Un sistema aeronautico di Health Monitoring e prognostica

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INTRODUZIONE

- Un sistema di trasporto complesso, regolamentato ed altamente affidabile quale quello aereo richiede un sistema di «Health Monitoring» altrettanto complesso ed affidabile che deve considerare ed includere molteplici aspetti tecnici, operativi e regolamentari.
- Tra molte sigle e nomi, un sistema di «Health Monitoring» in aeronautica è spesso chiamato Integrated Vehicle Health Management (IVHM) system per sottolineare l'interdipendenza tra tutti vari aspetti e tra i vari componenti e sistemi del velivolo.
- In linea di principio, in aeronautica ma vale in genere per tutti i mezzi di trasporto, non è possibile, o meglio di interesse, introdurre un sistema di Health Monitoring su una singola parte/sistema o su un singolo velivolo indipendentemente dagli altri velivoli della flotta.
  - In questo aspetto i sistemi IVHM dei mezzi di trasporto differiscono come concezione e realizzazione dai sistemi di health monitoring, pur estremamente complessi, pensati per applicazioni singole quali centrali nucleari o satelliti.

IVHM: what, how, why

➢System Architecture

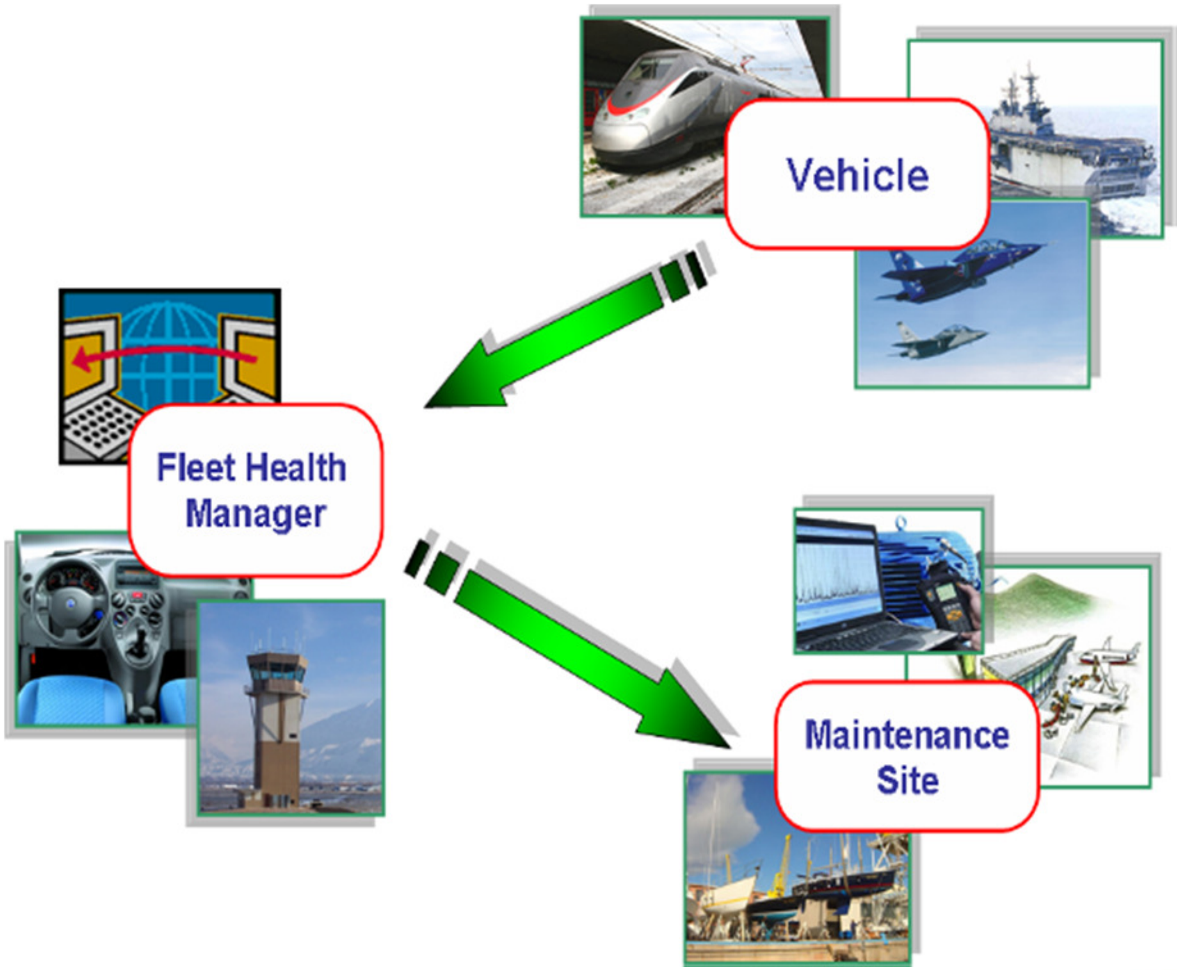
➔Means of transport (vehicle)
➔Fleet Management System
➔Maintenance Site

➢System Features

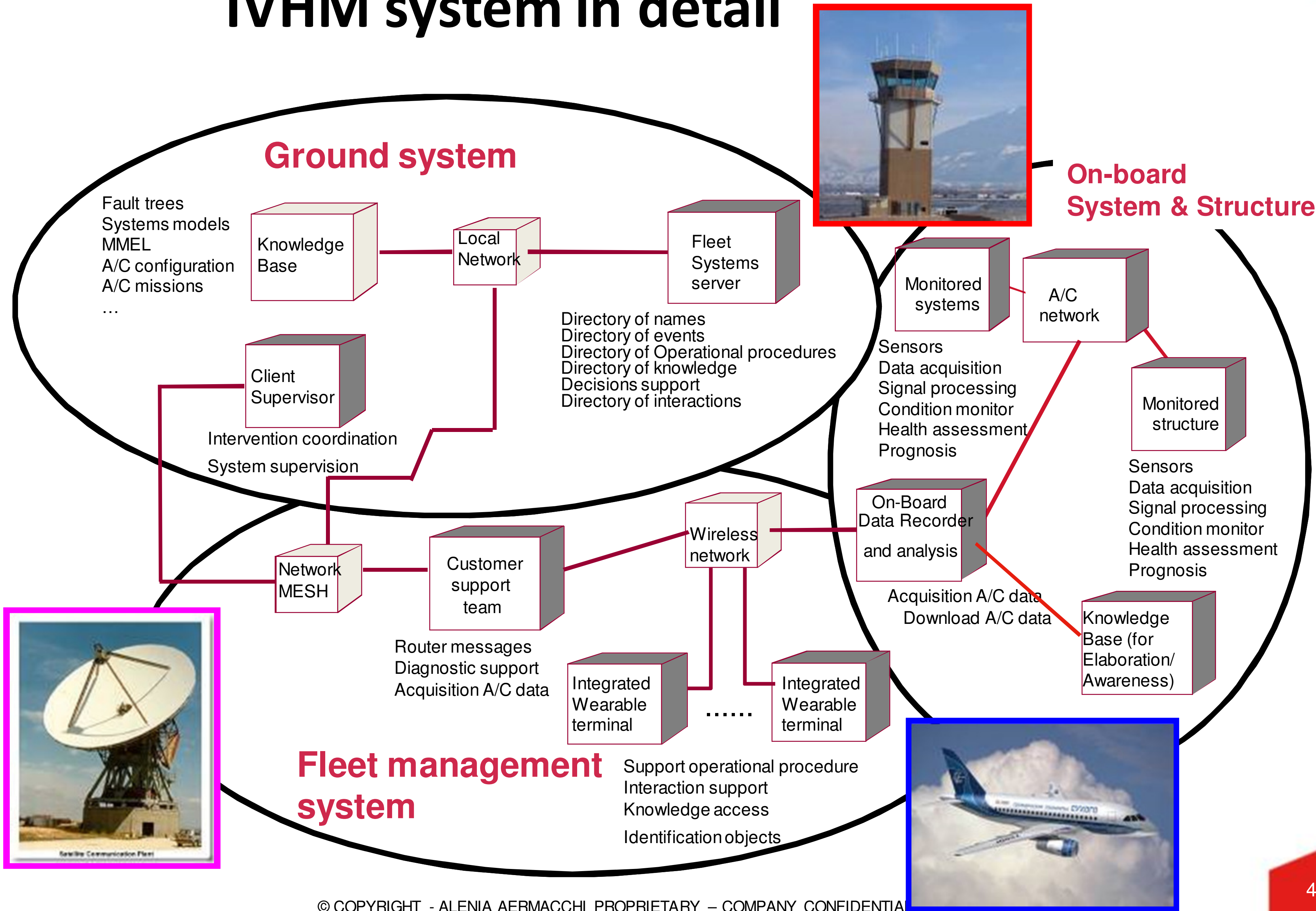
➔Open Architecture
➔High Reliability
➔High Level of Integration

➢Overall Objectives

➔Reduction of operative costs
➔Improvement of systems reliability
➔Improvement of in-service availability

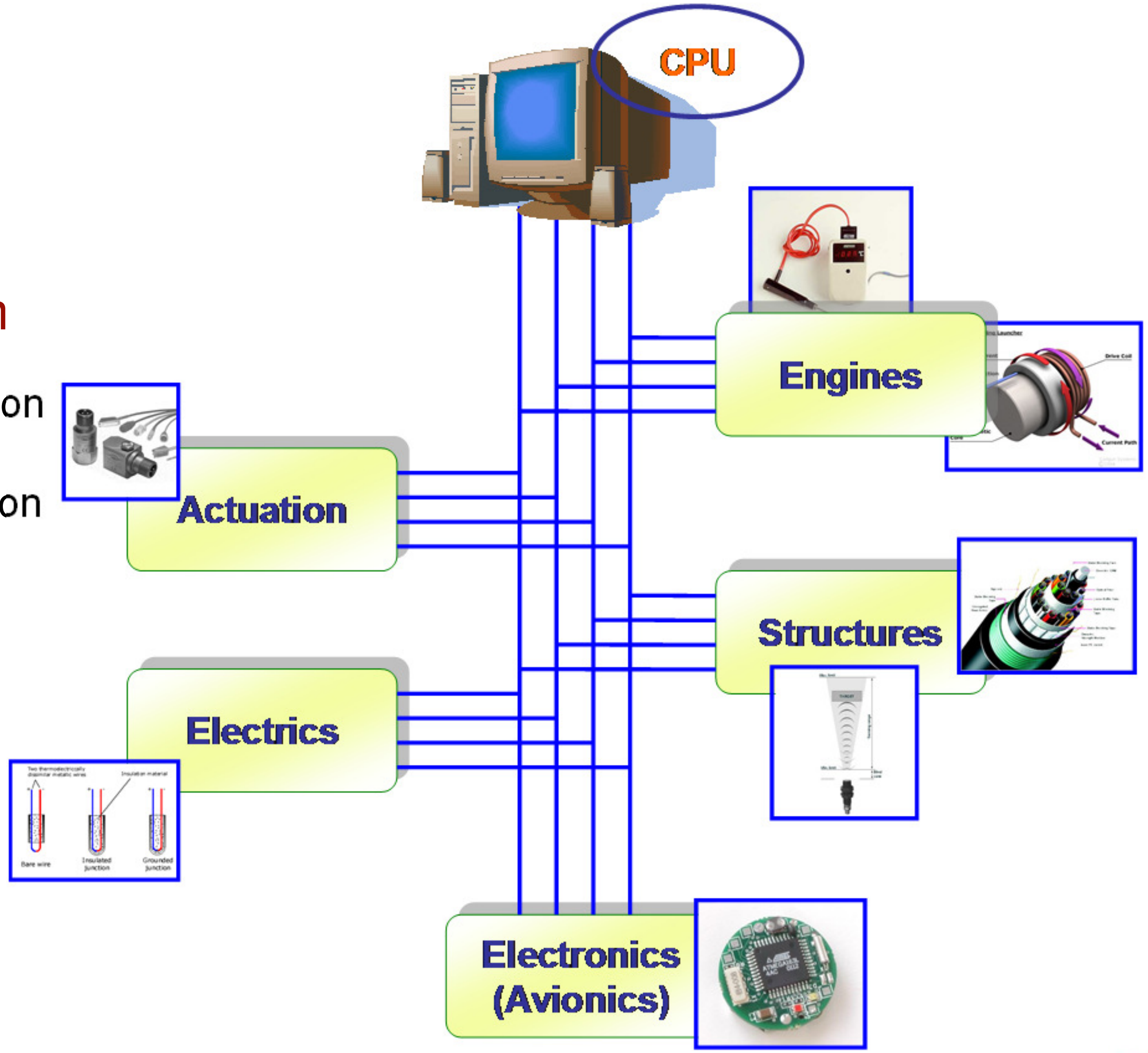


IVHM system in detail



On-board IVHM

- Data acquisition system
  - ➔ Sensors
  - ➔ Data acquisition system
- Data management system
  - ➔ HW on-board communication system
  - ➔ SW on-board communication protocols
  - ➔ Central elaboration and storing
- Data processing system
  - ➔ Fault detection tool
  - ➔ Fault diagnosis tool
  - ➔ Fault prognosis tool



