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Multi-Sensor Data Fusion on Intelligent Transport Systems

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Index

1. Introduction	1
Sensor	1
Multi-sensor Integration	2
2. Architectures.....	3
Architecture Concepts	3
Formal Frameworks.....	4
Esteban Framework.....	4
Mitchell Framework.....	5
Centralized and Decentralized Architectures.....	6
Centralized architecture	6
Decentralized architecture	6
Publish/Subscribe Architectures	8
Use of mobile agents.....	9
3. Models	11
Joint Directors of Laboratories (JDL) framework.....	11
Waterfall model	12
Thomopoulos Model	14
Luo and Kay Model.....	14
Omnibus model.....	15
Distributed Blackboard Model.....	16
4. Data Fusion on Intelligent Transport Systems	17
Generic Data Fusion on ITS.....	17
A Case Study.....	18
Lisbon City Council.....	18
Carris.....	20
Lisbon Metropolitan.....	22
Quadriga	25
Final Remarks.....	26
5. References	27

Images Index

Figure 1, Schematic representation of the framework proposed by Esteban.....	4
Figure 2, Schematic representation of the framework proposed by Mitchell.....	5
Figure 3, Centralized architecture.....	6
Figure 4, Publish/Subscribe architecture.	8
Figure 5, JDL framework.....	11
Figure 6, Waterfall model.	12
Figure 7, Thomopoulos model.	14
Figure 8, Luo and Kay model.....	15
Figure 9, Omnibus model.....	15
Figure 10, Distributed blackboard model.....	16
Figure 11, Schematic description of the system adopted by CARRIS to receive and transmit information to all the stakeholders.....	21
Figure 12, Frotcom vehicle tracking system.....	25

1 Introduction

With the increase in number and type of sensors available, and the need to manage a growing quantity of information produced by those sensors, emerged the need to fuse those data into high level information that a human can perceive and could act automatically in the environment. This led to the need for multi-sensor data fusion technology.

Multi-sensor data fusion technology concerns the problem of how to fuse data recorded from multiple-sensors, together with knowledge, in order to make a more accurate estimation of the environment and allow for a variety of applications, such as intelligent transport systems, traffic control, maintenance engineering, remote sensing, robotics, environment monitoring, global awareness, and others (Wang et al, 2001) (Esteban et al, 2005). Multi sensor integration can include data from various types of sensors that measure different environment variables, sensors of the same type that measure the same variable, or a combination of both scenarios. The basic problem is to determine the best procedure for combining input data from multiple sensors (Mitchell, 2007).

1.1 Sensor

A sensor is a device that can interact physically and directly with the environment through a *sensor element* that perceives a physical property. The environment is the source of the input data for the multi-sensor data fusion. The sensor output (known as *sensor observation*) includes different information, such as the name of the property measured; the spatial location where the measure was performed; the time when the property was measured; the value of the physical property measured; and an uncertainty that includes possible errors (systematic or random) associated with the measurement or calibration process (Mitchell, 2007).

A sensor is characterized in five different categories: the state; function; accuracy and range performance; output signal; and energy type transferred to the sensor.

In a multi-sensor data fusion system the tasks of information integration and data processing can be distributed through the system components. Therefore, a sensor must perform additional functions such as compensation, where the sensor has the capacity to perceive changes in the environment and self-adjust; information processing, where the output data is improved by the sensor himself; the ability to communicate with the system using a standard protocol; and the integration of different process in the same hardware component. This kind of sensor is known as smart sensor (Mitchell, 2007).

1.2 Multi-sensor Integration

There are several advantages in employing more than one sensor, enhancing the synergy of the system in several ways (Mitchell, 2007) (Thomopoulos, 1989):

- Higher signal-to-noise ratio (noise suppression);
- Increased robustness and reliability in the event of sensor failure;
- Information regarding independent features in the system can be obtained;
- Extended parameter coverage, rendering a more complete picture of the system;
- Increased dimensionality of the measurement;
- Increase spatial and temporal coverage;
- Improved resolution;
- Reduced uncertainty;
- Increased confidence;
- Increased hypothesis discrimination with the aid of more complete information arriving from multiple sensors;
- Reduction in measurement time, and possibly costs— there is a trade-off to consider in this issue.

Mitchell summarizes the improvement of the performance on multi-sensor data fusion in four different ways: a greater granularity in the representation of information; greater certainty in data and results; elimination of noise and errors producing a greater accuracy; and allowing a more complete view on the environment (Mitchell, 2007). Nevertheless, often the performance of a multi-sensor system can be worse than with the individual sensors, a situation named *Catastrophic Fusion* (Mitchell, 2007). This can be the result of a set of sensors being designed to operate correctly only under certain conditions.

A set of sensors (multi-sensor system) can be organized in three basic configurations: complementary, where the sensors are independent on each other and producing different outputs, but can be combined to produce a more complete view of the environment; competitive, where each sensor produces independent measures of the same property; and cooperative, where the combined information from independent sensors makes possible the access to information otherwise unavailable with single sensors (Mitchell, 2007).

2 Architectures

To develop a system for data fusion, we have to consider the possibility of working with different types of sensors, with distinct output formats and periodicity. This heterogeneous scenario may lead to a robust architecture that embody different levels of integration and some specific semantics or protocol to communicate between all components of the system. Usually, multi-sensor data fusion systems presents a 3 (or in some cases 4) layer architecture: a level to deal with the physical issues, a level to fuse information, and a level to present data to final user.

2.1 Architecture Concepts

Esteban (Esteban et al, 2005) presented a synthesis of architectural issues that must be taken in account to develop a platform for multi-sensor data fusion:

- How are sensors distributed to form a network? They could be organized in a parallel or a serial (iterative) bus, or even a combination of both. A parallel sensor configuration is more adapted to identical sensors, whilst serial configuration is appropriate to a system where one sensor delivers information to another one, augmenting therefore the knowledge available in a hierarchically form, suitable for environments with dynamical data sources.
- What is the level of data representation needed? An architecture with different levels can enrich the information provided fusing data and knowledge from different sources and with different treatments. It can also provide data with different degrees of representations according to the needs. Nevertheless it will make the system more complex and slower to deliver an output which can be a drawback in real-time systems. This issue implies the need to define the nature, resolution and computational capability of the sensors.
- What type of architecture for data fusion should be used? One can be use a centralized (using raw data) or decentralized architecture (using a preprocessed data). The former allows the sensors to have less computational capabilities, but the central hardware must be capable of dealing with a greater quantity of data, while the latter distributes the computational power through the nodes of the system, but adding complexity to the data fusion process. A centralized system also permits a global view of the environment with the original data collected, while the distributed system can enrich the data by adding new knowledge.
- Should the system have a feedback mechanism? This allows to control the system with the recommendations provided by different nodes and levels of the architecture. Of course, this implies a more complex architecture.
- How to deal with difficulties arising in data fusion? There can be sensor failures, corrupted data, and incompatibility with different sensors that can affect the performance of the system.

