CamInSens - An Intelligent in-situ Security System for Public Spaces

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Abstract— *In this paper we present a novel third-generation surveillance system for public spaces. In contrast to analyzing a threat after its occurrence, this systems aims on* in-situ *detection of salient trajectories and events. We use a network of smart camera nodes, which is capable of detecting and tracking people across an entire camera network. In addition, we developed an analysis framework which uses the extracted trajectory and event information from the smart camera network for autonomous online detection of potential threats in real-time. Finally, we present new visualization and interaction techniques for security control rooms and mobile devices based on an evaluation of existing infrastructures and components.*

Keywords: Surveillance Technologies, Security Operations, Event Detection, Trajectory Analysis, Human Computer Interaction

1. Introduction

Research on *Preventive Security* is concerned with looking for and implementing intelligent strategies and processes prior to security incidents happening and so minimizing security risks across all sectors. *In situ* event detection is the overall challenge. Security risks in this sense are process breaches, technical defects, and targeted attacks such as asymmetrical threats, cyber crime or human error. The objective is to develop concepts and technologies aimed at recognizing these security threats at an early stage. The disaster of the love parade in Duisburg, Germany, is an example where the application of preventive security strategies could have saved the life of many humans.

The CamInSens project [2] sponsored by the German Federal Ministry of Education and Research explores new ways of recognizing danger situations induced by people themselves. It is about the protection of public areas which differs from the protection of critical infrastructures because humans and the public become the center of interest. In order to protect public areas from dangers caused by people themselves, technologies are needed which can find the balance between increased levels of security and existing surveillance regulations.

The focus of the CamInSens project is to explore the possibilities of a practical and legally compliant surveillance system based on a network of smart video cameras and automatic event detection in order to increase the public safety without compromising data and privacy rules. We expect the output of the system to be highly relevant to operators and security staff to detect and assess critical situations in good time and to provide the information base for resolving them. One of the key components we developed is a new camera system which can acquire and process visual data cooperatively using intelligent camera nodes. This allows the detection and tracking of people across an entire smart camera network. In order to minimize the manual interaction in the data analyzing process, we further developed algorithms to automatically analyze and classify trajectories and other sensor events. This creates the possibility for an autonomous preemptive detection of potential threats and it decreases workload for the security personnel.

All information and classification results are transmitted to a security control room as well as to mobile devices of security personnel on patrol in real-time, where it is visualized and evaluated by the security personnel in a convenient way. We also examine questions of technical and operational reliability such as safeguarding against failure or failure tolerance. Another focus is the analysis of economic viability and the regulatory framework [6].

In the remainder of this paper we discuss related work, then we explain the overall system setup followed by a detailed description of the single components. Finally, we draw a conclusion and give an outlook of future work.

2. Related Work

Surveillance systems are technological tools that assist humans by augmenting their limited (physical) capabilities regarding data collection, storage and reasoning about situations of interest occurring within the monitored environment [19]. Over the last 20 years, much effort has been put into researching methods of automated monitoring, in particular video surveillance, in order to satisfy the ever-increasing need for safety and security within society [22]. During this time, video surveillance systems have evolved into three generations of surveillance systems ([7], [18]) by gradually replacing analogous hardware with digital equivalents.

The first generation of video surveillance systems, which still represents the most common practical application, is centered around human personnel performing visual inspection of video data. Security personnel typically monitors multiple locations simultaneously, which results in significant stress on the security personnel involved [8]. Later, second-generation surveillance systems tried to resolve the burden on security personnel by (partially) automatizing the monitoring task by using automatic object detection/tracking within sequences of images and automatic event detection. Most recently, the third generation of surveillance systems utilized distributed networks of smart cameras/sensors with fully digital back-ends allowing for integrated data collection, storage and analysis processes. For comprehensive reports on recent developments in object detection, tracking and classification, please refer to e.g. [4], [13].

