Monitoring and Control of Urban Critical Infrastructures: a novel approach to system design and data fusion

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ABSTRACT

The monitoring and control of urban critical infrastructures consists of the protection of assets such as houses, offices, government and private buildings, with low cost, high quality and high dependability. In order to satisfy all these requirements at the same time, the control of a number of assets has to be performed by means of automated systems based on networks of heterogeneous sensors. This new concept idea is based on the use of unmanned operations at each of the many remote assets (each asset is monitored through a network of sensors) and a man-in-the-loop automated control in a central site (Operational Center), which performs alarm detection and system management.

Keywords: Urban environment, wireless sensor network, artificial intelligence, monitoring and control, data fusion, big data, smart detection.

1. INTRODUCTION

Applications for monitoring and control of large areas by means of a wireless sensor network are already present in the literature [1], [2]. At present, the critical problems related to the control of urban critical infrastructures are high cost, low quality and limited dependability, due mainly to human based monitoring operations at each remote asset [3] -[10]. The basic reason for the involvement of personnel in the monitoring activity comes from the lack of technologies relative to the automatic detection of alarm conditions, which makes it necessary the replication of human activity on the different remote sites. The new technologies, included in the area of 2.0 Artificial Intelligence are: data fusion of heterogeneous sensors, big data processing and smart detection (including human in the loop) of alarm conditions.

2. THE NEW CONCEPT IDEA

The new concept for monitoring and control of urban critical infrastructures is focused on the application of new technologies for performing control of dedicated areas and locations by using automated mechanisms with very low involvement of human resources. The overall system (Figure 1) is composed of a multiplicity of controlled sites and one centralised operating station (Operational Center), to which all sites are connected. The Operational Center is the only site where a human control is available. The information produced by the different sites is processed partly at local level at the sites themselves and partly at the Operational Center. The overall process consists in examining the huge amount of data (big data) produced by the sites and detecting an anomalous behaviour at each of the sites considered (smart detection of alarm conditions). The anomalous behaviour detected enables the Operational Center to produce suitable alarms, which are used to generate the necessary reaction in real time and/or to create registered files in order to show the evidence of illegal actions for legal purposes. Due to the lack of human intervention in monitoring and to the high level of standardization of the system, the main economic benefit for the user is the low cost of installation and service.

Fig. 1: The new concept for monitoring and control of urban environment.

The envisaged solution introduces a new concept in monitoring and control of infrastructures, as it is based on a structured system, constituted of a large number of sites, each with a high number of heterogeneous sensors, deeply interconnected with each other by means of an ad-hoc network, and one centralised operating station. The advantage of this solution, with respect to competing solutions, consists mainly in offering to the potential customer the possibility to reduce costs consistently, due to the lack of human involvement at the local sites and to the use of standard tools and components. The key to the success of this initiative is in the development of automated mechanisms, implemented partly at the local sites and partly at the Operational Center, which substitute and outperform human monitoring. These mechanisms, at the central station, are complemented by the presence of human resources (man in the loop algorithms). The envisaged reduction in security costs is of the order of 90% of the actual costs. Moreover, the introduction of unmanned monitoring and the standardization of surveillance tools can enhance diffusion of monitoring and control in urban areas, thus making the above operations more effective and at lower cost and fostering creation of business for companies providing dependable monitoring services at a convenient cost for the end users.