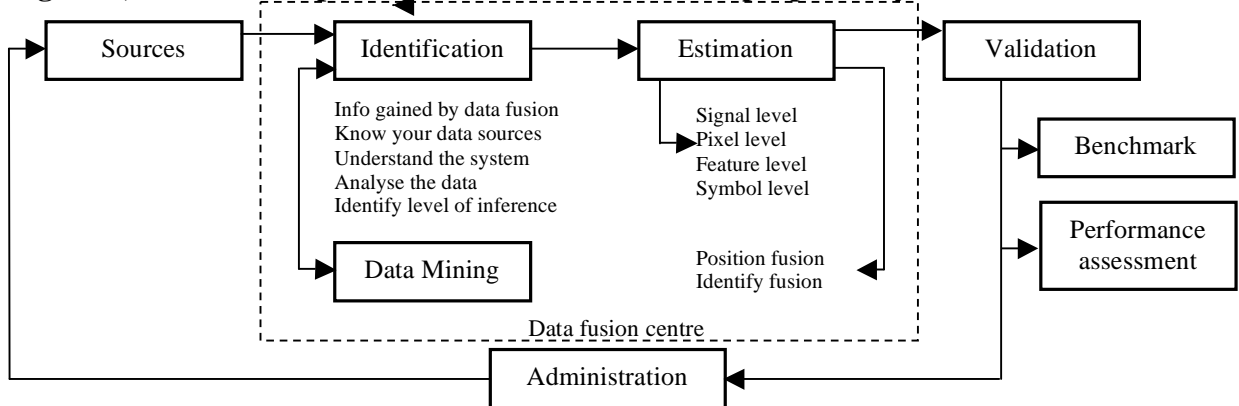
2.2 Formal Frameworks

Due to the size and complexity of the data fusion systems it is advisable to construct a formal framework to organize the knowledge about the environment (Mitchell, 2007).

2.2.1 Esteban Framework

Esteban (Esteban et al, 2005) proposed a formal framework for data fusion. He concluded that there are 3 fundamental steps to analyze the system: identification, estimation and validation (Figure 1,) (Esteban et al, 2005).

Figure 1, Schematic representation of the framework proposed by Esteban.



Source: (Esteban et al, 2005).

In the first phase (identification) is important to identify the factors that affect the data fusion process, namely, the phenomenon under study, the level at which fusion can take place, the data that can be collected and their sources. According to Esteban, it is also advisable to analyse the data before any manipulation been made to identify dominant uncertainty and how that can be overcome, how it is possible to reduce the data size without reducing the information content, if there is repeatability of measurements, if data can be pre-processed and if there is the need for a redundancy of the sensor system to ensure a robust data collecting process. The use of data mining techniques can aid this interrogation process.

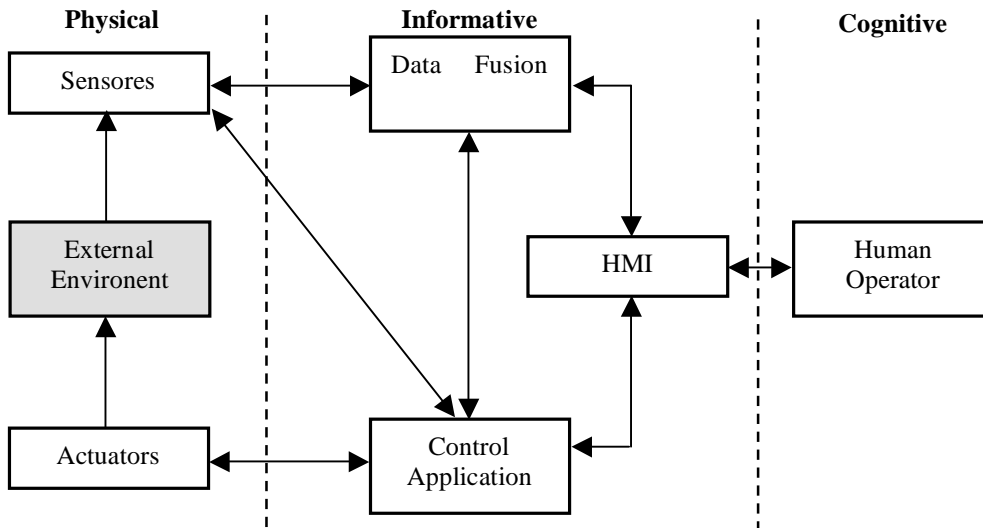
The estimation phase seeks to determine the appropriate level of inference. It is suggested two approaches: a hierarchy with four levels consisting of signal, pixel, feature, and symbol levels, or the classical Joint Directors of Laboratories (JDL) model of data fusion.

The last phase (validation) allows to confirm the data pre-processed and the fused process. On this step a performance assessment is made to act on the other components of the architecture with proper adjustments, forming a closed loop.

2.2.2 Mitchell Framework

Mitchell (Mitchell, 2007) adopted a distributed network of autonomous models, where each module represents a distinct function of the data fusion system. This decreases the complexity by subdividing the issues to deal with in a more simplified problem. Such as Esteban framework, the Mitchell framework presents three levels of domain: physical, information and cognitive (Figure 2) (Mitchell, 2007).

Figure 2, Schematic representation of the framework proposed by Mitchell.



Source: (Mitchell, 2007).

The first level concerns with the physical phenomenon and the sensors that monitor and collect their data. That information should be delivered to the informative level where the data fusion from multiple sensors will be fused and processed to be available to a human operator (the cognitive level). Still in the informative level, correctional and adjustment commands area created and sent to the actuators over the external environment. According to Mitchell, the association of multi sources with a priori information can be improved with statistical framework.

Both, Esteban and Mitchell, proposed a framework with 3 levels. The first and second levels are similar, concerning with the issues about the sensors and the physical phenomenon (first level) and the interpretation and fusion of data (second level). The third level is distinct in both models, though. The third level proposed by Esteban is focused on the validation of the data produced by the data fusion process, while Mitchell proposes a presentation of the information to a human operator. Nevertheless, both frameworks include a closed loop to control and adjust the system.

2.3 Centralized and Decentralized Architectures

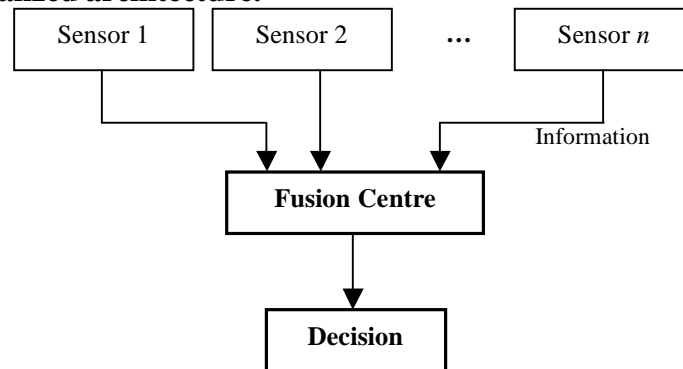
Centralize or decentralize the process of data fusion is a topic studied for some authors and with implications on the data fusion system.

2.3.1 Centralized architecture

A centralized process has only one point for data fusion process (a fusion centre). This module must have a great computational capability to deal with the enormous quantity of data that will receive from the sensors, being computationally intensive. Likewise, this data must be transmitted from the sensors to the fusion centre and therefore is necessary a good communications system with great bandwidth to allow an efficient transmission of data. Because the fusion is only made in the fusion centre that means the sensors can have less computational capacity, and the fusion is performed over the raw data with no modifications, like it was gathered (which means more data to be transmitted). This allows a global view of the object from the original data. However, a major drawback of this architecture remains in the use of a single centre fusion. Two problems can arise from this: the bottleneck of input data, where the fusion module receives more data than it can handle, and a failure on this module affects all system.

Figure 3, (Esteban et al, 2005) represents a simple centralized architecture, where the fusion centre receives all data gathered by the sensors, perform the fusion and delivers the information to the decision module (that can be a human operator or an automated system to act on the environment):

Figure 3, Centralized architecture.



Source: (Esteban et al, 2005).

