Sensor data fusion: state of the art survey

I. Preface

This survey is organized into three research directions driven by somewhat different research communities: (1) sensor networks, (2) robust navigation and (3) situation awareness. The current and future progress in these areas will affect security and crisis management needs as treated in [1], for instance in the areas: surveillance of environment, borders, harbors, critical infrastructure and private properties; secure transportation systems; rescue operations and post-crisis exploration. Particular future systems requiring advanced sensor data fusion solutions include: portable and distributed systems for detecting dangerous substances or concealed threats, autonomous surveillance systems for critical infrastructure, robust portable navigation systems and remote sensing systems for monitoring environmental changes and border/harbor activities.

The focus of this report is on technical issues as enablers for security applications. The general needs, threats and vulnerability issues are treated in [1] and another state of the art survey on Intelligent Sensor Systems.

II. Introduction

“Fusion can refer to combining two or more distinct things”, according to Wikipedia, and the word is used in many different contexts ranging from nuclear power to cuisine. The same source defines sensor fusion as

“Sensor fusion is the combining of sensory data or data derived from sensory data from disparate sources such that the resulting information is in some sense better than would be possible when these sources were used individually.”

This is a clear definition that reveals the main objective with sensor fusion. The raw data may be preprocessed before the fusion process, and the goal is to get as accurate information as possible. The literature mentions three different levels of fusion: information fusion, sensor fusion and data fusion. The highest level of information fusion is often used in artificial intelligence contexts for fusing information that cannot always be represented with real numbers. This may include databases and data mining. In contrast, sensor fusion and data fusion merge numerical data from multiple sources. The distinction is not always clear, but data fusion is considered to take place closer to the sensors often on raw sensor data, and sensor fusion is the next level of fusion.

This survey focuses on the sensor data fusion, which can in general be classified as one or more of the following categories. (i) Sensors with different modality, meaning that they measure physically different things. This requires models for how the different physical quantities relate to the sensor observations. (ii) Spatially distributed sensors. This requires spatial models for how the sensor observation depends on its position. (iii) Temporal information from sensors. This requires dynamical models describing how the parameter/state evolves in time. In summary, mathematical models of various kinds are central in sensor fusion.

The state of the art and prospects for future development are split into the following areas:

1) Sensor networks for surveillance. Spatially distributed sensors (microphones, radio beacons, radars, etc.) are used to detect, localize, track and identify targets (humans, objects, vehicles, gas clouds, pollutions, etc.).

2) Robust navigation solutions. Sensors with different modality (satellite positioning systems, inertial measurements, odometry, markers/beacons, etc.) are used to get the sufficient amount of redundancy for robust and high-performance navigation solutions.
3) *Situation awareness, including mapping and tracking.* Sensors with different modality that can sense the environment (electro-optical (EO) video, laser, radar, etc.) are used on a, usually moving, platform to explore and map the environment around the platform.

Table I summarizes the security aspects of these areas. There are clear connections to the related knowledge areas *Intelligent sensor systems* and *Decision support.*

### III. OUTLINE

The report is organized in three main sections:

- Section IV, *State of the Art for the Application Areas,* exemplifies what can be achieved in the application areas with concrete examples, and hints on possible future security solutions.
- Section V, *Research Venues and Clusters,* first surveys the main books and conferences, and then gives examples of national and international research clusters.
- Section VI, *Research Renewal,* discusses some selected gaps where more research and development are needed.

Sections IV and V include one subsection per research area. Section VII summarizes the reports with recommendations.

### IV. STATE OF THE ART FOR THE APPLICATION AREAS

Sensor fusion applications are mostly in the defense, security and safety areas, and the distinction between these are sometimes a bit ambiguous. We here discuss applications with the highest potential for security in the areas listed in Table I.

#### A. Sensor Networks for Surveillance

Sensor networks (wired or wireless) can be used to detect, localize, track and identify various things:

- Chemical sensors for explosives, nuclear substances or different kinds of smoke (as recently installed in the Stockholm metro).
- Radio or radar receivers for active users of the radio or radar spectrum.
- Seismic sensors for a range of activities from far-away explosions to near-by footsteps.
- Acoustic microphones for vehicles or humans.
- Magnetometers for metallic vehicles.

Basically the same sensor data fusion framework is applicable to all the cases above. One common property is that the signal strength decays exponentially with the distance. Comparison of signal signatures in radio, seismic or acoustic waves can further be used to get time differences between each pair of sensors, which can be converted to range differences using the speed in the media (air or water).