On ground IVHM

➢Benefits Analysis

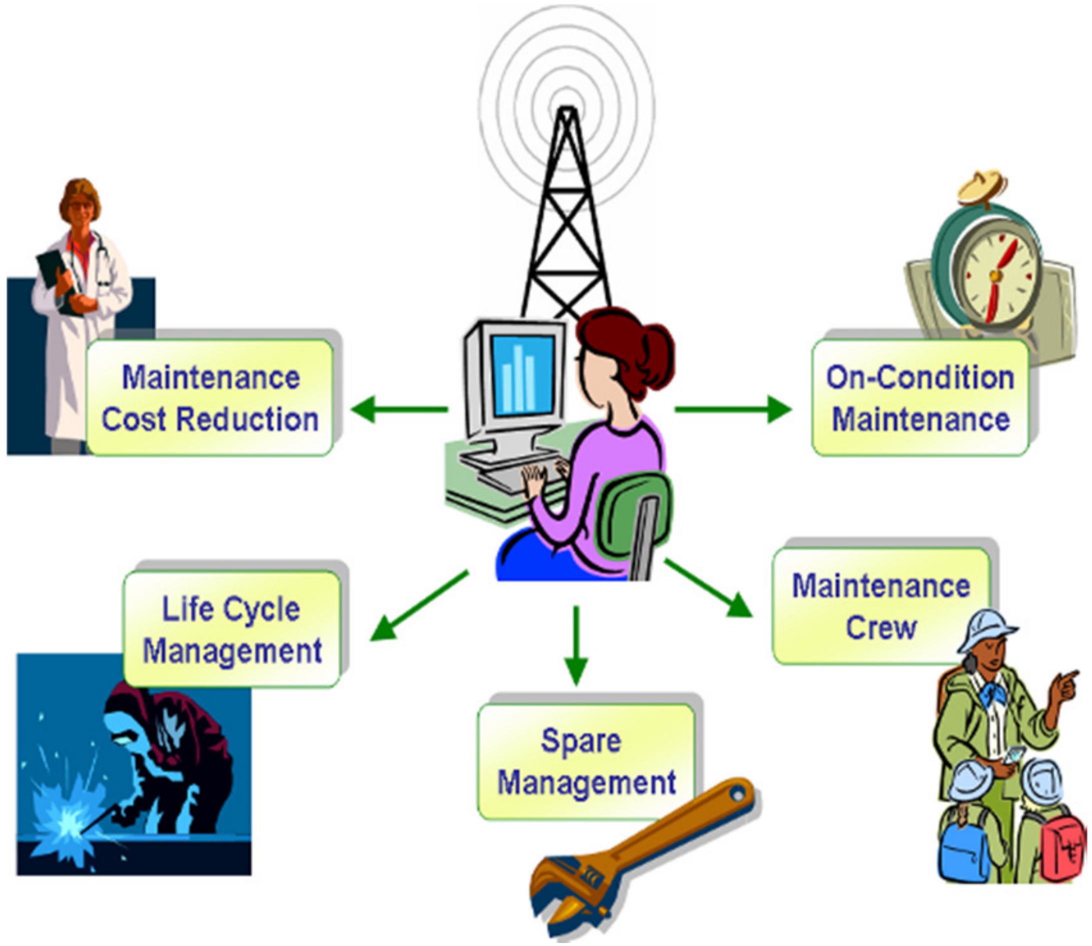
➔ On-condition Maintenance
➔ Full LCM

➢Communication & fleet management system

➔ Communication HW
➔ Communication SW & protocols
➔ Fleet monitoring tool

➢Maintenance management

➔ Database
➔ HW & SW tool for maintenance crew
➔ Training of maintenance crew



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IVHM layers (from OSACBM)

- ➔ **Sensors** Items collecting data from every systems and sub-system of aircrafts.
- ➔ **Sub-System Monitoring** Collects data from sensors – Perform single and/or multi-channel signal transformation – Compares features against expected values or operational limits – Outputs enumerated condition
- ➔ **Data Management Network** A Global Maintenance system architecture which can manage data collected. It shall store data and get them available on-board and at ground by using a linking system
- ➔ **Data Analysis Methods** Algorithms and methods to analyze data stored by using models describing both healthy and faulty functioning.
- ➔ **Diagnostic/Prognostic** Algorithms to provide a correct fault diagnosis and predict remaining life of subsystems - Determines if the health of a monitored system or subsystem is degraded. Project the current health state into the future, accounting for estimates of future usage profiles. Reports health status at a future time, or may estimate the remaining useful life (RUL) of an asset given its projected usage.
- ➔ **Fleet Consequences** Provide recommended actions and alternatives. Recommendations include maintenance action schedules, modifying the operational configuration, or modifying mission profiles.
- ➔ **Human Interface** A tool to support decision of maintenance ground crew - Displays high-level status (health assessments, prognosis, or support recommendations) to human user.

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Scenario 1: Maintenance (short term)

Objectives		Direct and indirect maintenance cost reduction: reduction of time and delay for corrective actions, improve reliability of decisions
Design target		IVHM failures have "major" (10*E-5) consequences
State of the art		Some partial solution existing (B 787 will the most advanced) TRL 7
Decision scheme		Cost/benefit analysis
Features	**Sensors**	• Integrated on monitored subsystems and components • Mainly COTS
	Data acquisition	• No real time
	Data storage and distribution	• Data bus: adapting of existing solutions, even not aeronautics • Database: COTS
	Data exchange	• Priority to failure data (imply preliminary evaluation at sensor stage) • Reliability compatible with design target
	Diagnostic/ prognosis	• Specific methods • Reliability compatible with design target
	On board crew Interface	• Basically for information only • No real time
	Data transmission	• On ground download mainly at aircraft stops • In flight data transfer is a plus (but no replacing of in flight data recorder, otherwise critical system)
	On ground HW	• Multimedia interface and data access for on ground crew interface with aircraft
	On ground SW	• Complete and structured data base of maintenance actiond, troubleshooting, parts catalog, …
	Certification and maintenance consequences	• New maintenance procedures to be certified
	Training	• Training for maintenance crew
Applications		Regionals
		Fighters
		UAV

Scenario 2: Design (medium term)

Objectives		Reduction of safety margins (thickness for structure, stand-by for systems), fuel reduction, emissions reduction
Design target		IVHM failures have "hazardous" (10*E-7) consequences
State of the art		Some subsystems solutions existing (TRL 3-4 at aircraft level)
Decision scheme		Cost/benefit analysis
Features	**Sensors**	• To be integrated on monitored components • Not feasible in no access areas • Mainly COTS
	Data acquisition	• Real time preferred
	Data storage and distribution	• Data bus: adapting of existing solutions, even not aeronautics • Database: COTS
	Data exchange	• Data shall be timely and safely transmitted • Reliability compatible with design target
	Diagnostic/ prognosis	• Specific methods • Reliability compatible with design target
	On board crew Interface	• Suggested for pilot intervention and actions • Real time
	Data transmission	• On ground download mainly at aircraft stops • In flight data transfer is a plus (but no replacing of in flight data recorder, otherwise critical system)
	On ground HW	• Multimedia interface and data access for on ground crew interface with aircraft
	On ground SW	• Complete and structured data base of maintenance actions, troubleshooting, parts catalog, …
	Certification and maintenance consequences	• New maintenance procedures to be certified • New design and system architectures to be certified adding on the failure detection provisions
	Training	• Training for maintenance crew
Applications		Regionals
		Fighters
		UAV

Scenario 3: Safety (long term)

Objectives		No redundancies on safety critical systems, safety improvement, increase of autonomy
Design target		IVHM failures have "catastrophic" (10*E-9) consequences
State of the art		No solution existing (TRL 3 at aircraft level)
Decision scheme		Cost/benefit analysis
Features	**Sensors**	• Very reliable • New concepts to be developed
	Data acquisition	• Real time necessary and high reliability
	Data storage and distribution	• Data bus compatible with design targets, wide band • Database: COTS but following design targets
	Data exchange	• Data shall be timely and safely transmitted • Reliability compatible with design target
	Diagnostic/ prognosis	• Specific methods • Reliability compatible with design target
	On board crew Interface	• Mandatory for pilot intervention and actions • Real time
	Data transmission	• On ground download mainly at aircraft stops • In flight data transfer is advisable
	On ground HW	• Multimedia interface and data access for on ground crew interface with aircraft
	On ground SW	• Complete and structured data base of maintenance actions, troubleshooting, parts catalog, …
	Certification and maintenance consequences	• New maintenance procedures to be certified • New design, system architectures and components to be certified adding on the failure detection provisions
	Training	• Training for maintenance crew and pilots
Applications		Regionals
		Fighters
		UAV

Alenia activities on IVHM

- Alenia is investing several resources on IVHM covering several and different technologies
- Alenia is concentrating its own resources in those technologies necessary for the integration of a IVHM on the aircraft
- Alenia is supporting the supply chain to invest, following or taking into consideration our specifications and needs, to develop items and solutions for the other technologies necessary to the IVHM but not within the scope and core of Alenia

Alenia interests on IVHM

- **Sensors:** we invested in the past (Bragg sensors). Today we are interested our supply chain develops smart miniaturized sensors, based on MEMS technologies for instance, capable of measuring the physical quantity and able of data transfer to central HM elaboration unit, may be partially self powered by energy harvesting
- **Sub-system monitoring**: to include in the sensor a minimal local elaboration and storage capability. The integrated miniaturized sensor should have the capability to interface an open architecture network including software layers enabling the connection (wireless?)

Alenia interests on IVHM

- **Data Management Network**: COTS architecture to be developed together by supply chain starting with an application to scenario 1 (maintenance only) usage. In the medium term wireless communication
- **Data analysis/Diagnostic and prognostic**: seeking for effectiveness and quality of solutions aiming at application to basic design cases. Several cases under study and development.
- **Fleet consequences**: Open area, need a general review of the maintenance process
- **Human Interface**: Started activities in TATEM and past military projects on training of maintenance crew and support to collection of aircraft data (e-log book, configuration control, manual tracking, enhanced and virtual reality for training and contextual data recovery).

