been used in a close cooperation between the municipality, police, catering industry and public transport operators. In addition to the research questions for Kingsday, two specific indicators were asked for. The first related to the number of pedestrians on Dam Square: when this would exceed a certain threshold value, the inflow would be limited. Secondly, the amount of participants on the Pridewalk was observed. The Pridewalk is a walk from the Vondelpark towards the Dam Square. Especially in case of a crowded Dam Square, space should be available for the Pridewalk participants. To this end, a counting system was mounted just after the start of the Pridewalk, and the corresponding cumulative number of visitors passing this system was included in the dashboard. While the second indicator was accurate, and as such very helpful for the organization, the first one did not provide accurate results. This was mainly due to the measurement errors, which caused a cumulative error in the system (*34*). Currently, we are working on other ways to come up with the required numbers, see (*26*).

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8. CONCLUSIONS AND RECOMMENDATIONS

This paper has introduced a crowd monitoring dashboard. We have shown that this dashboard has been successfully applied as input to crowd management for decision making on the operational level during large scale events in Amsterdam. Moreover, the data collected in the dashboard is used for policy making on the tactical and strategic level. These applications are explored in the near future. The crowd monitoring dashboard can be used in real-time, but the collected data can also be used as historical data to perform longitudinal analyses.

The core of the crowd monitoring system consists of traffic state estimation functions to calculate indicators, such as density, speed, flow, travel time and route splits. The input for this crowd monitoring system consists of real-time data coming from counting systems, Wi-Fi sensors, and GPS trackers. Special attention has been paid to the visualization of the indicators, as it needs to be accurate, intuitive and flexible, to adjust to the user needs.

The crowd monitoring dashboard has been applied for different events in Amsterdam (SAIL 2015, Kingsday 2016, Europride 2016), and as well as to monitor daily operations in the Red Light District in Amsterdam, which is an area used by both commuters and visitors. From the above, we can conclude that the crowd monitoring dashboard has advanced during each pilot project. This does not only hold for the visualization and the underlying traffic state estimation algorithms, also the integration in the organization has been improved. Currently, we are working together with the municipality on ways to further exploit this crowd monitoring dashboard, focusing on generic applicability for events and 24/7 application in parts of the city center.

Future research entails different directions. First of all, the traffic state estimation methods can be further developed and better calibrated, in order to provide more accurate, more reliable and more suitable information. Secondly, other data sources can be added to the system. Especially data from mobile phone apps and moving Wi-Fi sensors are potential candidates to provide a more diverse range of data collection techniques. Thirdly, the visualization can be further developed, included dedicated requests from the users. This way, the use of the dashboard could be better integrated in the various departments of the municipality, but also its suitability could be increased for the police, the public transport operators and other first responders.

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