Figure 1 illustrates the potential of an acoustic network for sniper detection. The position of the shooter is estimated quite accurately from the supersonic shock wave and the muzzle blast, but a bit more surprisingly also the shooting angle and various feature of the ammunition (bullet length, speed and air drag) can be

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**TABLE I: Security aspects of sensor fusion**
estimated. Besides being an interesting application in itself, it highlights the real strength of sensor fusion: by combining multiple sensor signals with accurate physical models, surprisingly much information can be extracted. Dedicated expensive sensor systems can many times be replaced with several standard sensors (in this case cheap microphones) and sophisticated signal processing algorithms.

Wireless sensor networks is today a well established area with more than 90000 publications (all citation data are according to Google Scholar). The research ranges from cheap hardware components, communication protocols to high-level algorithms. There are today off-the-shelf components on the market, but still a limited number of applications reported in literature.

Wireless networks itself is a challenging and well established area (more than 300000 publications), where localization or a mobile user is one key problem. In wireless telephone systems, the radio signal from and to the closest base stations contain a lot of information. Still, the billion of cellular phone users only get a crude position. One limitation is in the protocol layer, where higher layers do not get access to the most important information from the physical layer. In new standards for rescue services, such limitations can be avoided.

![Fig. 1: Acoustic sensor network for estimating shooting directions.](image)

**B. Robust Navigation Solutions**

A GPS (Global Positioning System) and an IMU (inertial measurement unit consisting of accelerometers and gyroscopes) combination is a perfect illustration of the sensor fusion principle: sensory data from disparate sources are combined such that the resulting information is better than would be possible when these sources were used individually. This combination is today standard in most transportation systems. One remaining area is rocket launching as illustrated in Figure 2, where export restrictions in the GPS software for high-speed objects (such as missiles) prevent a direct application. Instead, dedicated fusion solutions for rockets, not useful for other similar applications, are needed.

However, the total reliance of GPS today comes with obvious risks. For critical navigation applications, GPS cannot be the only positioning sensor. In military applications, an independent backup sensor insensitive to GPS jamming is often used, but also in civil applications the robustness against jamming may constitute one of the main design issues in the future. For marine applications, [2], [3] discuss the problem of intentional or unintentional GPS jamming and alternative backup systems are strongly recommended. Basically, the required redundancy can be achieved either with an existing wireless network, as mentioned above, or with a dedicated network of sensors or beacons, or with support from a geographical information system (GIS).

Figure 3 shows four state of the art examples of how GPS can be replaced by sensor fusion solutions and a GIS. In all cases, the achieved navigation performance on real data is in the order of ten meters without using GPS. Such algorithms are required in security applications underground (mine rescue operations) and in-doors (firefighters) to mention a few.
We know where it starts, but where will it land?

Fig. 2: This Maxus launch is one of the 470 rocket launches at Esrange. All these have been based on only IMU navigation, and the rocket have in most cases landed inside the huge area of Esrange, since even very expensive IMU systems drift over time. With robust fusion with GPS, the landing area could be restricted considerably, with a cheaper and lighter navigation system as a bonus.

The combination of databases and sensor data is, as illustrated in Figure 3, particularly promising for robust navigation. Google Maps has one interesting fusion feature, in that users with GPS equipped phones report radio parameters to a Google database, which in turn is used to position users without GPS in their phones.

C. Situation Awareness (Mapping and Tracking)

Autonomous vehicles have a large potential in security for post-event mapping. New rescue and exploration systems can benefit from the progress in this research area.

Situation awareness is the key enabler for developing autonomous vehicles. Autonomous vehicles equipped with vision sensors (camera, radar, laser, sonar, etc.) have a huge potential for the security area, in that they can continuously survey environment and critical infrastructure. They are also an excellent complement to a sensor network, and the moving platform can be used to examine critical regions detected by the sensor network.

The development of autonomous road vehicles has been tremendous during the last years sparked by the DARPA (US Defense Advanced Research Projects Agency) Urban Challenge [4], prestigious competitions with cash prizes. The first Grand Challenge was a desert race over 300 km in 2004, where no vehicle made it. This concept was repeated in 2005, and now five cars reached the goal. The DARPA Urban Challenge in 2007 aimed for the ultimate goal: autonomous vehicles driving along manned vehicles in city traffic and obeying the traffic rules. Several cars reached the goal after 100 km in the stipulated time, see Figure 4 for pictures of the first four cars. What is striking in all these cars is the large amount of external sensors. All competitors succeeded in fusing all these sensor measurements to extract high-level situation awareness information for control and decision making, see the triple special issue [4].

