An Innovative Health Monitoring System for Aircraft Landing Gears

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Abstract

The health monitoring of structures has been receiving increased emphasis especially in the design phase of modern aircraft and any transportation system, where dynamic loads can produce high amplitudes of vibration leading to undesirable effects, or new materials susceptible to hidden damages are used, leading to frequent and costly maintenance operations.

The main goal of the project is to study and develop a Health Monitoring & Management System (HMMS) capable to give information about the health status of a landing gear of a military trainer aircraft. The HMMS is a distributed system able to prevent and diagnose possible defects or failure occurrences, to analyze its effects and evolution, and to trigger the maintenance workflow in order to safely maintain of the aircraft at reduced costs, requiring minimum human intervention only when needed. This is done by gathering data from a network of sensors, and using specific algorithms to perform a data signal processing and a health status estimation. Then an appropriate DSS (Decision Support System) has been developed to calculate, on the basis of the actual load history, the remaining life according to the standard procedure adopted and accepted by the certification authorities but taking into account the actual scenarios experienced by the aircraft.

The SHM system is based on a multiple sensor approach:

- *ultrasonic waves, activated and sensed by piezoelectric patches bonded to the most critical structural component;*
- *MEMS accelerometers, measuring in differential system parameters evolution at crucial locations of the landing gear*
- *optical fibers (FBG) bonded to the most stressed locations of the landing gear.*

This integration allows to reduce non-routine maintenance because of its effect on schedule reliability and airplane downtime. Over the aforementioned sensors the HMM system integrates also the traditional ones adopted in landing gears.

All the HMM system featured have been widely investigated using numerical tools and subcomponent testing. Finally fatigue and drop tests have been executed for the final assessment of the HMM system capabilities.

1 INTRODUCTION

In recent years, Health Monitoring & Management Systems (HMMS) have extended considerably their potential [1-2]. The tools, that a few years ago allowed a human operator to monitor the functioning indicators of the system under observation, have evolved into complex measuring and computing systems, to which are demanded not only monitoring tasks, but also management functions and support to decisions. Several data acquisition subsystems, connected to networks of heterogeneous and redundant sensors, are combined to create a database of measures; the processing of this information, by advanced mathematical models and algorithms, enables fault detection capabilities as well as diagnostics, prognostics and maintenance management capabilities.

HMM Systems, therefore, are able to provide the diagnosis of the current state of the monitored system as well as to predict the remaining useable life-time, suggesting maintenance strategies and actions “on condition”, as an alternative to the planned maintenance that does not care about the real usage history of the system.

In this paper the design and the development of a HMM System, modular and scalable, and able to be installed on complex structures subjected to heavy strain and operating in hostile environments is presented. The work is part of the project SiHM, which has carried out by a team of nine partners, in which there is a large company, five SMEs and three research organizations. Specifically, the partners are: *Magnaghi Aeronautica SpA (leader), Euro.soft srl, Mare Engineering SpA, Marotta srl, Megaris srl, Techno System Developments srl, CRDC Nuove Tecnologie per le Attività Produttive scarl, Osservatorio Astronomico di Capodimonte, Consorzio Technapoli*.

The system has been designed with a modular approach to be sufficiently general and suitable for many applications. The logical architecture of the HMMS solution developed, has been designed as a stack of logical layers:

- the upper layers, which compose the Decision Support System, compute measurements and data collected on the field providing fault detection, diagnosis and prognosis functions, and maintenance managing features regarding the operation of the monitored process; at these layers there is a big amount of data to be stored and computed by complex algorithms, at a low-medium processing rate, making necessary the availability of large amounts of storage and computing resources.
- the lower layers, consist of sensors, signal acquisition and A/D conversion devices, data handling firmware, and communication systems that enable local coordination and real-time acquisition of the raw data. At these layers the data must be processed in real time at very high-rate frequencies. For these reasons an high-performance distributed architecture of the electronic subsystem is recommended.

A similar logical architecture can be adapted to a plurality of applications and the “content” of the individual modules must always be more customized (concernign sensor part and the modeling and predictive part of the monitored object), depending on the nature of the monitored process. The paper is structured as follows: some remarks on the research topics are given in the introduction. In section 2 an overview of the experimental investigation, with description of the test article, sensors, hardware and software systems is provided. Hence, the achieved results are summarized in Section 3, in section 4 an approximate evaluation of cost and benefits is reported and finally some concluding remarks are given in Section 5.