Structural Health Monitoring features

- Development of suitable tools to obtain a health monitoring assessment on structural parts
- Acquiring static or dynamic sensor data
- Integrating data with architectural information on the monitored structure and data elaboration
- Giving information on damage and/or defects (diagnosis)
- Evaluating structure reliability (prognosis)

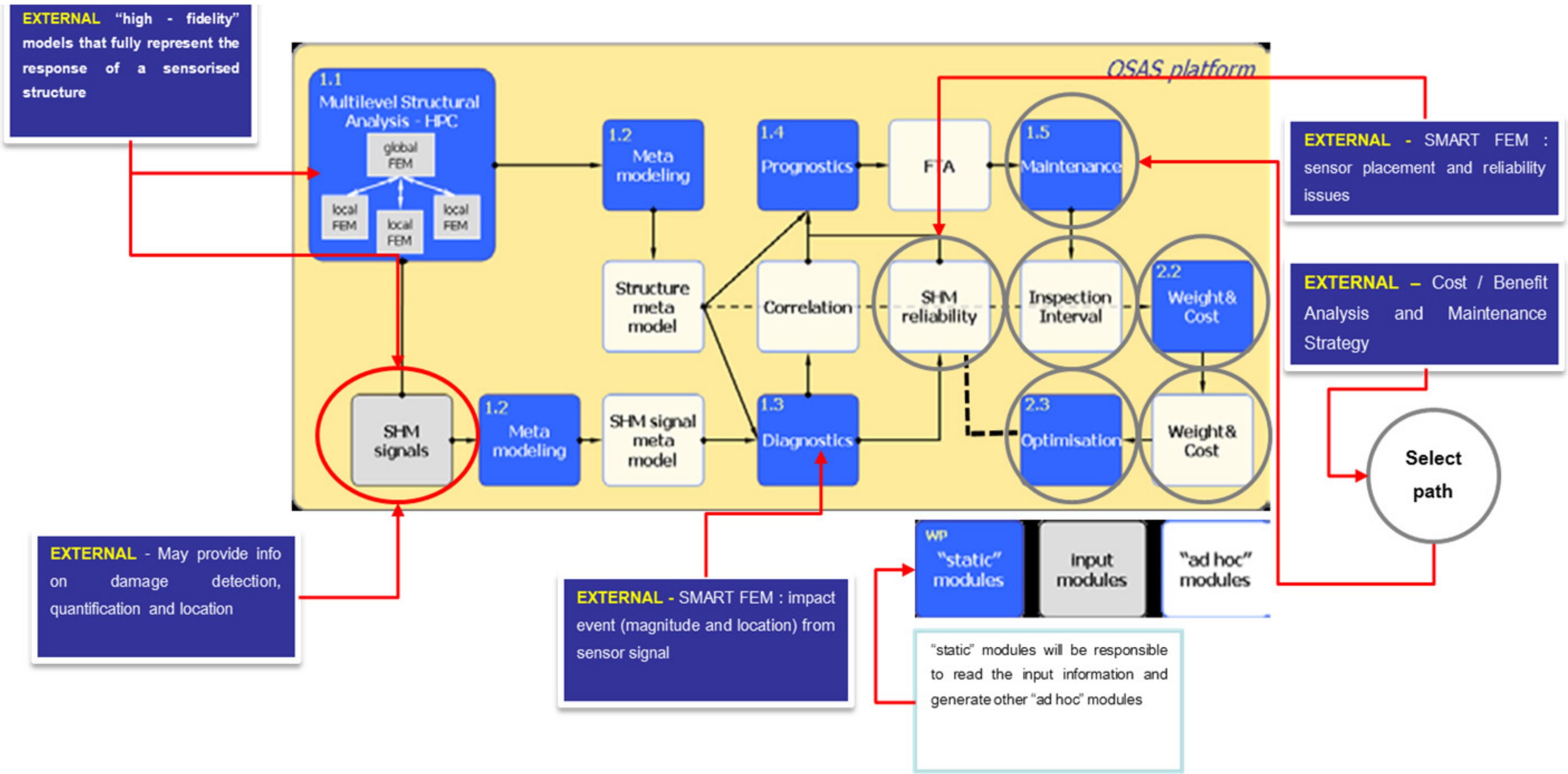
SHM Methodologies Large Scale Stiffened Composite Panels

Main innovations achieved within SMASH for "***Smart SHM technologies (SMASH Platform)***"

- ***"Passive Sensing"***
  - Demonstration of SMASH platform – Impact detection and characterisation
- ***"Active Sensing"***
  - Demonstration of SMASH platform – Damage detection and characterisation
  - Ultrasonic Guided Wave Based
  - Electro-mechanical Impedance Based
- ***"Optimisation"***
  - Demonstration of SMASH platform – Optimisation of sensor placement
- ***"Reliability Oriented Optimization of Structural Replacement Strategies for Aircraft Structures "***

SHM Methodologies

Large Scale Stiffened Composite Panels



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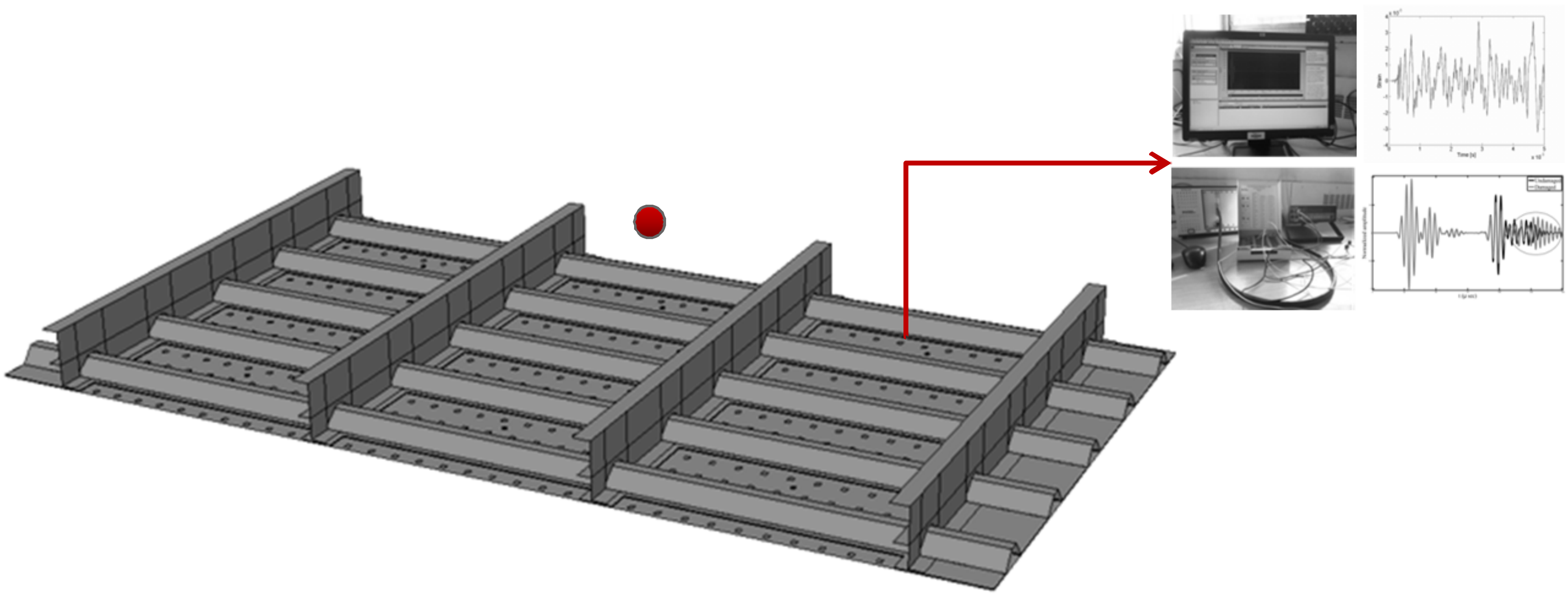
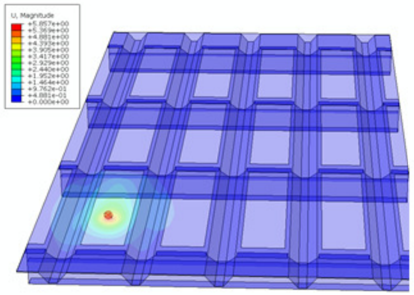
SMART SHM Platform for Sensorised Stiffened Panel

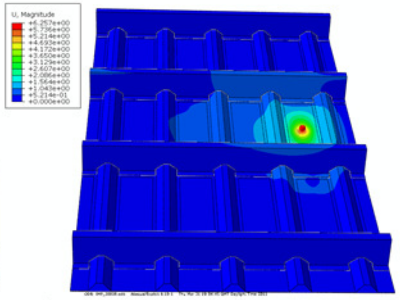


Passive Sensing – Impact Simulations

Impact at mid-bay

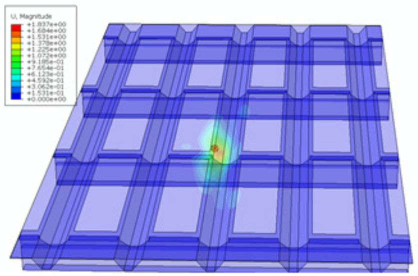


Debris impact
Impact energy: 5.4 J
Snapshot at 1.6 ms

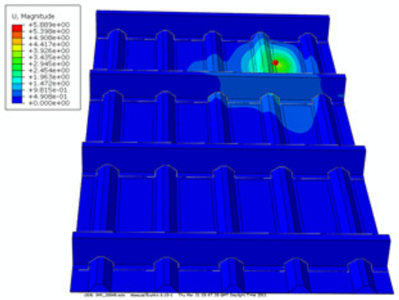


Tool drop
Impact energy: 6 J
Snapshot at 5 ms

Impact at the foot of the stringer

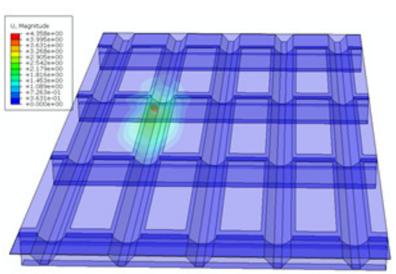


Debris impact
Impact energy: 5.4 J
Snapshot at 0.4 ms

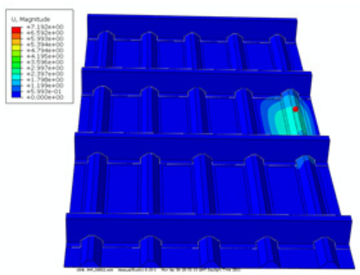


Tool drop
Impact energy: 6 J
Snapshot at 4 ms

Impact at under/over the stringer



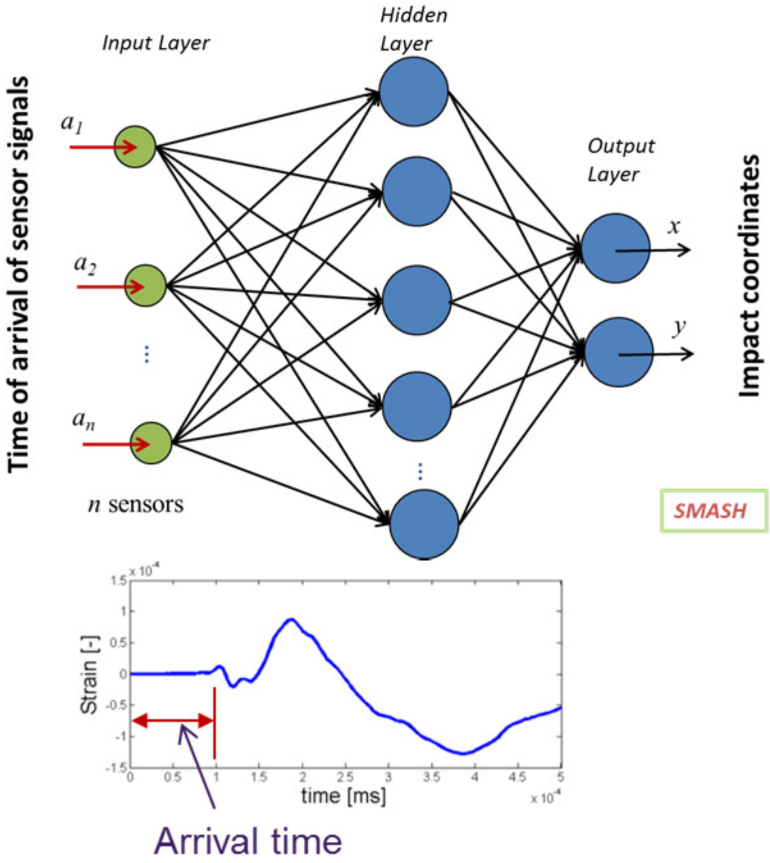
Debris impact
Impact energy: 5.4 J
Snapshot at 1.2 ms

