Distributed Multi-Sensor Surveillance: Issues and Recent Advances*

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Abstract: Distributed multi-sensor surveillance systems are becoming increasingly important in a variety of military as well as non-military applications. This chapter discusses three important issues regarding design of such systems, namely sensors and sensing technologies, system architecture, and information processing and fusion. Some underlying concepts are illustrated by considering the problem of concealed weapon detection.

Key words: Integrated surveillance systems, multi-sensor systems, information fusion, concealed weapon detection.

1. INTRODUCTION

Conventional surveillance systems of the past were devised to monitor the activities of large military units or entities such as aircraft and ships. These missions were accomplished by using sensors such as radar and sonar that could view large volumes of interest in more or less continuous manner. Times have changed and one may need to monitor the activities of humans and vehicles for a variety of law enforcement, security and defence applications. There has been an increasing interest in the development of surveillance systems for other non-military applications. By surveillance of a particular environment, we mean the monitoring of that environment for the detection and tracking of specified activities. For the design of such a system we need to develop an integrated architecture and define tasks for efficiently

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collecting, storing and processing all the data that is relevant to the monitored activities within the environment for fast and reliable human or automated decision making. It is a very important and complex problem arising today in both public and private sectors, e.g. medicine, environment, defence, communications systems, and building systems. In general, for surveillance applications one has to take into consideration the following: sensing device development, system and network design, and information processing tasks.

As a specific application, one can consider a surveillance system for monitoring changes in the living environment. Important chemical, biological, and physical modifications occur continuously in our environment that can have a short-term and/or long-term impact on our living environment and our quality of life. Many of these modifications, especially the ones that occur in harsh environments, can be monitored through sensor technology. They can be embedded into Intelligent Distributed Systems (IDS) which can provide accurate Intelligence, Surveillance and Reconnaissance (ISR) capabilities. The dependability of ISR systems can be increased, at a reasonable additional cost, by using a large number of small inexpensive sensors with different functionalities that are connected in a network using wired or wireless links. In such Intelligent Real-time Integrated Sensor (IRIS) systems redundant sensors are useful in decreasing system vulnerability to sensor failures. Due to the presence of a large number of sensors, the quantity of information increases and it becomes very important to find methods to efficiently combine this information and store the relevant data. Otherwise, the decision makers (human or automatic) will not be able to make timely decisions and the network might become overloaded because of insufficient bandwidth and/or computing power. An IRIS System not only will inform the human decision-maker about changes/problems in the monitored environment but also will indicate the location and time when the event occurred. Through the analysis performed by the intelligent system, IRIS could provide solutions and even execute a course of action to find a remedy for the problem.

Another interesting example of such a prototype system used for human health monitoring is the Georgia Tech Wearable Motherboard™ (GTWM)[4, 9]. The GTWM is a wearable vest which through sensors mounted on the vest, and using optical and other special fibres meshed with the vest's material is able to sense, process, transmit and monitor different vital signs, e.g. body temperature, and ECG.

Development of systems for surveillance applications relies on new smart sensors, integrated system design, data storage, real-time data analysis, data fusion and system control functions. Research and development in this area is highly interdisciplinary, where electronics, mathematics, physics, signal processing, communication theory, data networks and computer science play major roles. Since the physical implementation and experimentation can be quite costly, it is expected that theoretical approaches and computational modelling and simulations will be widely used for system design.

This chapter is organised as follows. In Section 2, we propose a model of a distributed multi-sensor surveillance system. We briefly discuss the past, present and future research in sensor technology and the main components of a distributed surveillance system. We also present several problems that arise in these systems in terms of data processing, e.g. communication and data fusion. Section 3 contains a case study dealing with a particular multi-sensor surveillance problem, namely Concealed Weapon Detection (CWD). In this particular problem one has to determine whether or not a weapon is concealed under a garment by fusing data sensed through different imaging technologies (infrared and millimetre wave). Final remarks are presented in Section 4.

2. DISTRIBUTED SURVEILLANCE SYSTEMS

A distributed surveillance system is usually composed of a large collection of simple and inexpensive *smart sensory devices* (infrared (IR), chemical, biological, acoustic, magnetic, motion, etc.). For instance, in a military surveillance application [1], such systems may consist of 10^2 to 10^7 sensors, placed on fixed or mobile platforms, able to collect data locally or remotely. Some of these sensory devices are included to provide complementary data, while others are just redundant to minimise data inaccuracy due to potential device failures.