2.3.2 Decentralized architecture

A decentralized process distributes the process of data fusion. This can be made on dedicated fusion modules that receive data from some sensors and deliver the information to the next module, or even performed on the sensors themselves. Therefore, the computational capacity is distributed for several elements of the architecture, being more scalable. Sensors are no longer a passive equipment that only gather and outputs data. They must have some computational capability to process the data, reduce the size (without reduce the content) and introduce some knowledge before they outputs the information. Mitchell (Mitchell, 2007) call these a *smart sensors*. This is less demanding on computational capabilities, but the system becomes more complex.

The decision module receives information that is the interpretation of data made for different fusion modules and doesn't allow a global view of the environment. Distributing the fusion process can prevent the failure from some fusion module. If a

module fails for some reason, the others continue to work and the system as a whole isn't affected (at least in a way like a centralized architecture).

The decentralized architecture is also suitable for systems with a redundant array of sensors that gather information for the same phenomenon. In this case, the redundancy in the sensor readouts is used to provide error tolerance (Wang et al, 2001).

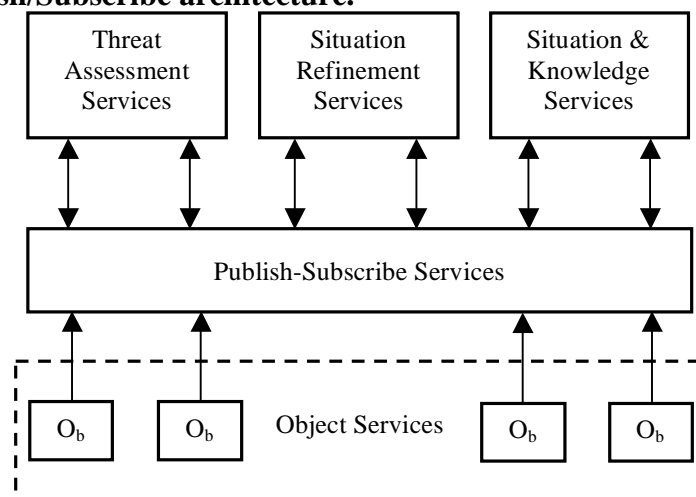
According to Esteban (Esteban et al, 2005), usually, data collected from similar sensors can be combined at the lowest level of inference, while data arriving from dissimilar sensors must be fused at higher levels. Concluding, the fusion of data can be done on either raw data (centralized process) or on pre-processed locally fused data (decentralized). The centralized architecture is computationally intensive, but it carries the advantage of developing a global view of the object from the original data. On the other hand, decentralized architectures are less demanding on computational capabilities at the cost of adding complexity to the data fusion process, since each sensor has a processing unit (Esteban et al, 2005).

2.4 Publish/Subscribe Architectures

Publish and subscribe architectures have been presented for some authors (like Bass (Bass, 2002) and Wuny *et al* (Wuny *et al*, 2007)) as an efficient solution to distribute data within and across sensor networks to where is needed. Instead of transmit all data gathered from the sensors to all the modules in the system, the main idea on this architecture rests in the publication of the information about the data gathered. The modules that need that data will seek and retrieve it (instead of just receive a great quantity of data that has no meaning for that module). To accomplish this there is the need to implement an efficient semantic event detection and the use of ontologies to translate the events (Wuny *et al*, 2007), that will behave as a protocol which all interlocutors will understand. So, it is possible to define Content-based Publish/Subscribe as an event-driven messaging model in which event notifications are delivered to clients based on their interests (Wuny *et al*, 2007).

The use of a semantic to interpreting the context and meaning of sensor data can produce high-level events, where data is filtered, aggregated, correlated, and translated from heterogeneous and dispersed sensors sources. Therefore, it is possible to decouple application semantics from sensor network, independently from the sensor networks (Wuny *et al*, 2007). Figure 4, represents a publish/subscribe architecture, as proposed by (Bass, 2002):

Figure 4, Publish/Subscribe architecture.



Source: (Bass, 2002).

On this architecture, services can be a subscriber or/and a publisher. The object database (where multi sensor data fusion is performed) publishes objects to information sharing or event notification services. The services that have showed interest in a specific information by subscribed its events will be notified. After being notified, if a service needs some data it will retrieve that specific piece of information. The communications component is a simple event notification that is technically scalable (Bass, 2002). Moreover, beside the notifications messages, only intended data is transmitted. Therefore, no bandwidth is wasted in the transmission of data not requested.

Wuny *et al* (Wuny *et al*, 2007) developed the concept of Content-based Publish/Subscribe furthermore, defining 3 different roles: subscribers, publishers, and brokers. Subscribers and publishers are similar to the model described above.

Subscribers express interest by issuing subscriptions that describe the content of notifications they wish to receive and the subscriptions are stored by the brokers.

Publishers issue publications to brokers, who are responsible for matching publications against known subscriptions and subsequently forwarding these publications to the appropriate subscribers as notifications. Publications are sets of attribute-value tuples while subscriptions are expressed as filtering constraints on an set of tuples (Wuny et al, 2007).

The major improve made by Wuny *et al* was in the content based Publish/Subscribe matching, using semantic awareness defined in a domain ontology. It is based on synonym and taxonomy translation to expressing equivalence and hierarchical relationships between terms. To accomplish this, mapping functions were developed to translate attribute-value tuples to semantically related attribute-value tuples, allowing to express arbitrary relationships (Wuny et al, 2007). This is an improvement to the traditional content based Publish/Subscribe, where the same syntax is used for publish and subscribe events, and where strictly string matching was made to send notifications to the subscribers.

2.4.1 Use of mobile agents

The use of agents can also improve the distributed sensor networks. They have been used on a number of environments, such as networked electronic trading; distributed information retrieval; information dissemination; network and global awareness, although security issues can arise (Wang et al, 2001). Its polyvalency is due to its simple structure: agents can be seen as objects with attributes. A mobile agent as an entity is characterized with four attributes: *identification*, *itinerary*, *data space*, and *method*.

According to Wang *et al* (Wang et al, 2001): “(...) *mobile agent adopts a new computing model: data stay at the local site, while the execution code is moved to the data sites.*”. With this approach it is possible do reduce the network bandwidth, overcoming network latency, implement robust and fault tolerant performance (Lange & Oshima, 1999), and better network scalability and stability can be achieved (Wang et al, 2001). The use of agents appears as an alternative to traditional client/server architectures, were agents can migrate from node to node performing data processing autonomously. Agents are used to be aware of and reactive to the continuously changing network conditions (Wang et al, 2001). Any change on the sensor network will be automatically detected and reported, improving the system efficiency and performance.

Wang *et al* presented a Decentralized Multiresolution integration (MRI) algorithm, based on the Centralized MRI algorithm proposed by Prasad *et al* (Prasad et al, 1994). The Centralized MRI algorithm consists on a cluster of redundant sensors measuring the same parameter where the output is applied to a function (called *overlap function*) with successively finer resolutions to the region or data with interest. Therefore, the details are analyzed from a coarse resolution to a finer resolution.

The decentralized MRI algorithm distributes the integration process and implements a mobile-agent-based distributed sensor network (MADSN) to handle the high quantity of data. The agents move between the outputs of the sensors collecting their data and carry pieces of information that will be delivered into the processing module, where the information is couple all together after all agents delivered it (Wang et al, 2001).

Like in the decentralized MRI algorithm, in a publish/subscribe architecture agents can be used to gather and deliver information. Agents can be responsible for collecting the

data to be published from the publishers and delivered it to the broker service, where other agents will inform and distribute the new data available to the subscribers.