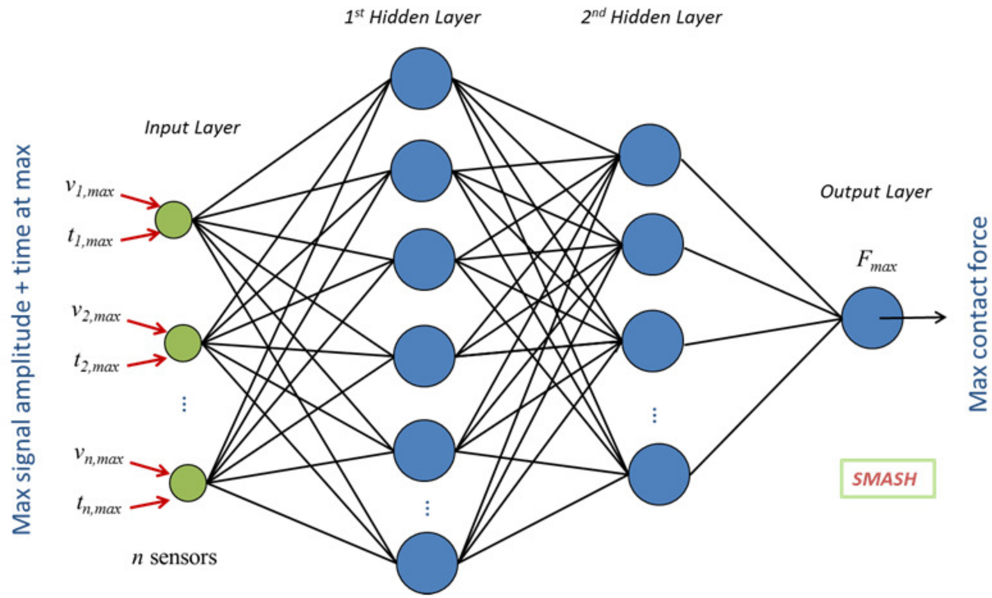


Tool drop
Impact energy: 6 J
Snapshot at 3 ms

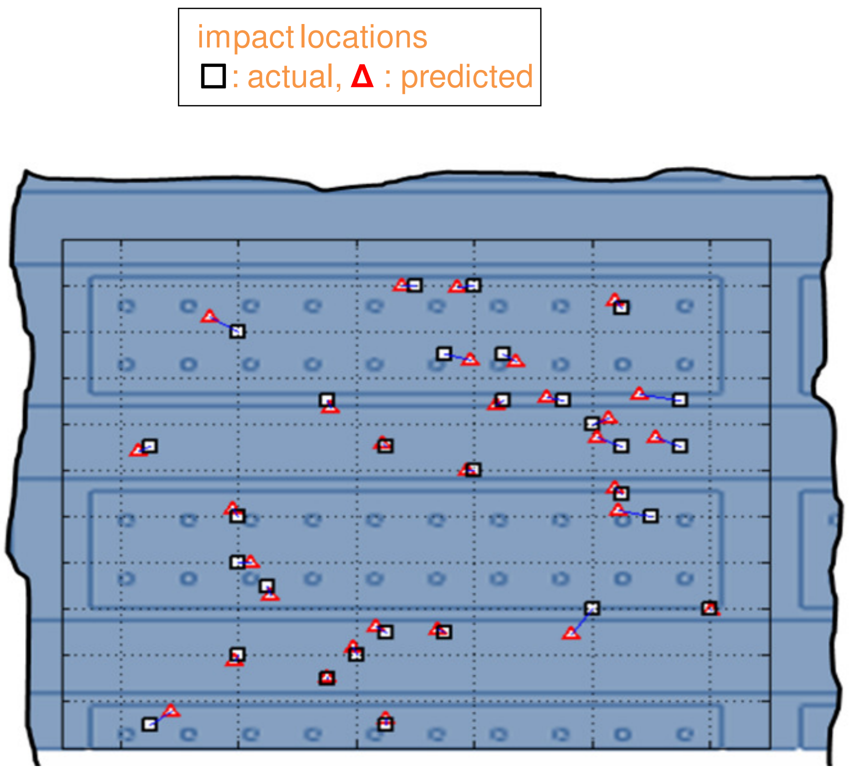
Passive Sensing – Meta-models

Trained Artificial Neural Network (ANN) for impact detection – location and force magnitude

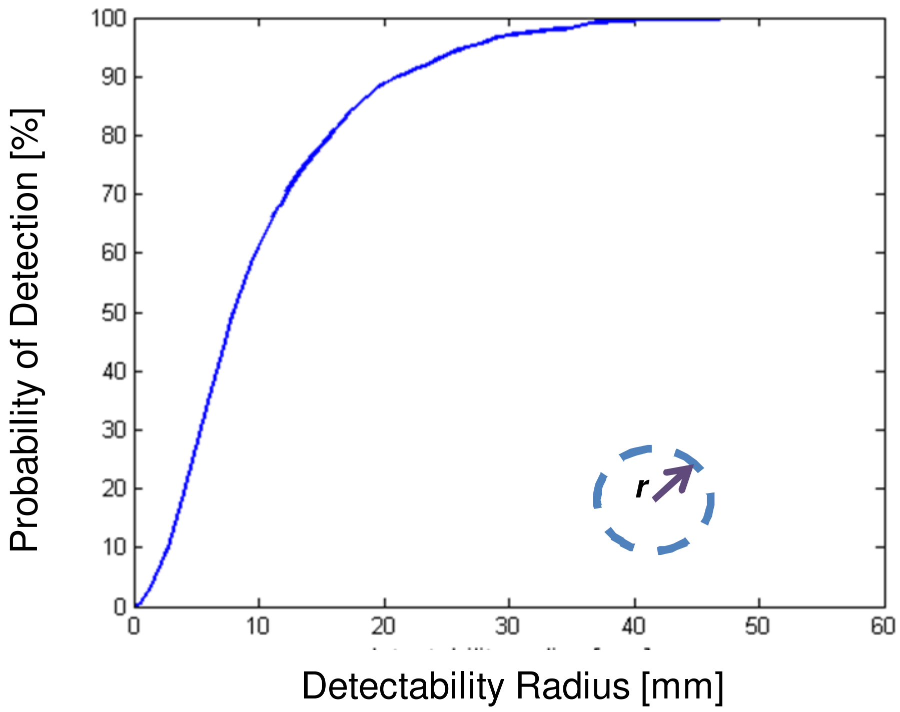




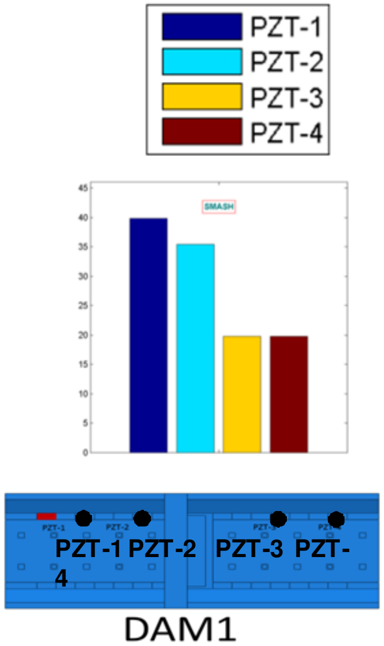
Passive Sensing – Meta-models

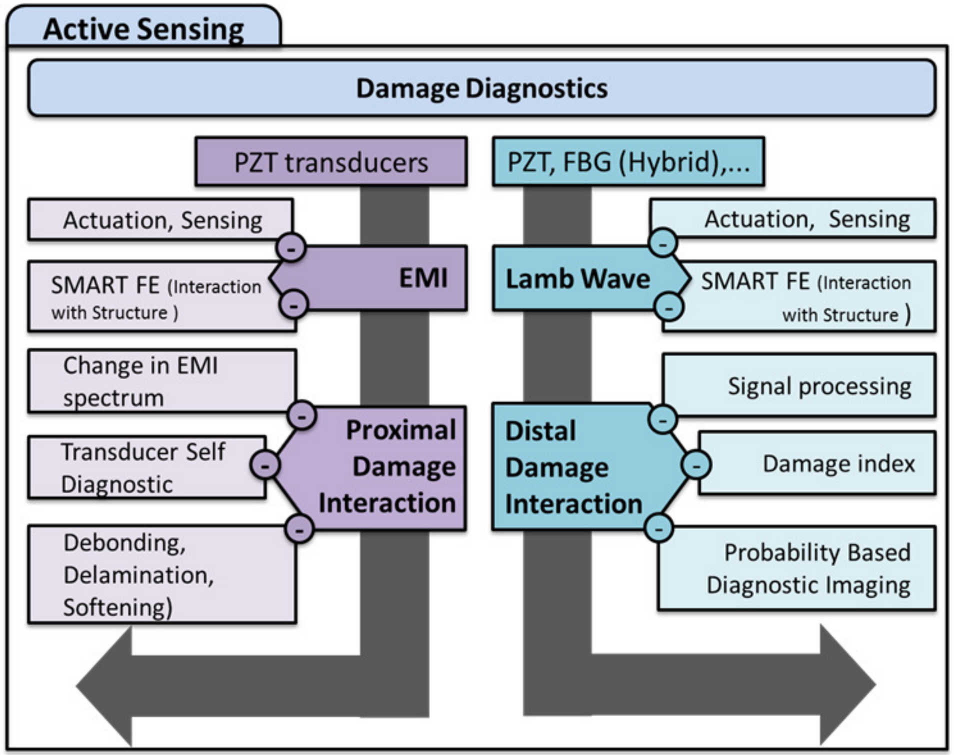


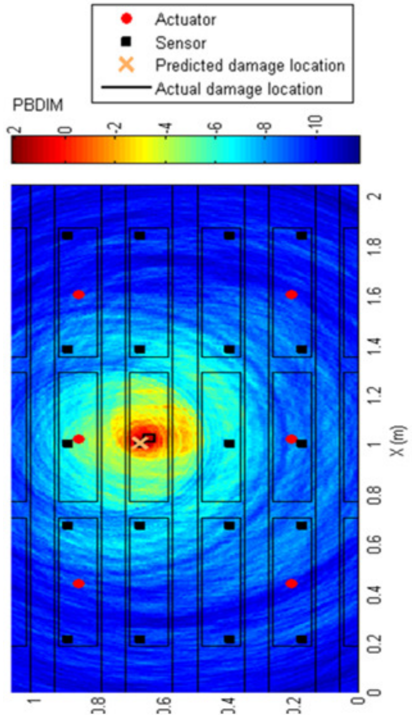
200,000 impact scenarios by adding noise to the signals.