The surveillance system evolution process is driven by the continuous increase of cost-efficient hardware availability. Contrary, these surveillance systems are restricted by real-time performance needs and limitations in terms of available resources. Several automated surveillance systems have been proposed in recent years; a comprehensive review of several video surveillance systems can be found in [22].

3. System Description

This section describes the overall *CamInSens* system architecture, followed by a detailed description of the single components.

Apart from its legal compliance, the system under development had to fulfill several requirements in order to meet today's standards in terms of third generation video surveillance systems. This includes an in-situ event detection, an autonomous online detection of potential threats, autonomous and smart cameras, an automatic tracking of persons over multiple cameras, an automatic classification and analysis of trajectories and a strong coupling of the security control center with mobile operators on patrol. These requirements will be described in this chapter in great detail.

3.1 System Design

The two main input data sources of the system are a smart camera network and a set of additional sensors, which are combined into a smart sensor network (see 3.2). These autonomous sensors can be of arbitrary nature, such as theft, glass breakage or fire sensors and every state change of interest is directly reported to the central CamInSens gateway server. Each smart camera runs a *Multi-Object Tracker* instance, which accesses a camera's image data and extracts partial human movement trajectories. These results are passed to the *Multi-Camera Tracker* in the central control room, which generates global trajectories. This mechanism allows the tracking of persons over multiple camera viewports and represents the basis data set for subsequent trajectory analysis (see 3.3).

On demand, the video data acquired by the camera network can be sent to a streaming server, where it is accessible to other components of the system.

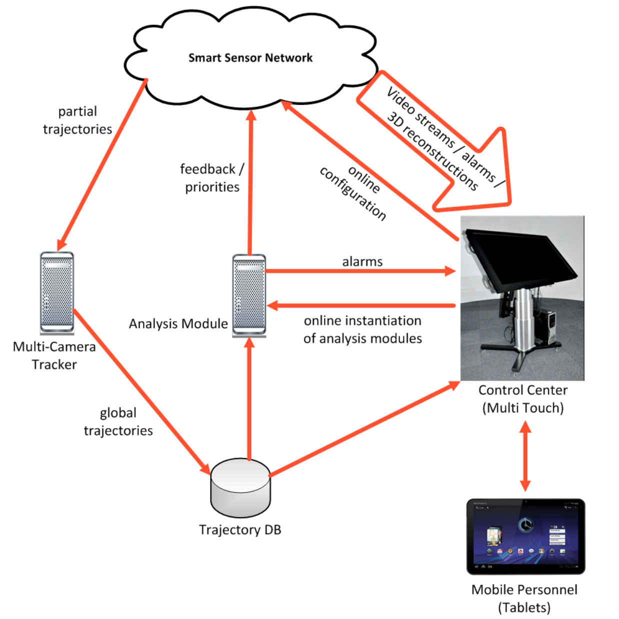

Fig. 1: Schematic overview of the *CamInSens* system setup

Furthermore, the smart camera system provides a 3D reconstruction component, which can be used to generate a detailed 3D model of a potential offender. To meet existing legal regulations [21], this component needs to be started by a human operator.

The complete data is automatically sent to and visualized in the connected security control room in real-time (see 3.4). This gives the security personnel the possibility to quickly assess the current situation and take counter measures if needed, e.g. give orders to the mobile personnel (see 3.5). Those are equipped with custom tablets, which gives them the possibility to access approved information and also to input data into the *CamInSens* system. Figure 1 shows a simplified overview of the system architecture.

3.2 Smart Sensor Network

The input source for the CamInSens system is a sensor network consisting of smart cameras and different additional sensors, which make up a *Smart Sensor Network*. One of the main challenges faced in the CamInSens system is the integration of a variety of highly heterogeneous hardware platforms into a self-organizing distributed system. Because of the huge differences in performance (i.e. CPU speed, RAM, battery lifetime, network speed, etc.) the authors chose to extend two smart sensor platforms to be part of one large distributed system.