3. Models

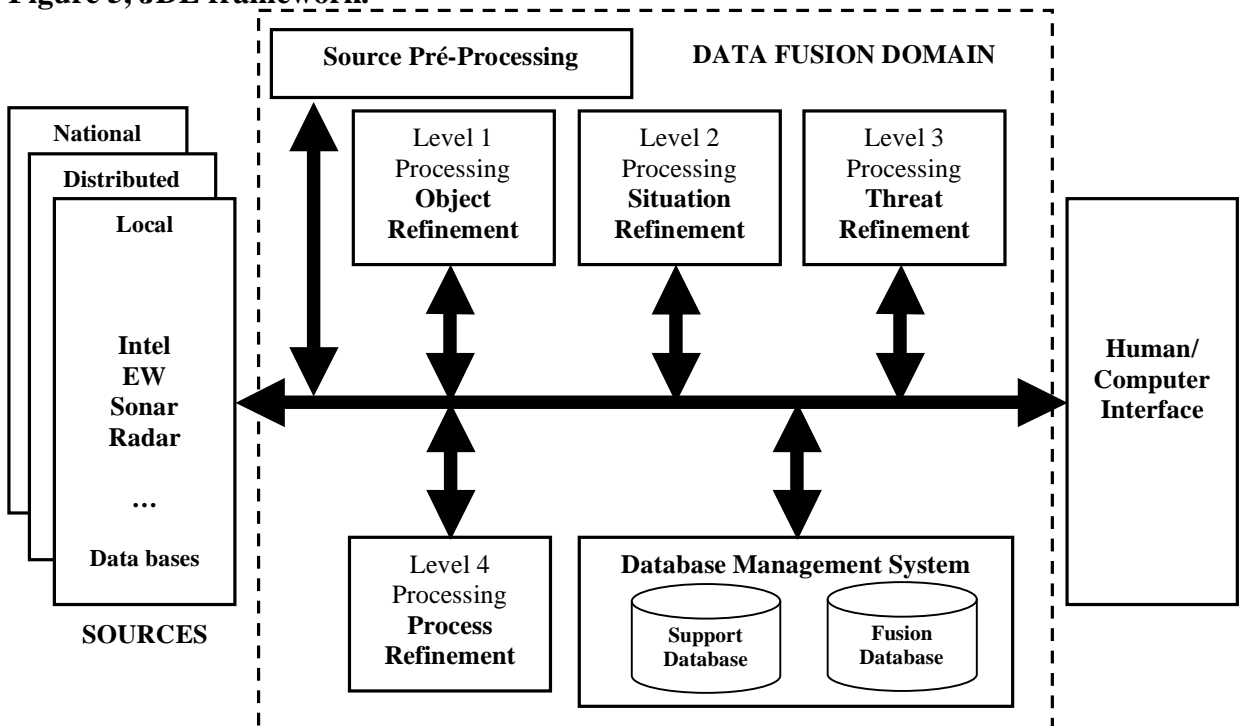
Several models have been developed to deal with the multi sensor data fusion issues. Generically, these models use 3 or 4 levels, as presented in the frameworks by Esteban and Mitchell. Usually, there is a module to deal with the sensors and their output, other to make some pre-processing or full processing of the data and a module to output the data processed or act on the environment. A closed loop to act over the sensors parameters and adjust/calibrate the system is also common.

3.1 Joint Directors of Laboratories (JDL) framework

The JDL was one of the first data fusion systems, as a result of a sub panel from the US Department of Defense, to aid the developments in military applications (Esteban et al, 2005). According to *Llinas et al* (Llinas & Hall, 1998), this framework presents 4 levels, as presented on Figure 5,:

- Level 1, object refinement, attempts to locate and identify objects (could be further divided into four processes: data alignment, data association, object estimation, and object identity).
- Level 2, situation assessment attempts to construct a picture from incomplete information provided by level 1, that is, to relate the reconstructed entity with an observed event.
- Level 3, threat assessment interprets the results from level 2 in terms of the possible opportunities for operation. It analyses the advantages and disadvantages of taking one course of action over another.
- Level 4, process refinement, loops around these three levels to monitor performance, identify potential sources of information enhancement, and optimise allocation of sensors.

Figure 5, JDL framework.



Source: (Llinas & Hall, 1998).

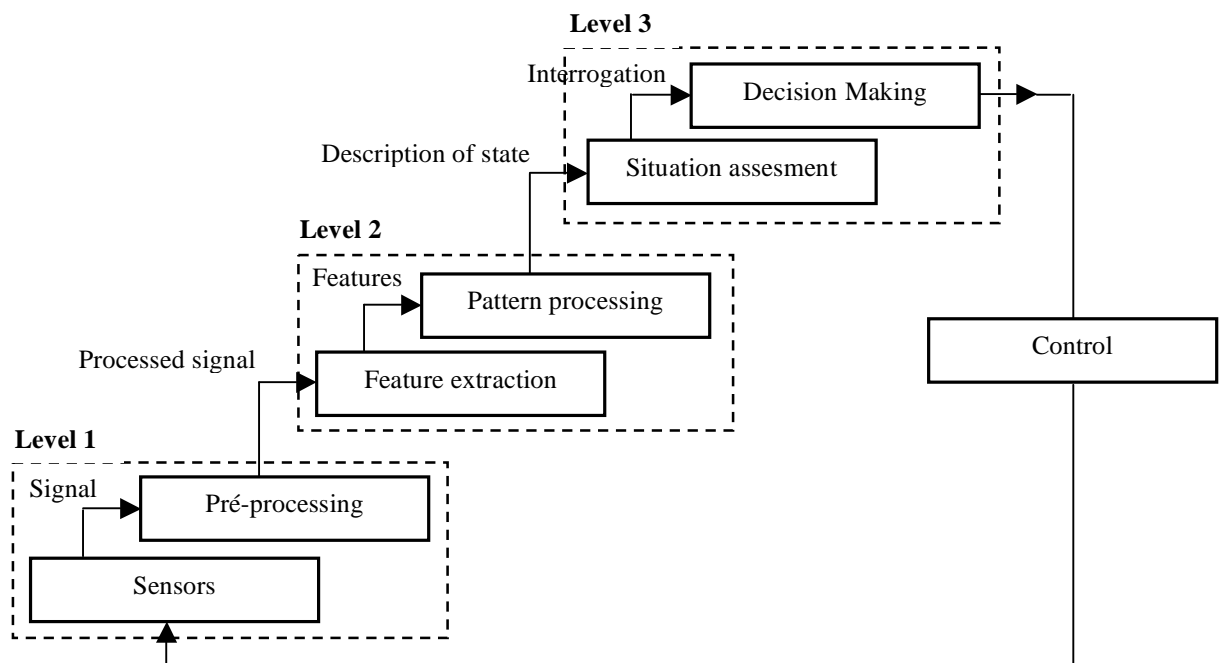
This framework is further integrated with a process refinement via fusion agents, which act as fusion centre (Esteban et al, 2005). It assumes a parallel organization of input data (all information fed into the pipeline), although a serial process could be acceptable. It has several internal levels of information representation, not implying a specific one for input. A centralized architecture, it does all the “pre-processing” itself. Finally, the system has a feedback mechanism (Zegras et al, 2008).

3.2 Waterfall model

The waterfall model proposed by Harris *et al* (Harris et al, 1998) is an hierarchical architecture where the information outputted by one module will be inputted to the next module, as depicted on Figure 6,. The last module (Decision Making) delivers enough information to the control module to calibrate and configure the sensors.