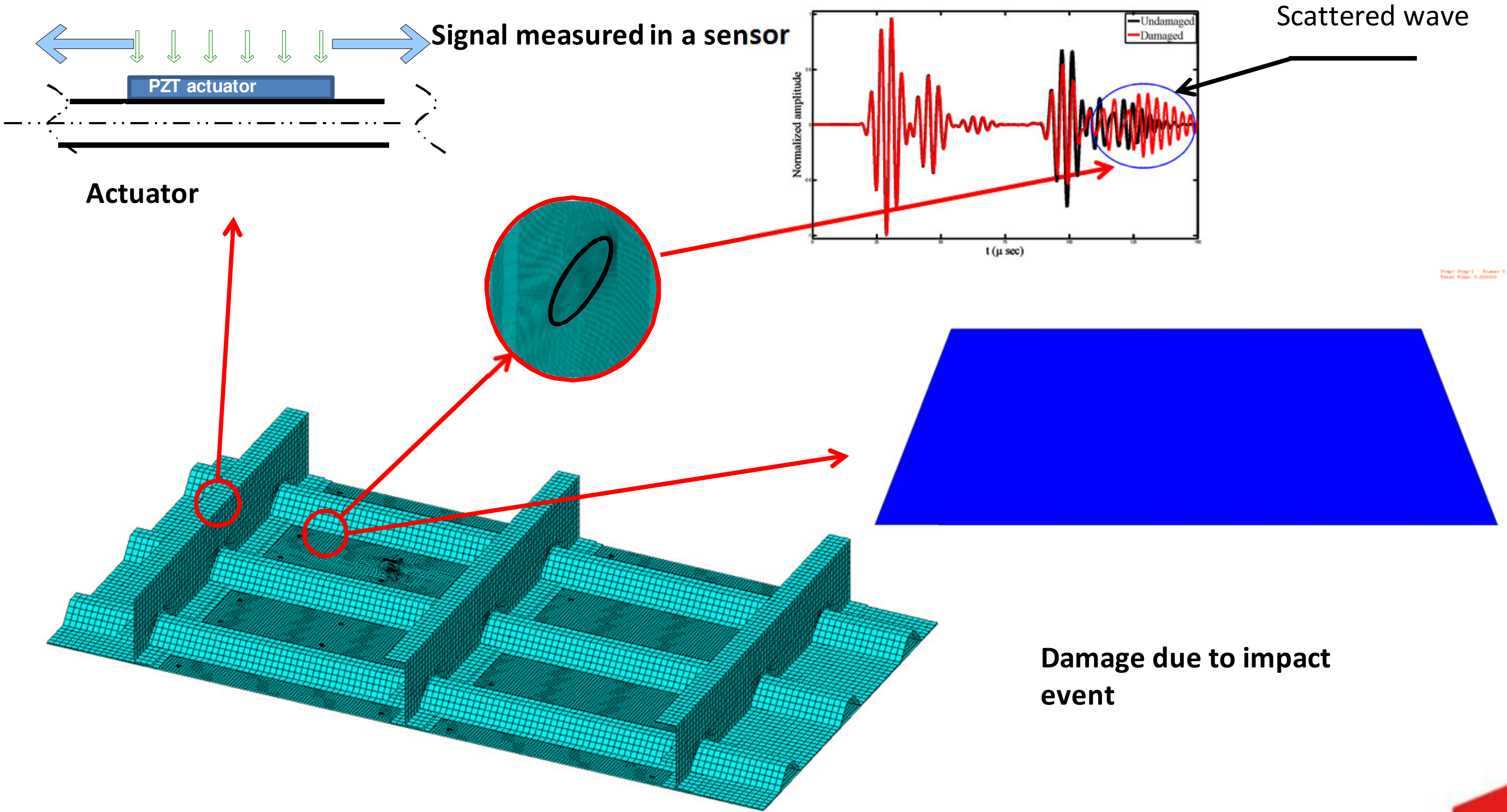
Platform Architecture –Active Sensing





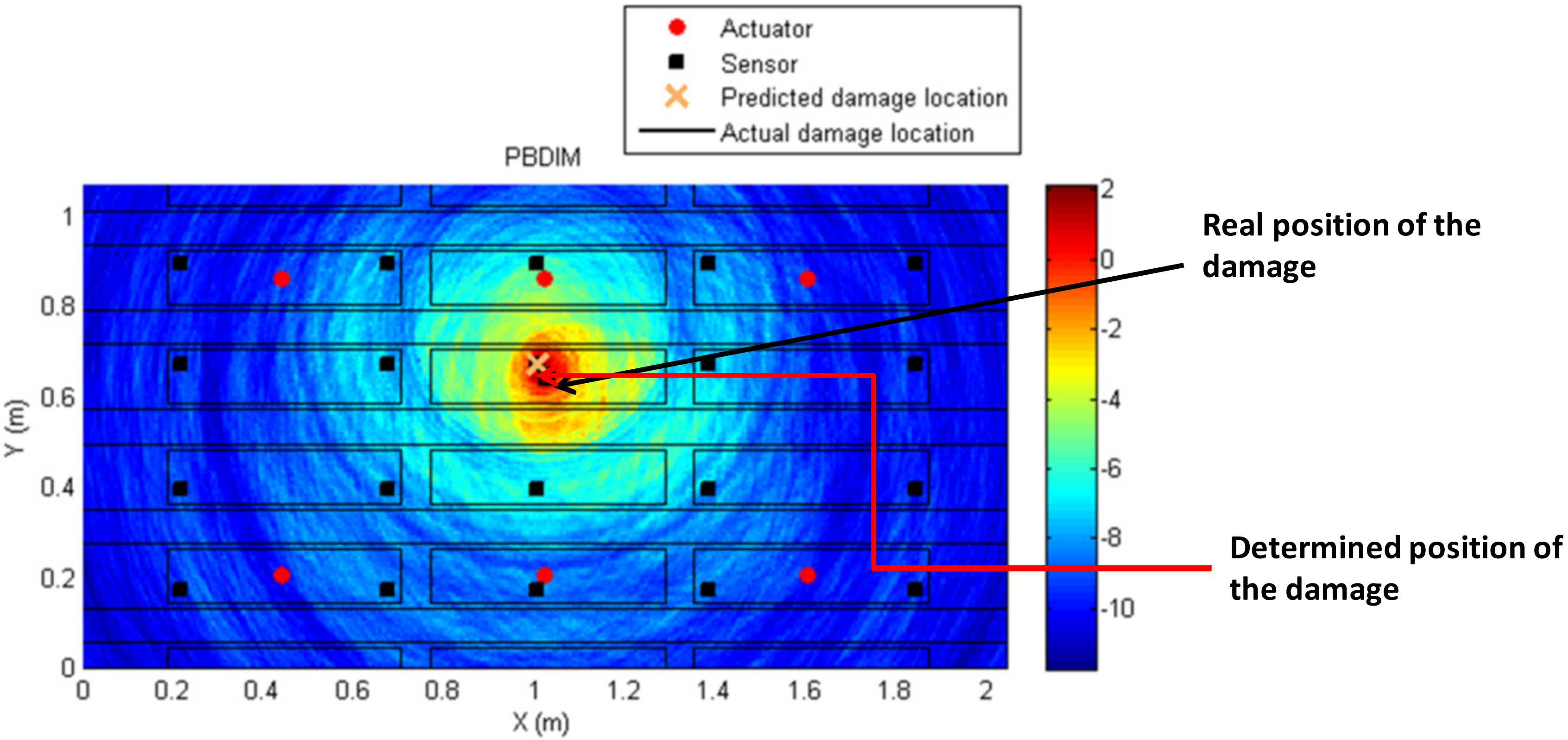


Active Sensing – Ultrasonic Guided Wave

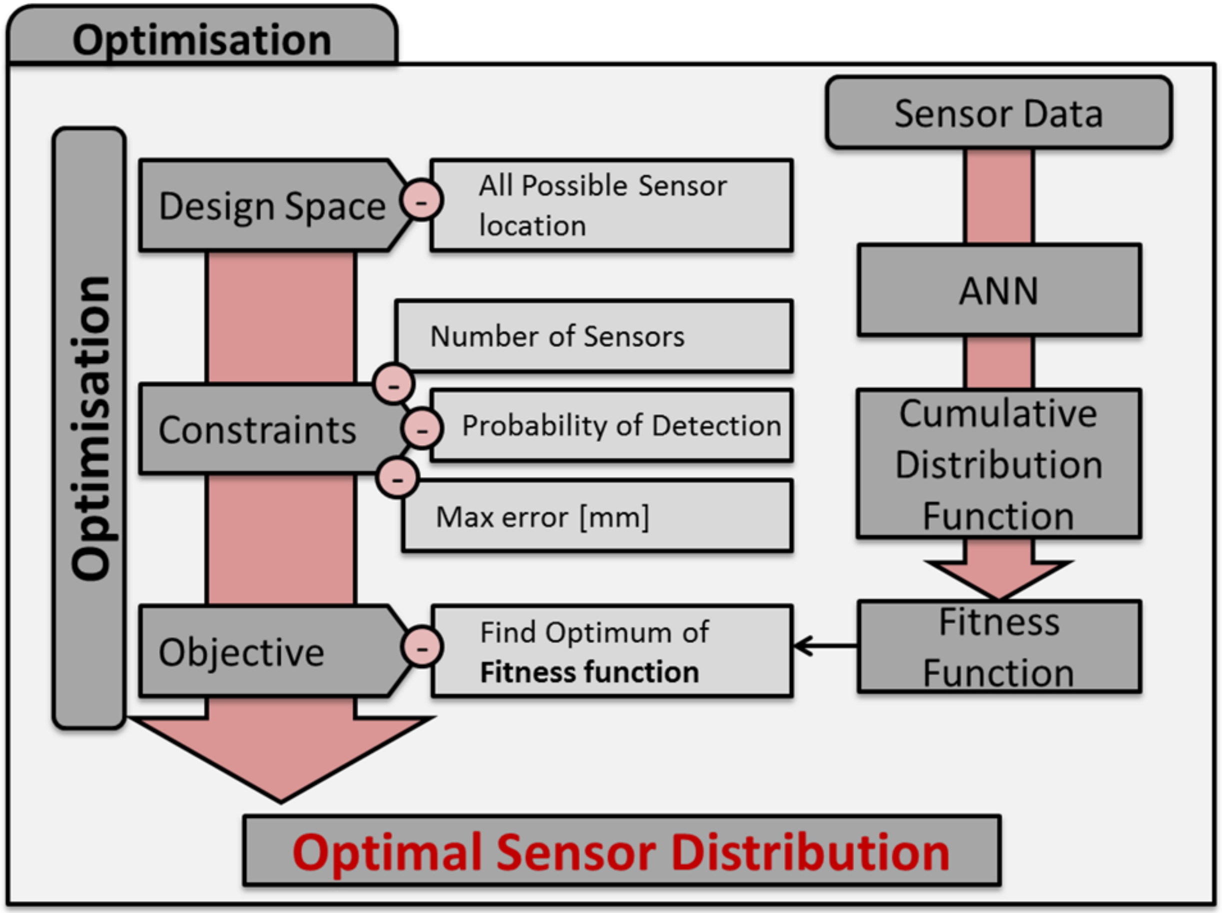


Lamb wave based damage localization-Stiffened panel diagnostic imaging algorithms

