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# SENSOR FUSION: THEORY REVIEW AND APPLICATIONS

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***Abstract.*** *The sensor fusion, sensorial fusion or fusion of sensorial data is a term used in the scientific community which describe the utilization of the magnitudes collected for several measuring systems to obtain a best value for describe the variable of interest. This paper shows the basic theory to understand the more simple techniques for the sensor fusion and several applications, about navigation of mobile robots, automobiles, environmental monitoring systems, welding process control and sensor visual networks. As a result of this work, the current status and future trends of this technology is analyzed.*

***Keywords:*** *measurements system, mobile robots, sensor fusion, TIG welding*

## 1. INTRODUCTION

The design of a measurement system is a complex task and that involves many approaches and decisions. Most of the times should delimit or restrict the use of the system in function of the selected sensor, since it possesses invariable characteristics defined by the maker as the measurement range and the precision.

It also happens that the behavior of a sensor is not lineal, mainly in the ends of the measure range, for what won't have the same measurement error under those conditions. In numerous applications, an only sensor does not cover the whole measurement range. In this case, the system are complicated even more, because it has to commute to another sensor, maybe with another measurement principle and with different characteristics.

It's same when they change the measurement conditions, the environmental conditions of illumination for example, temperature, relative humidity, powder in suspension, altitude, magnetic fields, materials of the element to measure; or it even changes the means like it can be the measurement of distances for ultrasound in the water and in the air. In these cases, it can need more than a sensor.

It is possible also, that it is required to increase the accuracy of a measurement system. A possible way is to increase the number of sensors and process its measurements statistically.

The fault tolerance is another topic to keep in mind. Habitually it is solved duplicating the device and establishing mechanisms of faults detection and strategies to take the same magnitude of another sensor.

All these methods need mechanisms for select and integrate the measurement of several sensors or measuring systems, to complete a specific objective. The objective can be to increase the accuracy or precision of the system, to increase the measurement range, to support environmental changes, to tolerate the break of one or several sensors, among other. The above mentioned is in fact one of the tasks of the algorithms of sensorial fusion.

This paper show the basic theory to understand the more simple techniques for the sensor fusion and several applications, about navigation of mobile robots, automobiles, environmental monitoring systems, welding process control and sensor visual networks. The method used was the conceptual review and classification of sensor fusion techniques.

In the section 2 are explained some of the possible classifications and techniques used in the sensorial fusion, with illustrative examples in each case. In the section 3 are shown several applications in different areas. Finally, in the section 4, are presented a synthesis based on the conceptual review, the current state and the future tendencies of this technology.

## 2. SENSOR FUSION

The use of the magnitudes recovered by different sensors or measurement systems, to obtain a value that describes from a more convenient way to the variable measure, has been popularized in the scientific community with the term of fusion of sensors, sensorial fusion or fusion of sensorial data. Next, we will comment shortly how it takes place the fusion of these devices, their different classifications and some of the used algorithms.

### 2.1 Classification of sensor fusion.

The sensor fusion can be classified in different ways. In this section, we will see three of the most used classifications: classification according to the relationships of the input data, classification based on the input and the output and classification based on the types of architectures.

They also exist other classifications in function of different objectives, not commented here. In (Castanedo, 2010) we can find a description of other two classifications.

#### 2.1.1 Classification according to the relationships of the input data.

This classification defined how the information relates between the sensors. According to Castanedo (2010) the fusion can be complementary, competitive or redundant, and cooperative, but it is very common to find more than a work way in the same group of sensors. This classification are shown in the figure 1.

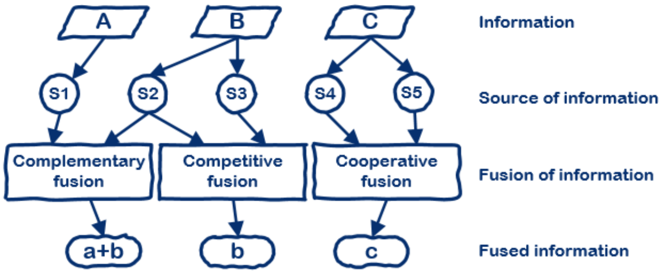


Figure 1. Classification according to the relationships of the input data.

