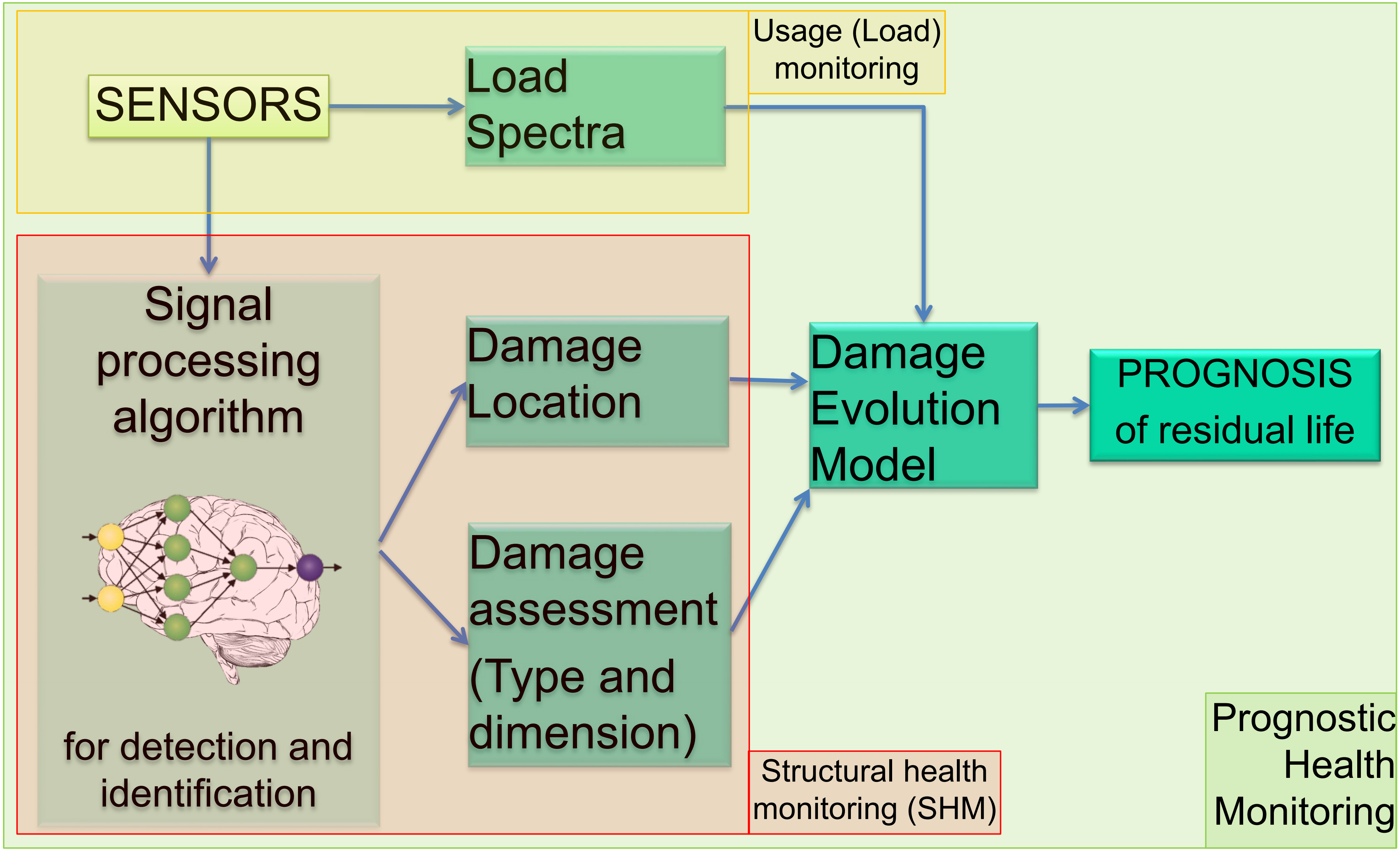
Introduction to SHM and prognosis

SIGMALAB

What to bring home (table of contents) ?

- Definition of the monitoring framework
- Design and maintenance criteria adaptation
- SHM and PHM definition as a multidisciplinary problem
- The hierarchical structure of diagnosis and prognosis
- The role of models
- SHM/PHM as a problem of statistical pattern recognition
- EXAMPLES

The monitoring framework



Final objective:
Automated Residual Useful Life (RUL) estimation of the system

Why?
Mainly, to optimize the maintenance (cost reduction)

Applied to which systems? Systems, that are:
- Critical for the safety
- Critical for the operations

Cost is a critical discriminant

What DAMAGE is in the SHM framework?

- Damage is defined as changes to the material and/or geometric properties of a structural or mechanical system, including changes to the boundary conditions and system connectivity, that adversely affect current or future performance of that system.
- Implicit in this definition of damage is a comparison between two different states of the system.

Examples:
– crack in mechanical part (stiffness change)
– scour of bridge pier (boundary condition change)
– loss of tire balancing weight (mass change)
– loosening of bolted joint (connectivity change)

Examples of structural damages (focus on mechanical & aerospace components)

- Fatigue cracking, particularly in joints at countersunk hole edges
- Corrosion, particularly inside joints and closed compartments
- Paint damage as an impact event signal
- Debonding, due to corrosion in joints
- Harsh landing damage
- Impact damages in composite materials
- Manufacturing damages in composite materials
- Debonding in stiffened composite panels

How to deal with damage?

- All materials used in engineering systems have some inherent initial flaws.
- Under environmental and operational loading flaws will grow and coalesce to produce component level failure.
- Further loading causes system-level failure.

Safe-life: damage will never occur

Flaw tolerant: flaws will never propagate

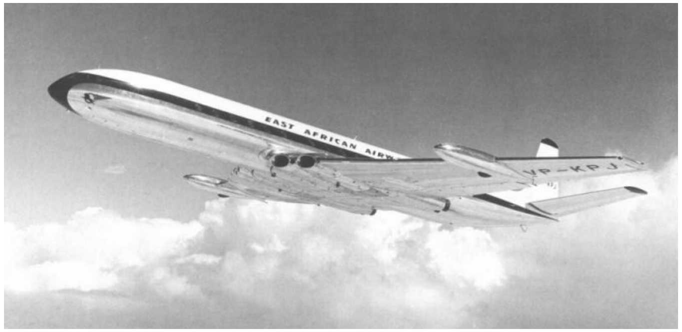
Damage tolerant: probably damage will occur but I'm ready to deal with it

- Fail safe
- Slow crack growth

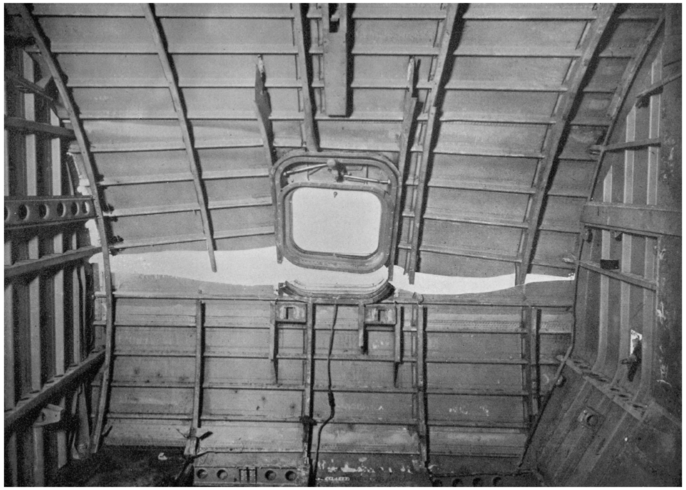
Maintenance costs drive research on SHM/PHM

Wrong design can lead to failure

The COMET (de Havilland Aircraft Company) was the first jet-propelled airliner (1950s).



The major impact on studies about fatigue of aircraft structures came in January 1954 after the fatal accident of the DeHavilland Comet aircraft, operated by British Overseas Airways Corporation, causing 35 victims. **Crack propagation started at the edge of a window**, though the same structure had been successfully tested on laboratory, where its fatigue resistance was largely overestimated.



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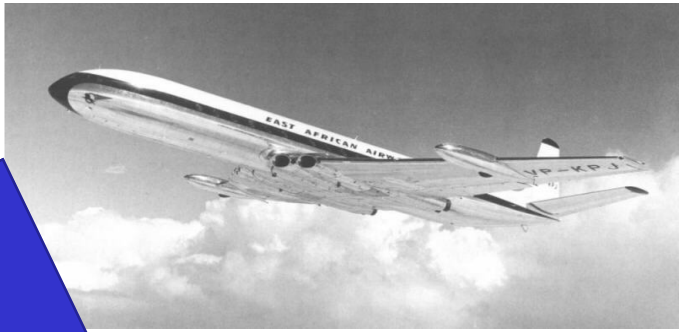

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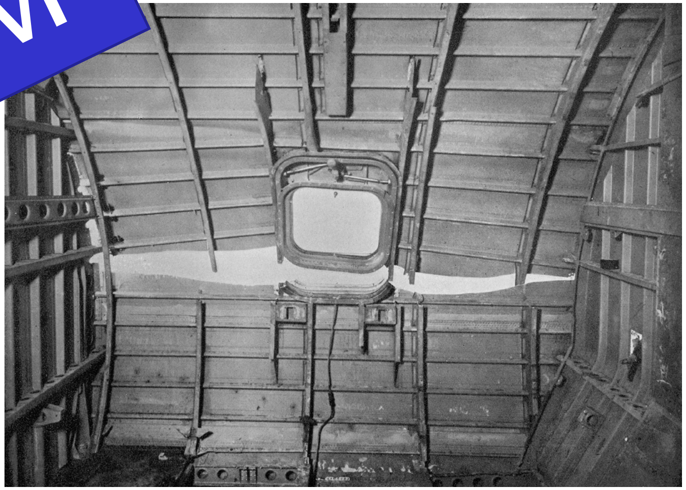

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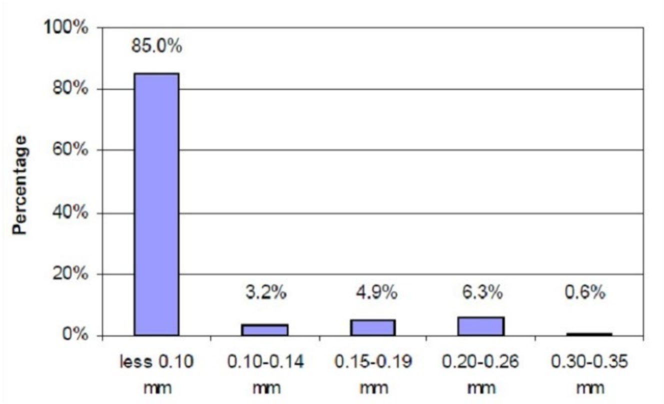
FLAW TOLERANT

- **Flaws are present also in brand new components** because of material non-uniformities causing unexpected premature crack growing.
- This aspect has to be taken into account especially if a safe-life is expected, thus coming to the concept of **flaw tolerant safe-life**.

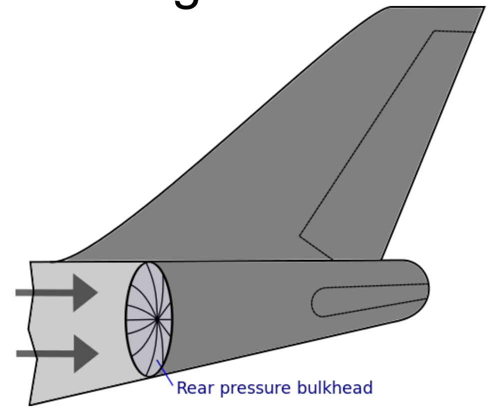
- Capability of flawed structure to **sustain the spectrum of operating loads** expected during the operative life of a component/structure or during an established replacement time, **without measurable flaw growth.**
- United State Air Force specified the requirements for initial damage sizes in MIL-A-83444.