2 EXPERIMENTAL INVESTIGATION

2.1 HMM System

The HMM system has been appliend to a “landing gear” prototype and consists ofnovel and standard sensors,and a dedicated software capable to interact with the sensors and process the the received information by comparing it with the preliminarily input data or with a dedicated database. It also provides proper measurements of the current structural state of the landing gear, so it will be able to:

- provide the status (structural integrity) of the main critical components of the landing gear (potential risk of structural damage, properly defined by finite elements mathematical modeling);
- provide the functional and performance status of the landing gear during landing;
- effectively respond to the possibly actions of heavy external loads (landing loads and environmental), providing a warning to operators (pilot in the cockpit or control inspectors on board the aircraft) to the onset of structural damage;
- work as a gage of the lifetime, by providing in percentage the lifetime already consumed by the landing gear in its critical points (that have been provided by sensors).

Two different architectures of a HMM system can be adopted: centralized and distributed. A distributed system allows to implement signal acquisition and local processing, near the sensors, removing limitations in terms of number and type of sensors, that is typical of centralized architectures. However, a distributed architecture must be based on small components with low power consumption, allowing an easy integration on the monitored structure, thus avoiding impacts on its functionality and performance.
The system specifically developed for the project has a distributed architecture and is composed by the following parts:

- Centralized Data Processing Unit (CDPU)
- LLocal Acquisition & Processing Module (LAP)
- HHigh-performance Local Acquisition & Processing Module (HLAP)
- HHigh-performance Local Driving Acquisition & Processing Module (HLDAP)

Different Communication links (CAN-Bus, Ethernet) are used on board between the various modules and CDPU, depending on the different data throughput; one workstation on Ground controls and monitors the SHM system operations, while other workstations, connected via Ethernet link, perform the data processing. The HHM system architecture is shown in Fig. 1:

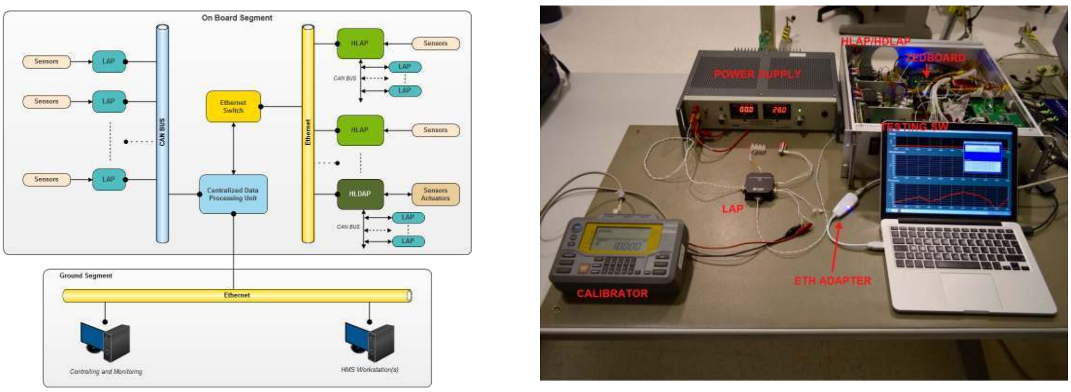

Figure 1: HHM system architecture

2.2 Sensors

The goal of the Health Monitoring and Management system is to develop advanced technologies for the health management of structural component to enable effective detection, diagnosis, prognosis, and mitigation of damage into structures.
At this level it is fundamental to select the right sensors which are able to carry out the wanted information. The present HHM system consists of different sensors:

- MEMS accelerometers;
- piezoelectric patches;
- optical fibers (FBG).