***Complementary fusion:*** The complementary fusion is about fusing incomplete information that are obtained starting from different sources. This is the case in that several sensors are measuring different parts from an atmosphere or phenomenon, covering a bigger area and allowing a more complete and more global vision of the process.

This fusion type is generally easy to make and it is observed in the following examples:

- Several distance sensors in a mobile robot that they point in different addresses and they provide information of the objects that surrounds it (see figure 2a and 2b)
- Several radars which covering different regions, but the system merge the information as if a single radar covered the whole territory.
- A speedometer and an odometer in a vehicle, both provide useful information for the navigation.

***Competitive or redundant fusion:*** In some cases, multiple sensors are used. For example, when a sensor is very imprecise or noisy as to give reliable data or it is wanted that the system to be tolerant to faults. In this case, all the sensors are monitoring the same area, working in a redundant and competitive way. They can be seen as that compete to publish the best perception. These sensors can have a measurement principle similar or different, this will determine a physical or logical redundancy. Some examples are described next:

- A mobile robot with two rings of ultrasonic sensors to different height. The system returns the smallest distance measure. In this way, he can obtain a more reliable reading for low objects that would not usually be detected by the superior sensors. These possess physical redundancy.
- A mobile robot with two distance sensors, one optic (infrared) and other ultrasonic. In this case, the optic sensor allows to obtaining a reliable measurement in very small distances, where the ultrasonic one cannot work. These possess logical redundancy.
- Several radars that cover the same region but they allow to increase the resolution of the measuring system. In this way, the system continues working even when it fails some of the radars. These possess physical redundancy.

The figure 2c show the ultrasonic sensors in the same level. They work in a complementary way, but they compete with those of the other level. In the figure 2d, it passes something similar, since the ultrasonic sensors work in a complementary way, but they competing with the infrared sensor. These are examples in that you combine two fusion ways.

***Cooperative or coordinated fusion*:** This fusion used the information of independent several sensors to obtain a new information. A single sensor can never obtain this new information. For example:

- The Percentage of Saturation of Dissolved Oxygen is obtained with the measurement of the temperature of the water and the Dissolved Oxygen in her.
- The Water Quality Index are obtained with several parameters like the pH, Total Coliforms, Nitrate, Demand of Oxygen, Electric Conductivity, Percentage of Saturation of Dissolved Oxygen, Chloride, Obvious Contamination and others.
- The obtaining of a three-dimensional image starting from two photographic cameras or of video (see figure 2e)
- Elaboration of a profile of temperatures in an oven, starting from the measurement of several thermometers distributed in their interior.

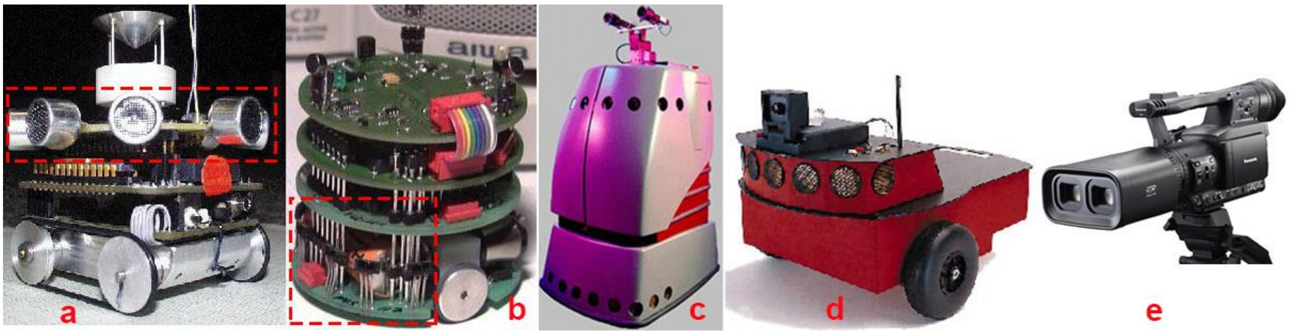

Figure 2. Sensors ultrasonic (a) and infrared (b) working in complementary fusion. Sensors ultrasonic (c and d) and infrared (d), in complementary and competitive fusion. Two video cameras working in cooperative fusion (e).