3. STATE OF THE ART AND NEW TRENDS

The existing solutions for monitoring and control critical infrastructures are based mainly on total human intervention, with relative disadvantages in high costs and low reliability. Due to the above drawbacks, only a small fraction of critical infrastructures can be controlled, with consequent additional risk and cost for the whole community, in terms of loss and damage caused by crime and terrorism. Thus, the implementation of the new concept can not only lower the direct costs for the end users, but can also extend the end user area and lower the security costs for the whole community, by enhancing the role of prevention of crime and terrorism over recovery and repair actions. It is expected that the user needs can be widely differentiated, due to the different nature and scope of each application. As an example, in the case of monitoring and control of an industrial plant or infrastructure, the attention is mainly devoted to possible accidents or malfunctions, which can generate big damage to the plant itself. In these cases, it could be enough to act by means of automated actuators (such as in the case of fire) or by local human intervention. In other cases, such as protection of Government sites or other critical infrastructures, the user can focus mainly on people incursion or terrorist attack and the reaction must be adequate and massive, in order to stop the intrusion or attack. As a consequence, after the detection of any type of suspicious behaviour, a local task force should be immediately activated to perform a rapid intervention on the interested site. In general, the service must be oriented to satisfy the needs specifically defined by the user. The new technologies, included in the area of 2.0 Artificial Intelligence are: data fusion of heterogeneous sensors, big data processing and smart detection (including human in the loop) of alarm conditions. These technologies can be synthetically named TERADATA (Technologies for Enhancing Real Time Automatic Detection of Alarms in Tactical Areas). Substitution of personnel with automatic operation, made possible by the application of TERADATA technologies, will save cost and will move human resources from unreliable monitoring operations to more effective operations (e.g. real intervention in case of recognized alarm conditions). The introduction of the three concepts forming the TERADATA context, namely data fusion of heterogeneous sensors, big data processing and smart detection, will also drive the scientific and industrial community to standardize the surveillance tools (sensors and networks) by using common equipment for different systems.

4. DATA FUSION BETWEEN HETEROGENEOUS SENSORS

The data fusion process (Figure 2) is a tree structured process, which can be represented by K data fusion threads, where each thread corresponds to a partial data fusion sub process of a specific piece of picture in the scenario and the K different picture pieces are assumed to be uncorrelated.

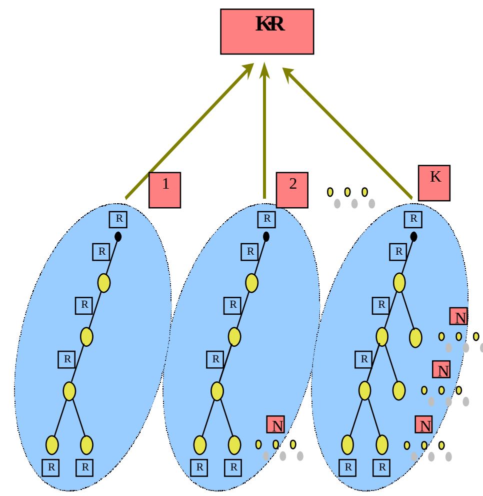

Fig.2 Data Fusion Process.

More specifically, the K different picture pieces are related to a scenario where K different targets are tracked by K different data fusion threads. Each of the K threads performs data fusion by merging data collected by different types of sensors, e.g. radar, optical, acoustic, etc. The unified global picture at the top of the data fusion process is composed of a collection of K different fusion threads.

With relation to the model previously defined, the K data fusion threads represent different picture pieces or picture sections, which are assumed to be uncorrelated. In order to perform this decomposition, it is necessary to determine, at distributed level, that there is no correlation or very loose correlation, between the targets belonging to a thread and the targets of another thread. At the same time, in order to associate to the same track different plots, coming from different sensors, it is necessary to compare the characteristics of the targets and apply a suitable relationship algorithm, in order to decide commonality between targets. Note that the association between targets and nodes is also temporary and it is possible that, along time, due to the dynamic nature of both the targets and the network, the same node can contribute to data fusion in different threads. As a matter of fact, all targets evolve over time and their number can increase or decrease, depending on the evolution of the targets and network topology. If the targets are concentrated on a determined subarea and the gateway node is constituted of a specific node in the network, there will likely be some specific nodes that convey most traffic, while the majority of nodes could remain idle. This is mainly due to being the routing algorithms designed in order to choose the shortest physical path, instead of the less congested one. There are different solutions to this problem, ranging from the possibility to design traffic adaptive routing algorithms, to rearranging routing paths after discovering some inhomogeneous traffic load when monitoring the network. All this process should carry out its effects automatically and without human intervention, being the same routing algorithms dedicated to intelligent rerouting of packets.