V. RESEARCH VENUES AND CLUSTERS

A. General Books in the Area

Fig. 3: Robust navigation systems as a support, backup or even replacement of GPS are possible by fusing Geographical Information Systems (GIS) and on-board sensors: (a) sonar and bottom map for underwater vessels, (b) radar and sea chart for surface ships, (c) wheel speeds and street map for road vehicles and (d) down-looking radar and altitude map for aircraft.

Fig. 4: The winners of DARPA Urban Challenge 2007: 1 (top left) Boss from Tartan racing, Carnegie Mellon, 2 (top right) Junior from Stanford racing, Stanford, 3 (bottom left) Odin from VictorTango, Virginia Tech, 4 (bottom right) Talos from MIT.
Fig. 5: Exploration by autonomous vehicles requires sensor fusion for joint navigation and situation awareness. Automotive state of the art: (a) Camera view of a traffic situation. (b) Situation awareness map from sensor fusion of camera and radar, where the own vehicle (circle), tracked vehicles (black rectangles), road geometry (solid and dashed lines), stationary obstacles (dots) and drivable area (white regions) are marked.


B. International Conferences in the Area

The International Conference on Information Fusion (FUSION) can be regarded as the main conference with a pure focus on sensor and information fusion. Security is one outspoken application domain. This yearly conference is relatively new, in 2010 the 13’th conference will be held. It was from the beginning more of a meeting place for researchers in the defense area, but a major shift to a high-quality peer-reviewed conference was initiated by FOI, who hosted the conference in Stockholm 2003.

The IEEE Aerospace Conference (AERO) also has a clear focus on sensor fusion theory. The SPIE conferences (non peer-reviewed) publish a lot of fusion related work, though the focus is on optics and photonics. In principle all major conferences in the signal processing and automatic control areas have special sessions on sensor fusion related themes.

In the robotics area, the main conference is the IEEE International Conference on Robotics and Automation (ICRA). The IEEE Intelligent Vehicle (IV) conference reports fundamental research on autonomous functions and navigation solutions in vehicles. In the AI community, there are conferences as International Conference on Principles of Knowledge Representation and Reasoning (KR) for fusion related research.

C. Swedish Research Clusters

FOI has the most extensive activity in information fusion, where this competence area has involved a lot of researchers for a long time. FOI arranged the Fusion conference 2003.

University of Skövde has a KK funded center for fusion from databases, sensors and simulations involving more than 20 researchers. The center organizes the yearly Swedish workshop SWIFT, and applied for the 2010 Fusion conference (ranked second in the end). The research is mostly in the computer science area.

The sensor fusion group at the division of automatic control, Linköping University, has a wide range of projects (including participation in four excellence centers) involving some 20 researchers, where 10
has a PhD degree. The research is focused on statistical approaches and applications. The first project phrased “sensor fusion” started already 1995, and the project’s home page is the fifth hit found in google on this search phrase.

The Center for Autonomous Systems (CAS) at KTH has a long-term research background on sensor fusion, with particular emphasis to ground robots. The signal processing group at KTH also has certain activities in sensor fusion, with a focus on statistical methods and applications. The funding includes a new “rambidrag” from VR.

Advanced systems engineering of sensor fusion solutions for autonomous systems can be found in several groups. The UAlVTech group at Linköping University, emanating from the Wallenberg funded WITAS project, has performed very well in many international competitions on unmanned aerial vehicles. Luleå Technical University has developed robust navigation solutions for ground robots based on reflective markers. Örebro University has a research center AASS (applied autonomous sensor systems) in robotics and a master programme in Robotics and Intelligent Systems. Both research and education are focused on computer engineering.

The classical problem of target tracking using radar is a strong area in Sweden. Various SAAB companies, in particular SAAB Systems and former SAAB Microwave, have contributed to the Swedish knowledge base. Among the universities, Chalmers has the lead in research in both radar technology and tracking algorithms.

D. European Research Clusters

Most European research institutes and defense oriented companies have excellent knowledge in sensor data fusion and contribute to the development of methods and applications. There are TNO (NL), Thales and ONERA (FR), Fraunhofer (DE), DSTL and Qinetics (GB), VTT (FI), FFI (NO) to mention some important actors. A background in military technology has in many cases proven to be fruitful for converting the applications to the security domain.

E. Other International Research Clusters

Sensor data fusion has the longest tradition in the US, and there is a clear US dominance at the Fusion, SPIE and AERO conferences for instance. There are American workshop proceedings with the name ‘Sensor fusion’ dating back to the eighties.