Microelectromechanical systems (MEMS) refer to devices having dimensions in the range from a micron to a millimeter that combine electrical and mechanical components and that are fabricated using the same technologies of integrated circuits [3]. The accelerometers are made by a polysilicon surface with a micro machined structure built on top of a silicon wafer. Silicon springs suspend the structure over the surface of the wafer and plates attached on the fixed and moving mass form a differential capacitor. Acceleration deflects the moving mass and unbalances the differential capacitor resulting in a sensor output with an amplitude proportional to acceleration. Phase-sensitive demodulation techniques determine the magnitude and direction of the acceleration.
A **piezoelectric** material is a material able to generate an electric field when it is subjected to a mechanical strain (direct effect), or, conversely, to generate a mechanical strain in response to an applied electric field [4-6]. This means that piezoelectric material devices can be used as both source and receiver. Piezoelectric sensors have been used to detect small dimension damages by means of ultrasonic waves in the frequency range 30kHz – 350kHz; MEMS, indeed, have been adopted in the low frequency range say 20Hz – 5kHz.
A **Fiber Bragg grating** (FBG) is a periodic modulation of the refractive index in the core of a little length of an optical fiber (FO). We all know that FBG works like a narrowband reflecting mirror. The Bragg reflection wavelength (λ_B) of an FBG is directly dependent by effective refractive index of the grating and the imposed grating period (Λ). So, the FBG sensors are sensitive to both temperature and strain [7]. The strain response arises mainly from the physical elongation of the length of the sensor. Being spectrally encoded, the FBGs are insensible to EM interference, intensity modulation of the optical carrier and losses along all the length of connection between the sensor location and the opto-electronic readout apparatus. This allows to have high multiplexing capability on a single FO connection (more than 60 for a single FO cable).
All these characteristics, connected to high strain sensitivity (order of 1 $\mu\varepsilon$) and high time bandwidth response (up to MHz), confer to such kind of sensing system to be one of the most eligible monitoring system for the SHM field [8].

2.3 Nose landing gear test article

In order to demonstrate, validate and appreciate the potentiality of the designed and developed HMMS solution, the system has been installed and tested on a landing gear prototype.
An aircraft landing gear system presents geometrical, structural and functional complexities [9]. Its components are subjected to high loads, static and dynamic, so they must be appropriately dimensioned and made by materials with high mechanical characteristics; these materials have to be able to meet both the strength/stiffness and the lightness requirements. The working conditions of these parts may cause defects that can compromise structural

integrity up to the collapse. It could lead to terrible consequences for on board and ground persons safety.
The goal of landing gear health monitoring technologies is to know at any time, for any aircraft in the fleet, the structural integrity of the landing gear, the amount of remaining fatigue life, the landing gear servicing information (such as shock strut pressure and volume, tire pressure and temperature, and brake condition), and the internal status of all on-board electronics and systems related to the landing gear system [10-11].
The test article used for the validation of the HMM system is a real scale one-wheel nose landing gear (Fig. 2), installed on an aircraft used for military training, with a maximum weight of 4.000 kg during take-off. It has an integrated shock absorber within its own structure and it has been equipped with the aforementioned innovative sensors, over the traditional ones such as pressure/temperature transducers of the nitrogen, weight on wheel switch, linear transducers, triaxial accelerometers, etc.

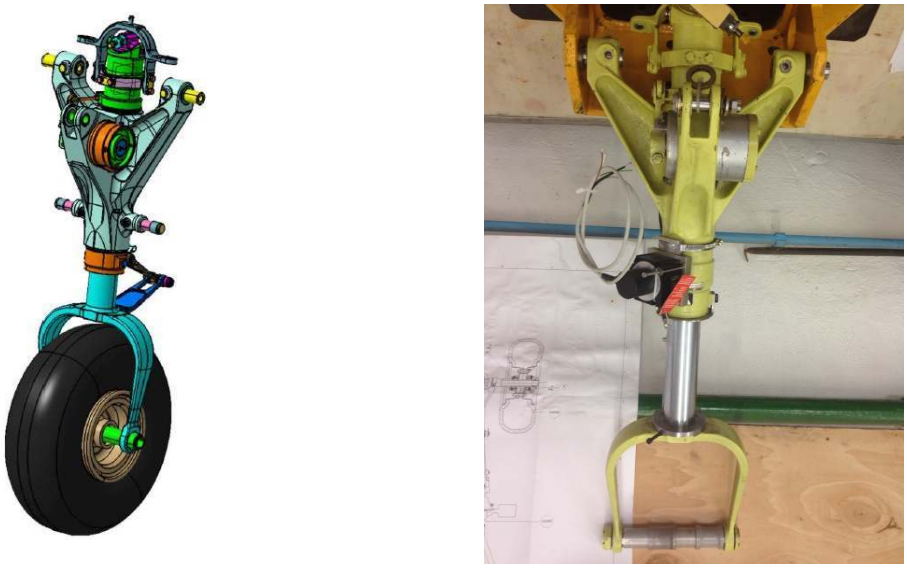

Figure 2: Landing gear test article.