5. CASE STUDY 1: DATA FUSION BETWEEN RADAR AND OPTICAL SENSORS

In this Section, the sensor fusion between a radar sensor and an optical sensor is analysed in terms of selection of sensor fusion strategies and obtainable performance. In particular, in a distributed multi-sensor environment, where each sensor processes its own measurement, an important step is to decide whether data coming from different sensors represent the same target. If so, the next step is how to combine them together. Heterogeneous sensor tracking methods are based on state vector fusion (track fusion) or measurement fusion (plot fusion). Track fusion can be performed by merging the filtered state vectors into a new estimate of the state vector. Plot fusion combines the measurements from the sensors and then tracks those merged measurements to obtain an estimate of the state vector In the following, a typical case study is presented about combination of radar and optical sensors to improve the detection and tracking of ground moving targets. The case study refers to the data fusion of two heterogeneous sensors, but the proposed architecture can straightforwardly be extended to the fusion of N heterogeneous sensors. A discussion about general fusion of N sensors is then carried out. The case study is analysed by means of a simulation process, by providing the typical characteristics of radar and optical sensors.

We consider an X band Radar as radar sensor and an optical triangulation correlation sensor as optical sensor. The two sensors are assumed to be located at short distance between each other. A scenario is considered, consisting of a snapshot of 150 sec., during which a target, namely a vehicle, follows a rectilinear track at uniform speed, performs a manoeuvre after 50 sec. and continues through a rectilinear motion until the end of the snapshot. The vehicle is assumed to be visible from both sensors during the whole snapshot. The radar is assumed to feature a range accuracy of 60 m and an azimuth accuracy of 0.3 deg, while the optical sensor is assumed to have a range accuracy of 5 m and an azimuth accuracy of 0.05 deg.

We report the estimation errors in position, in particular the estimation RMSE (Root Mean Square Error) of the radar only, optical sensor only, radar/ optical sensor plot fusion and radar/ optical sensor track fusion, in the case of Pd (Probability of detection) = 0.85 for radar and Pd = 0.3 for optical sensor. Figure.3 shows the position RMSE, during the considered snapshot.

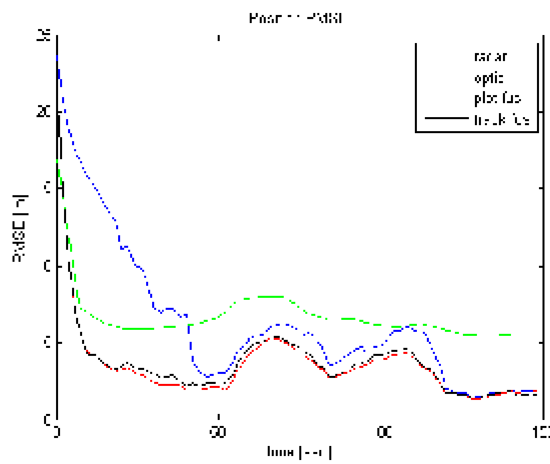

Fig. 3. RMSE of the position estimation vs. time.

The exercise shows that, for the first 50 seconds, the data fusion (plot or track) position RMSE decreases by 70% respect to optical position RMSE and of 50% respect to radar position RMSE. For the interval 50–120 seconds, the data fusion accuracy has a 10% improvement with respect to optical accuracy and 30% with respect to radar accuracy. For the last 30 seconds, the data fusion accuracy is almost the same as the optical accuracy.

The results demonstrate that, by performing radar/ optical sensor plot or track fusion, it is possible to achieve a RMSE of the position estimation less than 5 meters (typical requirement), for most of the time, when the target is moving at constant speed and far away from steep turns. These performances would not be obtainable by using the radar sensor only. On the other hand, the coupling of radar and optical sensors can improve the overall performance of a system, not only in this scenario, but also in other scenarios, described in the following sections.

6. CASE STUDY 2: RADAR CUEING OF AN OPTICAL SENSOR

In this case study, it is assumed that the optical sensor cueing region for its initial pointing is determined based on the estimated target position calculated by using the radar sensor measurements only. In this multi-sensor configuration, the radar is used to monitor continuously the environment and the optical sensor is activated only when a potential threat is detected. In practice, radar is used for the surveillance while the optical sensor is used to track/classify/identify single localized targets. Since the initial optical sensor pointing is based on the estimate provided by the radar sensor, the initial accuracy of the optical sensor is larger than the instrumental accuracy. In particular, the following assumptions have been done: the initial accuracy of the optical sensor is equal to the variance of the estimated target position provided by the radar sensor; the accuracy of the optical sensor converges linearly to the instrumental accuracy in about 8 seconds.