The main goal is a fully decentralized sensor system with a high level of abstraction towards users and connected systems (e.g. computing components as the central control room and trajectory analysis systems). This high level of abstraction enables the system to serve surveillance requests coming either from a human operator or other connected

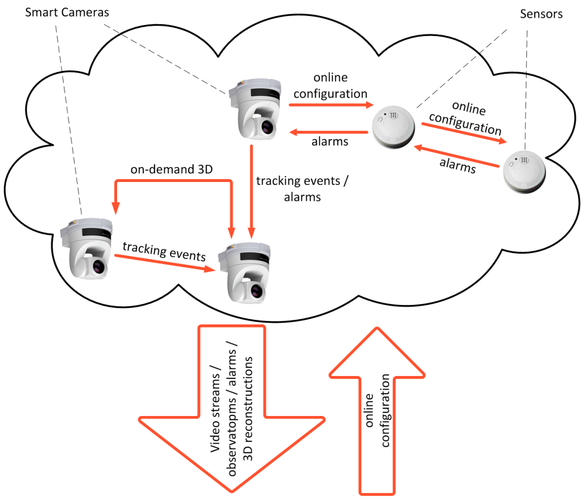

Fig. 2: Data Flow in the Smart Sensor Network

systems in a self-organizing way. Furthermore, the system contains some new highly-developed modules, i.e. a self-organizing field of view calibration, in-network event processing and dynamic on-demand 3D-offender reconstruction. Therefore, new distributed algorithms have been developed to build a reliable and responsive system.

3.2.1 Smart Cameras

Each *Smart Camera (SC)* consists of an Axis 214 PTZ IP-camera, local processing capabilities and two or more communication interfaces. At least one interface is used for SC-to-SC communication, while another one connects a SC to a subset of the *additional sensor motes* (see 3.2.2).

Smart cameras distinguish themselves from "classical" sensor nodes (e.g. temperature sensors) in their primary sensor being a photosensitive chip. This leads to two main differences: Smart cameras generate a high volume of data which is magnitudes higher than that of other sensor nodes. Furthermore, the directional characteristic makes it infeasible to cover a whole region of interest all at once [9]. To overcome the latter limitation, distributed algorithms have been developed, which make use of the pan, tilt and zoom capabilities of the camera to reorganize its field of view (FoV) in a distributed fashion to suit the current task [12].

To lessen the interconnection network's burden of all the image data generated, many efforts have been taken to analyze the pictures inside the SC itself or at least near their point of creation. This means, that only high-level event information representing events in the observed environment is delivered to a sink. The image streams of cameras are only sent on demand, i.e. when the security personnel actually want to look at them.

The concepts for the *Smart Camera Software* itself, which had been introduced in earlier works [11], have been extended in different ways. The most important extension is a dynamic plug-in structure to enable the concurrent use of different control and analysis modules. The modules can make use of the local camera control, consume image data and communicate to module instances on remote SCs.

To make the usage of arbitrary modules in different configurations feasible, new challenges arise (see sections 3.2.4 and 3.2.5).

3.2.2 Additional Sensor Motes

Our additional sensor motes are build upon standard Mica2 motes used in wireless sensor networks [5]. The Mica2 motes can be connected to various types of sensors, e.g. temperature and humidity sensors, simple switches, photoelectric barriers, etc. Due to their main power supply being a battery and their small size, they have a much smaller performance profile than SCs considering their computational power and (wireless) connectivity.

3.2.3 Interconnection Networks

In classical WSNs based on MicaMotes, each packet intended for a sink (e.g. the central control room) has to travel through the network. That is why sensor nodes in a geospatial neighborhood of a sink may have to communicate exceedingly just to forward packets of other nodes, leading to so-called *routing hotspots*. The routing algorithms developed for the CamInSens system have been designed with the heterogeneity of the system nodes in mind and making use of the higher performance profile of SCs. The sensor nodes organize themselves in different ad-hoc networks depending on their configuration. While the Smart Cameras auto-configure their IP-based communication, the sensor motes self-organize themselves in different routing trees, each one rooted at a Smart Camera. To meet the requirements of a robust and self-healing system, the nodes react on changes in their environment and they reconfigure to overcome any disturbances.