These devices would be of little value unless they are equipped with communication and processing capabilities that would allow them to self-organise into independent subsystems. These subsystems would exhibit emerging behaviours and capabilities to further integrate into a *super-system*. However, when these distributed super-systems contain large numbers of subsystems, issues such as system organisation and topology, protocols for subsystem interactions including communication standards and information processing become important. Systematic consideration of these issues and design of distributed sensor networks are open research problems.

2.1 Sensing Devices

Over the past decades, great progress has been made in research and development of sensing devices. Early research and development in this area was especially fuelled by military applications. In the 1960s and 1970s increased effort was devoted to the development and integration of different types of sensors, such as acoustic/sonar, IR, seismic, and magnetic sensors. An example of an application is the Remote Battlefield Acoustic Sensor System (REMBASS) developed during the 1970s, which incorporated acoustic, seismic, magnetic and IR sensors connected by radio communication links. Unfortunately, the sensor systems at that time had limited signal-processing capabilities that resulted in large amounts of data being sent to a central unit, which eventually overloaded the operators. During the 1980s and 1990s, new advances in material sciences, microelectronics, physics, biology, chemistry and computer science provided new technologies for the sensor industry. The MEMS technology provides substantial information processing capabilities at the device level, which greatly reduces communication requirements. Research groups are continuously working in developing new low cost, low power, and wireless sensors with various sensing capabilities that can withstand harsh environments for long periods of time [2, 6]. Desired features of these sensors include self-monitoring capabilities for reliability, power efficiency for long term operation, autonomy for local control operation, and re-configurability for easy adaptation at different base stations.

2.2 Distributed Multi-Sensor System Architecture

The overall architecture of an integrated surveillance system depends greatly on the application. For an airport surveillance application, for example, such a system could include video cameras (to monitor traffic), chemical and biological sensors (to monitor gas/toxic emissions and possible medical/biological outbreaks), and motion sensors (to trigger other more advanced surveillance devices). While data is currently collected for many of the factors mentioned above, it is usually not integrated into an overall system. Due to a lack of information fusion and resulting improvement of diagnosis, decision-making and control action, many factors that might induce short-term and long-term effects in the environment are "missed".

Each device or groups of devices can be viewed a subsystem since many of them are equipped with local processing and communication capabilities. Based on this assumption, the architecture of such a system can be envisioned as having a self-adapting hierarchical structure, where the lower-level subsystems can self-organise based on the requirements and the health of the device (See *Figure 1*).

Such a system should allow the following [7]:

1. Operational Independence of the Subsystems: The subsystems must be able to usefully operate independently.

2. Managerial Independence of the Subsystems: The subsystems are separately acquired and integrated but maintain a continuing operational existence independent of the integrated system.
3. Evolutionary Development: The development of the integrated system is evolutionary with new functions added, removed, and modified based on the experience gained.
4. Emergent Behaviour: The integrated system performs functions and carries out tasks that do not reside in any subsystem. They are emergent properties of the entire system and cannot be localised to any subsystem. The principal purposes of the integrated system are fulfilled by these new properties.
5. Geographic Distribution: The subsystems can exchange only information and not substantial quantities of mass or energy.

Next, we describe the architecture of a two-level hierarchical system (see *Figure 1*) that is being considered for the monitoring of indoor environmental quality (IEQ) at Syracuse University [16]. At the lowest level are the *sensor-level intelligent subsystems*, containing a single or several sensing/monitoring devices, which are able to respond rapidly to local conditions and communicate with the *regional* or *local subsystems*. The