The estimation RMSE of the previous four tracking architectures (radar only, optical sensor only, radar/ optical sensor plot fusion and radar/ optical sensor track fusion) are compared in this scenario. It has been assumed that optical sensor is activated at time t=30 seconds. Figure 4 and Figure 5 show respectively the position and speed estimation RMSE.

In the first 30 seconds, only the radar sensor is active. At time t=30 seconds, the optical sensor is switched on. It can be noticed that the estimation accuracy of the plot fusion and track fusion architecture improves sensibly after the activation of the optical sensor.

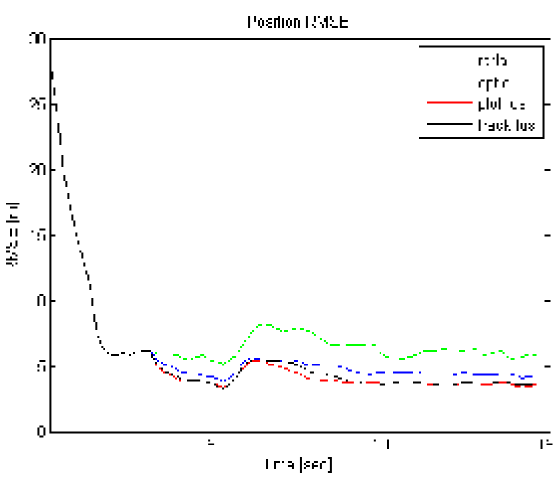

Fig. 4. RMSE of the position estimation vs. time (radar cueing optical sensor).

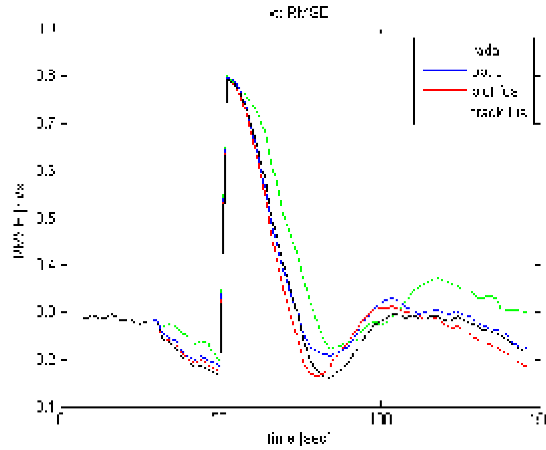

Fig. 5. RMSE of the speed estimation vs. time (radar cueing optical sensor)..

Also in this case study, the results demonstrate that, by performing radar/ optical sensor plot or track fusion, with the radar sensor cueing the optical sensor, it is possible to achieve a RMSE of the position estimation less than 5 meters (typical requirement), for most of the time and a RMSE of the speed estimation less than 0.2 m/sec (typical requirement), when the target is moving at constant speed and far away from steep turns. These performances would not be obtainable by using the radar sensor only.

7. DATA FUSION STRATEGY IN COMPLEX SCENARIOS

In a complex environment, it is shown that the multi-sensor architecture can provide several advantages. Depending on the probability of detection of the single sensors, the overall probability of detection is generally increased. Total accuracy also increases, compared with single sensor accuracies and probabilities of detection.

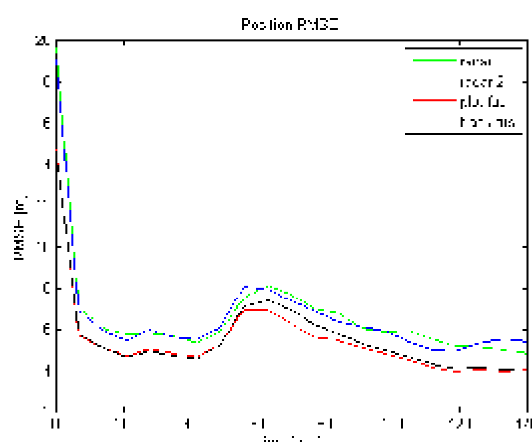

Fig. 6. Position RMSE (fusion of two radars).