2.4 Landing gear drop test

Drop tests have been performed at the drop tower facility available at Magnaghi Aeronautica SpA. In order to preserve the landing gear structure (attachments landing gear-structure, wheel axle and the fork), and also to avoid conditions of hydraulic bottoming preserving the tire, the presence of damage (or better of an anomaly) was simulated by changing some parameters of the set-up, such as shock absorber and tire inflating pressure (Table 1).

	Test 1	Test 2	Test 3	Test 4
Drop weight, Mr (Kg)	415	415	415	415
Vertical component of impact velocity, Vz (m/s)	3	3	3	3
Drop height, H (mm)	459	459	459	459
Shock absorber pressure, Pa (bar)	9.6	9.6	8.6	8.6
Tire inflating pressure, Pp (bar)	5	4.5	5	4.5

Table 1: Drop test matrix

Preliminary experimental tests have been carried out for different impact velocity and drop height, to define and verify that the set-up was fine. In Figure 3 the sensorized landing gear installed on the drop tower is shown.

Figure 3: Drop test facility.

2.5 Software architecture

The data collected during the test will be processed, managed, displayed and stored in the subsystem software, developed within the project, which has been designed to achieve the following objectives:

- Receive the acquired measurements from the custom acquisition subsystems;
- Store the data acquired in a specifically designed and implemented database;
- Process the data that are not accessible in a direct way;
- Detect critical events: crack growth, loss of oil or nitrogen pressure in the damper of the landing gear;
- Define the prognosis and diagnosis for each event;
- Make the acquired and calculated data available for accredited users;
- Deliver the events to the users through a specific mode.

Measurements, process data, events, prognosis and diagnosis are associated with the components of the observed system. Each identified component is a line-replaceable unit (LRU).

The architecture of the software subsystem is organised in services: Services that implement the CCSDS (Consultative Committee for Space Data Systems)standard which receives via TCP / IP socket data from the general acquisition device; parsing services for interpretation of the data provided by the control device of the optical fibers using text files; elaboration data services (fatigue life, take off/landing detection); event detection services (crack, attitude problem, hard landing, etc.); event notification system.

Two users have been defined: the operator (for example the pilot) and the maintainer.

The fruition data system has been implemented through a WEB technology so that it can be used in any place in which an internet connection and a device equipped with a browser are available at website *"www.sihm.it"* (Figure 4).

The technologies used for software subsystem development are:

- java jsp and servelet java that communicate with each other through json;
- output html5 with framework bootstrap to have a responsive result;
- highchart library for the graphics representation;
- regarding the DBMS has been used MySQL with ibates fremework and mybates.

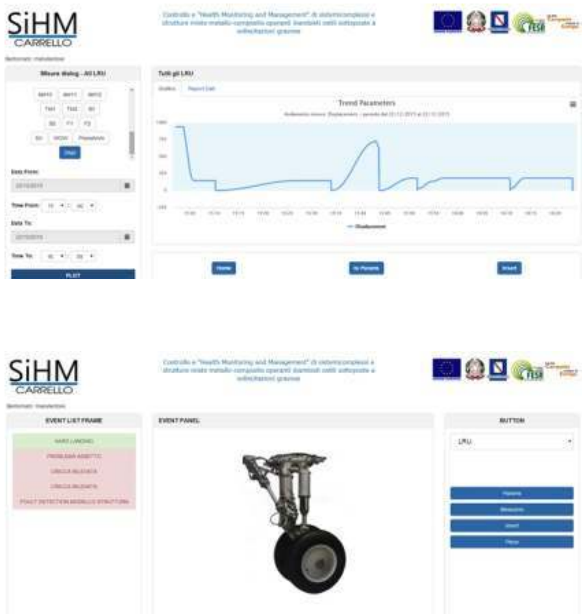

Figure 4: Screenshot of the website.

3 RESULTS

Some of the results obtained from the different sensors during the drop tests are reported below.

In Fig.5 the Bode diagrams obtained from MEMS accelerometers for three configurations: baseline (Test1), baseline with varied tire pressure (Test2) and baseline with varied shock absorbers pressure (Test3), simulating an issue and evidencing important changes in the parameters that look promising for the proposed technique, are reported.