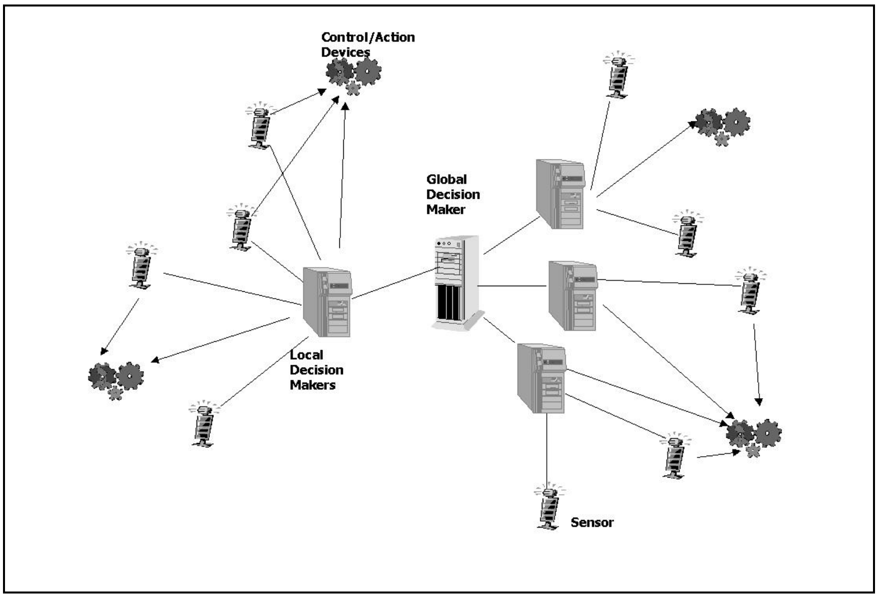


Figure 1. Example of an integrated system architecture

regional subsystems are integrated in a distributed environment where data fusion is performed to allow regional-level actions to be taken. They communicate with *central intelligence units* (for large coverage area applications, e.g. military surveillance, urban environment surveillance and IEQ monitoring for large buildings) as well as with sensor-level systems. The data processing tasks of a regional subsystem may be distributed to other units (regional subsystems or central units), depending on the communication capabilities, the activity of the other regional subsystems and the response time requirements. The central intelligence units communicate with the regional subsystems in order to make complex decisions, including evaluating and overriding decisions and actions taken at a lower level, future decision planning and communication with human operators.

2.3 Information Processing

Information processing tasks vary greatly and depend on the type of application, the sensory devices integrated in the system and the type of data provided by these devices (images, numeric, sound, etc.). In general, these systems have to consider the communication network, low-level information processing tasks (at the sensor level, in case it has computational capabilities), information fusion processing (at different levels in the system architecture), data manipulation in real-time or near-real-time (storage, searching, retrieval and visualisation) and decision making. In a distributed surveillance application, information processing tasks can be divided into two categories: those performed at the sensor subsystem level (the lowest level) and the ones performed at higher levels, namely at the regional or central levels.

Tasks that a sensory subsystem may perform include the following: a). Periodic broadcasts of the current status and location. b). Responding to requests from control centres and/or neighbours. c). Acquisition, pre-processing, compression, encryption and transmission of the data. For imaging sensors, local data processing consists of image processing tasks (e.g. restoration, segmentation, etc.), feature extraction and object recognition. Depending on the communication and processing capabilities of the subsystem, it can also acquire and process network data (e.g. data fusion and system status management), refine and extract knowledge (e.g. scene analysis, target recognition, situation status analysis, information reliability status, etc.), make decisions and execute control protocols (activate alarm, close security doors, etc.), and monitor the activity of its neighbours (e.g. monitoring the health of the neighbouring sensory devices, reduce message redundancy, etc.)

At the higher level (with or without a control centre), the tasks include support of the knowledge base, communication among subsystems, integrated system strategic planning and optimisation of system resource utilisation. Since most of the subsystems (see Section 2.2) are independent, they can collaborate only through information exchange [7]. To allow efficient collaboration, standards and protocols need to be specified for communications among different units. The seven-layer OSI model [12] for network architecture may be considered for network design. However, a subset of these layers may suffice for the design of this special purpose network. Resource optimisation may include strict time restrictions on the data processing and data communication within the system for the applications that require real-time or near real-time responses.