The area of sensor networks has also been driven by US initiatives. The US impact is manifested in the fact that when the high-impact journal IEEE Signal Processing Magazine had a special issue on wireless networks in 2005, four US papers from major universities and only one other (a Swedish one) were selected among some 20 contributions. This special issue is very well-cited today (180–480 citations per paper).

VI. RESEARCH RENEWAL

This section lists some areas where research has just started but where the state of the art is rather immature and where substantial progress can be expected in the next decade. The areas are selected both to suit Swedish industry and societal needs as identified in for instance [1].

A. Sensor Fusion Theory

1) Parallelization: The signal processing community has for a long time been relying on Moore’s law, which in short means that the computer capacity doubles for each 18 months. This technological evolution has been possible by down-scaling electronics where the number of transistors has doubled every 18 months, which in turn has enabled more sophisticated instructions and an increase in clock frequency. The industry has now reached a phase where the power and heating problems have come to a limit. The increase in processing speed of the CPU (central processing unit) has been exponential since
the first microprocessor was introduced in 1971 and in total it has increased one million times since then. However, this trend stalled a couple of years ago. The new trend is to double the number of cores in CMP (chip multicore), and the number of cores is expected to follow Moore’s law for the next ten years. The software community is now looking for new programming tools to utilize the parallelism of CMP’s, which is not an easy task. The signal processing community has also started to focus more on distributed and parallel implementations, and this also applies to the core algorithms used in sensor fusion systems.

2) Holistic Frameworks: Despite the success of the DARPA Challenges, see Figure 4, the sensor fusion algorithms in these vehicles are still quite basic. The DARPA vehicles rely on an abundance of expensive sensors and a distributed implementation of autonomous functions. The same holds for many successful developments of autonomous vehicles, where the (i) navigation, (ii) mapping, (iii) tracking, (iv) obstacle avoidance and (v) path planning are to a large extent separated. There is clearly a need for a holistic approach and a joint design of these interconnected functions.

One such joint high-level approach was initiated by the robotics community ten years ago. It is called Simultaneous Localization and Mapping (SLAM), which is an intense research area today. The idea is to create a map on the fly and use it for positioning the vehicle. The application area was and still is dominated by ground in-door robots, but the principle applies to general platforms. There are today several trends to extend SLAM to cover also tracking, obstacle avoidance and path planning.

B. Sensor Networks for Surveillance

1) Smarter Sensors in Wireless Networks: Sensor networks is today a hot research topic. The cheap sensor nodes proposed in sensor networks are basically energy constrained. One proposed state of the art processor for sensor networks consumes only 2.7 pJ per instruction, while short range low rate communication using for instance the Zigbee IEEE 802.15.4 standard consumes about 15 µJ per transmitted bit of information. That is, about 5 million instructions can be performed at the sensor node at the same cost as transmitting one bit of information. The conclusion is that quite advanced pre-processing at the sensor node is possible to mitigate the effects of the quantization implied by the energy induced bandwidth constraint:

- Distributed sensor fusion algorithms. As many operations as possible should be distributed to the sensor nodes to avoid excessive signaling. This is related to but not identical to parallel algorithms, since the information exchange differ several orders of magnitude on multi-core processors and in sensor networks.
- The transmitted sensor readings have to be quantized, and intelligent mitigation actions are required to avoid unnecessary information losses.
- The higher bandwidth in the down-link can be used to optimize the sensor algorithms so that less information is needed to be communicated in the up-link.

2) Portable Radar Networks: Small, cheap, energy efficient and portable radar networks can be developed, if the radar transmitter is separated from the portable receiver. One challenging idea is to utilize the wireless cellular phone network. The tens of thousands base stations in Sweden illuminate almost 100% of the country with in total megawatts of radio energy at a wavelength suitable for radar systems. One single radar receiver can detect a Doppler shift, which is useless information in itself, but with a network, the position and velocity of multiple moving targets can be estimated jointly with the position of the radio base stations (compare to the adaptive GIS below).

3) Acoustic Ranging: The localization and tracking theory has emerged from radar applications. Characteristics here are that the speed of the target is negligible compared to the speed of light, that there is a line of sight (LOS), and that the Doppler shift can be used to separate targets. This is not the case when using passive microphone, geophone or sonar networks for instance. A lot of research still remains until tracking in sensor networks reaches the same maturity as conventional tracking theory.
4) **New Applications:** A striking fact is that there is an abundance of theoretical papers on wireless sensor networks, but very few applications are reported so far. This is in contrast to classical wired sensor networks as used in for instance weather forecasting and earthquake monitoring. There is a great potential for event detection and source localization in surveillance systems for power plant protection, airport security, border control, and other infrastructure and private property protection.