3.2.4 Task-Oriented Abstraction of Surveillance Tasks

The Smart Sensor Network is able to fulfill a variety of different surveillance tasks without overwhelming a user with configuration issues. This is done by using self-organizing software-agents that occupy cameras and work on their computational resources. These agents can execute object tracking, pattern recognition and camera alignment. [14]

While some modules run most of the time (e.g. person tracking), others are triggered by human operators or other systems.

The following modules have been implemented:

Distributed Tracker Component The *distributed tracker component* is a single-camera multi-object tracker. It generates as long trajectories as possible out of the local cameras' image stream. These trajectory parts are sent towards the *Multi-Tracker* component, which combines these parts of the same person to global tracks spanning the field of view of many cameras (see section 3.3.1 ff.).

3D Online FOV Partitioning The goal of the online partitioning agent is "an overlap-free monitoring of the observation area, considering the distinct priority of an area element" [15]. This enables the tracker component to collect as many trajectories as possible while also ensuring to meet the user's demands of seeing video streams from a certain area, which can be expressed by such priorities. Another system, which makes use of this module, is the analysis module: Depending on the current trajectory analysis, certain regions may be assigned with a priority.

Dynamic 3D Reconstruction The user can trigger a *dynamic 3D reconstruction* of a selected person. This leads to the instantiation of a reconstruction agent taking care of acquiring the needed data, i.e. selecting two cameras that are able to generate a multi-view of the person, taking two timely synchronized pictures (one from each camera) and generating the 3D model on one of the participating cameras.

3.2.5 On-Demand Reorganization of Data Storage and Forwarding

As said before, the CamInSens sensor network consists of different ad-hoc networks, which are build using wired as well as wireless network technologies. Despite the ongoing advances in computer architecture concerning computational power and communication interfaces, energy consumption is still a major concern while designing sensor networks. This is why, the system's design takes advantage of the heterogeneity present in the following ways:

Smart cameras and the additional sensor motes do not form disjoint ad-hoc networks, but are integrated into one large sensor network with the smart cameras acting as access points for the sensor motes. This is achieved by extending the smart cameras with another communication interface that acts as a base station towards the sensor motes. This way, the set of sensor motes becomes partitioned into different ad-hoc networks with each one connecting to another smart camera.

Since it is not a given, that each sensor node is in a spatial proximity to a smart camera to be able to connect to it directly, the sensor nodes still need to build up routing trees to make use of multi-hop communication towards the next smart camera.

3.3 Trajectory Analysis and Event Detection

The presented surveillance system is designed to perform automated recognition of safety critical behavior of observed persons (carried out by individuals or groups of persons) within the scene. To this end, a centralized trajectory analysis module assists the security personnel in detecting indications for such behavior, which can be roughly classified into criminal acts against other persons (e.g. assault or theft) or inanimate objects (vandalism) as well as self-endangerment (intentional or unintentional). There are two mechanisms for feedback based on analysis results: notification of the security personnel (raising an alarm), detailing on the origin of the detection as well as feedback towards the self-organizing camera network, introducing priorities within the distributed tracking task based on observed uncommon movement behavior.

The analysis module is physically linked to the output of tracking processes within the self-organizing camera network, using the extracted movement trajectory information within the observed scene as a basis for further analyses in real-time. The analysis module, however, does not perform image processing on image sequences in order to reduce data transfer volume and allow for better scalability of the system in terms of performance with increasing numbers of sensors/cameras.

The module does not provide a fixed set of rules for safety critical behavior, as the definition of safety relevant behavior may vary in different application scenarios. Instead, the module provides highly configurable analysis techniques. Positive responses to an analysis for a given set of observations do not automatically trigger counteractive measures but notify the security personnel providing details of the detected (potential) incident.