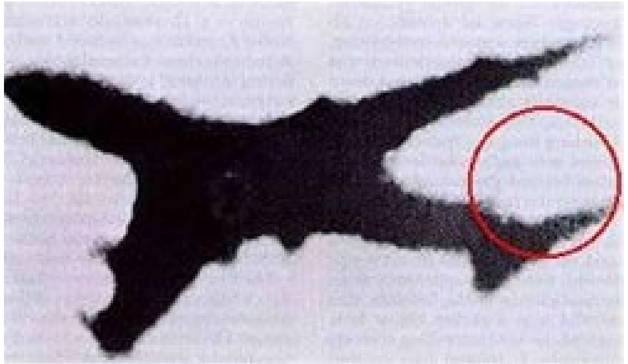
Example data for some critical helicopter components

Improper design can lead to failure

In 1985 an 11 years old **Boing 747SR-46** operated by Japan Airlines crashed due to rupture of the aft pressure bulkhead and the subsequent ruptures of a part of the fuselage tail, vertical fin and hydraulic flight control systems, resulting in 520 fatalities out of 524 occupants.



- F**atigue cracks propagating at the spliced portion of the bulkhead's webs**, thus making it unable to endure the cabin pressure in flight.
- Due to **improper repairs** of the bulkhead conducted **in 1978**, after a **harsh landing condition**.
- Fatigue **cracks not found in the later maintenance inspection** is contributive to their propagation to failure.



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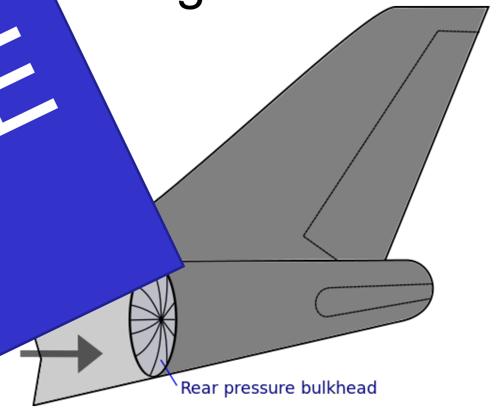
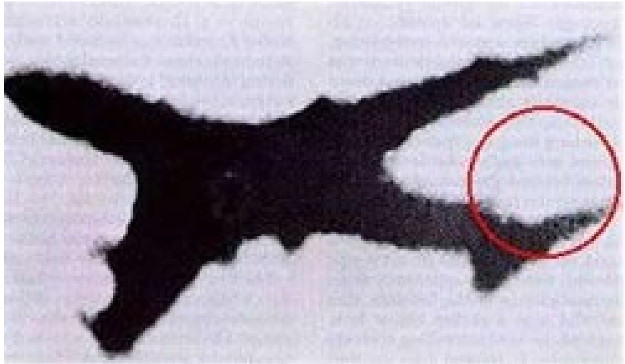
DESIGN & MAINTENANCE PROBLEM

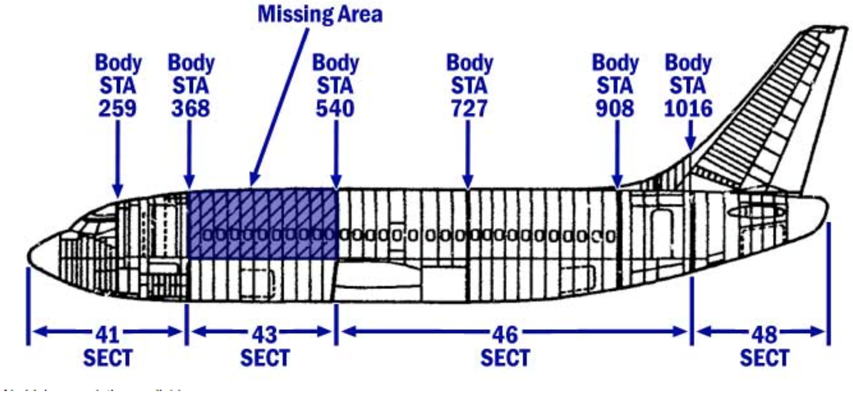




Damage tolerant design…BUT

Aloha airlines, 1988

A 19 years old Boing 737-297 successfully landed at Honolulu International Airport after the complete separation of the fuselage upper lobe, only 1 fatality.



The maintenance program failed to detect the presence of significant de-bonding and fatigue damage, which ultimately led to failure of the lap joint connecting the upper lobe of the fuselage.

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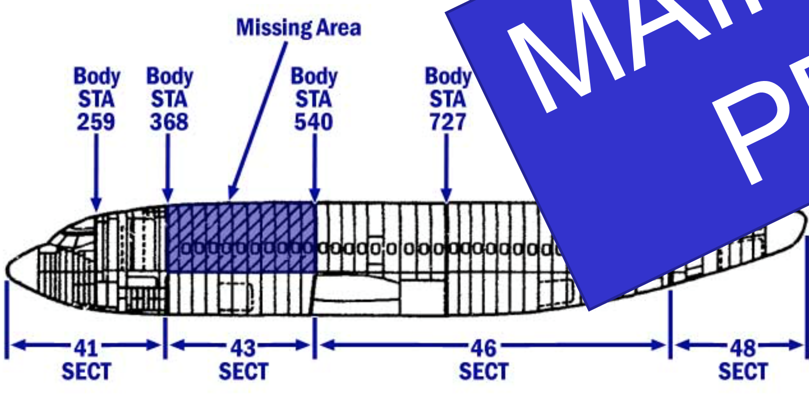

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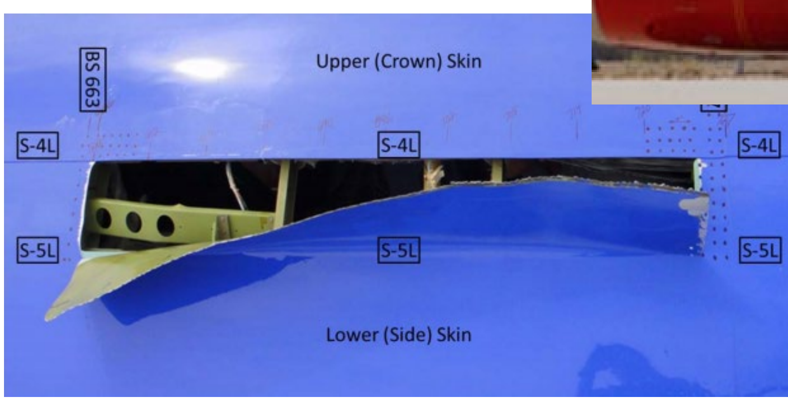
Southwest 2009

Fail-safe example:
Some components fail and the load is passed through adjacent components



- Depressurization
- No fatalities

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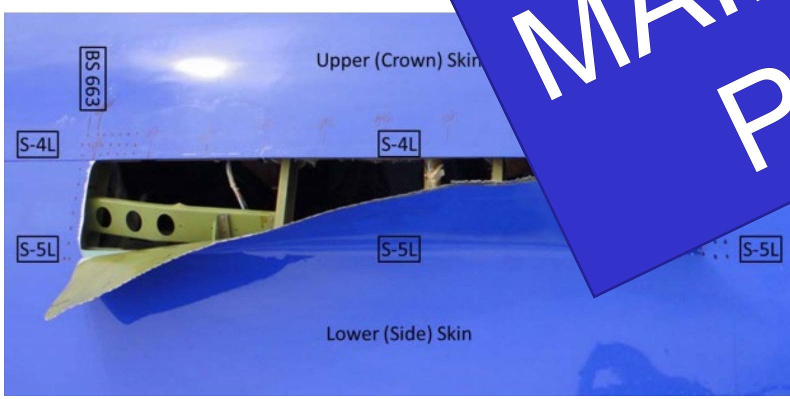

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- No fatalities

Today, design and maintenance work appropriately…BUT

Airbus A380

JAN. 19, 2012

PARIS — Airbus confirmed Thursday that new cracks had been found in the wing ribs of a small number of its twin-deck A380 planes, a discovery that industry officials said would most likely prompt European safety regulators to order mandatory inspections across the superjumbo fleet as a precaution.

Less than two weeks ago, tiny cracks were found in a different part of the same wing component of five A380s, including planes flown by Qantas Airways and Singapore Airlines.

The problems are viewed by the European Aviation Safety Agency as significant enough to merit closer inspection of a large number of the 68 A380s in service with seven airlines, said the industry officials, who requested anonymity because the regulators' recommendations were not expected to be made public until Friday.

The European Aviation Safety Agency (EASA) issued an airworthiness directive requiring inspections and possibly modifications to the Airbus A380, stating that cracks discovered during fatigue testing could "reduce the structural integrity of the wing."

Earlier in 2012, the EASA mandated inspections for cracks in wing-rib feet for the entire A380 fleet. This action caused Airbus to arrange both retrofits and production modifications. The manufacturer estimated the total cost of modifications to be €260 million ($340 million).

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Cracks on BOING 737

Crepe negli aerei, a terra 50 Boeing 737. Anche Ryanair ferma tre jet

Nuovi guai per il costruttore Usa dopo i due incidenti che hanno bloccato i voli del nuovo Boeing 737 Max. A seguito dei controlli chiesti dalla Faa, 50 velivoli della vecchia versione del 737ng sono stati fermati per il rilevamento di crepe all'attacco tra ali e fusoliera

The problems began a month ago when the US Federal Aviation Administration ordered a thorough inspection of all aircraft with more than 30 thousand flight hours, after some airlines had identified cracks of the structure at the height of the connection between the wings and the fuselage.

After four weeks of investigations, the companies that have this model in their fleet stopped 50 aircraft (5% of those examined) and sent them for maintenance to repair the cracks.

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Evolution of maintenance approaches

CORRECTIVE maintenance (fault driven) — ↓ Cost ↑ Risk

Performed after a failure and aimed at returning a the component to the state in which it can perform the required function

PREVENTIVE maintenance — ↑ Cost ↓ Risk

- Scheduled maintenance
- Condition-based maintenance
- Predictive maintenance

PROACTIVE maintenance

Includes activities that avoid the underlying conditions that lead to machine faults and degradation

Focus on PREVENTIVE maintenance

Scheduled: periodic preventive maintenance based on predetermined cycles of usage; it is a type of scheduled maintenance, i.e. performed in accordance with an established time plan, in which the time plan is expressed according to the most appropriate cycles of usage (operating times, kilometers, strokes, etc.).

> Defined during design

On condition: preventive maintenance subject to the achievement of a predetermined limit value.

> Needs for a usage/load monitoring

Predictive: preventive maintenance carried out following the identification and measurement of one or more parameters and the extrapolation according to the appropriate models of the time remaining before the failure.

> Needs for SHM/PHM tools

What SHM is in this framework?

"The process of implementing a damage detection and characterization strategy for engineering structures"

SHM Involves:

- Health monitoring
- Operational Evaluation
- Data Feature Extraction
- Statistical Models Development

"prognostic approach to monitor the ability of structures, systems and components to withstand loads over the planned service lifespan"

PHM adds:

- Material characterisation
- Damage mechanics
- Load monitoring (structural, thermal, etc.)
- Statistical residual life estimation and risk assessment

The SHM-PHM structure

Source: Introduction to Structural Health Monitoring, Charles R. Farrar, Los Alamos Dynamics - Structural Dynamics and Mechanical Vibration Consultants

Operational evaluation

Defines the damage to be detected and begins to answer questions regarding implementation issues for a structural health monitoring system.