### 2.1.2 Classification based on the input and the output.

Other classification of the fusion processes, submitted by Castanedo (2010), are based on the abstraction of the input and output of the information. This is divided in: data in-data out, data in-feature out, feature in-feature out, feature in-decision out and decision in-decision out.

***Data in-data out (DAI-DAO:*** This is the most low-level fusion or most elementary form that is considered in this classification. This used rough data and the results usually are more precise and more reliable. The fusion is carried out immediately after the acquisition of the data for the sensors. The fusion paradigms in this category are generally based on techniques developed for the signal treatments and images processing.

***Data in-feature out (DAI-UGLY):*** It is used when in the fusion process uses rough data of the sources to extract characteristics that describe an entity in the environment. The fusion is known as fusion of characteristics, symbolic fusion, fusion of information or fusion at intermediate level. An example of this fusion is the form in which the human perception distinguishes the depth of the objects, with the combination of the information of the two eyes.

***Feature in - Feature Out (FEI-UGLY):*** In this classification, the input and output to the fusion process are characteristics. Therefore, the fusion process works with a group of characteristics to improve, to refine or to extract new characteristics. This is what is usually known as fusion of characteristics.

***Feature in - Decision Out (FEI-DEO:*** This fusion type is one of the most common focuses used in the literature. They take a series of characteristic of input and are generated decisions in the output. Most of the systems of pattern's recognition that make a decision in function of the value of the input of the different sensors are carrying out this fusion type.

***Decision in - Decision Out (DEI-DEO):*** It consists on fusing the decisions to obtain better or newer decisions. The input and output of process are decisions. It is also known as fusion of decisions.

### 2.1.3 Classification based on the types of architectures.

One of the main decisions that should take in the systems of sensorial fusion is where to carry out the fusion of the information. Depending on how it is carried out the fusion process, according to Castanedo (2010), the architectures of the systems can be divided in distributed centralized fusion, decentralized, and hierarchical.

The selection of an appropriate architecture depends on the necessity, the demand, the existent connections, the readiness of the data and of the organization of the system of fusion of data, therefore an architecture is not better than the other.

***Centralized fusion:*** In this architecture, the fusion is located in the central processor that he obtains all the information of the different sources. Theoretically it is the best fusion architecture, but in the practice it is not always possible to have these conditions.

***Decentralized fusion:*** This architecture consists on a net of nodes, where each node has its own processing capacities and each one carries out the fusion being based on the own information and of the neighboring nodes. It has the inconvenience that when increasing the number of nodes $n$ times, the cost in communication are increased $n^2$ times. This makes that these algorithms are not easily scalable when the number of nodes grows.

***Distributed fusion:*** In this architecture, the measurement of each sensor are processed in an independent way before sending the state to a central processor for a later fusion with other distributed input sources. Therefore, each sensor provides an estimate of the phenomenon being based alone in its local information. This information is the input for the process of fusion that provides the global output. This architecture offers flexibility to locate the nodes.

***Hierarchical fusion:*** This is a combination of the previous architectures where the fusion of the data is carried out in different layers of hierarchically related nodes.

### 2.2 Fusion techniques

The techniques or algorithms of sensorial fusion are diverse and they depend on the application, but some of those more employees are the Kalman filter.

The Kalman filter consists on a group of equations that it provide an optimum recursive solution, for the method of least squares, for a dynamic lineal system. A method can be implemented as computational algorithm. This algorithm was developed by Hungarian Rudolf Emil Kalman and published in 1960 in (Kalman, 1960), it assumes a dynamic lineal system and one observable, corrupt with white noise.

This filter is distinguished for its ability to predict the state of a model in the past, presently and in the future, even when the exact nature of the modelling system is unknown. The dynamic modelling of a system is one of the key characteristics that distinguishes the method of Kalman. The lineal dynamic models are model with a lineal transition from one period to the next one, which can describe most of the models commonly used in works of series of time. The Kalman filter had a dramatic improvement ahead of his predecessor the Error Half Quadratic Minimum, invented by Norbert Wienner in the years 40, which was limited to signs scalars with stationary statistic.