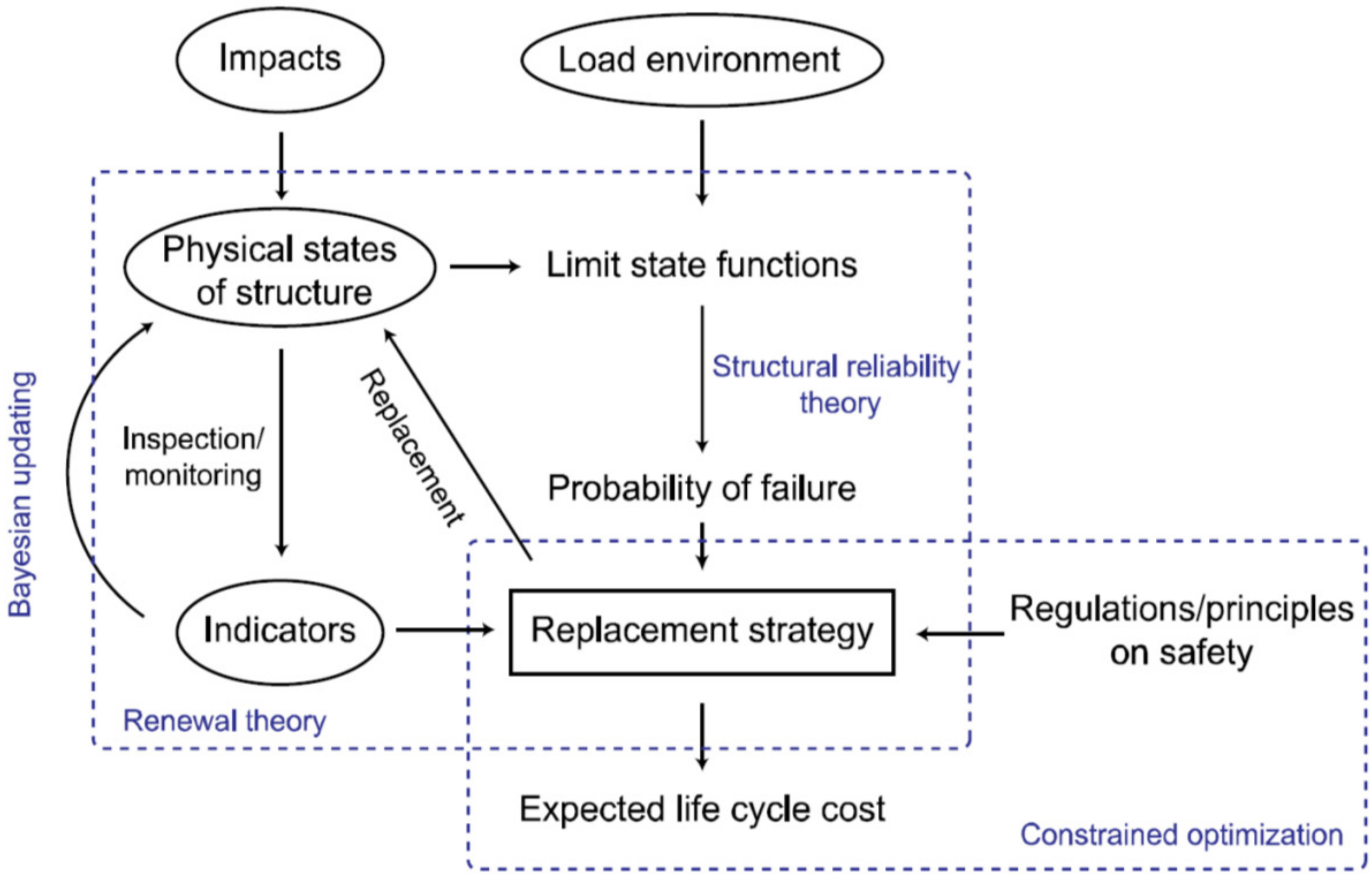
Difference in the energy transported by the incident and the scattered Lamb waves in order to determine the possible location of the damage area.



Optimisation – Sensor position



SHM Reliability Framework



Demonstration – Lower (from DOT/FAA/AR-97/79)

The structural configuration of the F/A-18A inner wing upper skin, has been divided in 45 stiffened panels.

The wing skin material is AS4/3501-6 graphite/epoxy with 100 laminates, thickness varying from wind root to wing fold.

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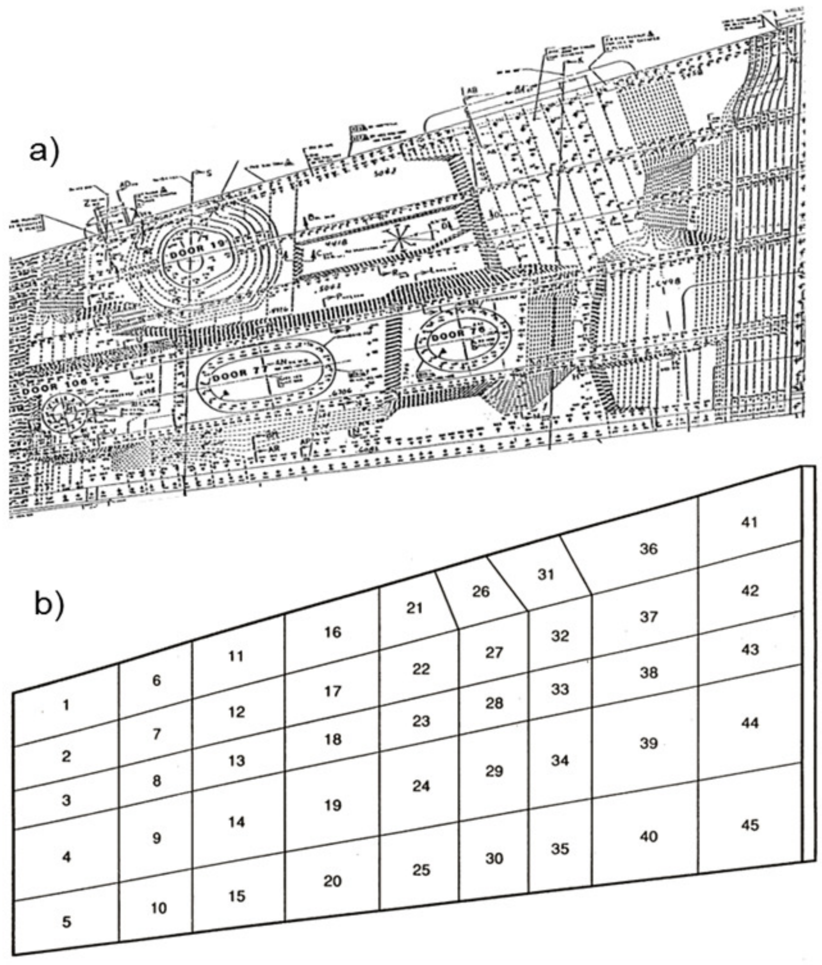
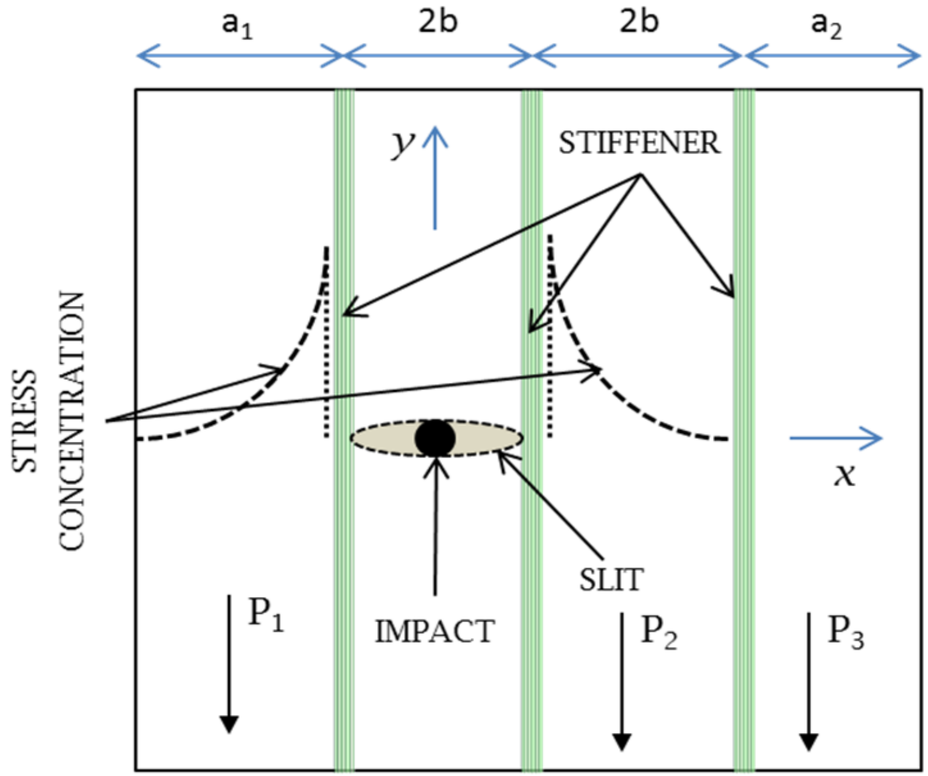
- $E_L = 18.7$ msi (128.9 GPa)
- $E_T = 1.9$ msi (13.1 GPa)
- $G_{LT} = 0.8$ msi (5.52 GPa)
- $\nu_{LT} = 0.3$
- $G_{IC} = 0.750$ in-lb/in^2(131.36 Pa)
- $A_{sp}E_{sp} = 6.0\ 10^6$ lb (26.7 10^6N)
- $\epsilon_0 = 11000\ \mu$in/in (μmm/mm)
- $\epsilon_{DUL} = 3000\ \mu$in/in ($\mu$mm/mm)



Mechanical Model per areas (from DOT/FAA/AR-97/79)

After the initial failure, structural effects based on the support condition are considered.



$$P_{TOT} = P_{sp} + P_1 + P_2 + P_3$$

P_{TOT} is the total applied load,
P_{sp} is the amount of load carried by the stiffeners,
P_1 is the amount of load carried by the adjacent partial bay,
P_2 is the amount of load carried by the adjacent full bay, and
P_3 is the amount of load carried by the remote partial bay.

↓

$\sigma_{1,\, str}$

$\sigma_{1,\, str} > \sigma_{1,\, elem}$	$\sigma_{1,\, str} < \sigma_{1,\, elem}$
Damage arrested by the stiffeners	Damage propagates

Parametric Model - Meta Model

(from DOT/FAA/AR-97/79)

Model parameters :

- E_X is the laminate Young's modulus in the loading direction.
- E_L is the longitudinal Young's modulus of the lamina.
- t is the laminate thickness.
- G_{IC} is the first Mode fracture toughness of the resin.
- k is the support condition coefficient.
- σ_0 is the failure stress of the undamaged laminate.