The architecture is divided in 3 levels, each one with two modules, and a closed loop to act in the system. On the first level, data is gathered from the environment and properly transformed, delivering not only the data processed but also information about the sensors to the next level. At the second level, the main features are extracted from the data from the previous module and fused, thus reducing the quantity of data transmitted and increasing their information richness. On the third level, according to the processing from the previous levels, a scenario of events is created and possible routes of action are assembled.

Figure 6, Waterfall model.



Source: (Harris et al, 1998).

The Waterfall model does not clearly state whether the sources should be parallel or serial (although the processing is serial), it assumes a centralized control, and allows for

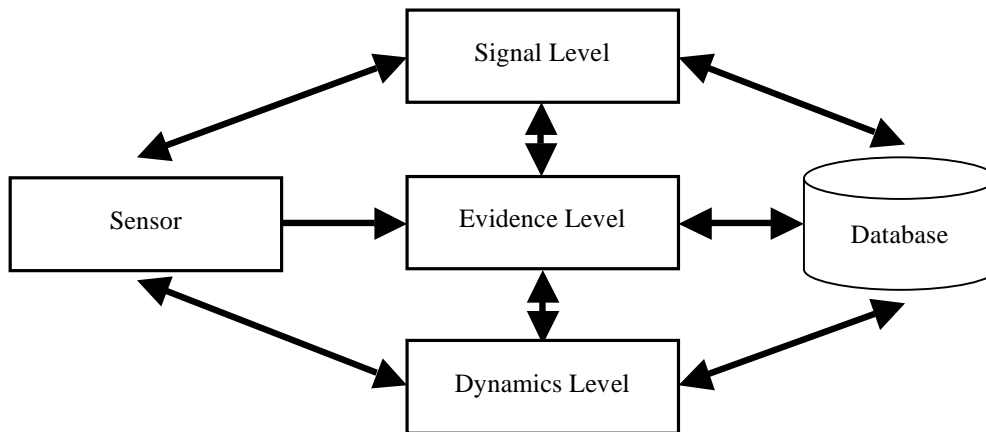
several levels of representation (similar, in this aspect, to JDL). The model also proposes a feedback mechanism (Zegras et al, 2008).

3.3 Thomopoulos Model

Thomopoulos (Thomopoulos, 1989) also proposed a three-level model, formed by the signal, evidence and dynamics levels. In each level, data gathered is confronted with data previously processed and stored, preserving a given order, which means the need to deal with delay or errors in the transmission of data.

After the sensors monitors the phenomenon and outputs their measurements, the signal level process that information, performing correlations due to the inexistence of a mathematical model. Therefore, the data gathered is correlated with information previously stored in the database, in a learning process. On the evidence level, data is combined at different levels of inference based on a statistical model and the assessment required by the user (e.g. decision making or hypothesis testing). On the last level a mathematical model is used to perform the data fusion (Esteban et al, 2005).

Figure 7, Thomopoulos model.

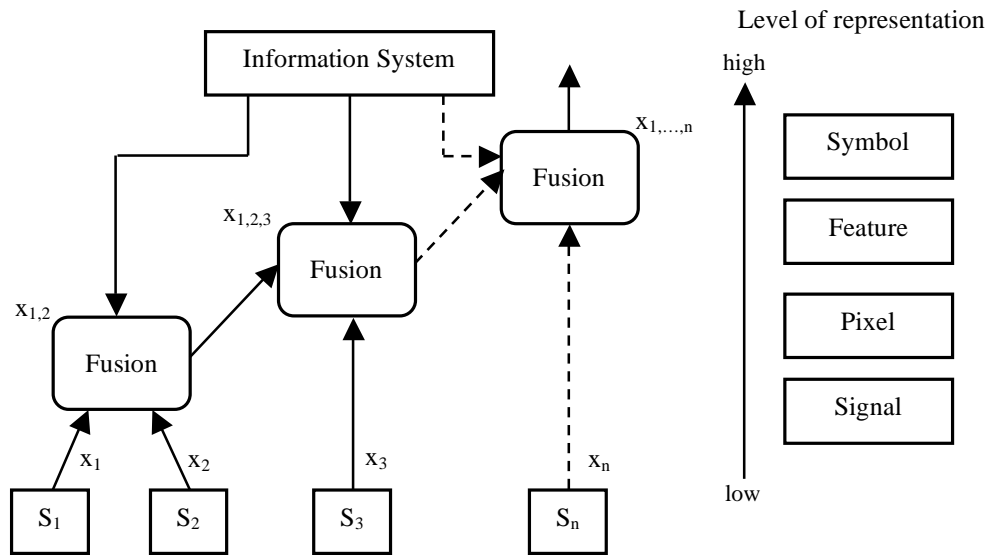


Source: (Esteban et al, 2005).

3.4 Luo and Kay Model

Luo *et al* (Luo & Kay, 1998) presented a hierarchical model, yet different from the waterfall model. While in the waterfall model all data gathered is processed in a sequential way for all modules, in the Luo and Kay model data from the sensors are incrementally added on different fusion centres (multi-sensor fusion), thus increasing the level of representation, from the raw data or signal level to more abstract symbolic representations of the data at the symbol level. This model explicitly proposes the parallel input and processing of data sources, which may enter the system at different stages and levels of representation. It is decentralized and does not assume a feedback control.

Figure 8, Luo and Kay model.

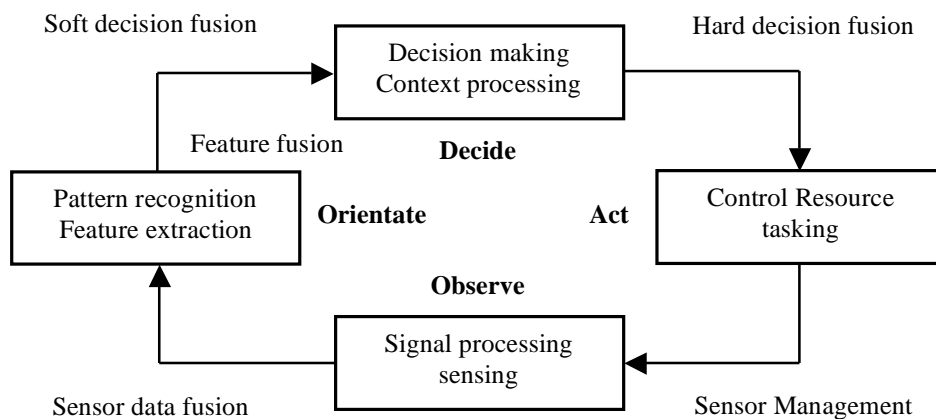


Source: (Luo & Kay, 1998).

3.5 Omnibus model

Bedworth *et al* (Bedworth & O'Brien, 1999) proposed a hybrid model which presents some features from the waterfall model. The first level (Observe) measures the environment, gathering and processing data from the sensors, delivering the information to the second level (Orientate). Here, the data is fused and the main features extracted in order to reduce the amount of data. The third level (Decide) concerns with the presentation of the processed data to the human operator or/and act on the environment. The model is in a closed loop with a control module to calibrate the sensors.

Figure 9, Omnibus model.

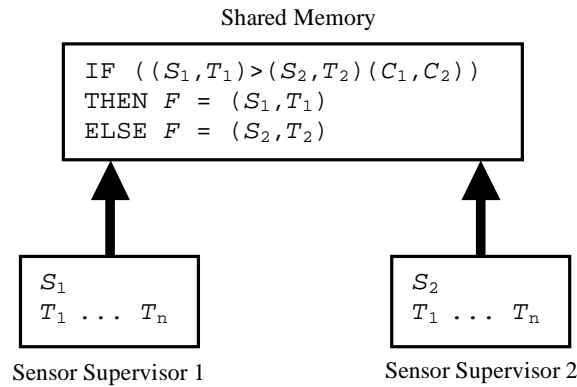


Source: (Bedworth & O'Brien, 1999).