3.3.1 Characterization of Input Data

Results from the person observation/tracking task performed by the distributed smart camera network are camera-local current observations, i.e. short trajectory pieces observed by the individual cameras. Camera-local identities are maintained as long as an object is successfully tracked within the respective camera's local field of view. This (local) identity is communicated using unique LocalIDs. Assigned IDs are maintained as long as the observed person remains visible within the camera's local field of view (FoV). If a previously tracked person re-enters the FoV of a camera, a new ID is assigned, as, for legal reasons, no identifying features of persons are communicated/stored within the system.

Local observations within individual camera images are aggregated for a brief period of time (up to about 1 second) and transmitted towards the analysis module as short trajectory segments, consisting of a list of tuples (CameraID, LocalID, position, timestamp). Discrete timestamps of observation are synchronized over all cameras within the network. Positions (using the bottom center point of the object's bounding box within the image plane as point of reference) of observed/tracked entities within the image sequence are transformed into a global coordinate system using the current local camera calibrations.

3.3.2 Preprocessing Steps

In a first step, those local observations need to be integrated with each other in order to obtain a global view on all currently observed pedestrian trajectories, performed by a multi-camera tracker, including an assignment of unique GlobalIDs. Data integration is based only on the trajectory geometries, as image features are not communicated. The multi-camera tracker needs to deal with local positioning errors resulting from different angles of view and different qualities of occlusion which may lead to different trajectory locations (and thus differing trajectory geometries). Simultaneous observations (in overlapping areas of view within the camera network) need to be matched in terms of person identity, as no identifying features are used/communicated within the system. Global representations of trajectories are then stored/updated within a central trajectory database for retrieval by the security central within a limited period of time after the observation, after which data needs to be deleted for legal reasons.

3.3.3 Conceptual View on the Analysis Module

Due to the self-organization capabilities of the camera network, the observed trajectories feature a number of additional properties: as one of the goals of the system is to demonstrate resource-efficient observation of a large scale scene with a relatively low number of cameras, the coverage of surveillance is incomplete. This can lead to an incomplete and/or fragmented knowledge about the people within the scene. Persons will usually be tracked for only a limited amount of time, before resources within the network are redistributed in order to maximize coverage. This requires the trajectory analysis module to also work on short episodes of movement behavior in order to quickly decide whether a currently observed movement requires further tracking. Positive analysis results based on short trajectories trigger a priority change (degree of priority changed based on the severity of the corresponding alarm) for continuation of tracking for the currently observed individual. This guarantees a continuous tracking until the alarm has been resolved by the security personnel.

The analysis software itself provides a number of analysis modules for different purposes that offer a set of configurable types of analyses for, e.g., single trajectory analysis, analysis of trajectories within the spatio-temporal context of the system installation or group pattern analysis. Typical single trajectory analyses deal with primary spatio-temporal properties of the observed movement and geometric characteristics of trajectories like speed, heading, curvature as well as detection of changes of the aforementioned parameters, i.e. acceleration and stops or sudden turns. In preparation for analyses in relation to spatio-temporal context, the analysis module continuously performs on-line learning techniques in order to create spatio-temporal models of typical movement behavior within the scene. This allows anomaly detection on trajectories within the learned context. For group pattern analysis, several algorithms for group movement patterns have been implemented, including well-known examples like leader-follower, flock/convoy, divergence/convergence or avoidance. All analysis techniques are implemented with regard to real-time capabilities.

3.3.4 Interaction with Adjacent Modules

All provided analyses are accessible by the security control room at runtime by defining analysis tasks providing values for required parameters, a unique analysis task ID and a degree of severity for the alarm associated with a positive detection. Each type of analysis may be defined with multiple different parameters sets in order to create multiple instances of similar analyses. Any previously defined analysis can be deactivated by the security personnel at a later point in time. Within the analysis module, a cascade of currently active analysis tasks is performed for incoming (current) observations, triggering individual alarms (according to the pre-defined degrees of severity) whenever the defined criteria for a positive detection are met. As analyses are independent from each other, this process is highly parallelizable.

