A Survey of Intelligent Video Surveillance Systems: History, Applications and Future

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Abstract. With advances in wireless network infrastructure providing powerful support for surveillance video communications, it is practical to meet the needs of intelligent surveillance systems in a wide range of applications. This survey offers a comprehensive overview of state-of-the-art technologies for intelligent video surveillance systems so as to provide researchers in this field with a summary of the progress achieved to date. The evolution of surveillance systems is outlined as well. In addition, the representative technologies for environment modeling, object classification, object tracking, behavioral analysis, and database implementation are summarized. Finally, we list several detailed discussions on possible future research directions.

Keywords: Surveillance system, image processing, remote monitoring.

1 Introduction

Nowadays, automated surveillance systems are one of the most actively researched topics due to their wide range of potential applications, such as traffic surveillance in cities and detection of dangerous behaviors. An intelligent surveillance system attempts to detect and track objects from video acquired by cameras in the monitored area. The goal of an intelligent surveillance system is to obtain the description of what is happening and automatically take action. In other words, the purpose of the intelligent surveillance system is to replace the conventional passive video surveillance system that is proving ineffective as the number of cameras exceeds the capability of human operators to monitor them. In short, the intelligent surveillance system is designed not only to deploy cameras in place of human eyes, but also to achieve the entire surveillance task as automatically as possible.

Video surveillance in dynamic scenes is one of the most promising research issues as well. For the last two decades, the scientific community has concerned itself with experimenting with video surveillance data to improve algorithms in terms of object detection and tracking within a specific environment, and human activity recognition

(HAR). The phases of processing in intelligent surveillance systems are environment modeling, object classification, object tracking, behavioral analysis, and database implementation. We will describe these processes in more detail in Section 2.

1.1 Evolution of Surveillance Systems

"First generation" video-based surveillance systems began with analog closed-circuit television (CCTV) systems. These systems consist of a number of cameras connected to a set of monitors via automated switches. Most CCTV systems utilize analog techniques for distribution of images and storages. In general, traditional CCTV cameras use a digital charge coupled device (CCD) to capture images. Then, the digital image is converted into an analog composite video signal via coaxial cables. By combining computer vision technology with CCTV systems for automatic images and signal processing, it is possible to detect alarming events proactively rather than recording them passively. This technological improvement has led to the development of semi-automatic systems called "second-generation" surveillance systems. Most of the research in second-generation surveillance systems requires automatic detection and tracking algorithms for behavioral analysis. The principal difference between first- and second-generation surveillance is the change from a "silent camera" that needs a human eye to estimate its images to a computer-linked camera system that estimates its own video images. Second-generation systems diminish the human factor in surveillance and highlight basic concerns (e.g., data swamping and profiling) associated with first-generation surveillance systems.

The goals of "third-generation" surveillance systems are to design large, distributed, and heterogeneous surveillance systems (e.g., fixed or pan-tilt-zoom (PTZ) cameras) for wide-area surveillance (e.g., monitor the movement of military vehicles on borders or surveillance of public transport). For example, the Defense Advanced Research Projection Agency (DARPA) supported the Visual Surveillance and Monitoring (VSAM) project [1], whose purpose is to exploit automatic video understanding technologies that enable a single human operator to monitor behaviors within complicated areas (e.g., battlefields). The primary research topics involved in these systems are the integration of information via various sensors, setting up signal correspondence in time and space, coordination of processing tasks and video communication. Table 1 summarizes the intelligent surveillance systems in terms of the first, second, and third generations, while outlining the main problems and current researches.

Table 1. Evolution of the intelligent surveillance systems.

	First Generation	Second Generation	Third Generation
Technique	Analog CCTV systems	Combine computer vision technology with CCTV systems for automatic video surveillance	Automatic broad area surveillance system
Problem	Utilize analog techniques for image distribution	Robust object detection and tracking algorithms to recognize events	Distribution of information
Research	CCTV video compression	Real-time robust computer vision algorithms	Multi-camera surveillance techniques

Recently, rapid developments in wireless networks and digital video cameras have increased the opportunities to deploy huge scope distributed video surveillance (DVS) systems on top of inherent IP-network infrastructure. In other words, IP-based surveillance solutions are now provided by many companies, such as Sony and Intel (e.g., designing smart cameras), and Cisco (e.g., providing networking devices for video surveillance). All of these are conducive to the latest stage in the evolution of video surveillance systems for migration to digital IP-based surveillances.

1.2 Applications

The demand for the safety potential of remote monitoring has received considerable attention in wide areas, such as public places (e.g., parking lots [2–4], supermarkets [5], banks [6], and department stores [7–8]), transport applications (e.g., railways [9], airports [10–13], maritime environments [14], and motorways to supervise traffic [15–16]), and remote surveillance of human activities [17–22].

In addition, research issues tend to improve image processing tasks by exploiting more accurate algorithms in terms of object detection, object recognition, object tracking, and tracking performance evaluation tools. Moreover, several researches suggested novel solutions (e.g., video compression techniques, protocol techniques, network techniques, and distribution of processing tasks) for video communication in distributed surveillance systems. The development of integrated systems, distributed automatic surveillance systems by utilizing multi-cameras, multi-sensors or fusion of information acquired across cameras represent active areas of research as well.