3.6 Distributed Blackboard Model

Schoess *et al* (Schoess & Castore, 1988) suggested a simple fusion model based on the confidence of the values produced by each sensor (sensors that measure the same phenomenon). This confidence is supported by a set of transducers associated with the sensors, whose job is to supervise each sensor. Simultaneously with each sensor the set of transducers tries to gathered as much information as possible about the physical phenomenon. Accordingly to the confidence in the measurement (produced by the supervisor of each sensor) the fusion is performed and the data from one sensor or another can be disregarded, depending of its confidence level. The transducers act as a mechanism of validation to the measures performed by the sensors (Figure 10).

Figure 10, Distributed blackboard model.



Source: (Schoess & Castore, 1988).

4. Data Fusion on Intelligent Transport Systems

On this chapter we present the technology usually in use to measure and act in traffic management and transport systems control. We also describe a real case study of traffic management in a Portuguese city.

4.1 Generic Data Fusion on ITS

As presented before, there are different sources of data to aid the management of transport systems, such as (Pan et al, 2006) (Bento & Pereira, 2008)(Klein , 2001):

- Road sensors: Inductive loop detector (for traffic data collection, vehicles count, traffic lane detection and traffic intensity), image cameras, infra-red sensors, toll-collectors, laser and radars, car-park occupancy, dynamic monitoring of the infra-structures, advanced license plate recognition, automatic incident detection, priority vehicle detection;
- Public Transport: rail sensors (for train and metro location), GPS and Radio-Frequency devices for bus location, passenger count devices;
- Communications: GSM¹ (cell phone usage), Wi-Fi and Bluetooth;
- Radio frequency devices: RFID sensors, on-board / vehicle mounted sensors and equipment;
- Environment sensors: weather, ozone, CO₂, and other chemical elements detectors, noise and temperature sensors.

On the other side, the system can act on the environment to manage the traffic through different devices and technologies, such as (Bertini et al, 2005):

- Variable Message Systems (VMS), Informative Panels;
- Portable VMS;
- Changeable Message Signs (CMS);
- Changeable Directions Lanes (CDL);
- Lane Use Signals (LUS);
- Variable Speed Limits (VSL) and Variable Speed Warnings;
- Toll Plaza Signs;
- LED Traffic Lights and Semaphores;
- Car Park Navigation;
- Park & Ride;
- Tunnel Signage;
- Electronic Custom Signs;
- Traffic message channel (Radio).

Some mechanisms are simple to implement (like de Variable Message Systems), others (like changeable direction lanes, for example) are more complicated to perform (due to technical difficulties or financial questions).

4.2 A Case Study

In Portugal, the biggest city is Lisbon, the country capital, with more than 500 000 residents (more than 2 600 000 residents including the suburban areas that form the Lisbon metropolitan area). Each day more than 2 100 000 people circulate on this area (CML, 2008) (INE, 2008).

We interviewed the main stakeholders in traffic management on this city, namely the Lisbon city council, CARRIS (bus public transport system), Lisbon metropolitan, Brisa (one of the national enterprises that manages the expressways and developed an automatic toll system called “Via Verde”), and Quadriga (a company that built a system for vehicle tracking).

4.2.1 Lisbon City Council

Lisbon City Council² (or “Câmara Municipal de Lisboa”, in Portuguese), has a department responsible for the traffic management – Department of Traffic Security and Prevention (DTSP). They resort essentially to inductive loop sensors and radars (mainly the former) and video cameras to collect information and informative panels and traffic lights to act on the environment.

The traffic lights are controlled accordingly to the information provided by the sensors in the pavement, being the system based on the GERTRUDE³ technology. The system seeks to reach two purposes:

- fluidity on the traffic, where main arterial roads of the system must be clear of traffic jams, always presenting moving vehicles;
- to support to priority vehicles, helping the public transportation vehicles.

Fluidity of the traffic is maintained using essentially two types of inductive loops: vehicles count sensors and traffic intensity sensors inlaid in the pavement. In order to keep the main arterial roads free of traffic jams the system detects the intensity of traffic on those roads. If the traffic intensity is high the traffic lights close the traffic from the adjacent roads, and open it when it's possible to go through the main arterial roads without halts. On the adjacent roads, the sensors on the pavement make a count of the number of cars passing by, for statistical purposes but also to automatically close the traffic lights if the number of cars is superior in comparison to the main arterial road.

Therefore, the traffic lights aren't pre-programmed. Instead they work accordingly to the current traffic status in an automatic closed system, where there is no human intervention. The system tries to facilitate the entrance (of the traffic) in the city in the early hours of the day, and the exit from the city at the end of the day, creating open corridors where the traffic lights form a “green wave” making possible the movement of vehicles without halts in one direction or another (accordingly to the period of the day). Of course, this implies that when the system benefits some arterial roads (usually the main ones), it will congest others (usually the adjacent roads).

Some criticism that is made to this system concerns to the absence of learning capabilities. If for some reason the traffic scenario changes (for example, if a holiday occurs in a week day, or an event like a strike happens) and the movement of the traffic is different from the usual, the system keeps acting like in a normal situation and disregards the changes in the environment.

The system also seeks to help the movement of public transportation vehicles like buses. When a pavement sensor detects the proximity of a bus and the next light is about to change to red, the system delays that change and allows the public transportation vehicle to cross the intersection without slow down or stop. Therefore the public transport can keep its schedule and gain some time to compensate for future delays (e.g. caused by a traffic jam further ahead). As a side effect, traffic lights on the other roads of the intersection will keep the red light for more time than usual. Nevertheless the system cannot recognize or identify the vehicle approaching. Any citizen or company can acquire the same transmitters that are used by the priority vehicles and couples them in their own vehicles, benefitting equally from the system.

This system has a high impact on the public transportation system. If a bus stops on a red light may delay. If so, more passengers will accumulate on the next bus stop. Therefore, more time is lost for the entrance of a higher number of passengers than usual. This will increase the bus delay and more passengers will accumulate on the next bus stops, and again the delay will increase. Contrarily, the next bus will have less passengers waiting, thus it will arrive ahead in time to the next bus stop that will have even less passengers. The behavior of those two buses will reach to a point when the faster and empty bus will catch the bus ahead. The two buses will travel side by side and the gap to the next bus will be greater – more passengers will be waiting and for longer time. With time, the buses will cluster in groups of two creating a greater gap between them – the passengers on the bus stop will wait almost twice the time. With time passing, if no action is taken, they will become in groups of four, after that in groups of eight, increasing the gap between the bus clusters, and so increasing the waiting time for the passengers in the bus stops. At the end, all buses will circulate together in a single group. This is called the “harmonic effect”, where little changes that affect a single delay in one bus eventually affects all buses after a while. So, a simple stop in a red light can affect the public transportation in an increasing way, and therefore the systems such as GERTRUDE are necessary to help prevent these situations.

Across the city there are video cameras with a 360° view angle (catadioptrics cameras) that allows to visually control the traffic. The information gathered (including the inductive loops) is centralized in the DTSP where the video data is visualized on real-time but not stored. It is also possible to act on the environment using the informative panels (or VMS) to display information and some traffic signal (usually located in tunnels) to control the flow of the traffic. The control of video cameras, informative panels and traffic signals is not automatic and centralized in the DTSP.