3.4 Control Center

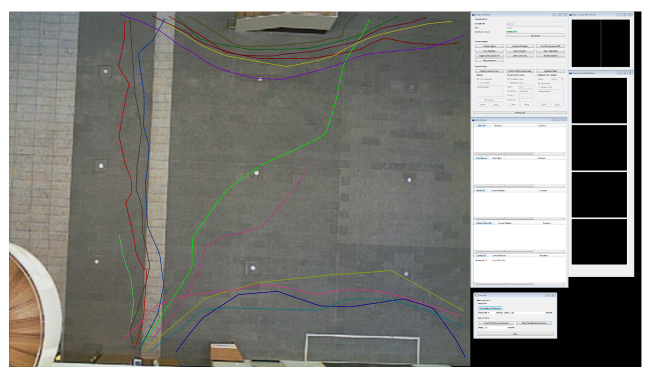

Fig. 3: Screenshot of the control center trajectory visualization module.

All data acquired by the automatic trajectory analysis and event detection system is transferred to the security control room in real-time for human evaluation and further processing. This puts special requirements not only on the used hardware but also on the visualization and interaction techniques.

At the heart of the CamInSens security control room is a 56" multi-touch enabled quad HD display (resolution: 3840x2160 pixels) from Barco [1]. The display has been specially designed for use in dedicated professional applications and delivers crisp, clear and color-accurate images on a large display size. The touch functionality is based on the *dreaMTouch* overlay manufactured by the German company Citron [3]. It differs from other multi-touch overlays for flat panel displays (e.g. [17]) in the choice and distribution of IR sensor elements and provides robust detection of 32 touch points at 50Hz.

Research on multi-touch started already in the early 1980ies (see [16]) and with the more recent advent of touch enabled smartphones and tablets it made its transition from a research prototypes into the mass market. We decided to use a fully multi-touch based interaction for the control center, since this allows a more parallel interaction, reduces task complexity and increases efficiency over standard WIMP (Windows, Icons, Menu, Pointer) interaction, which is based on serial discrete events.

The display area of the screen is split into a large map view of the surveillance area and into panels for different system control tasks. In the online mode, all global trajectories (a global trajectory can consist of multiple local trajectories detected by different cameras) are shown and updated in real-time (see figure 3). The system also has a trajectory database, which supports geometric queries, such as selecting all trajectories which passed a specific area in a certain time interval.

All alarms, automatically generated by the trajectory analysis module, or the sensor network, are received and displayed at their respective location on the main map. The module responsible for generating the alarm also automatically associates it with a severity level. This allows a priority sorting of the alarms in order to avoid an information overflow. In case an alarm cannot be resolved from the control center personnel directly, it can be assigned to available mobile personnel for further handling.

The CamInSens system allows the dynamic creation of different surveillance zones. Typical types are restricted zones, which people are not allowed to enter, or zones where people are not supposed to stay for longer periods of time. The security control room operators can create such zones by directly drawing polygonal shapes on the map and the trajectory analysis module updates itself.

In certain cases it is useful to generate a 3D model of a suspicious person or object. The operator can then generate such a task and the smart camera network will automatically reconfigure itself to process the request. Please note that 2 cameras with overlapping field-of-view are needed to successfully calculate the 3D reconstructions, and depending on the system configuration this may not be possible for all locations. In addition, the system assigns all task requests with a certain priority which is used to avoid contradicting tasks, or deadlocks.