Data acquisition & networking

Defines the sensing hardware and the data to be used in the feature extraction process.

Feature selection & extraction

The process of identifying damage-related information from measured data.

Probabilistic diagnosis and prognosis

Using statistical models to transform features into actual decisions, both for diagnosis and prognosis

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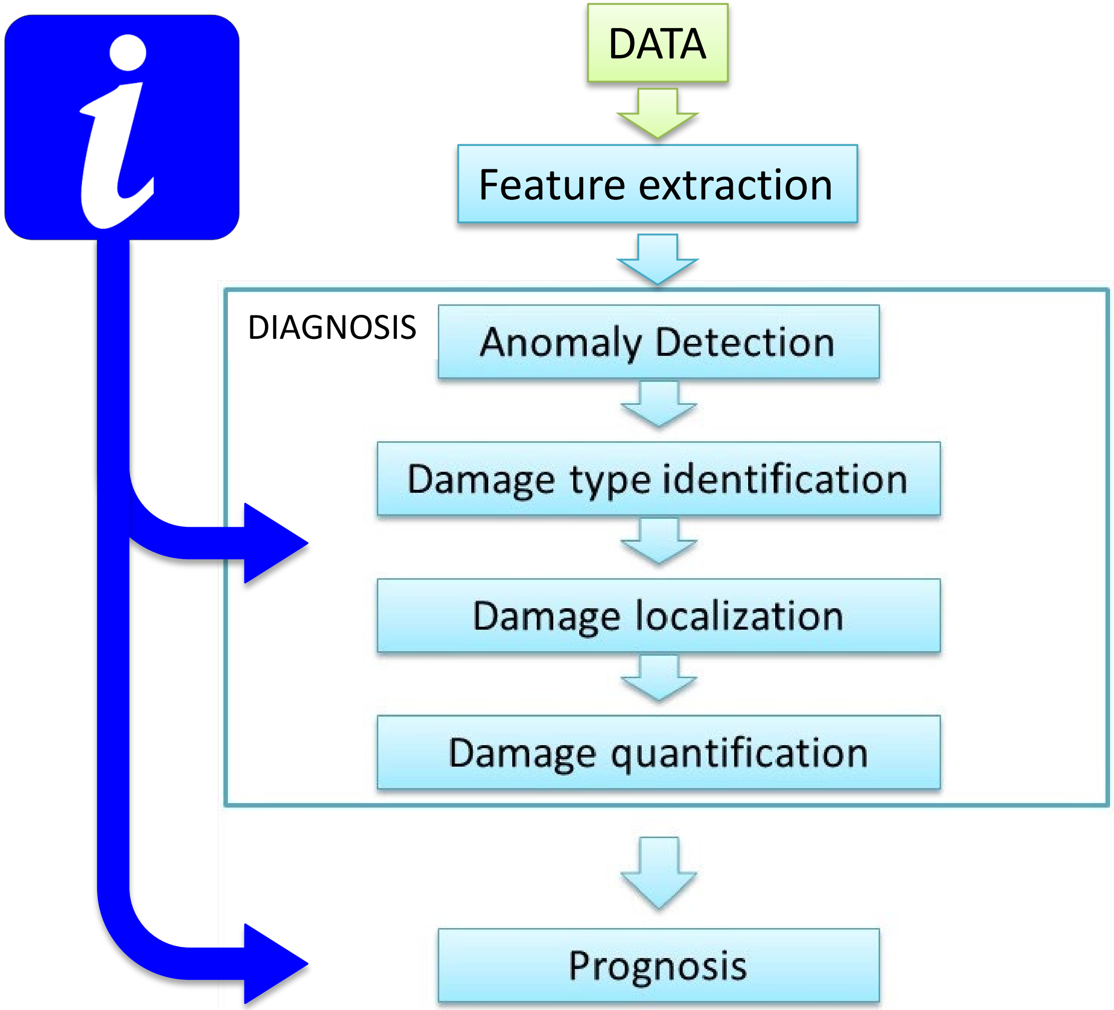
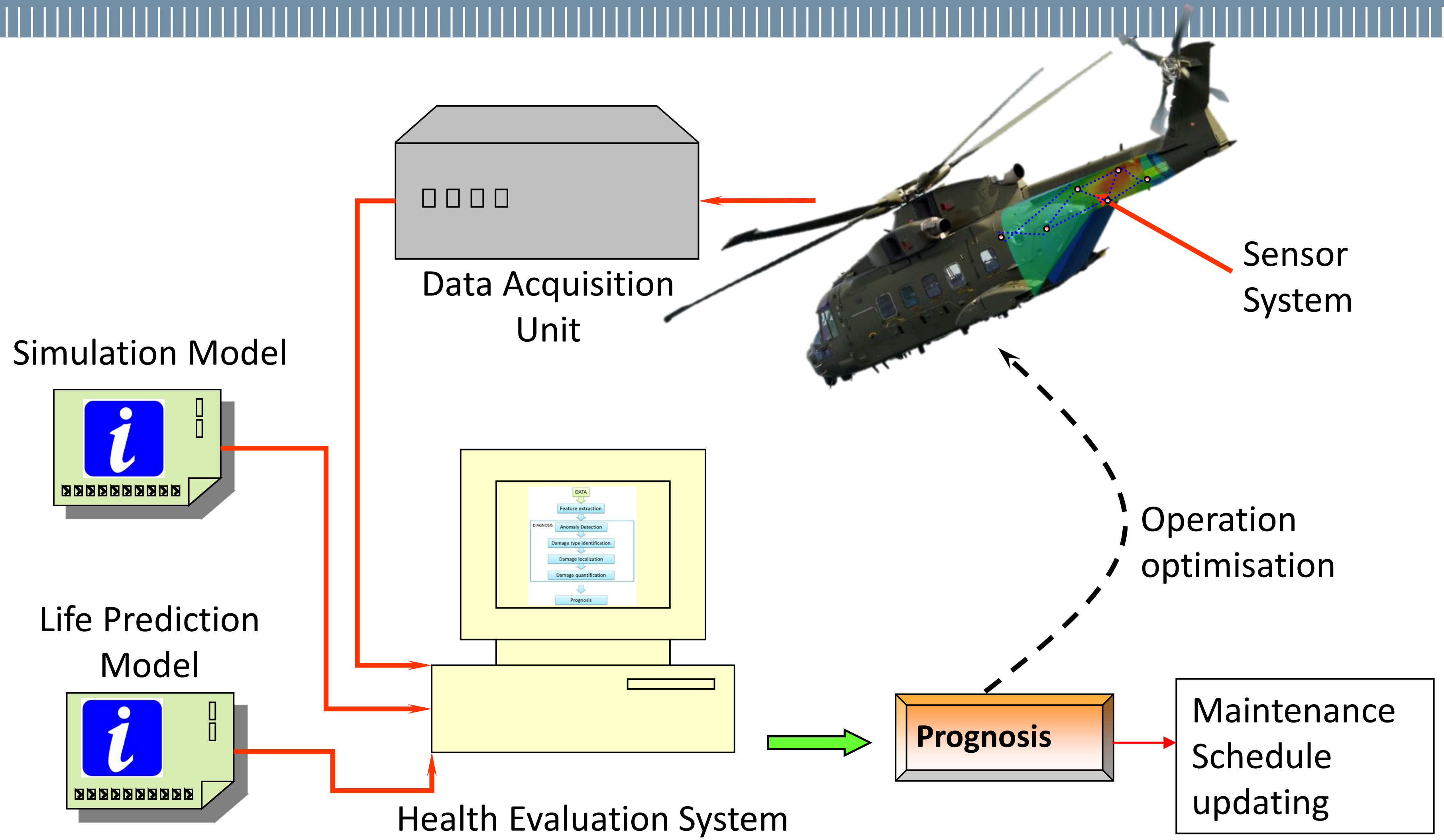
DIAGNOSIS AND PROGNOSIS
The hierarchical structure

A. Rytter. Vibration Based Inspection of Civil Engineering Structures. Ph. D. dissertation. Department of Building Technology and Structural Engineering, Aalborg University, Denmark, 1993. pp. 193.

- After data normalisation and feature extraction, **damage identification and prognosis** is structured into 5 levels of increasing complexity.
- Each level will benefit from information gained at previous level.
- Signal observations alone are not sufficient to solve the multiple levels
- **Additional information is needed at each level for interpreting the signals**

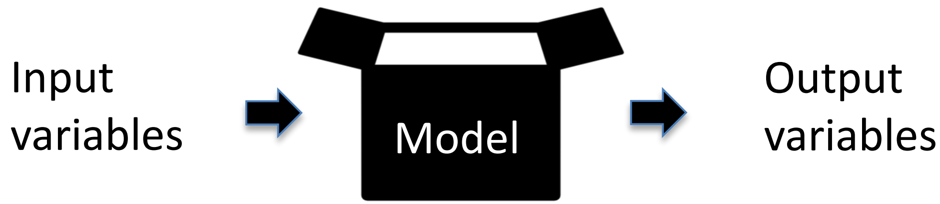


The role of MODELS



Types of MODELS

Models relate some input variables with some output variables



Models can be built based on data (DATA-BASED) (e.g. after data regression):

- ➢ Experimental data: too expensive for some SHM applications (the effect of any potential damage must be experimentally observed)
- ➢ Analytical/numerical data: experimental costs translates into computational costs (lower for many applications), but model uncertainty is an issue

Models can be built based on physical laws (PHYSICS-BASED):

- ➢ Pure physical models
- ➢ Semi-empirical models, where physics is taken into account but some parameters are tuned based on experiments

The course will show how these can be used for damage identification

DIRECT vs INVERSE modelling approach

Cause (force, damage, temperature, etc.) → **Direct way** → Effect (stress and strain fields, displacement, etc.)
For us, potential OBSERVATIONS

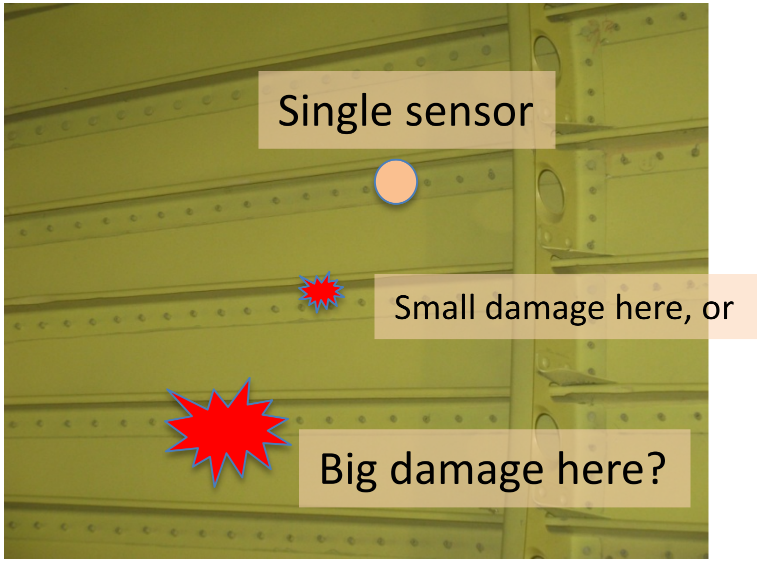
OBSERVATIONS, something we can measure → **Inverse way** → Cause (force, damage, temperature, etc.)