4.2.2 Carris

Carris⁴ is a public transportation enterprise that manages the buses in Lisbon. It has approximately 700 vehicles for public transportation (only 500 operate on “low seasons” such as school vacations where the demand is lower).

Some technologies were implemented to manage all transportation system (such as GSM and TETRA communications standards) that allow a bidirectional communication between the central control station (CCS) and the buses. It is possible to identify the location of the vehicles in real time (with a 30 seconds rate), check the schedule and inform the passengers of the exact arrival time for each bus (using informative panels or an SMS service). It is also possible to collect information about vehicle occupancy, but not on a real time basis.

There is a central control station where all the system is managed. Every vehicle is equipped with a computer and a complete database of all schedules, an odometer that converts electric impulses into distance, a GPS receiver and a Radio-Frequency (RF) equipment (a transceiver) to support the communications with the CCS. In intervals of 30 seconds every bus transmits its identification, along with the distance travelled and the GPS location. With that information the CCS can update the informative panels near the bus stops (e.g. time waiting for the next bus) and allow the users to receive messages in their cell phones (using the Short Message Service of the GSM system) with an accurate waiting time for the next bus in a specific bus stop.

The communication between buses and the CCS, and between the informative panels and the CCS is made using the TETRA⁵ system. The localization of the bus is inferred using the information produced by three data sources: the odometer, the information from the door sensors (they detect if the doors were open) and the detection of the next bus stop in a range of 50 meters (the informative bus stop panel also detects the proximity of the bus and can automatically update the information that is displayed). If two of the three data sources reply positively they concluded that the bus has reached a bus stop. The GPS data is used only to validate the position that was previously computed.

Inside the bus exists an equipment to validate the passenger travelling cards using Radio-Frequency Identification (RFID), and allowing to control the number of entrances in the vehicle. Nevertheless, the data is not available in real time. Only when the bus goes for refueling it is possible to transmit that information to the CCS, using the Wi-Fi technology (with access points available in the gas station). Thus, the data could be delivered until 5 days after being collected. Only entrance information is collected, and there is no control on the exit. To do this the exit would be slower (which is not desirable) and force the passenger to execute an additional action (such as for entrance) or new technology should be applied to automatically verify the bus passes without implying a direct action from the passenger. This last solution could imply the use of more powerful RFID system which could conflict with pacemakers and other equipments.

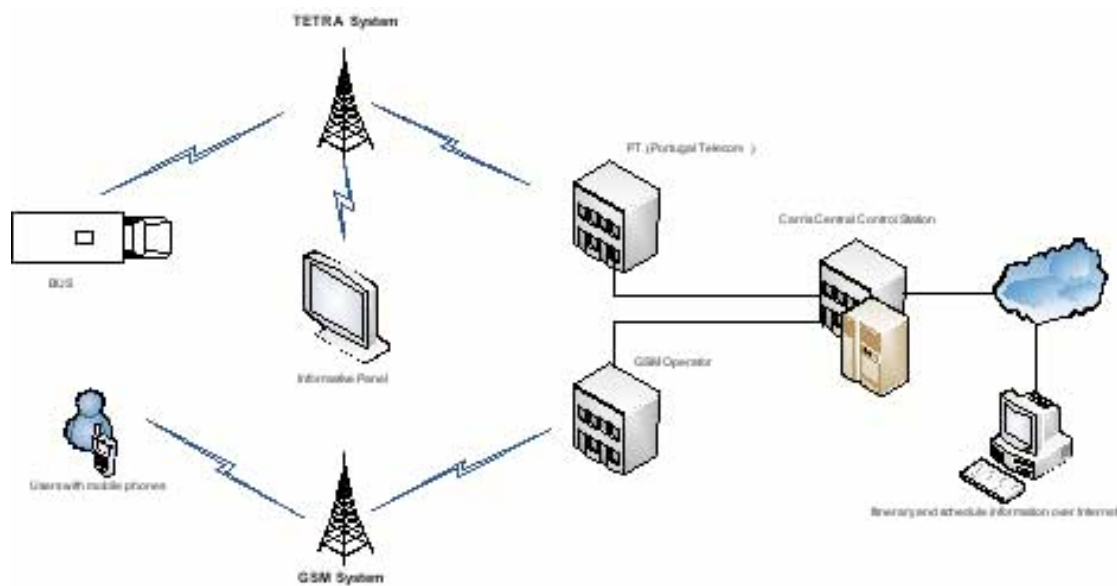
Each bus is completely autonomous. It only needs to connect with the CCS once to update the internal database (an un-normalized relational database) with all itineraries available and perform the bus-driver authentication. After that the vehicle can control his course in an offline mode. If the communications with the CCS are interrupted the bus can keep tracking of its location accordingly to the planned itinerary and inform the bus-driver if the vehicle is in advance or on delay accordingly to the schedule.

All vehicles are equipped with video cameras; however the video system does not transmit in real time due to bandwidth limitations and it only links on anomalous situations. Along with the video capture, there is a silent alarm with a protocol to detect incidents inside the bus (but without audio or video transmission). Future plans include the implementation of audio and video in real-time. Due to limitations of the TETRA system (it theoretically allows the transmission of data such as video, but there is not enough bandwidth for this service), the CDMA⁶ system will be adopted.

As presented above, little delays in a single bus can affect all buses. The previously described GERTRUDE system helps the buses from CARRIS to fulfill the schedule. Moreover, it is possible to introduce (or remove) buses on an itinerary and update the schedules of the remaining ones, or even send orders from CCS to speed up or slow down a single bus in order to maintain a cadence with a regular interval between, thus allowing a more predictable environment for the passengers.

The schematic illustration of the described system is depicted in Figure 11, Schematic description of the system adopted by CARRI Figure 11,.

Figure 11, Schematic description of the system adopted by CARRIS to receive and transmit information to all the stakeholders.



Source: CARRIS.

4.2.3 Lisbon Metropolitan

The Lisbon Metropolitan⁷ is the company responsible for the subway transport. It uses three components to manage the system:

- gates information, collecting data about the passengers entering and leaving the network;
- video cameras;
- Radio-Frequency (RF) communications between the trains and the Central Control Station (CCS).

To enter or leaving the train stations the passengers have to overcome a physical barrier and to do so they have to validate their tickets (magnetic cards). This information allows the estimate of the occupancy of the train stations with data collected in real time, although the system only presents statistical information on every 15 minutes. However, it is not possible to predict the number of passengers on each train. The gates allow knowing the number of passengers entering or exiting from the stations, but there is no information about their current location inside the facilities. , there can be more than one passenger entering or exiting from the train carriage shutting out the possibility to detect and count each of the passengers.

The gates to access the station platform are automatically controlled by the validation of the tickets, but the CCS can manually control those barriers in anomalous situations (like an incident inside the station that implies to take out all passengers and the gates being opened, or an abnormal increase of passengers due, for example, to a sports event, that implies stopping entrance in the station with the risk of augmenting the crowd inside, decreasing the security conditions,. On this scenario the gates must be closed).

Each train carriage and trains station is equipped with video cameras. The majority of the videos captured by those cameras is stored and accessed only on anomalous situations. Only strategic locations (like the access to the tracks) are continuously monitored in real time by an employee. No treatment of the images is made. If an incident occurs inside a carriage and the alarm is pressed, the video and audio is automatically redirected and transmitted in real time, also allowing for a bi-directional communication between the carriage where the alarm was activated and the CCS.

The communication between the train and the CCS is based on RF channels (using voice and data communications). The CCS can monitor every component of the system and manually control each device. All the information gathered is monitored and centralized in the CCS where a Business Warehouse manages all data.