3.5 Mobile Personnel

In current security systems, mobile personnel typically have only very limited data access. This is mainly due to the lack of sensors and connectivity functionality of exiting devices. E.g. most devices are limited to voice communication between the mobile security personnel and the security control room. In the interviews, which we conducted with the

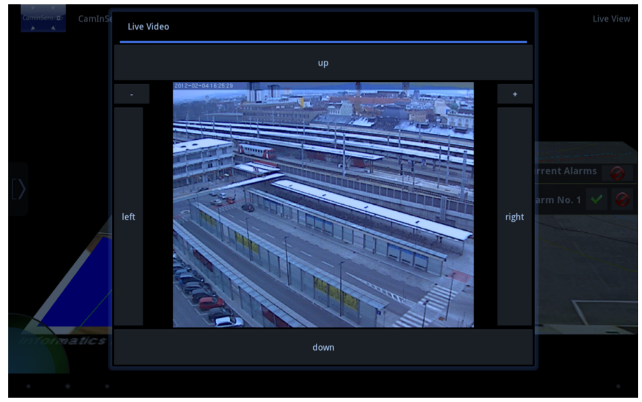

Fig. 4: Screenshot of the mobile user interface. In this case, a synthetic alarm was triggered and the system automatically shows a video stream containing the area. Note that the camera network is automatically reconfigured in case not camera monitoring this area.

mobile personnel of large train stations and a state prison, it became clear, that this restriction is seen as one of the major shortcomings of the currently used devices. To overcome this limitation, and to allow a tighter coupling of the security control room and the mobile personnel we developed a novel *Mobile Control System* (MCS), using tablets running the *Android* operating system as hardware devices.

The core of the MCS visualization is a geo-referenced map visualization module to display the monitored area and its surroundings. This provides the personnel with a reference for additional data, such as global trajectories, events, alarms, or locations of mobile personnel, which are received and displayed in real-time. In most cases, the system simultaneously detects a large number of trajectories, so it is crucial to provide mechanisms to cluster groups of similar trajectories and quickly find abnormal trajectories, which may be of interest. To achieve this on the limited computation resources available on the tablets, we implemented a simplified version of the algorithm proposed by Hoeferlin et al. [10]. All alarms, automatically generated by the trajectory analysis module, or explicitly by the personnel in the security control room, are always visualized in the foreground and also trigger haptic and audio feedback (see figure 4). An informal user study about the multi-modal alarm feedback showed, that the visual and audio feedback were rated as most valuable [20]. Another important functionality of the MCS is the possibility to access the video streams of the entire camera network.

In addition to the data visualization, it is crucial to provide an efficient interaction concept, taking the special requirements for mobile security personnel, e.g. the system is most often used while standing or walking, into account.

Since we are using multi-touch tablets as hardware basis of our mobile devices, an important part is the selection of natural gestures, which can be learned by the security personnel without the need of extensive training. Because of this, our gestures are based on the work of Wobbrock et al. [23] who analyzed a large number of gestures, provided by users who didn't have any prior experience with multi-touch devices in order to find and classify sets of natural and intuitive gestures.

In addition, all navigation and system control tasks can either either be triggered via a menu system or by drawing gestures on the device. The system furthermore provides functionality to create and map custom gestures to all system actions.

4. Conclusion and Future Work

This paper proposed a novel system design for a third-generation surveillance system. During the first chapters, we motivated the need for such systems and derived both mandatory and optional system requirements. Design decisions and interdependencies of these requirements are illustrated for both the overall system and the main system modules, i.e. the self-organizing smart camera network, the trajectory analysis module, and the visualization and interaction concept for both the security control room and the mobile personnel.

The proposed design has been implemented and tested in a first prototype, which demonstrates the feasibility of the chosen approach. A second demonstration of the complete system is planed for late 2012. The system's promising approach of integrating different types of sensors into self-organizing networks, that can be controlled from unified interfaces, makes way to support even more types of sensors, e.g. mobile camera nodes based on quadcopters. Future work will also include the evaluation of 3D visualization and its requirements on new gesture based interaction models for security control rooms.

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