Among the disadvantages of the filter, according to Sergio (2005), Choque (2013) and Welch (2006), are that requires initial conditions of the average and the variance of the state vector to begin the recursive algorithm and doesn't exist a collective agreement about how to determine these initial conditions. On the other hand, for the total understanding and development of the Kalman filter it requires a wide knowledge of the theory of the probabilities, that which can originate an obstacle for their study and application.

In spite of this, the Filter of Kalman is used in many applications that include robots navigation, global positioning system (GPS), inertial navigation systems (INS), audio processing, measure of meteorological and environmental variables, etc.

The Kalman filter can be applied in linear systems or that they can approach to a linear model. For their employment in nonlinear systems are applied variations defined in the extended Kalman filter, developed by Stanley F. Schmidt for the space navigation in the Apollo project, according to comments Sergio (2005)

In the literature, they are also numerous references to the use of other fusion methods focused to each stage of the process. Some examples posed by Castanedo (2010) are show below:

***Association:*** Neural networks, fuzzy logic; associative methods as nearer neighbours, k-neighbors; probabilistic data association (PDA) or modified filter of all neighbors; joined probabilistic data association (JPDA); multiples hypothesis test (MHT) and association graphs.

***Estimate of the state:*** Maximum verisimilitude, maximum to posteriori, filters of particles, statistical Bayesians, systems based on rules, Kalman filter, neuronales networks and fuzzy logic.

***Fusion of decisions:*** Inference Bayesian, Bayesians networks, Dempster-Shafer inference, abductive reasoning, semantic fusion and voting methods.

Many of the previous methods are applied alone in centralized fusion architectures, but others versions of several of these algorithms can be applied to distributed architectures.

Next, we will comment several applications in different spheres, like the navigation of mobile robots, systems of environmental monitoring, welding process and nets of visual sensors.

### 2.3 Aplications.

The sensor fusion can be applied in many areas of life. In this section we look at some of the most common applications of this technology.

#### 2.3.1 Navigation of mobile terrestrial robots.

The relative positioning of a robot is usually based on odometry. This technique obtain the new vehicle's position starting from the current position and the speeds of the wheels. In most of the robots, this it is implemented using optic decoders that offer information of the rotation of the wheels and of the turn angle. These data are used to calculate the displacement starting from an initial well-known position. This is simple of implementing, not very expensive and it allows its employment in real time, but it has as disadvantage that the error is accumulative in each successive calculation.

According to Santiago (2009), other technology used for odometry is the Inertial Navigation Systems (INS) that measure the movements through accelerometers and gyroscopes. They are adapted for soft movements, without blows or abrupt movements, and they can reach precisions of 0.1% of the travelled distance. The objective of these sensors, in general, is to measure the movement in three axes to achieve localization or to stabilize autonomous vehicles. These units in they have multiple applications in robotics, airships, air unmanned vehicles, satellites, among many others.

However, this technology are expensive (between $50.000 and $200.000 USD) and is not available for mobile robots since the mobile robots generally violate the restriction of carrying out soft movements. They frequently receive blows or abrupt turns being able to exceed the measure range of the accelerometers. These are generally used for big systems. However already you can find integrated in oneself semiconductor the sensors that require the INS functionalities. An example are shown in the figure 3a. This integrated a gyroscope of 3 axes and an accelerometer of 3 axes, is development for Invensense (2014). Another example of this technology can be found on (Murata Manufacturing Co. Ltd., 2014).