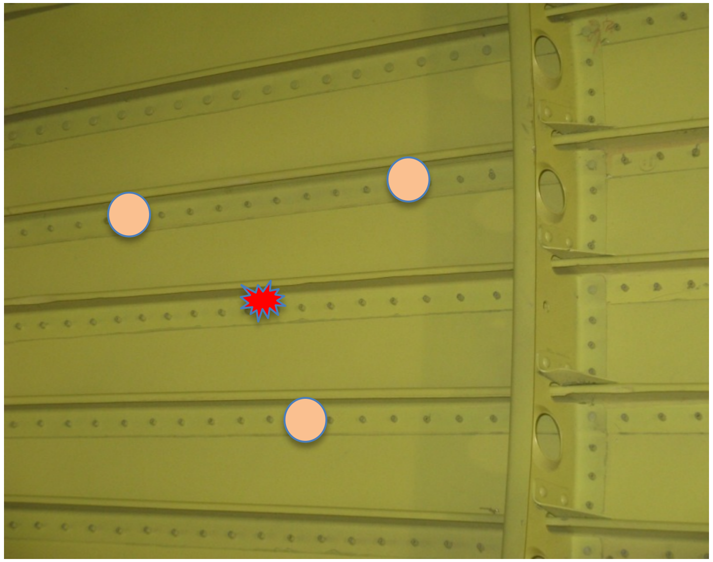
SHM/PHM involve solution of INVERSE problems, to associate the observed patterns with the causal factor → Keyword: PATTERN RECOGNITION

- Direct problems are typically well-posed
- Inverse problems can easily be ill-posed, manifesting as:
  - Multiple possible solutions for the same input observations
  - Wrong solution

→ Keyword: OBSERVABILITY

INVERSE methods: we need to guarantee observability





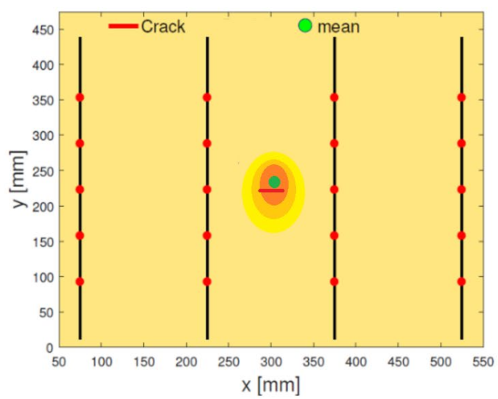
Multiple, and well positioned, sensors allow to clearly identify damage

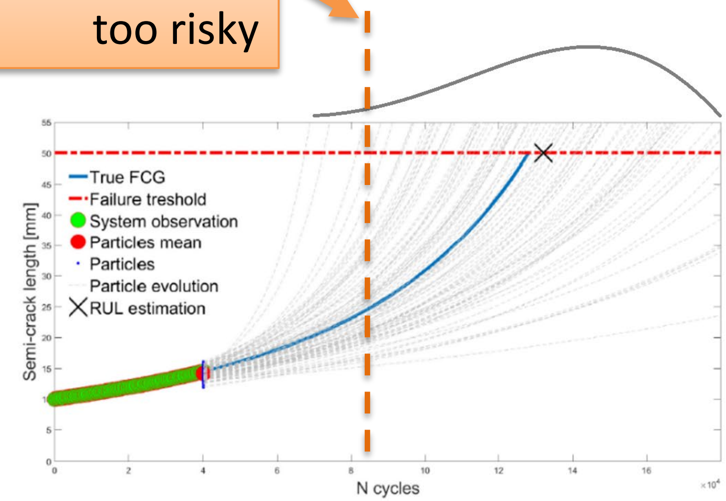
STATISTICAL pattern recognition

One additional challenge in SHM/PHM is the need to treat pattern recognition in a statistical way, by including:

- Model uncertainty
  - ✓ Model approximation uncertainty
  - ✓ Material uncertainty
  - ✓ Uncertainty related to confounding influences (load, temperature, etc.)
- Observation uncertainty

Not convenient to exceed this limit: too risky





STATISTICAL pattern recognition
Monte-Carlo sampling

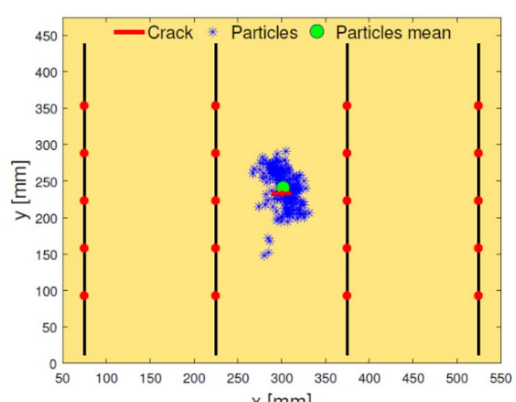
HOWEVER, it is not easy to combine the multiple uncertainties involved in a SHM/PHM problem.

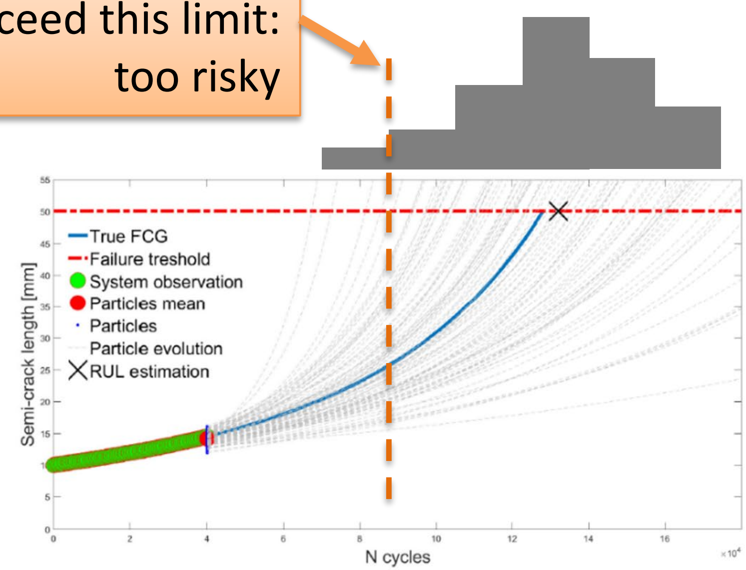
- Problems can be non-linear
- Uncertainties can be non-Gaussian

Closed-form solution for the probability density functions (PDF) of the desired variables do not exist for realistic problems.

An approximated solution can be obtained via Monte-Carlo Sampling

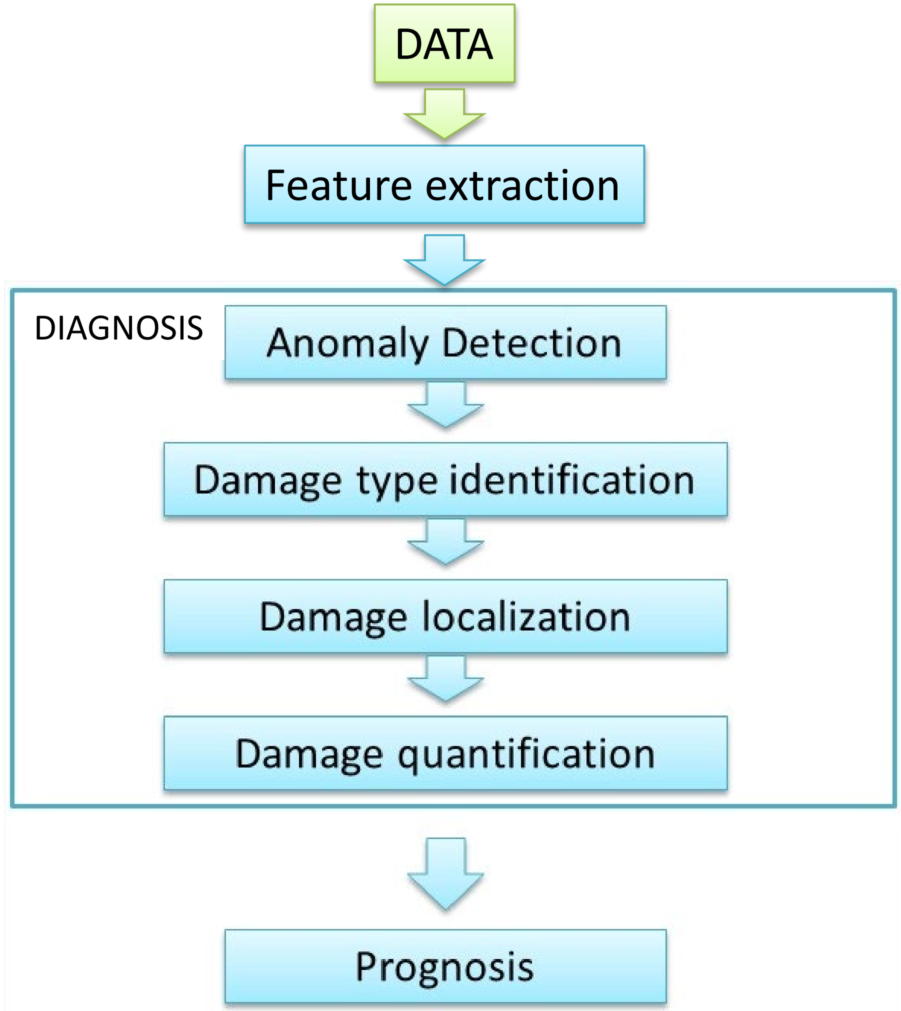
Not convenient to exceed this limit: too risky





Methods and Keywords

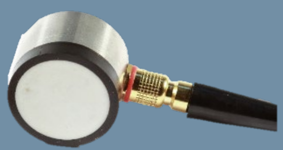
- Feature selection and extraction
- Methods for anomaly detection:
  - Outlier analysis (unsupervised)
  - Effect of environmental Influences
  - Support Vector Machine (supervised)
- Methods for damage assessment:
  - Artificial Neural Network (supervised)
  - Gaussian Processes (supervised)
- Monte-Carlo sampling theory, importance sampling
  - Metropolis-Hastings MCMC algorithm for parameter identification
  - Sequential Monte-Carlo sampling theory for damage identification and prognosis



EXAMPLES

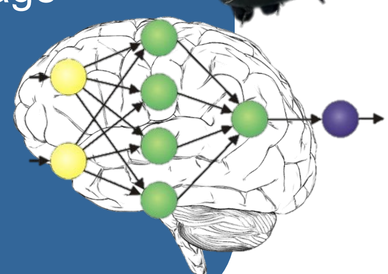
HUMS: model-based methodology

Sensors provide a signal dependent on **damage** that has to be interpreted.



Models provide **simulated signals** in presence of **damage** to be used as examples for real signal interpretation.

Signal processing tools combine numerical and sensor data to provide feature classification and damage diagnosis and prognosis.



WHAT A DIGITAL-TWIN CAN BE USED FOR?