Impact parameters :

- $\sigma_{1,elem}$ is the failure stress of the impact-damaged laminate without including the structural effect of the spars
- $C_1 = 0.547(E_X/E_L)^{0.524}$ is a parameter depending on the lay-up
- $C_2 = 3.707$ is the full penetration stress concentration parameter
- $C_3 = 0.499/t^{0.5056}$ is the laminate thickness parameter
- $C_4 C_5 = A(k\ E)^B$ material toughness and the impact energy
- $C_6 = C_1 C_2 C_3 W_e (Ak)^B$

$$\sigma_{1,elem} = \sigma_0/[1 + C_6 E^B]$$

Model for Impacts (from DOT/FAA/AR-97/79)

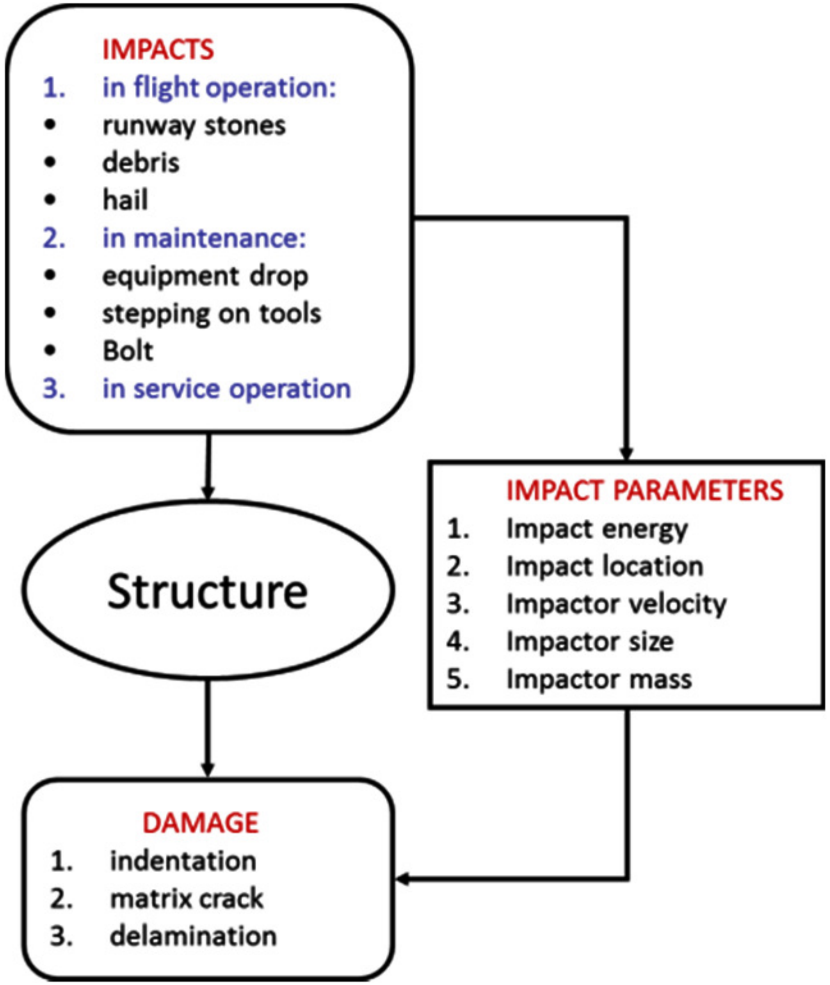
Impacts on composite laminates in aircrafts wings may occur:

- in flight operations
- during maintenance
- during in-service operation at ground

More frequent consequences of low velocity impacts are:

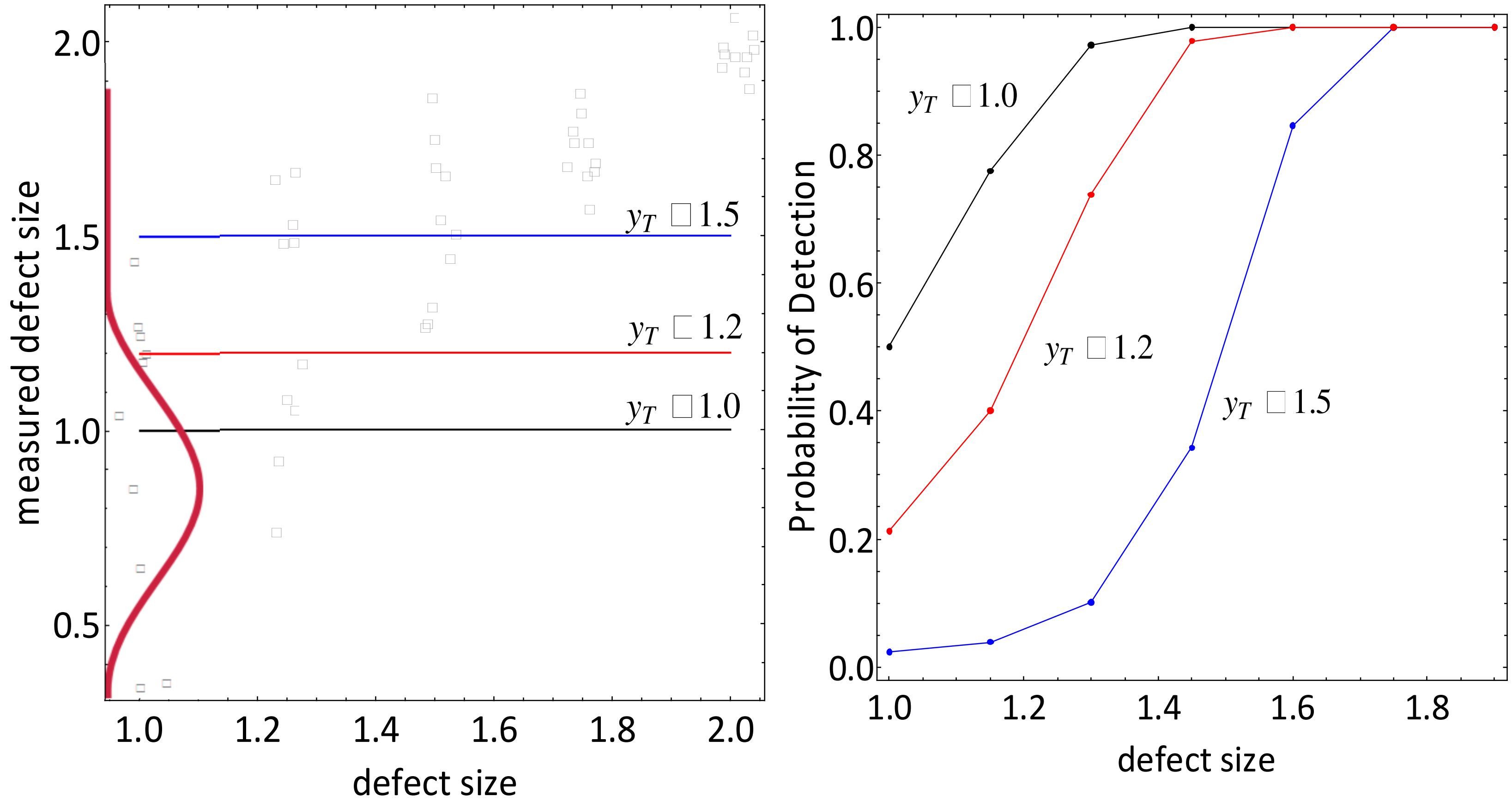
- indentation, matrix crack or delamination and these can cause a decrement of loading capacity of the laminate.

Barely Visible Impact Damage (BVID) can lead to failure



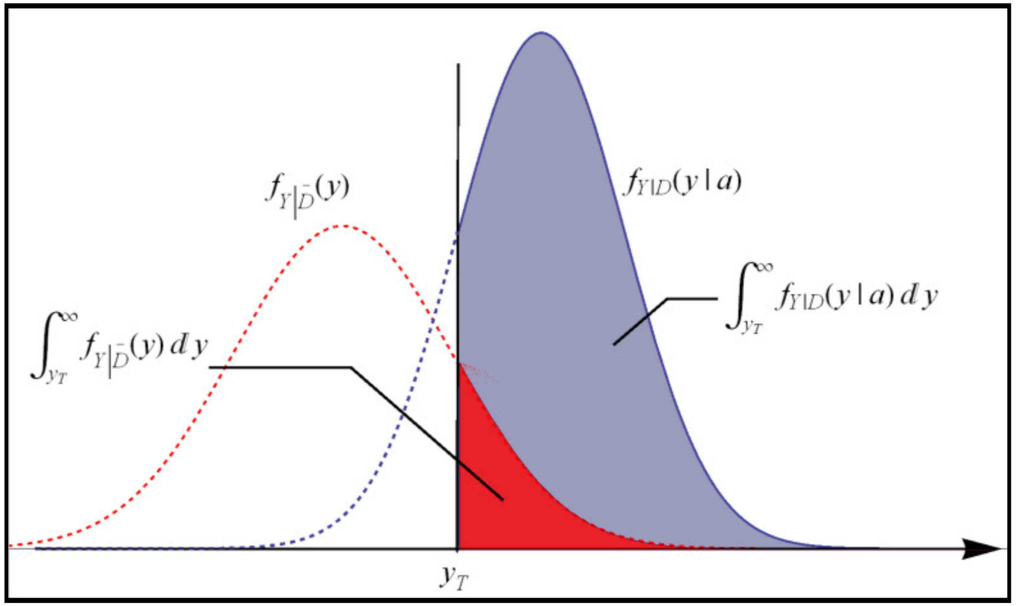
Receving Operating Characteristic (ROC)

Two competing aspects: POD and PFA



ROC and SHM

Definition of POD and PFA



$$\mathrm{PoD}(y_T, a) = \int f_{Y|D}(y|a)dy$$

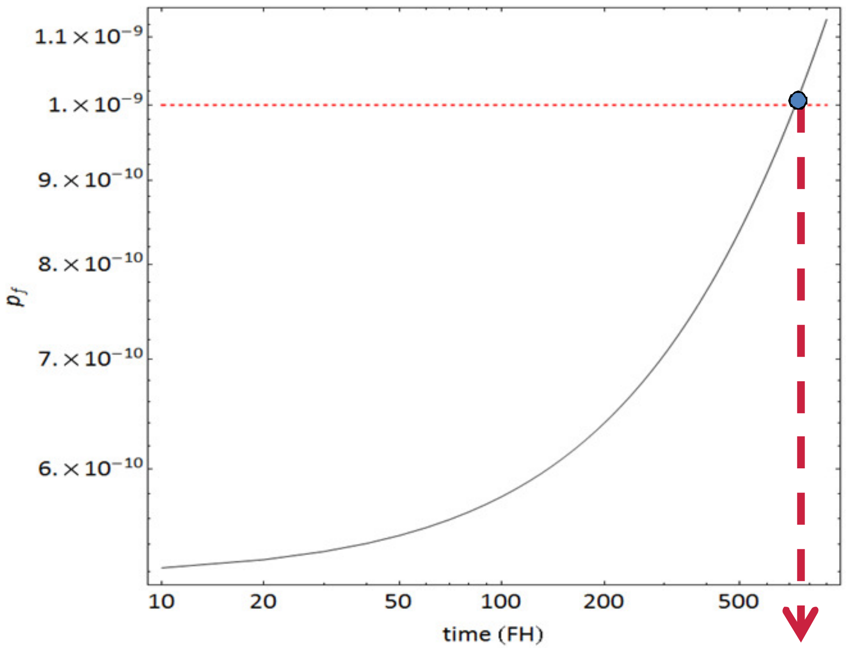
$$\mathrm{PFA}(y_T) = \int_{y_T}^{\infty} f_{Y|\bar{D}}(y)dy$$

Uncertainty in SHM:

- random noise that affects the SHM signal;
- statistical uncertainty due to the limited set of trials in the experiments;
- model uncertainty coming from the empirical nature of the parametric model;
- model uncertainty coming from omitting all possible influencing factors other than defect dimension.

Optimal Inspection Planning without SHM

Aim: optimal interval of time ΔT^{in}, such that the probability of failure of the wing component does not exceed the threshold $p_T = 10^{-9}$ per flight hour (FH).