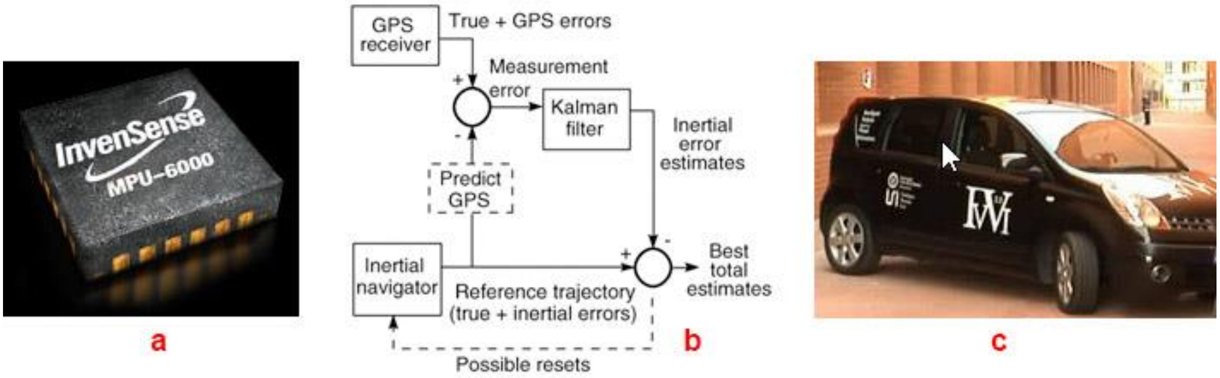


Figure 3. Gyroscope and accelerometer with 3 axes each one (a); GPS receiver and a system of inertial sailing, using a filter of Kalman to improve the sailing (b); Experimental vehicle of the University Carlos III of Madrid that it uses sensorial fusion (c)

According to Espinoza (2000.), the integration of the GPS with an INS and a filter of Kalman provides a global result improved in the whole navigation. The INS can present an accumulative error that grows slowly in each one of its measurement. The measurement of the GPS, on the other hand, has an accumulative error very small but it is much noisier. The errors of the GPS can be due to imprecisions in the receiving clock, the receptive readiness, the ionosphere's state, the troposphere, the "multipath" phenomenon and multiple roads that it can follow the signal. The processing with the Kalman filter can solve this situation according to the diagram show in the figure 3b.

Investigators of the groups of Artificial intelligence Applied (GIAA) and of the Laboratory of Systems Intelligent (LSI), of the Carlos III University in Madrid (Spain), they have developed a navigation system based on a conventional GPS and an INS of low cost, according to Motorpasion newsletter (2013). The margin of error of a conventional GPS, as those that are used in the automobiles, is of about 15 meters in open field, and it can arrive to 50 meters inside the city. This Spanish development has been able to assure the positioning of a vehicle between 1 and 2 meters in urban environments.

The new system is based on the sensorial fusion that integrates the measurement provided by the GPS and that of the three accelerometers and three gyroscopes. This INS can measure the changes of speed and manoeuvres developed in the vehicle. The signals are sent to a calculation unit endowed with an algorithm, based on a filter of Kalman. This algorithm remove the instantaneous deviations caused by the degradation of the signals received in the GPS and the total or partial loss of the satellites. A prototype is working in an experimental vehicle in this university.

### 2.3.2 Navigation of mobile air robots

One of the main problems in the control of a mobile air robot is the measurement of the position, turn speed and altitude. The orientation is defined for the drift or yaw, the inclination or pitch, and the warp or roll, as shown in the figure 4.

Many sensors can help to know these data, among them GPS, gyroscopes, accelerometers, barometers, altimeters, magnetic compass, INS and others. The signals of the sensors should be processed and be combined to eliminate the noise and error of the system. Espinoza (2000) present a typical example about the estimate of the height starting from the measurement of an altimeter and an accelerometer, knowing the dynamic equations of the mobile robot.

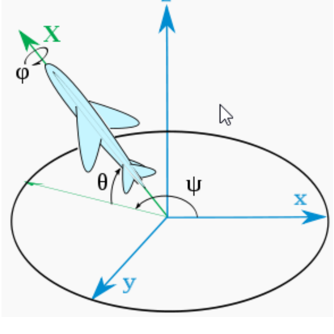


Figure 4. Variables that define the orientation of an air motive: yaw angle (ψ), pich (ϴ) and roll (φ).

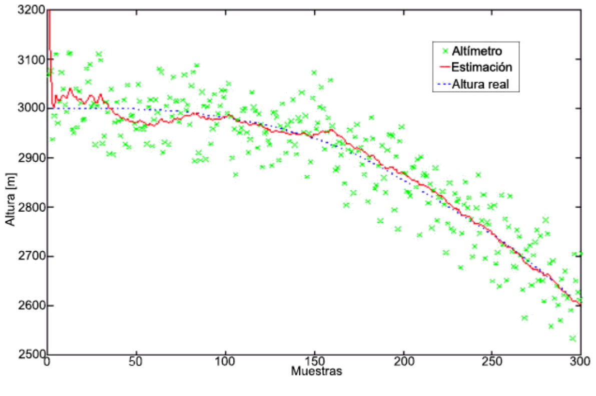


Figure 5. Estimate of the height starting from the measurement of an accelerometer and an altimeter, processed by a filter of Kalman.