See our vision…

Optimisation

Model to assist the SHM designer for sensor network optimisation

Identification

Example data to assist pattern recognition

Prognosis

Damage evolution models to predict material degradation

Decision-making

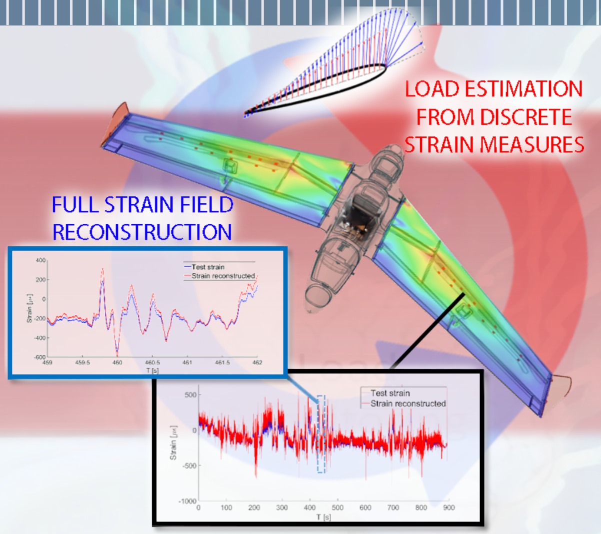
Modelling of the operative scenario to predict costs, risks and benefits of decisions and configurations

SAMAS

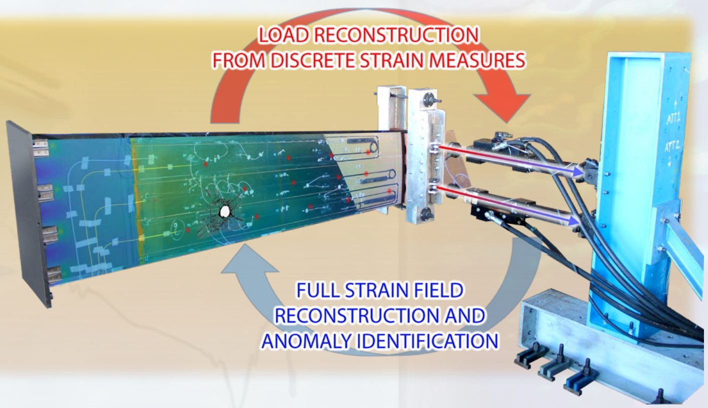
Application #1: Health and Usage Monitoring

Increasing complexity

2 Flight test experimental validation



1 On-ground experimental validation (load, strain, anomaly detection and localization)



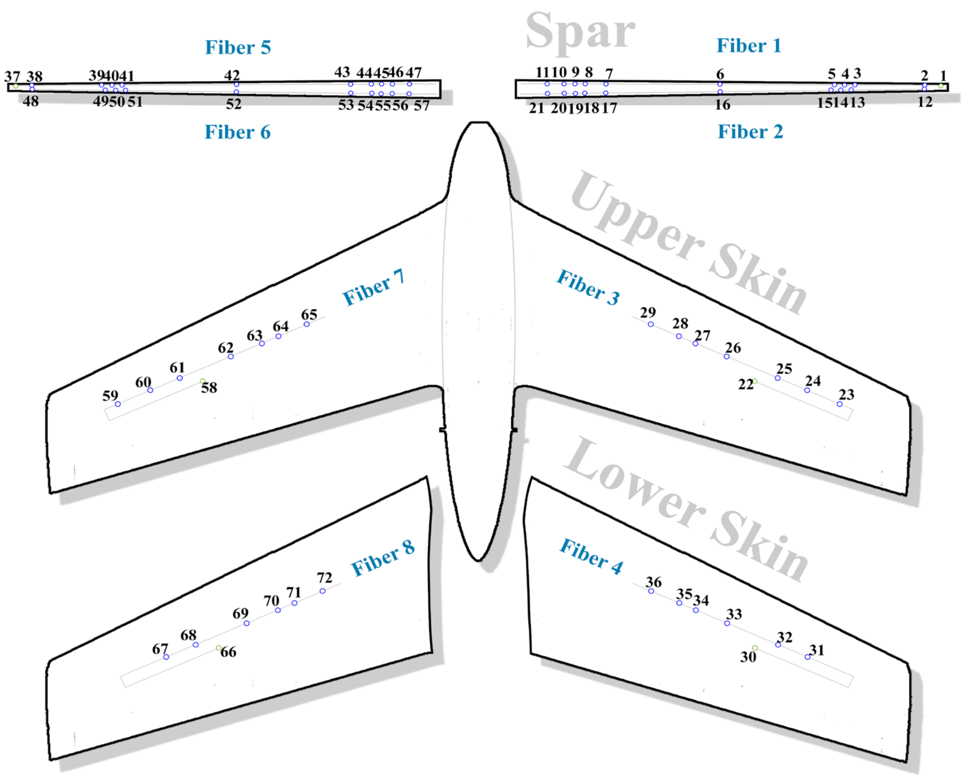
SAMAS
Application #1: Health and Usage Monitoring

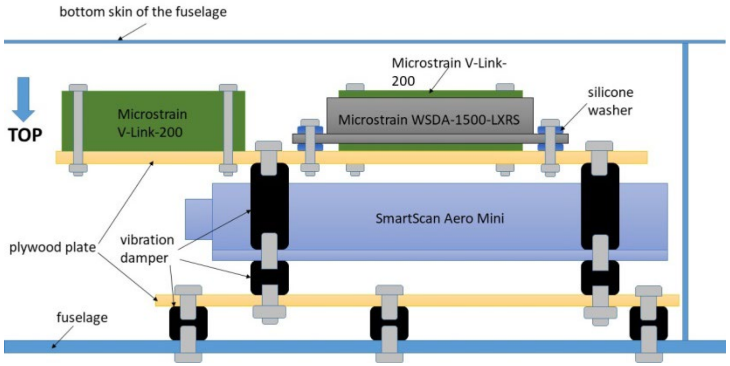
The Hornet

Plaftorm self weight	30.5 kg
Power unit, sensors, hardware	~ 3 kg
Wingspan	3.25 m
Length	1.7 m
Min. speed	75 km/h
Nominal speed	150 km/h
Max. speed	225 km/h

SAMAS

Application #1: Health and Usage Monitoring





System of load monitoring based on electrical sensors (strain gauges, MEMS accelerometers) and optical sensors

SAMAS

Application #1: Health and Usage Monitoring

INPUT: strain at few points

OUTPUT: loads and strains everywhere in real time

Ref.: Colombo, L., Sbarufatti, et. Al., Numerical and experimental verification of an inverse-direct approach for load and strain monitoring in aeronautical structures (2021) Structural Control and Health Monitoring, 28 (2), art. no. e2657.

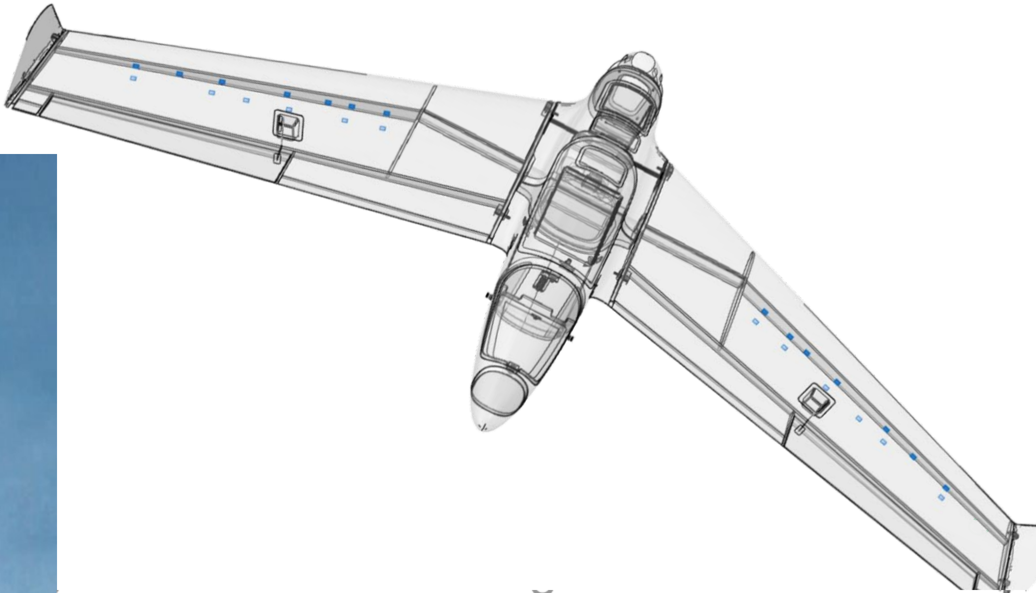
SAMAS

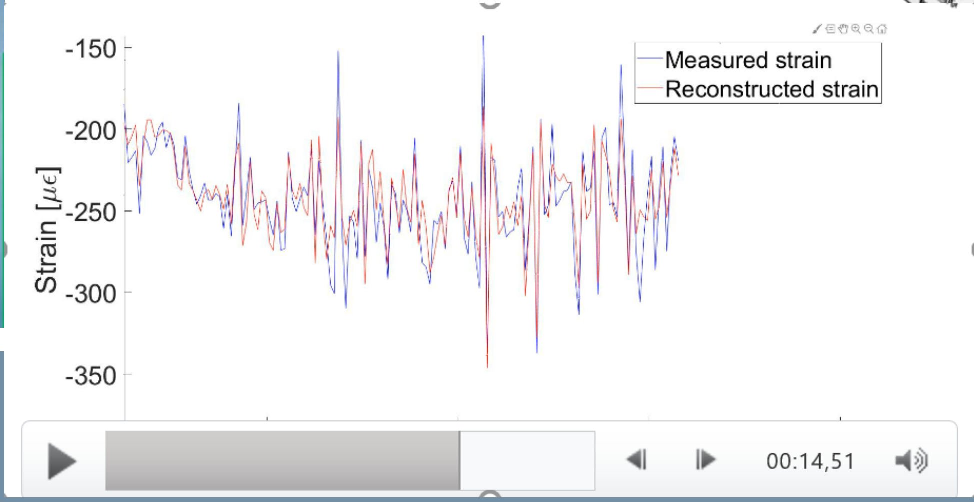
Application #1: Health and Usage Monitoring

INPUT: flight parameters and 1 strain gauge

OUTPUT: strain at virtual nodes

METHOD: Artificial Neural Network



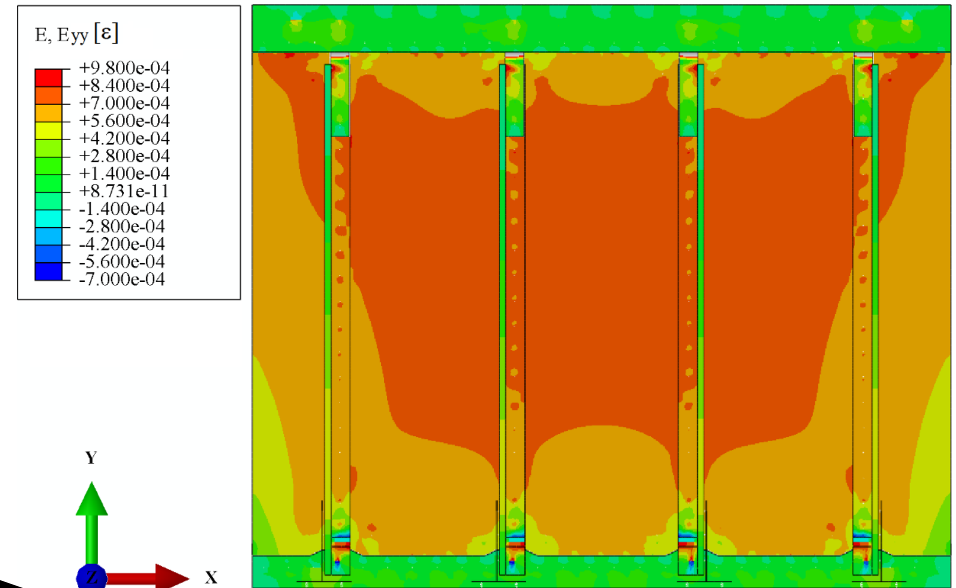


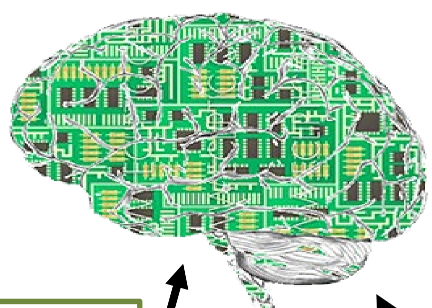
Structural Health and Usage Monitoring and prognosis:

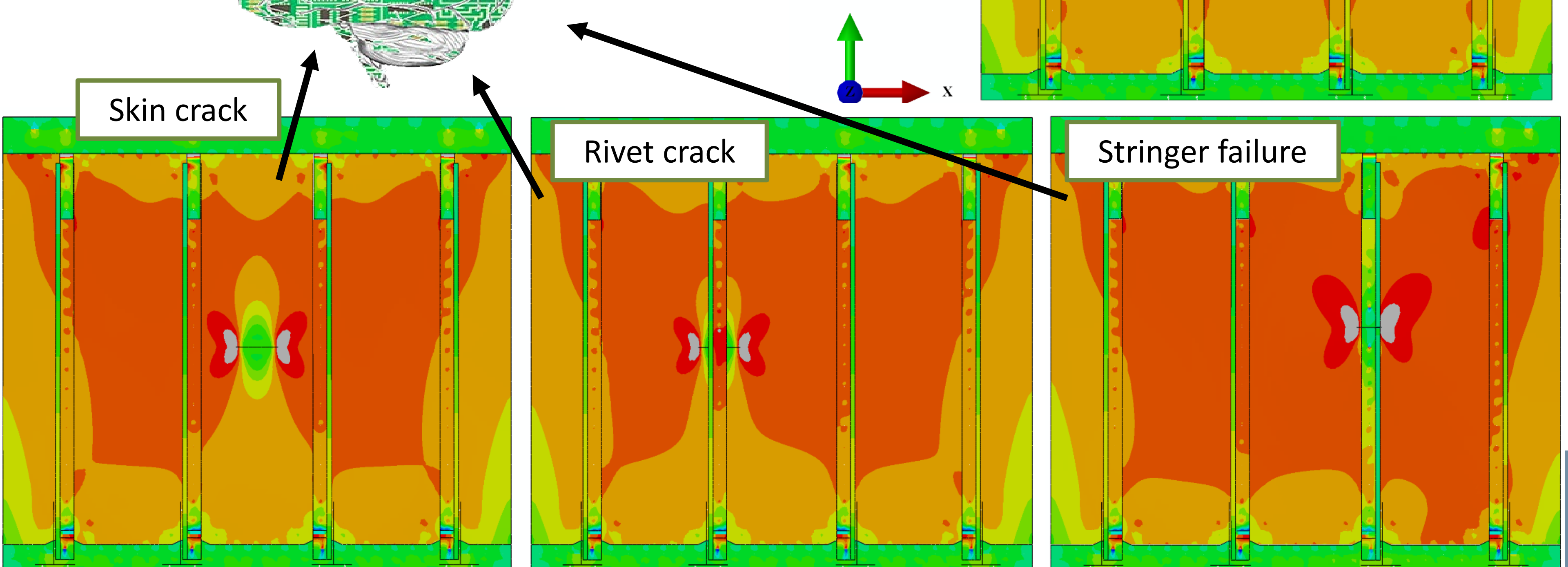
Different damages induce different strain field patterns

Numerical generated strain used to train an Artificial Neural network (ANN)

→ damage type, position, dimension





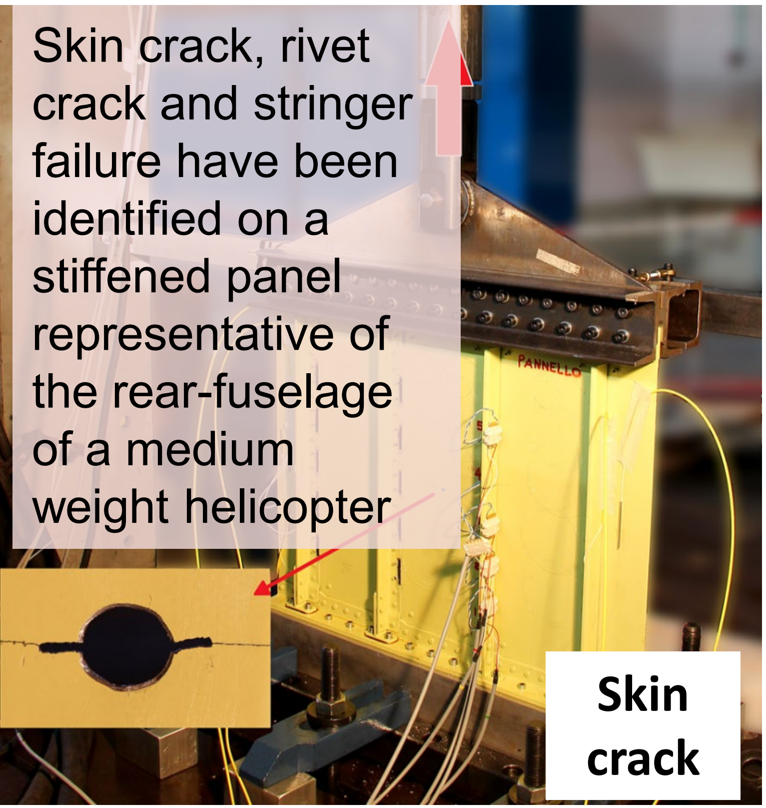


Structural Health and Usage Monitoring and prognosis:

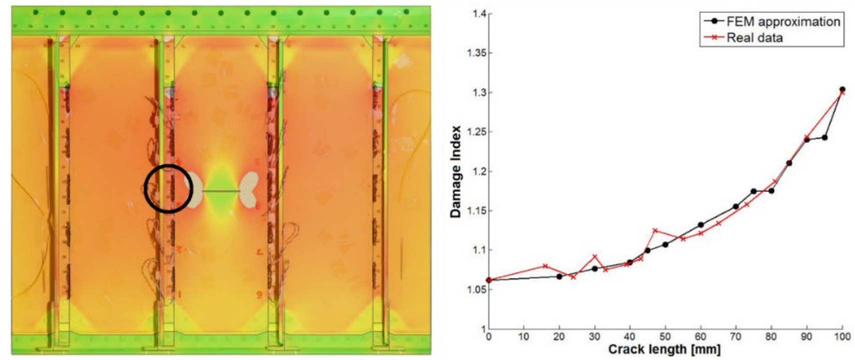
HECTOR - HElicopter fuselage Crack moniToring system and prognosis through on-board sensOR network

Diagnostic system based on strain field measures (FBGs) for damage identification, localisation and quantification

Skin crack, rivet crack and stringer failure have been identified on a stiffened panel representative of the rear-fuselage of a medium weight helicopter

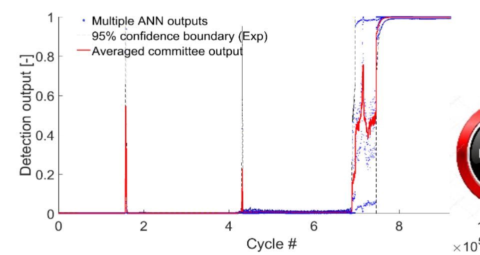


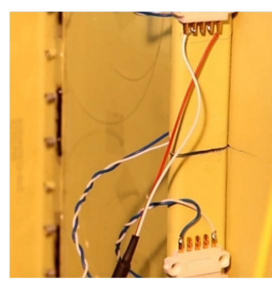
Skin crack



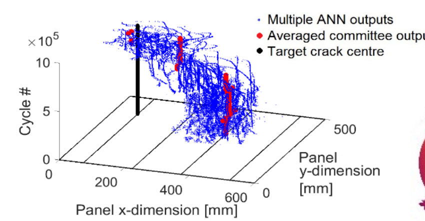
Numerical strains are used to train artificial neural networks for damage classification

Rivet crack

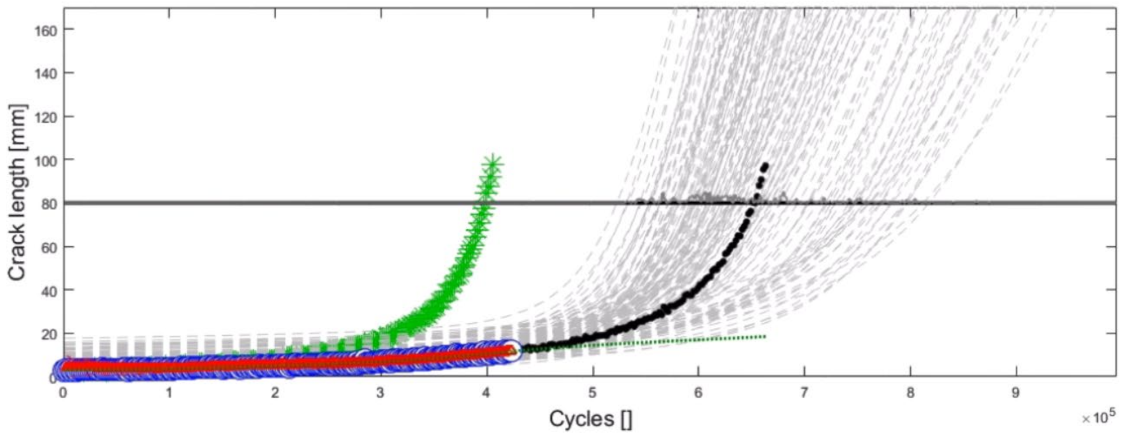




Stringer failure

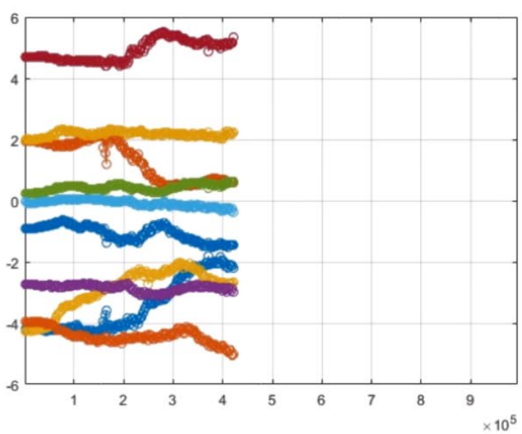


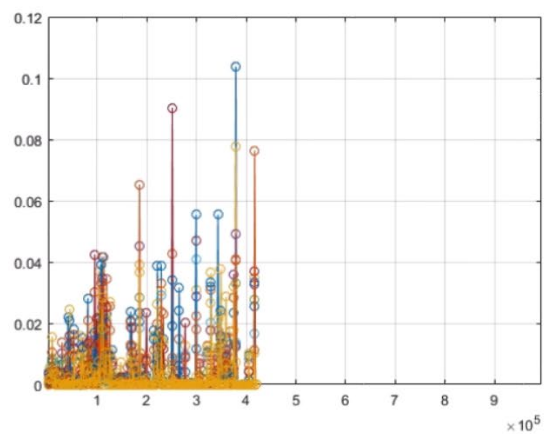
Example of prognostic results by Sequential MonteCarlo sampling