**C. Robust Navigation Solutions**

1) **Adaptive Geographical Information Systems:** Geographical Information Systems (GIS) are typically developed for illustration and survey purposes, and they are not directly aimed for autonomous navigation systems. By letting the users update these maps, one can develop even more robust and secure navigation solutions. The adaptive radio strength map in Google Maps shows the potential of adaptive GIS. All applications in Figure 3 can for instance be improved by letting users report their measurements and estimated position to a central which updates the database accordingly. It is a well-known fact that today’s sea charts and road maps are not very accurate, and adaptive GIS would assure that the maps are always up to date. The principle of adaptive GIS is also important for indoor, underwater and underground applications (rescue operations), where robust navigation solutions are today lacking.

**D. Situation Awareness (Mapping and Tracking)**

Ever since the first radar system was demonstrated a hundred years ago, the returned radar echo has been thresholded in analogue hardware to give range and bearing measurements from the strongest echo as in indicator of a point object. The new trend is to extract more information from the returned radar signal, as the input to higher-level fusion algorithms. The *second century radar systems* will generate (i) intensity volumes rather than bearing–range pairs, and the output from the system will be (ii) extended targets rather than point targets.

A further challenge is to merge information from different vision sensors such as camera, radar, laser, IR, etc.

1) **Imaging Radar and Laser:** There is a general trend to handle larger parts of the radio spectrum in the digital domain. By sampling the complete returned radar echo, a 3D volume is obtained where each voxel contains intensity (and range rate).

The tracking community has adopted to this fact, and phrased the area of *track before detect*, in contrast to classical approaches that detect strong echoes and then apply a tracking algorithm. This leads in fact to theoretically more appealing algorithms where the conventional data association and track handling problems are partly circumvented.

The potential for the security area is here vast. Objects concealed by curtains, vegetation or even solid walls may be tracked, individuals in crowds may be followed and their activity monitored etc.. Similar radar networks and surveillance systems used today in air traffic control and marine surveillance can tomorrow be used at any place for any purpose.

There are commercial off-the-shelf (OTS) products already today to experiment with in the development of sensor fusion algorithms. OTS automotive radars save 20–60 echoes from each sweep, which gives a kind of 3D image of the most important objects. There are also IR-based OTS 3D sensors with 40 kpixel resolution.

2) **Extended Targets:** The classical tracking literature considers the objects to be points in space. A modern trend is to, more realistically, model the objects as a geometrical shape. In the computer vision literature, algorithms called *active contours* and *snakes* have been proposed and successfully applied to video data for segmenting foreground (aircraft, vehicles and humans for instance) from the background, with a big leap in performance. There are still limited results for 3D shapes.

The object shape is useful for the tracking performance itself, but in particular for object identification and anomaly detection.
3) **Fusion of Vision Sensors:** Automotive applications have shown that a radar and camera are in many senses a perfect combination, see Figure 5. For land surveys, scanning laser systems in combination with multi-spectral images have a great potential. The theory for such fusion systems is still in its infancy, and a lot of development can be expected in the future. Potential applications include stand-off scanning of people and detection of concealed threats in general. There is still no advanced theory for how to do sensor fusion on vision sensors.

**VII. Recommendations**

Sensor data fusion is quite an intense research area, where considerable developments are on-going in all three areas listed in Table I. As have been pointed out at several places, the applied studies are in many cases lagging behind the vast number of theoretical contributions. This can be utilized by supporting more applied initiatives to conceptual studies and to build demonstrators. It is here important that academy, industry and institutes collaborate on applied projects attacking important societal needs.

There is also a need for stimulating the theory–application feedback loop. New promising theory should be tested, evaluated and judged on real problems, which in turn should stimulate new relevant research questions. It is not necessarily the case that theory develops in a direction useful for the society without this feedback mechanism. Here, the academic partners and other funding agencies have an important role.

Section VI lists a number of research directions where promising initial results already exist on important problems with potential for the security arena, but where no or a limited number of applied studies exist. The list is meant to give a glimpse of hot areas selected as suitable for Swedish industry and societal needs as identified in for instance [1], but is by no means complete. By supporting applied studies in these or similar areas, new solutions may emerge at the same time as the research community gain valuable insights for new research directions.

**REFERENCES**