Figure 6 shows the reduction in the estimation error in the case of two homogeneous sensors, e.g. two radars. In this case, the advantage of plot fusion versus the fusion of the radar and optical sensor is more evident.
Finally, it is also worth showing the case of N homogeneous sensors (not reported as a specific case study in this paper), where the improvement in the final accuracy results roughly proportional to the square root of the total number N of sensors (Figure.7).
The combination of heterogeneous sensors, such as radar and optical sensors, presents additional advantages besides the improvement of the estimation accuracy. In particular, as they operate at different frequency bands, they are characterized by different kinds of attenuation in different operating environments. In general, the contribution of radar can be very important in adverse environments with fog, dust etc. The radar sensor is in general strategically decisive for the alerting and cueing function of the overall system, since its range is greater than optical or other sensor range. In a multi-sensor system with heterogeneous sensors, a good design strategy is to mix cueing sensors with high resolution sensors, which means to use many frequencies and different technologies, in order to improve the overall performance of the surveillance system.

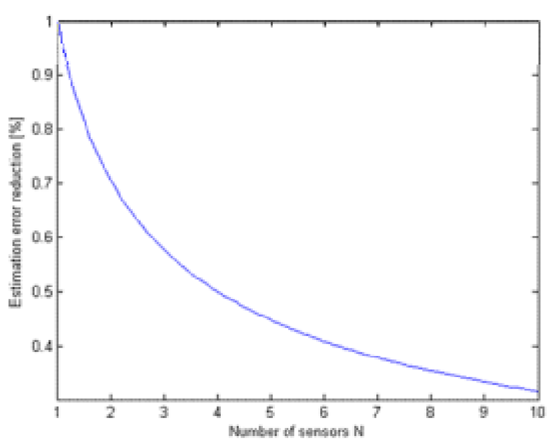

Fig. 7. Estimation error reduction with N sensors.

Concerning the comparison of the plot and track fusion architectures, track fusion estimation is characterized in general by a lower accuracy but it presents other advantages (reduced transmission bandwidth, lower computation resources) over the plot fusion.

8. CONCLUSIONS

The new concept idea for monitoring and control of critical infrastructures is based on the use of unmanned operations at remote assets and a man-in-the-loop automated control in a central site. The introduction of unmanned monitoring and the standardization of surveillance tools will allow low cost, high quality and high dependability of monitoring operations. In addition, the same methodology will promote the expansion of these kind of systems, thus improving the business and creating new opportunities, both for developers and for users.

9. REFERENCES

[1] Paul J. Croft et al. “UrbanNet: Urban Environment Monitoring and Modeling with a Wireless Sensor Network”, 90th American Meteorological Society Annual Meeting, Atlanta, 2010.

[2] U. Lee et al. ” Mobeyes: Smart mobs for urban monitoring with a vehicular sensor network”,Wireless Communications IEEE, Vol.3, Issue 15, October 2006.

[3] M. LaManna ”Urban Environment Monitoring: System and Technology Issues”, IMCIC 2012, 25-28 March 2012, Orlando, FL.

[4] M. LaManna “Data Fusion of Heterogeneous Sensors in Urban Environment Monitoring” IMCIC 2013, 9-12 July 2013, Orlando, FL.

[5] M. LaManna “Monitoring and control of urban critical infrastructures” IMCIC 2015, 10-13 March 2015, Orlando, FL.

[6] B. A. Warneke, et al., "Smart Dust: Communicating with a Cubic-Millimeter Computer", Computer Magazine, Jan. 2001, pp. 44-51.

[7] B. A. Warneke, K. S. J. Pister, “Exploring the Limits of System Integration with Smart Dust”, ASME International Mechanical Engineering Congress & Exposition, 2002-

[8] Charles E. Perkins, Pravin Bhagwat: DSDV Routing over a Multihop Wireless Network of Mobile Computers, Charles E Perkin (Editor) Ad Hoc Networking, pp. 53-74, Addison-Wesley, 2001

[9] M. LaManna, “Architecture and Data Fusion Strategies for a Wireless Sensor Network for Urban Environment Monitoring” IASTED International Conference on Wireless Communications, Vancouver, Canada, June 2011.

[10] G. Ferrari, M. Martalo’, R. Pagliari, “Decentralized detection in clustered sensor networks”, IEEE Transactions on Aerospace and Electronic Systems, Vol.47, April 2011.