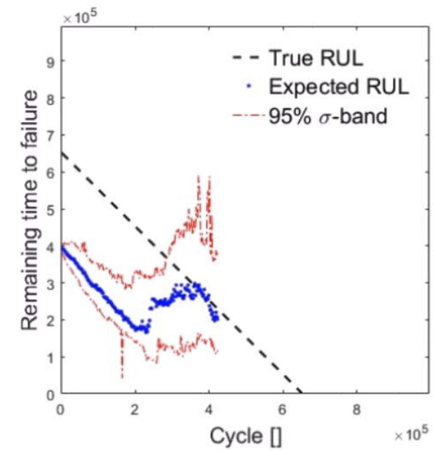


Self adaptive method:

adapts to damage degradation never seen during training







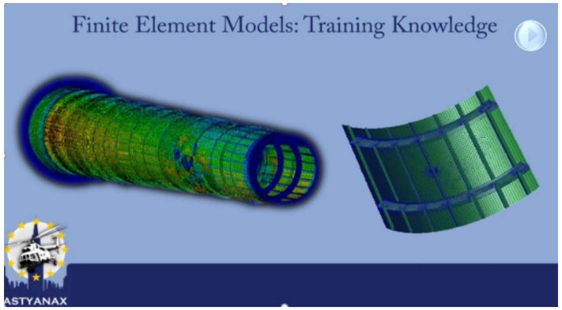
Structural Health and Usage Monitoring and prognosis:

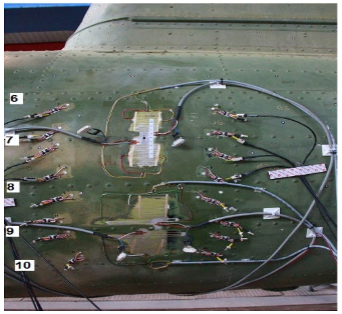
ASTYANAX - Aircraft fuSelage crack moniToring sYstem And progNosis through on-boArd eXpert sensor network

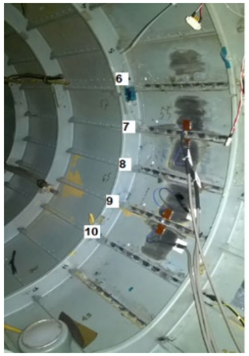
Harsh landing monitoring: Mil-Mi-17 Drop test execution

Repeated drops from different altitudes have been executed, **real-time processing** and **transmitting** data from a multitude of **sensors**, for real-time **harsh landing** assessment.

Fatigue crack monitoring: Full-Scale fatigue test of Mil-Mi-17 tail boom



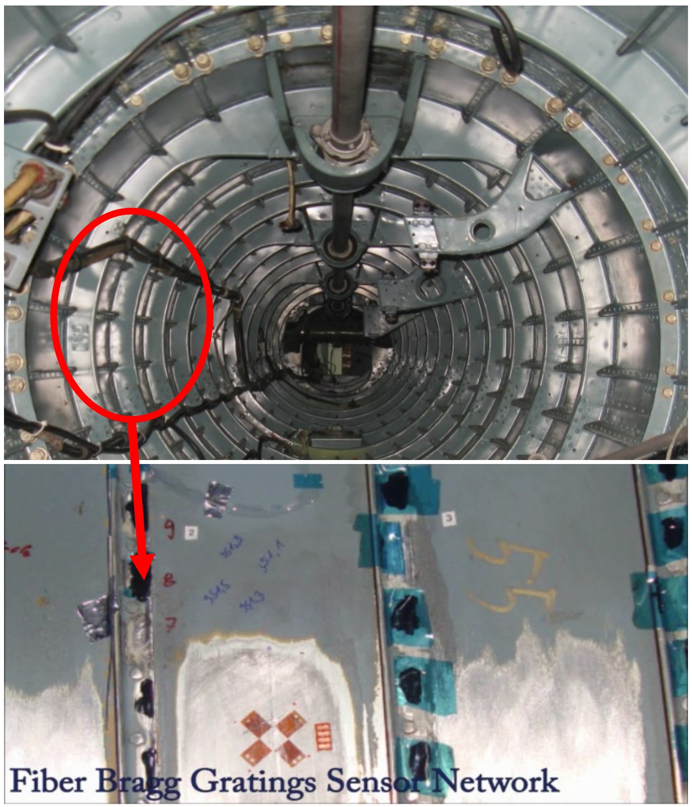




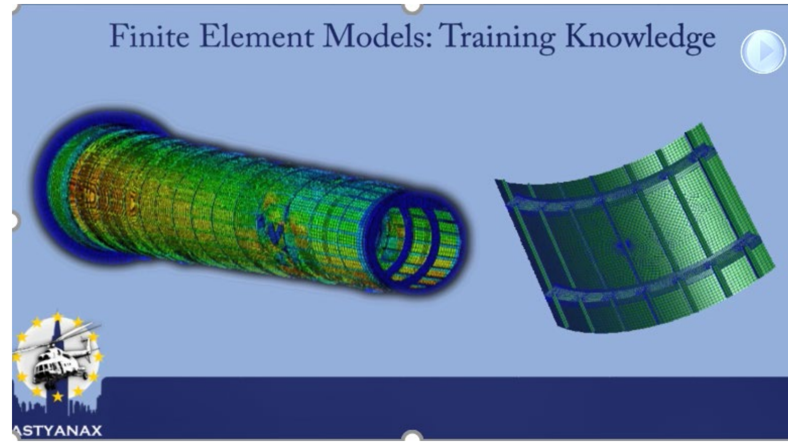
A **digital twin** of the structure provides **reference information** for **damage examples** and feature sensitivity, to be used for SHM system **design**, **verification** and **algorithm training**.

ASTYANAX
Application #1: strain field damage monitoring

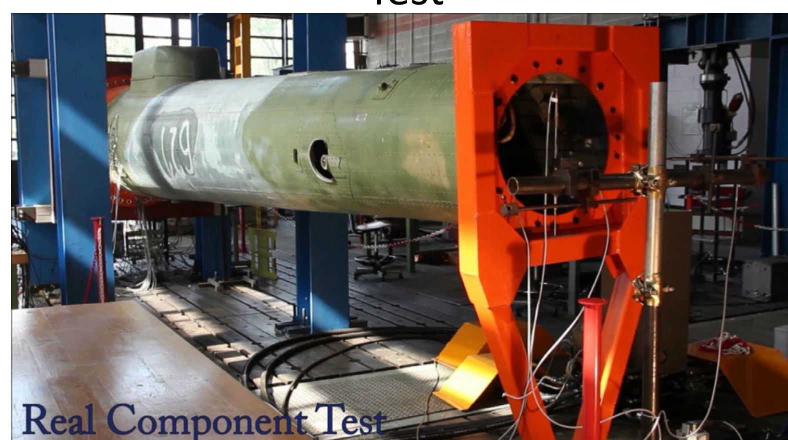
Strain field **model-based** diagnosis of the tail boom of a Mi-17 helicopter subject to fatigue crack propagation