This case is show in the figure 5. In it, the line discontinuous samples the true height, the crosses indicate the altimeter's measurement and the continuous line the estimate of the Kalman filter. It is observed as the measurement of the altimeter, which form a band of about 100m around the real height and as the estimate of the filter is nearest to this real value with each iteration.

Another example of this fusion type, implemented in a microcontrolador, you can appreciate with great level of details in (Starlino, 2009), (Starlino, 2010) and (Muñoz , 2011).

### 2.3.3 Welding TIG

As in any productive process, the control of the quality in the welding is an indispensable stage to guarantee a reliable product and with constant quality.

Non-destructive several methods exist to verify the welding, among them, they stand out those that are based on ultrasound and rays X, but hydrostatic methods and mechanics are used. All are methods that evaluate the welding after having concluded and it is not possible to modify their properties in real time. In addition, these tests habitually represent 10% of the total cost.

For correct the defects in the welding process, before the metal solidified, is necessary the implementation of methods of on-line monitoring that keep in mind their quality. This reducing considerably the time of production of each piece.

In this sense, several investigations are developed where they intend different methods, among them the employment of computer vision (image processing), plasma spectrometry, ultrasound and others. All have their advantages and disadvantages, in function of the materials that are used, the defect to detect and the environmental conditions. However, they do not have an algorithm that integrates these measurements to obtain a more reliable indicator.

According to Absi (2012), a proposal of the Group of Automation and Control (GRACO) of the University of Brasilia, are the integration of the measurement obtained by several sensors in the welding Gas Tungsten Arc Welding (GTAW), also well known as Tungsten Inert Gas (TIG)

This welding type is based on an electric arch formed between the tungsten electrode and the metals to weld. According to Kielhorn (2008), an inert gas (or a mixture of them, habitually Helium and Argon) insulated the arch of the atmosphere, to protect from pollutants to the welding, as it is shown in the figure 6.

It is one of the welding methods for more versatile arch, since it allows a wide range of thickness of the plates, of ferrous or not ferrous metals and of diverse alloys. It can be used in welder's robots and it accepts any position for the electrode. The equipment for this welding consists on a source of alternating or direct current in function of the material to weld, a tungsten electrode, a source of an inert gas and a refrigeration system that it can be water or air.

It is known, according Absi (2012) and Chen (2014) that it is possible to determine if the welding process is happening correctly through the measurement of the tension and the electric current that it is used in the generation of the electric arch. Investigations carried out by GRACO also demonstrate that the analysis of the sound signal that is generated in this process can be an indicator of some defects and that the sound pressure is increased when the longitude of arch increased. Other indicator is the temperature of the metal and their distribution in the welding, as well as the penetration of the welding, that which one can obtain analyzing the infrared images. These and others measurement can be integrated in an embedded system that it is able to govern the electric arch, as well as the flow of inert gas and of coolant. One of the proposals is to integrate this measurement by means of a Kalman filter.

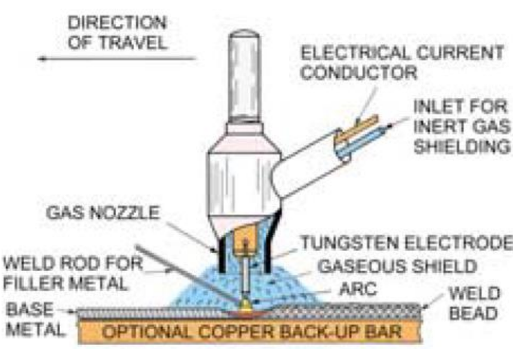


Figure 6. Welding process TIG.

Figure 7. Fusion of visual sensors and the players' pursuit starting from different views. To the right the result of the fusion is observed in the plan of the land.

### 2.3.4 Nets of visual sensors

The nets of visual sensors are directly related with the space distribution that exists in the multi-camera environments. According to Castanedo (2010), in a visual network the sensors should be able to process the data of the images in a local way and to extract the relevant information, to collaborate with other sensors for specific tasks and to provide detailed information of the captured events.