ΔT^{in}= 700 FH

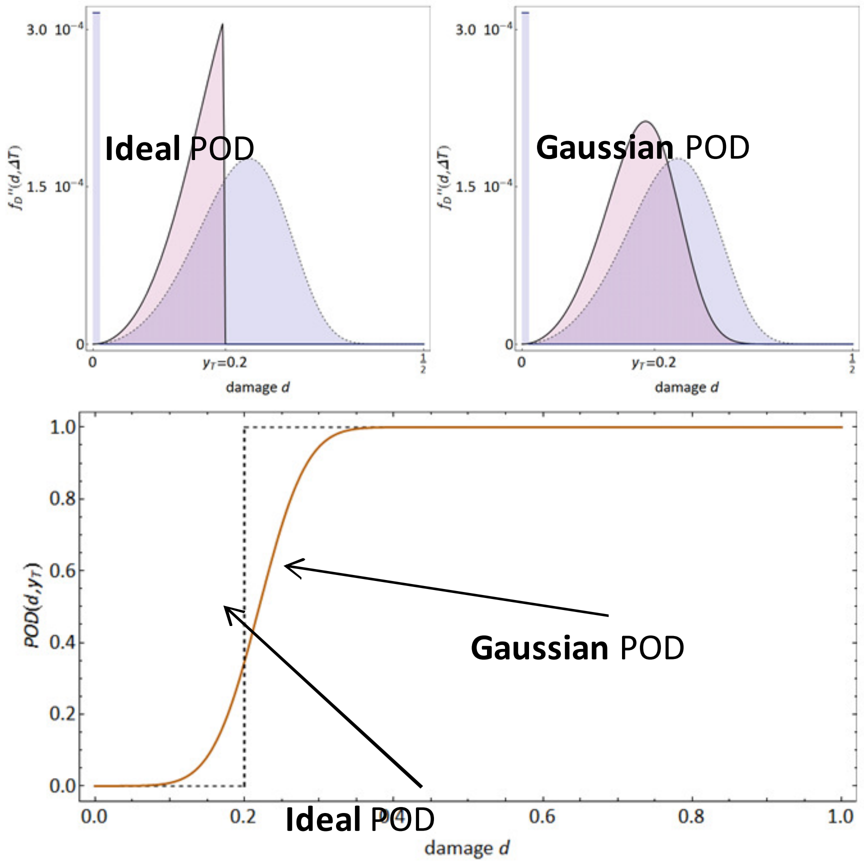
Optimal Inspection Planning with SHM

Strategy:

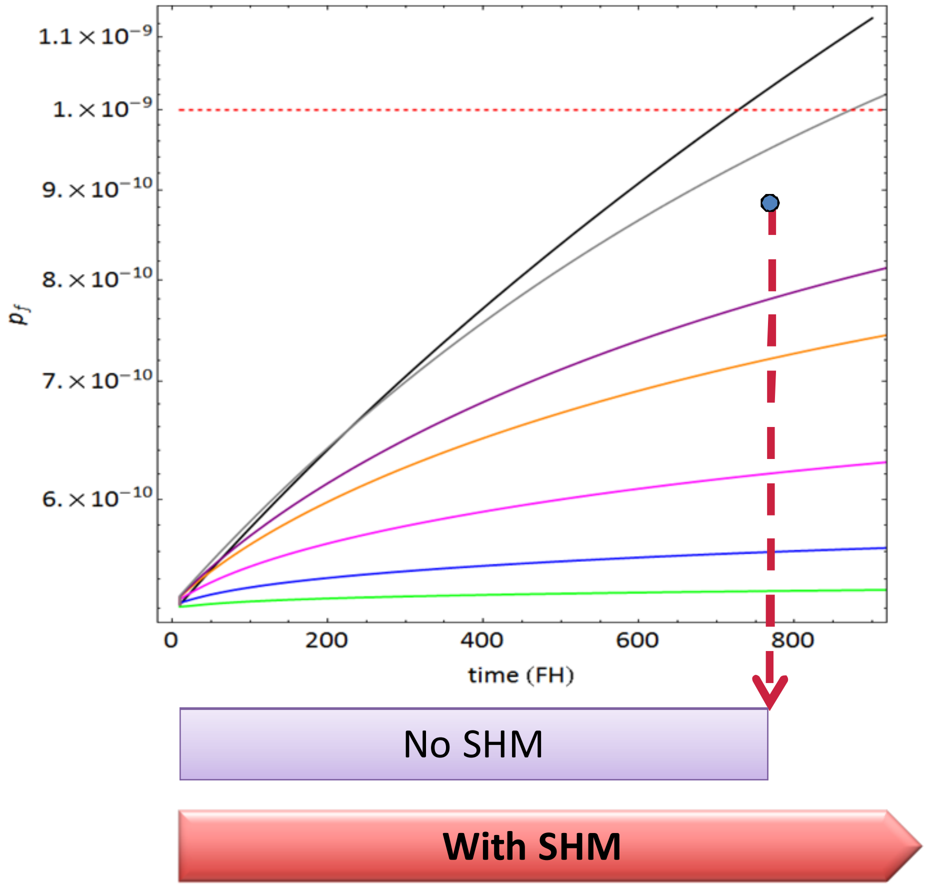
I. the monitoring is activated at constant intervals of time ΔT in terms of flight hours;

II. a fixed value of the monitoring identification ability, y_T, is considered for the whole time window $[0, T^{in}]$, i.e. degradation of the monitoring capability is not included

III. the probability of failure is evaluated until the level of p_T is reached, and correspondently the optimal T^{in} is found.

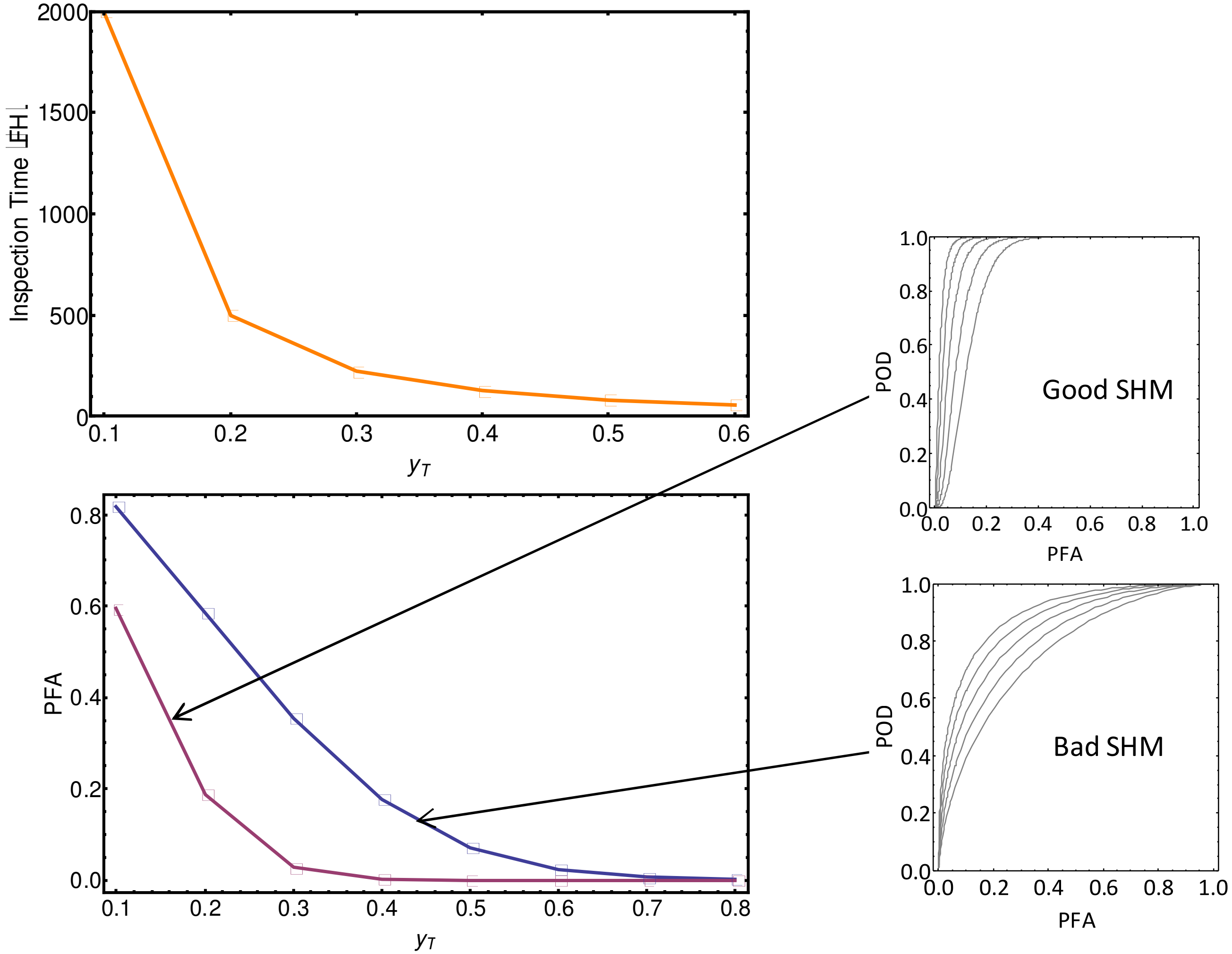


Optimal Inspection Planning with SHM

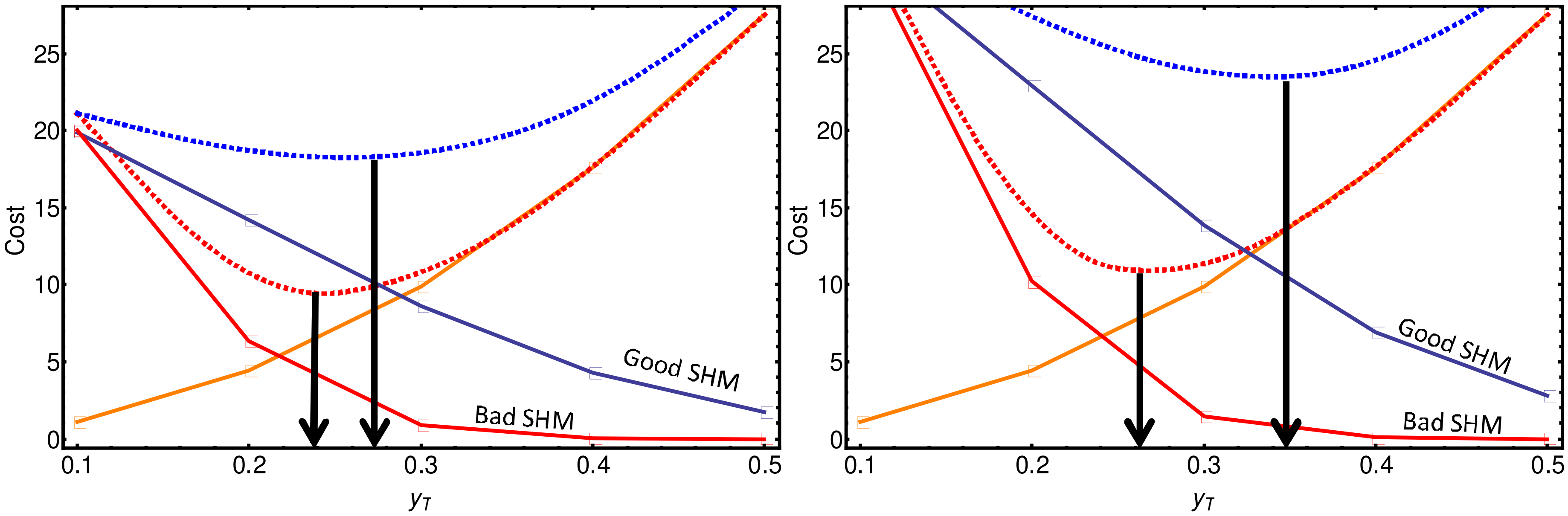


From above: no SHM (black line), SHM with $y_T = 0.5; 0.4; 0.38; 0.34; 0.30; 0.26$

Optimization for Inspection Planning with SHM



Cost optimization for Inspection Planning with SHM



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Summary

- A reliable SHM methodology for impact and damage detection was developed for a composited stiffened panel.
- PoD 95% with detectability radius of 25mm
- ToF not reliable for stiffened panel
- Developed PBDIM was able to detect damage in stiffened panel
- A theoretical framework for the optimisation of the replacement strategy for aircraft structural component subjected to reliability constraint has been developed

THANK **YOU** FOR YOUR ATTENTION

Un sistema aeronautico di Health Monitoring e prognostica

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