The rest of the paper is organized as follows: Section 2 describes the surveillance system techniques. Section 3 summarizes existing state-of-the-art wireless video surveillance systems. Section 4 concludes the paper by summarizing the discussion and suggesting possible future research directions.

2 Surveillance System Techniques

This section summarizes the main image processing techniques in surveillance systems, such as environment modeling, object classification, object tracking, behavioral analysis, and database implementation, as shown in Fig. 1.

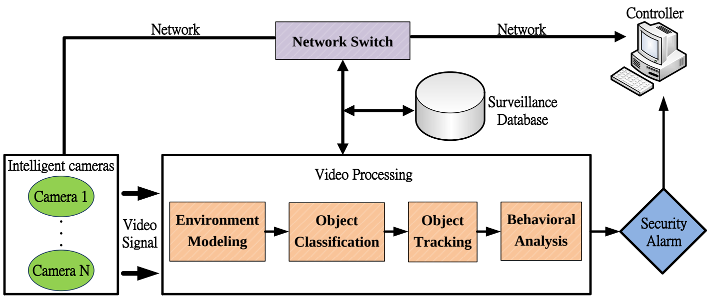

Fig. 1. A typical framework of an automatic video surveillance system

2.1 Environment Modeling

Environment models can typically be classified into two-dimensional (2-D) models in the plane and three-dimensional (3-D) models in real-world coordinates. In view of this visualization information, a 3-D model yields more useful information than a 2-D model.

A 2-D surveillance system involves the use of a single imaging sensor to obtain a single image view per moment. Generally, it is difficult to acquire accurate mapping information by using a single image. As a result, some researches make use of complex mathematics, assumptions, and approximations for the purpose of creating a useful 2-D map. According to [23], the 2-D techniques cannot resolve occlusions in images or track multiple individuals. On the other hand, 3-D techniques can reduce these factors.

A 3-D surveillance system utilizes two or more imaging sensors to obtain a larger coverage. Hence, some images are overlapped so 3-D measurement can be obtained accurately.

2.2 Object Classification

In order to easily track objects and analyze behaviors, it is essential to classify objects correctly. Object classification can be considered as a pattern recognition issue. Two main categories for classifying objects are discussed below.

Shape-based Classification.
Different descriptions of shape information (e.g., points, boxes, silhouettes, and blobs) are available for classifying objects. One well-known work [24] uses the dispersedness and area of image blobs as classification metrics to classify all moving-object blobs into humans, vehicles, and background clutter. Moving targets are detected by using the pixel-wise difference between consecutive image frames. Mohan-Raj et al. [25] give an overview of object classification and how it works in indoor and outdoor environments. A silhouette-based method is used to classify human and other objects. Kuno et al. [26] use simple shape parameters of silhouette patterns to classify humans separately from other moving objects (e.g., butterflies and autonomous factory vehicles). They also propose an approach to overcome the occlusion of humans.

Motion-based Classification.
Augustin et al. [27] propose a method to track humans in indoor surveillance video streams. The authors also make use of the color feature information to accurately identify moving persons, track them, and provide unique tags for the tracked persons. Cutler et al. [28] present a similarity technique to detect and analyze periodic motion. By tracking objects of interest, the authors compute the self-similarity of an object as it evolves over time. For periodic motion, the measurement of self-similarity is also

periodic. Examples of object classification (e.g., people, running dogs, and vehicles) and person-counting are given.

Shape-based classification and motion-based classification can be combined to classify moving objects. Stauffer [29] proposes a time co-occurrence matrix to classify both objects and behaviors. It is expected that more accurate classification results can be obtained by utilizing extra features (e.g., color and velocity).

2.3 Object Tracking

After successfully classifying objects, the next step is to track detected objects. Tracking techniques can be classified into two categories, including 2-D models with or without explicit shape models, and 3-D models. Tracking algorithms in general have significant intersection with motion detection. A number of useful mathematical tools for tracking are provided, such as the Kalman filter, condensation algorithm, dynamic Bayesian network, and geodesic method.

Yan et al. [30] propose a multi-object tracking method for real-road surveillance. It consists of three object states, such as normal state (e.g., to track the object), occluded state (e.g., to estimate the position of an occluded object), and split state (e.g., rematches an object). Experimental results show that their method correctly tracks multiple objects under partial occlusion and total occlusion. Won et al. [31] present a detection-based simplified multiple object tracking model with handling of slow or stationary object detection and occlusion problems for real-time intelligent surveillance systems. In order to solve the detection of slow and stationary objects, the authors propose an adaptive controlling background update parameter. They also propose modified moving average filter to predict the next position of a moving object for handling occlusion problems. Ferryman et al. [32] present 3D model-based techniques that are employed to obtain detailed information about vehicle movements on a highway.