The Lisbon Metropolitan has 4 different lanes, but only one (the red) is completely automated, presenting a driverless system. On the remaining lanes (blue, green and yellow) there is the need for two persons to control the train (one is the driver the other is the *inspector* who controls the overture and closure of the train doors). On the red lane there is no need for the driver. The tracks are coupled with emitters and the train has a sensor that detects their signals. Therefore the train computer knows its current location. If the train misses three consecutive signal detections, it automatically stops, losing its location. The red lane is so equipped with three systems that automate the control:

- ATP – *Automatic Train Protection*, consisting of the emitters on the track and the sensors on the train allowing to control the train velocity and location, as well as the train stop in the stations;

- ATO – *Automatic Train Operation*, to control the train doors, although a human action is involved;
- ATS – *Automatic Train Supervision*, to regulate the train traffic and fluidity, keeping the trains distant from each other, and augmenting or reducing the train's speeds to keep the cadency between them.

This system allows automatic control and updates the informative panels of the red lane with a precise waiting time for the next train to arrive. The other lanes don't present this feature, nevertheless they present some security mechanisms as the "dead man" monitor that detects if the driver is distracted or absent.

4.2.4 *Brisa*

Brisa⁸ is one (the largest) company that builds and manages the expressways in Portugal. The company has developed and implemented new technologies to help the management of the infra-structures, such as RFID, video cameras and inductive loop sensors.

One technology developed with high impact is the “Via Verde”⁹ (Green Way). In this technology the driver attaches a small device (an RFID transmitter developed by Q-Free¹⁰ called “identificador”, an idea taken from ski runs to control the access to the ski slope) to his vehicle and allows him to go through the toll plaza without stopping (for security reasons the driver is obliged to drive at a speed limit of 60 Km/h, but recent improvements on the system allow the vehicles to pass in some toll plazas at 120 Km/h, the expressway maximum limit in Portugal, using a system called Multi Lane Free Flow).

When a driver acquires the identifier, he has to associate a bank account and a license plate to the service, only then he can use “Via Verde” service. When vehicle enters into an expressway, passing by a toll plaza, a sensor detects the RFID in the vehicle and stores the ID, date, time and entrance location. When the vehicle leaves the expressway, passing by a toll plaza, once again the sensor detects the RFID from the device in the vehicle, retrieves the ID, date, time and location and computes the toll to pay (only the information about the entrance and exit location along with the ID is needed) that will be charged some days after into his bank account associated with that device. This system makes the traffic more fluid in the expressway, especially at the entrances and exits. Of course, there exists also the traditional toll method, where the driver must collect a ticket in the entrance (and stop for that), and at the exit he must pay the toll value (and once more making a stop).

To control the fluidity in the expressway and detect incidents, most of the road area is monitored with video cameras which are visualized in real time at the Operational Coordination Center (OCC). Due to a very high number of video cameras available (nearly 770, from which 530 are located along the lanes and the remaining 240 at the toll plazas) it is not possible to visualize all videos captured in real time. So, a system was developed to treat the images and automatically detect incidents, such as traffic accidents, vehicles in reverse direction, vehicles stopped in the curbside. This system is called “AVISAR” (to give warning). This can alert the human operator to take some action, or acts automatically, presenting information on the informative panels or even sends a message to the authorities, thus becoming an Automatic Traffic Surveillance System (ATSS).

The video information can also identify vehicles through Advance License Plate Recognition (ALPR), especially in toll plazas where vehicles can go across the facilities without paying the toll. In these locations there are three cameras: in front of the vehicle (using the Infra-Red spectrum) and 2 more pointed to the back of the vehicle (one of them is also an Infra-Red camera), that with the RFID sensors form the “Lidar” system (an Automatic Classification system).

Aside to the control of the traffic flow, it is also possible to manage the physical infra-structures such as bridges and viaducts. The SMART system (Dynamic Monitoring of Infra-Structures) is an installation of optical and electrical sensors in the infra-structures that detects vibrations and displacements.

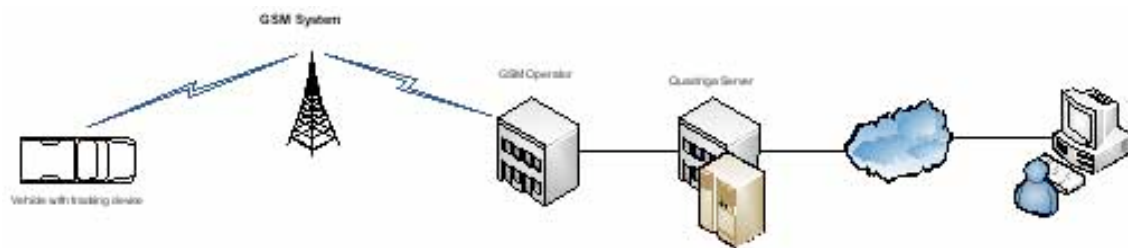
All data is centralized and processed in the OCC where human operators monitor the information and act on the system. However, the system can act automatically both on the toll collecting (through “Via Verde”) and incident detection (through “AVISAR”).

4.2.5 Quadriga

This enterprise developed a system for tracking vehicles called *Frotcom*¹¹ based on GPS and GSM technologies. The main purpose of the system is to produce reports about the course taken by a vehicle. It also can display the current location.

A vehicle is incorporated with a device containing a GPS receiver and a GSM (GPRS¹²) transmitter, connected to the vehicle ignition or including a movement sensor. Every 5 minutes (in national territory, in international territory the gap is 15 minutes and when the car is parked – ignition off – it increases to 30 minutes interval) the devices communicate with the server via GSM, transmitting the information about time, date, velocity, direction and GPS coordinates. The main server stores the data in a SQL Server relational database and produces reports about the movement of the vehicle along the day that can be access by clients using a web browser (HTTP protocol) or sent via email. The described process is represented in Figure 12,.

Figure 12, Frotcom vehicle tracking system



Source: Quadriga.

The GPS coordinates are overlapped on a geographic map (provided by Navteq¹³) but no correction on data is made.

4.3 Final Remarks

Despite the cooperation between Lisbon City Council and Carris, where the GERTRUDE system helps the traffic of public transportation, each company studied presents its own technology and implementation, with distinct software and hardware, making difficult to integrate and interact with all the information gathered by different data sources. However, all systems use informative panels to act on the traffic (and could thus also communicate with each other with that channel), which is a non intrusive and passive mechanism. All systems present a centralized control, although some subsystems can act automatically without human intervention.

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¹ Global System for Mobile communications, a standard for mobile communications, <http://www.gsmworld.com/>.

² <http://www.cm-lisboa.pt/>

³ Gestion Electronique de Régulation en Temps Réel pour l'Urbanisme, les Déplacements et l'Environnement (GERTRUDE), a system that allows a centralize management of the traffic in a real time bases, <http://www.gertrude.fr>

⁴ <http://www.carris.pt/>

⁵ Terrestrial Trunked Radio (TETRA) is an open digital standard defined by the European Telecommunications Standard Institute (ETSI), <http://www.tetra-association.com/>.

⁶ CDMA (or CDMA2000) is a technology of wireless telecommunications standards for voice and data transmission, <http://www.cdg.org/>.

⁷ <http://www.metro.pt/>.

⁸ <http://www.brisa.pt/>

⁹ <http://www.viaverde.pt/>

¹⁰ <http://www.q-free.com/>

¹¹ <http://www.frotcom.com/>

¹² General Packet Radio Service is a mobile data service included in GSM system.

¹³ <http://www.navteq.com/>.