An important aspect of these systems is the ability to integrate or fuse data from different sensors. This is required so that we can utilise the information collected by the system in the most efficient manner and make most effective and intelligent decisions for system control. Information fusion can be done at different levels. At the data level, we can combine raw sensor data. This is the most effective data fusion method but requires commensurate sensors and possibly large communication bandwidth. At the feature level, appropriate features and relevant information can be extracted and fused. Finally, fusion at the decision level involves the fusion of tentative decisions made at the lower level. This requires extensive signal processing capabilities at the lower level units. Bandwidth requirements are reduced but the performance of the overall system also degrades. For additional details on fusion architectures and decision fusion, the reader is referred to [5, 14, 15].

3. CASE STUDY: CONCEALED WEAPON DETECTION

Over the years, global terrorism and crime have grown. One key step in preventing terrorism and crime is to determine whether or not people are carrying weapons concealed underneath their clothing. Concealed weapons detection (CWD) is, therefore, an increasingly important problem in the area of multi-sensor surveillance. This technological challenge requires innovative solutions. A number of sensors based on different phenomenology are being developed to observe objects underneath people's clothing. However, each sensor has its limitations. For example, infrared (IR) imagery cannot penetrate heavy clothing and millimetre wave (MMW) images have poor resolution. In order to overcome these limitations, multiple sensors that provide complementary information may be employed for CWD. Recently IR and MMW sensors have been considered for CWD purposes [11] since an IR sensor provides a high-resolution image while MMW sensor can penetrate through clothing. By fusing this complementary information, more complete information is obtained which can then be utilised to detect concealed weapons.

A block diagram describing the major tasks in a multi-sensor surveillance system for CWD is shown in *Figure 2*. Once images from different sensors are available, it is necessary to find the corresponding points of those images before employing any fusion algorithm. In the literature, the process of finding the corresponding points from two or more images is called *image registration*. In addition to registration, filtering and noise removal are also carried out in the pre-processing stage. The resulting registered images are fused, features are extracted and then decision is made on whether or not the person under surveillance is carrying a weapon. The registration and fusion tasks for CWD are briefly discussed here. For details, see [13].

Several different registration problems arise in the CWD application. For example, images are taken at the same time from different but almost co-located (adjacent and parallel) sensors; images are taken simultaneously from sensors of the same type but located at different sites; images are taken from different sensors which are located in different places, etc. We have developed an automatic two-stage registration algorithm for images simultaneously taken from two parallel sensors that are of different type [3].

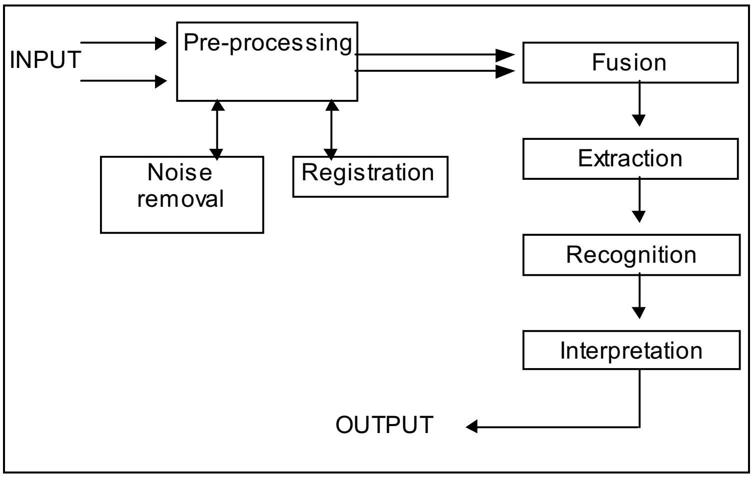


Figure 2. Multi-sensor image processing for CWD application

This case considers a simpler geometrical relationship between images, but it is quite difficult due to the use of different sensors, therefore different type of images. *Figure 3* shows a schematic of the set-up under consideration.

A typical image pair taken from IR and MMW sensors before registration can be viewed in *Figure 4*. *Figure 5* presents the registered MMW image. We superimposed the boundary of the body extracted from the registered IR image on the registered MMW image to evaluate the accuracy of the registration task.