The nets of visual sensors are extremely useful because they provide a bigger geographical covering and the possibility of exploiting the redundancy of the perceived information. These can be useful to create a great number of novel applications based on the artificial vision.

One of the main applications is that of video surveillance, like a potent tool of public security. With the growing demand of the security in the airports, marine environments and other critical environments, the necessity of quick and flexible developments in the systems of surveillance is growing.

The development and implementation of the nets of visual sensors generate several problems that it is necessary to solve. Some of these problems are related with the techniques of fusion of data to combine the information shared by the different sensors, while others are related with the aspects of treatment of the visual information, communication and of management of sensors. In the case of the nets of visual sensors applied to surveillance (known as systems of surveillance of third generation), their main goal is to detect and follow objects or peoples inside the visual field.

Castanedo (2010) intends the use of systems multi-agent BDI like the software architecture to manage a net of visual sensors and to carry out a fusion of distributed data. This system has been applied, using real visual sensors and groups of images, with the objective of fusing positions in the plane of the floor. The tests carried out also demonstrate the improvement in the fusion process when the number of sensors used is increased, because you exploits the redundancy of the data. One of their results is shown in the figure 7.

Other examples can be seen in (Rodríguez, 2003) and (Maldon, 2002).

### 2.3.5 Environmental supervision

The atmospheric contamination is an important problem of environmental health that affects too many countries. According to Barron (2014), the city of Salamanca in Guanajuato, Mexico, has serious problems of atmospheric contamination, and it is classified as one of the polluted in the country. The main causes of atmospheric contamination in Salamanca are the sources of emission like chemical industries and of electric generation. The environmental effects in the air are serious and they have making important efforts to measure the concentrations of Dioxide of Sulfur ($SO_2$) and particles smaller than 10 micrometers (PM10), main pollutants in the city. Now, the estimates of the Air Quality Index, reported by the Environmental Authorities, are carried out with the mobile average of the concentrations of pollutants. This estimate not consider the climatic factors.

On the other hand, studies related with the atmospheric contamination have demonstrated that the severe episodes of atmospheric contamination not only owe you to sudden increments in the concentrations of pollutants but also to certain meteorological conditions that diminish the capacity of the atmosphere to disperse these concentrations.

Barron (2014) intends the modelling of a system of supervision of the quality of the air using the technical of fusion of sensors and artificial neural networks (ANR). This work contributes to determine in an automatic way the air quality in the city of Salamanca. The process uses the meteorological variables of address and speed of wind, to determine the effects of these in the concentrations of pollutants and to determine the level of atmospheric contamination. The methodology consists on analyzing the temporary series of the concentrations of pollutants and the meteorological variables to generate patterns of training with outstanding and representative information. This information can be used to train an ANR of auto organized maps.

With the sensor fusion is obtained a quantitative gain regarding the classical methods. Also is possible to obtain a qualitative gain, with the information of the behavior of the atmospheric contamination that it helps to make decisions in this respect of some environmental contingency.

Other example can be seen in (Cotos, *et al.*, 2014).

## 3. DISCUSSION AND FUTURE TENDENCIES

After having appreciated through this bibliographical revision, anything exhaustive, some of the theoretical bases of the sensorial fusion and their applications, we can make some statements that are discussed below.

It is a multidisciplinary topic, where several intervene fields of the knowledge, so much of the calls pure sciences or basic sciences as of those applied sciences. Their total understanding requires the domain of several topics of each one of these disciplines.

They are big the applications for the future of the transport industry, some of which are already on test. The branches of the robotics and the surveillance are others of the big instigators of these techniques and they have a promising future. The environment and the life in the planet can benefit of these techniques, associated to the data that are obtained of the satellites and of the environmental monitoring network.

In the future, it will increase the use of the artificial intelligence in the algorithms of sensorial fusion, taking advantage of the big capacities of processing and storage of information that offers the current development.

Although their study began several decades ago, still has a long way to go, given the great quantity of diverse applications that it have arisen and that they are developed now with base in these techniques, and product that the technological development is a great condition for its application.

Their utility is undeniable. Every time its use are extends to sectors not approached, due to the tests contributed by the scientific community and the applications of its versatility, flexibility and scientific validity.

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