The FIT value expresses the level of confidence in the model and it is not very high due to noise and non-linearity. From the results, it is evident how tire pressure is not affecting very much the system behaviour, while acting on the shock absorber implies a growth in the system damping and a small reduction of the resonant frequency Fn.

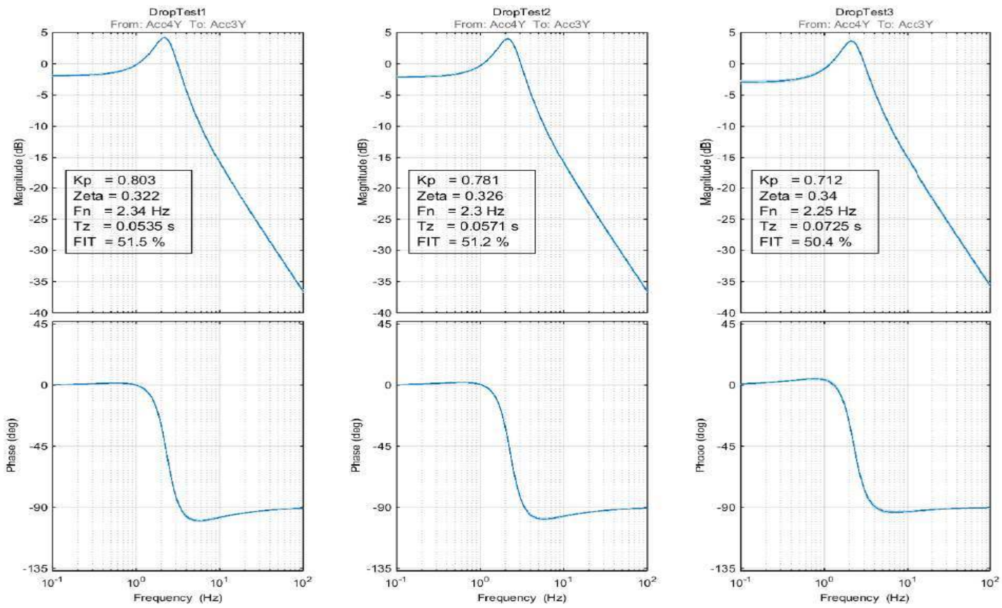

Figure 5: Bode diagrams of different drop tests.

In order to define the most suitable locations to glue FBG sensors, a detailed FEM analyses of the landing gear was carried out and the positions more critical were identified one on the tire support and one on the airplane-landing gear support connection. Data (shifts of lambda Bragg versus time) coming from the interrogator system (a MO sm130-700) have been elaborated by using a simply derivative and after DFT approach. So the plots shown into Fig. 6 are the frequency response of the structure (in term of equivalent displacement monitored by the FBGs) when an equivalent impulsive solicitation have been applied to the vertical axes of the landing gear, into four different structure conditions (variation of the tire pressure and shock absorbers pressure). As it can be noted the variation of the tire pressure is not much relevant as the variation of the shock absorber which leads to increase of the amplitude of the natural frequencies, especially at low frequencies: ≈1, 3, 8 *Hz*.