2.4 Behavioral Analysis

Once objects have been successfully tracked, the problem of understanding object behaviors from image sequences follows naturally. In fact, one of the most difficult challenges is behavior analysis from observing objects in video surveillance. Research topics focus on the development of methods to analyze visual data in order to recognize the behavior of objects in a scene. Behavior analysis corresponds to a classification problem of the time-varying feature data. It consists of matching a measured sequence to a pre-compiled library of labeled sequences that need to be learnt by the system. Some methods for matching time-varying data are described as follows. Dynamic time warping (DTW) is a time-varying dynamic programming matching technique widely used in the algorithms for speech recognition and image patterns. The advantage of DTW is its conceptual simplicity and robustness of performance. Recently, it has been used in the matching of human movement patterns [33]. However, DTW is less favored than dynamic probabilistic network models such as hidden Markov models (HMM) [34–35] and Bayesian networks [36–37].

2.5 Database

The final phase of a surveillance system is storage and inquiry. Some research has been done in how to efficiently store and inquire the surveillance data. Zhu et al. [38] construct the attributed pedestrians in surveillance (APiS) database with various scenes, including 3661 images with 11 binary and 2 multi-class attribute annotations. Bialkowski et al. [39] create a new multi-camera surveillance database designed for the task of person re-identification. It consists of 150 unscripted sequences of subjects traveling in a building environment. Connie et al. [40] propose a novel gait database to look into the more challenging aspects of gait recognition. Three elements in the database are included, such as walking with an umbrella that hinders the recognition of the actual gait feature, carrying a box that occludes the body part, and types of footwear that alter the way people walk.

3 Wireless Video Surveillance

The connection facility of a wireless node has representative issues for data transmission in video surveillance applications, such as signal interference, channel bandwidth, data security, and power constraint. Several researches have been presented to deal with these issues and been successfully applied in practice. However, for real-time demands, the transmission or processing process at each wireless node for a large amount of video stream is still challenging.

In a wireless video surveillance system, each node is in general equipped with a camera, a power supply, a microprocessor, the storage unit, and a transceiver. The essential operation of each node is to capture video, compress video, and transmit data to the data center. The current wireless sensor network (WSN) technologies can be used in all kinds of wireless video surveillance applications. For the traffic analysis application, Li et al. [41] present a traffic information and transmission system based on Zigbee and WSN to monitor the traffic flow in intersections. Luo et al. [42] propose another example of a wireless traffic monitoring system at the University of North Texas.

Video surveillance in other wireless communication applications is also intensively studied, such as the home security systems (HSS) with a modular self-reconfigurable robot that are used for security monitoring at home [43], surveillance and security robot teams (SSRT) to monitor indoor environments [44] for security purposes, smart camera network systems (SCNS) used for security monitoring in a railway station [45], real-time parking space locating system used for a parking garage on a campus [46], and an obstacle avoidance system using a weapon robot in an indoor environment [47]. Typical problems in these surveillance systems are to deploy sensors or configure systems for video communications. Table 2 summarizes the technical parameters in these intelligent surveillance systems.

Table 2. Wireless intelligent surveillance systems.

Surveillance System	**Li [41]**	**Luo [42]**	**HSS [43]**	**SSRT [44]**	**SCNS [45]**	**UNCC [46]**	**Weapon Robot [47]**
Environment	Roadway	Campus	Home	Indoor	Railway	Campus	Indoor
Application	Traffic	Traffic	Security	Security	Security	Parking Garage	Obstacle Avoidance
Mac protocol	802.15.4	802.11a/n	802.15.4	802.11	802.11g/j	802.11	802.15.4
Carrier Frequency	2.4GHz	5.4GHz	2.4GHz	2.4GHz	2.4GHz/ 5GHz	433MHz	2.4GHz
Maximum Throughput	N/A	20Mbps	N/A	N/A	13Mbps	N/A	250kbps
Network Topology	Mesh	Chain	Chain/ Tree	Tree	Mesh/Star	Star	Point to Point
Camera Control	Fixed	PTZ	Fixed	PTZ	Fixed/PTZ	Fixed	Fixed

4 Conclusions and Future Directions

Intelligent video surveillance is an active research area that is strongly driven by many promising applications, such as public places (e.g., parking lots, supermarkets, banks, and department stores), and transportation (e.g., railways and airports).

We have presented an overview of state-of-the-art researches for intelligent video surveillance systems. The evolution of surveillance systems is also summarized. We have described the existing approaches for each main topic, including environment modeling, object classification, object tracking, behavioral analysis, and database implementation. In addition, we have surveyed the state of the art of wireless video surveillance systems.

In spite of the intelligent video surveillance system having several advantages, it still faces difficulties, such as complex background, occlusion problems, fusion of 2-D tracking and 3-D tracking, 3-D modeling of humans, behavior prediction, data fusion from multiple sensors, and remote surveillance. Regarding the direction of future research, we may focus on the above-unsolved works. We believe that these challenges offer possible ways to extend the field of intelligent video surveillance systems to more realistic and pervasive scenarios.

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