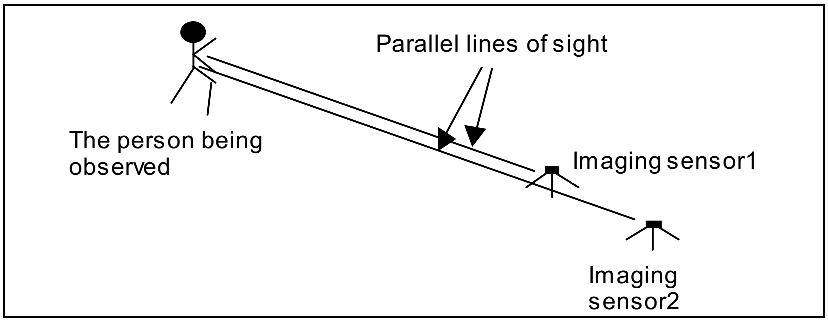


Figure 3. The set-up considered in our application.

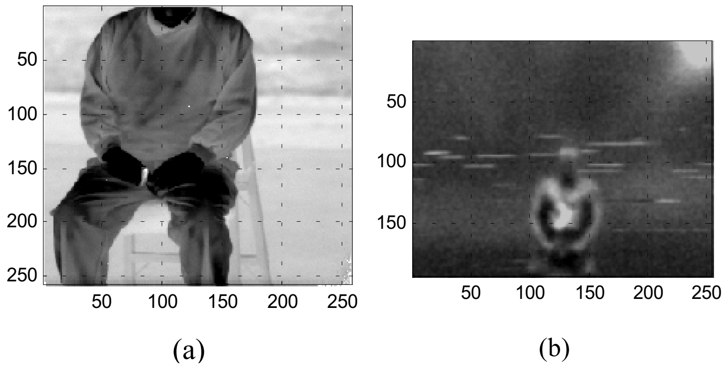


Figure 4. Typical (a) IR and (b) MMW images. Notice the strength of each sensor. (High resolution of IR and better penetration of MMW)

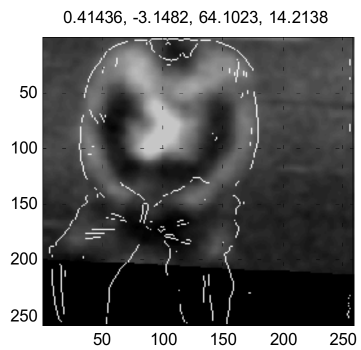
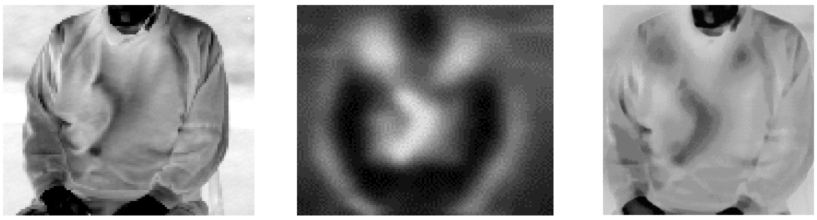


Figure 5. Registered MMW Image. The four numbers indicated above the image show the four transformation parameters (scaling, rotation angle in degree, vertical displacement, and horizontal displacement) found by the two-stage automatic registration algorithm.

The registration algorithm we developed consists of two stages. The main tasks involved in the first stage are two image segmentation algorithms and one binary correlation algorithm. The goal of this stage is to register the two images coarsely so that the result can be used as a starting search point of the optimisation process employed at the second stage, registration by maximising mutual information. The details of the registration algorithm developed are available in [3].

After the images taken from different sensors are registered, the next step is to integrate the information contained in each image. This task is referred to as *image fusion*. To accomplish this task we developed a wavelet based image fusion algorithm [10,13]. The examples shown in *Figure 6* are images before and after fusion. Thresholding (using Otsu's method [8]) was used to compare the fused results to the original IR and MMW images. *Figure 7(a)* and *Figure 7(b)* show the thresholded results for the original IR and MMW images. The IR image shows the gun, but it is also connected to wrinkles on the lower part of the image. In addition, several other wrinkles are visible for the IR image. No shape resembling a gun is apparent in the MMW image. *Figure 7(c)* shows the thresholded results for the fused image. It can be easily seen that the gun shape is very clear and completely separated.



(a) (b) (c)

Figure 6. Examples of images before and after the fusion process.