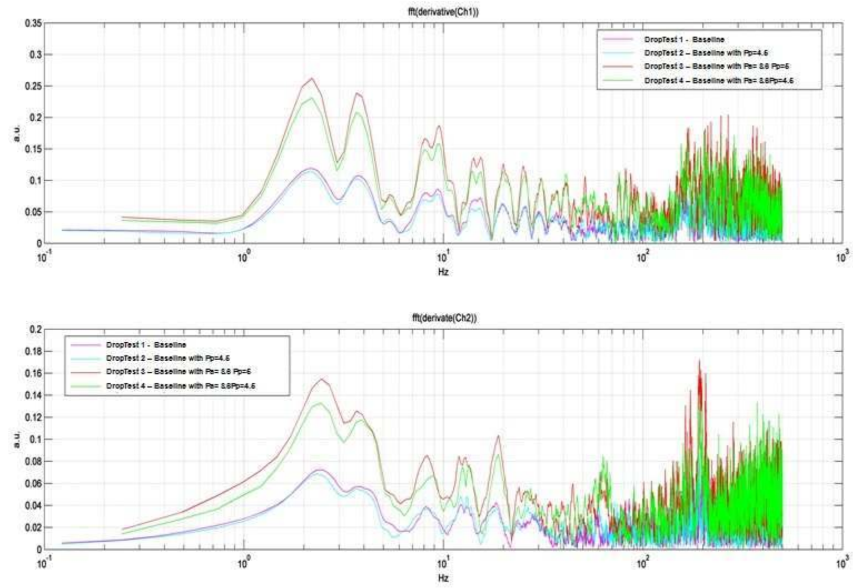

Figure 6: DFT diagrams of time domain derived data from the two sensors (up: on the tire support and down: on the airplane-landing gear support connection) with modified pressure in the landing gear shock absorber and tire.

The MEMS accelerometers and the FBG sensors are suitable for measurements in the low frequency range, where a global behaviour of the structure is measured and hence damage of certain dimensions should be identified. To detect smaller damages ultrasonic waves have been used, at the appropriate frequency to have a wavelength comparable with dimension of the damage. For this purpose piezoelectric sources and receivers have been adopted using the pitch-catch technique on a component of a landing gear. Known the generated and the measured signals it is possible to calculate the group velocity, the amplitude of the wave packet, the transmission factor and by comparing these parameters before and after an event occurs it is possible to report if a damage occurred or not (Table 2).

	Transmission factor					**Group velocity**			
freq [*kHz*]	**integer**	**damaged**	**Δ**	**Δ%**		**integer**	**damaged**	**Δ**	**Δ%**
100	0.001063	0.0010328	0.028136	3%		2.6607	2.6323	0.010674	1%
200	0.000436	0.0004506	-0.03434	-3%		5.4289	5.0291	0.073643	7%
300	0.001497	0.0006057	0.595438	60%		4.8721	5.3182	-0.09156	-9%
400	0.002092	0.0017187	0.178599	18%		4.3647	3.9559	0.093661	9%
500	0.001155	0.0011512	0.003635	0%		4.2005	4.0465	0.036662	4%

Table 2: Transmission factor and group velocity for different frequencies

4 COST AND BENEFITS

The implementation of the HMM system will provide benefits especially for the maintenance, which actually is scheduled. By using a HMM system, in fact, it can be possible to change this approach and try to intervene in constructive and proactive way in the regular program of the maintenance when the HMM system inform the maintainer. This approach will provide substantial savings in terms of time and costs.

In order to have an idea in this section an approximate estimation of the costs associated with inspection with and without HHM system is made.

Actually a programmed inspection of a landing gear, without HMM system, after 100000 hours of flight is pairs to 1,67 M€. In the case of a landing gear equipped with a HMM system the same inspection (always referred to 100000 hours of flight) will have a cost pairs to 435 k€, i.e. four times less of the actual programmed inspection. This cost consists of:

Cost	**Cost for 1 landing gear**	**Cost for 3 landing gears**
Cost associated to weight increase	94.5 k€ (0.07 €/h)	283 k€
Cost of sensors	4 k€	12 k€
Cost of sensors installation	5 k€	15 k€
Cost of electronics	80 k€	80 k€
Cost of inspections	15 k€	45 k€

Table 3: Costs of the landing gear equipped with the HMM system

Thus for a life cycle, estimated at 100000 hours of flight, an approximately 28% reduction of maintenance costs will be provided.

In terms of weight the HMM system will increase the weight of a single landing gear to 13,5 kg (consisting to sensors=0.5 kg, electronics= 8 kg, cables and other components= 5 kg), and hence pairs to 40,5 kg for three landing gears.

5 CONCLUSIONS

The main objectives of the investigated SHM system is to increase the reliability of a landing gear, reducing maintenance costs, since they help to provide technical information aimed to assess the possible extension of the operational life of the landing gear, expanding the standard intervals of the maintenance which have been defined during its homologation process. The results achieved are comforting and they were just as expected. They were achieved through the design and characterization of a HMM system extremely simple, that can easily reduce in dimension in order to be fitted directly on the landing gear and reduce its weight too. Moreover the developed software subsystem used during the testing phase was adequate to the set aims. Obviously it will need to be improved and optimized to become an actual working system: optimization of interfaces and database to deal with large amounts of data. Although it is a demonstrator, the subsystem was developed with very high level of parameterization (it is possible to set every condition linked to the events). This made the created system easy to extend to different application contexts.

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