(a) (b) (c)

Figure 7. Result images after thresholding was applied on the fused images

Concealed weapon detection (CWD) technology utilises multiple sensors to improve detection of weapons hidden underneath a person's clothing. This is a typical multi-sensor surveillance task. The processing steps in the CWD task include registration, fusion, noise filtering, data enhancement, partitioning, feature extraction, and weapon identification. Here we have demonstrated how to integrate information from multiple sensors to help in extracting gun shapes from the image, with improved detection of the weapons. Once the result of CWD is available, further actions can be taken. They may include letting the person go or stop them for further search.

4. SUMMARY AND CONCLUSIONS

A great deal of effort is being put on the design and development of distributed multi-sensor surveillance systems. This indicates the significance of this field. While research on different aspects of the problem is important and interesting, one of the extremely important tasks is to find a solution on how to integrate all these tools in creating new surveillance systems with superior capabilities. New theories and computational methods will be essential in efficiently processing the data acquired and manipulated through these integrated systems. It is also expected that highly interdisciplinary teams will be one of the keys in finding effective solutions to this increasingly important problem.

5. REFERENCES

1. Distributed Microsensing: Devices, Networks and Information Processing. Strategic Assessment Workshop, Technical Report, Army Research Laboratory, Jan. 11-12, 1999, Adelphi, Maryland.
2. Bult K. et. al. "Low Power Systems for Wireless Microsensors",*Proc. of the 1996 Int. Symposium on Low Power Electronics and Design*, Monterey, CA, Aug. 1996, pp.17-22.
3. Chen H. -M. and Varshney P. K. "An Automatic Two-stage IR and MMW image Registration Algorithm for Concealed Weapons Detection", accepted for publication in *IEE Proceedings of Vision, Image and Signal Processing*.
4. Firoozbakhsh B., Jayant N., Park S., Jayaraman S., "Wireless Communication of Vital Signs Unsing the Georgia Tech Wearable Motherboard", Proc. ICME2000 IEEE International Conference on Multimedia and Expo. (Latest Advances in the Fast Changing World of Multimedia), vol.3, pp. 1253-6.
5. Hall D. and Llinas J., "An Introduction to Multisensor Data Fusion",*Proc. IEEE*, vol. 85, Jan. 1997, pp. 6-23.
6. Lin T.-H., Sanchez H., Kaiser W. J. and Marcy H. O. "Wireless Integrated Network Sensors (WINS) for Tactical Information Systems"*, Proc. of the 1998 Government Microcircuit Applications Conference*.

7. Rechtin E. and Maier M. W. " The Art of Systems Architecting (Systems Engineering Series)", CRC Press, 1996.
8. Otsu, Noboyuki. “A Threshold Selection Method from Grey-Level Histograms”,*IEEE Transactions on SMC,* vol. SMC-9, Jan. 1979, 1: 62-66.
9. Park S., Gopalsamy C., Rajamanickam R., Jayaraman S., "The Wearable Motherboard: A Flexible Information Infrastructure or Sensate Liner for Medical Applications*", Proc. Medicine Meets Virtual Reality 7*, Jan. 1999.
10. Ramac L.C., Uner M.K., Varshney P.K., Alford M., Ferris D. “Morphological Filters and Wavelet Based Image Fusion for Concealed Weapons Detection”,*Proc. SPIE Aerosense* ’98, 1998, 3376: 110-19.
11. Slamani M. *et. al.*. “Image Processing Tools for the Enhancement of Concealed Weapon Detection,” *Proc. 1999 International Conference on Image Processing*, 1999, 3: 518-522.
12. Tannenbaum A. S., Computer Networks, 2nd Edition, Prentice Hall, Englewood Cliffs, NJ, 1989.
13. Varshney P.K., Chen H. -M., Ramac L.C., Uner M., Ferris D., Alford M. "Registration and Fusion of Infrared and Millimetre Wave Images for Concealed Weapon Detection", *Proc. 1999 International Conference on Image Processing,* 1999; 3: 532-536.
14. Varshney P. K. "Multisensor Data Fusion",*Electronics and Comm. Eng*., Vol. 9 , Dec. 1997, pp. 245-253.
15. Varshney P.K. "Distributed Detection and Data Fusion", Springer-Verlag, 1997.
16. "New York Environmental Quality Systems Centre: Intelligent Control and Management Systems", http://nyeqs.syr.edu/ .