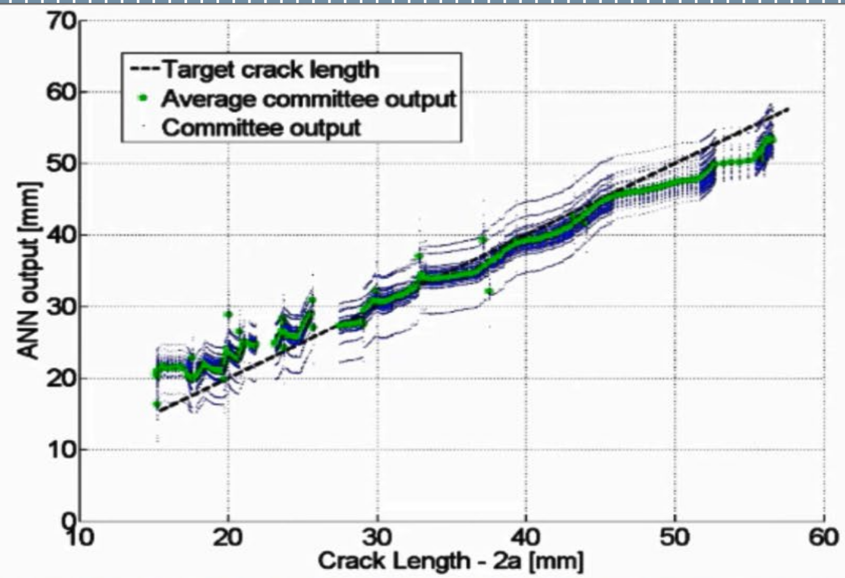
Simulation

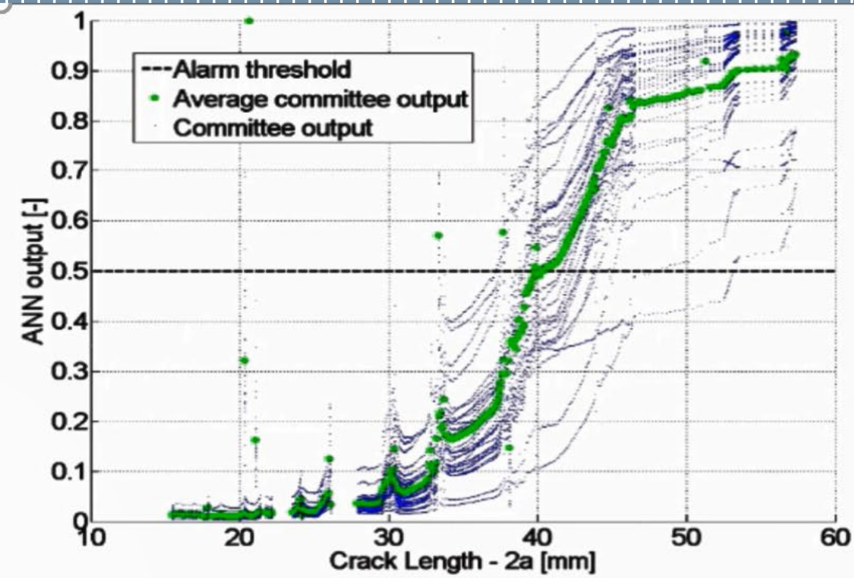


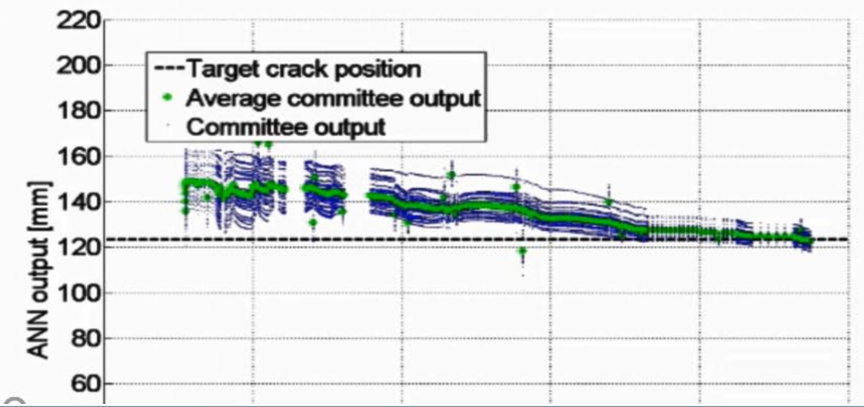
Test



ASTYANAX
Application #1: strain field damage monitoring



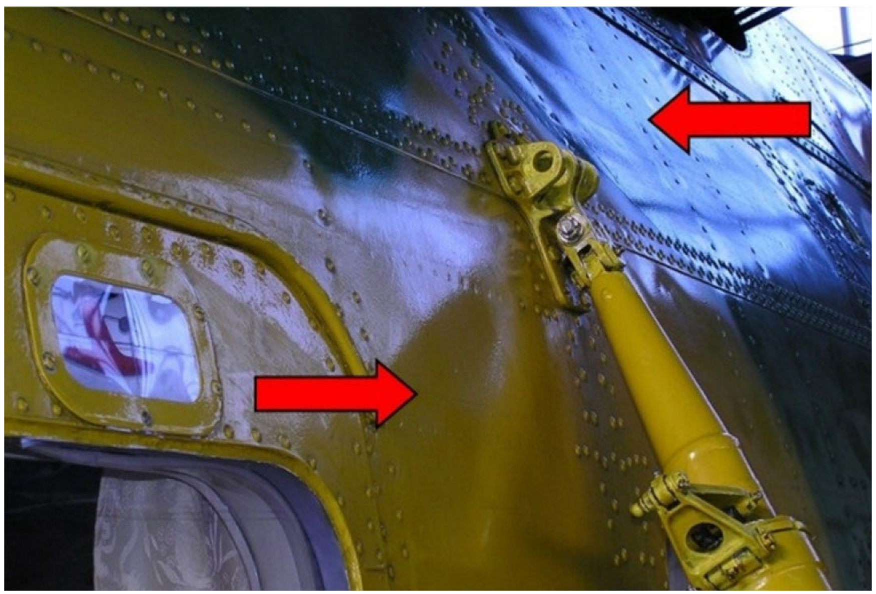




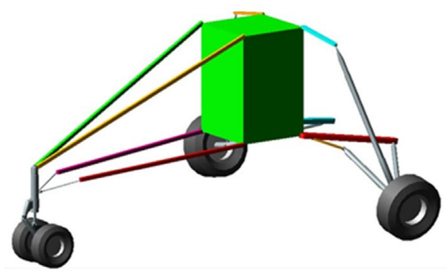
Application #2: Harsh landing monitoring

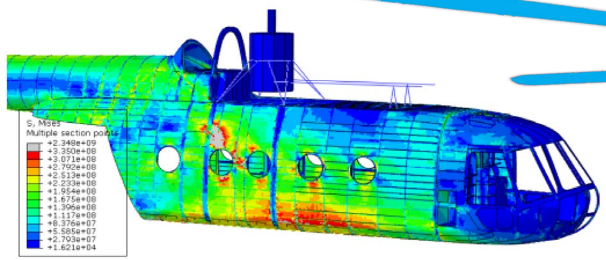
HARSH LANDING: landing conditions generate an impact greater that what is expected in design

- Damage appears in the form of plastic strains
- Damage is usually concentrated near the landing gear attachments
- Under some landing conditions, extensive plastic zones may arise along the fuselage

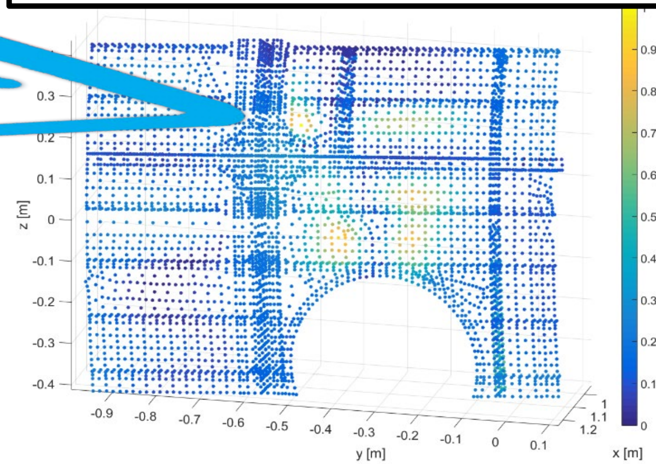


ASTYANAX
Application #2: Harsh landing monitoring

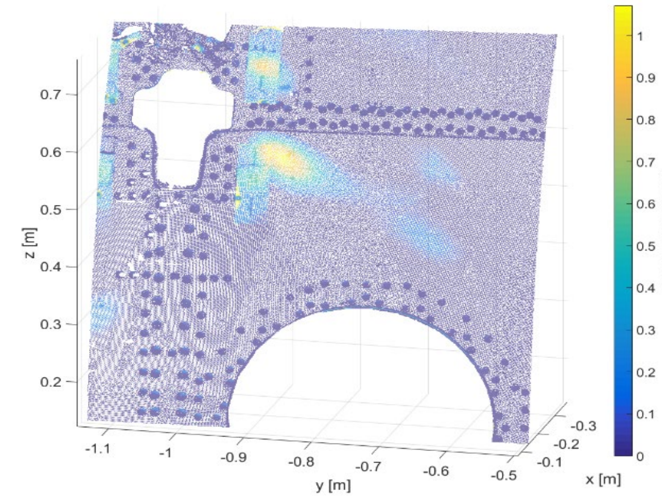




Drop from 75cm - Numerical

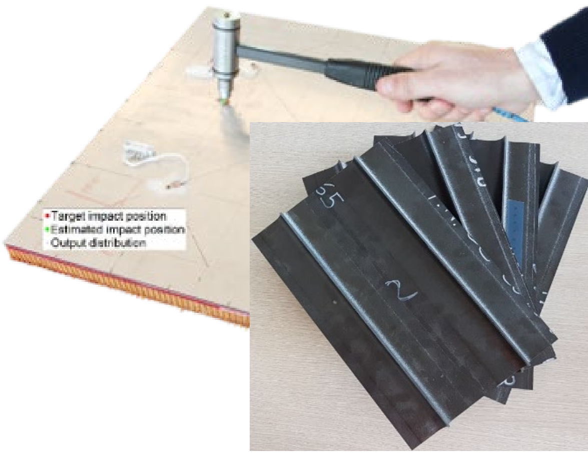


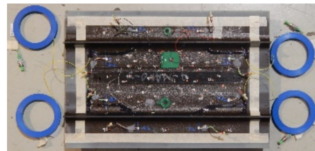
Drop from 75cm - Experimental

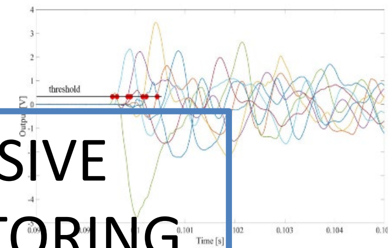


SAMAS
Application #2: Impact Monitoring

IMPACT EVENT



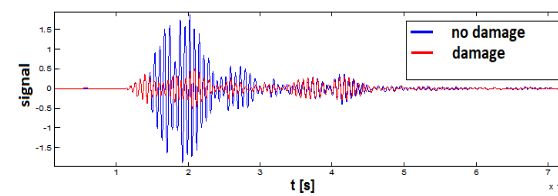


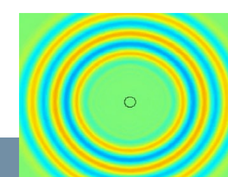


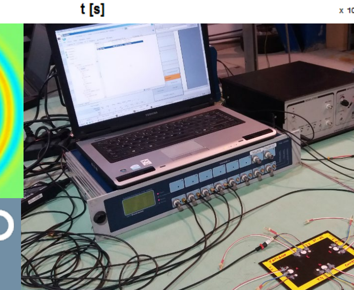
PASSIVE MONITORING
(Has something happened?)

DAMAGE ESTIMATION
(Is a damage *eventually* present?)

ACTIVE MONITORING
(Is a damage ***really*** present?)

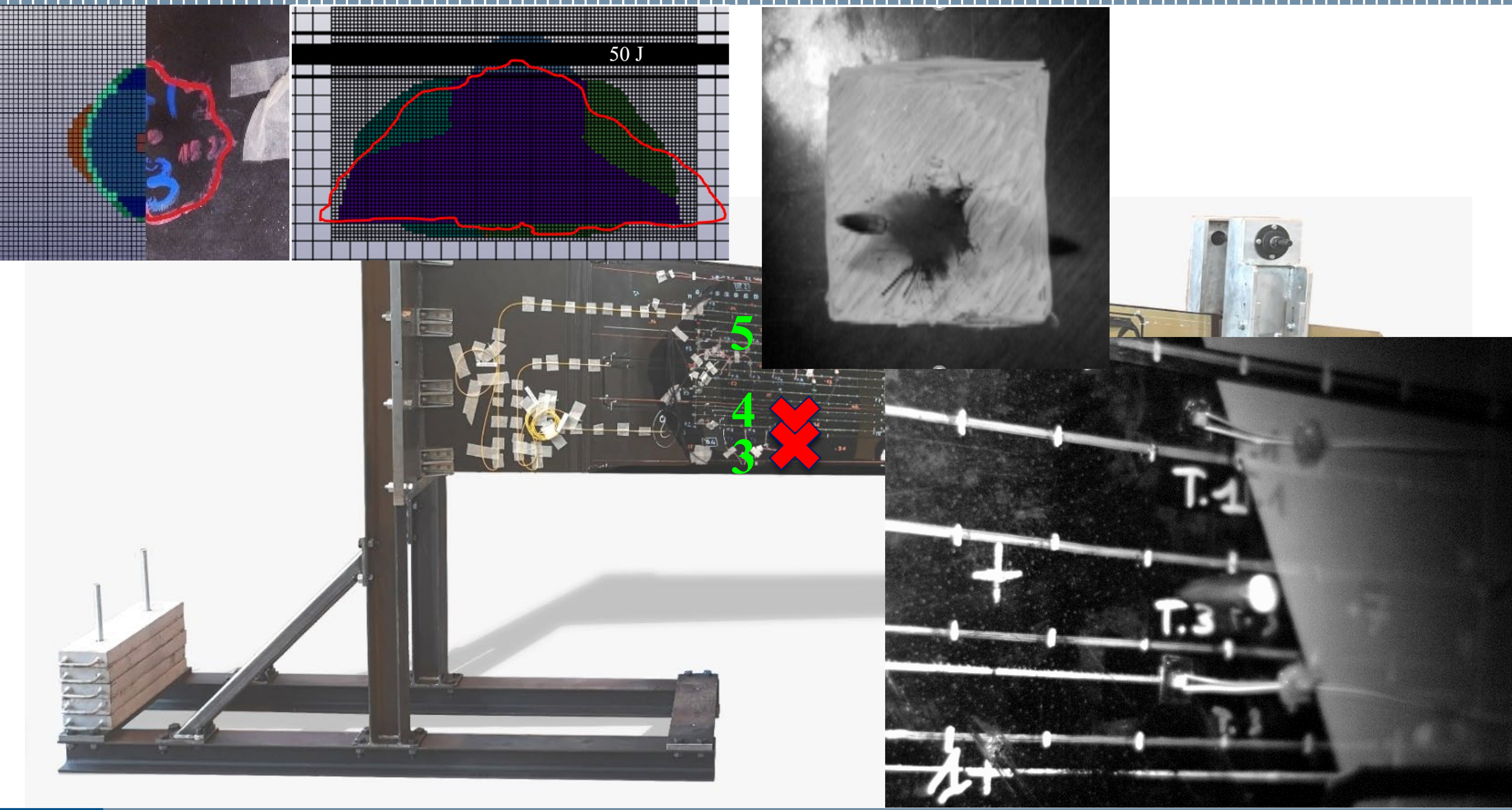






SAMAS

Application #2: Impact Monitoring

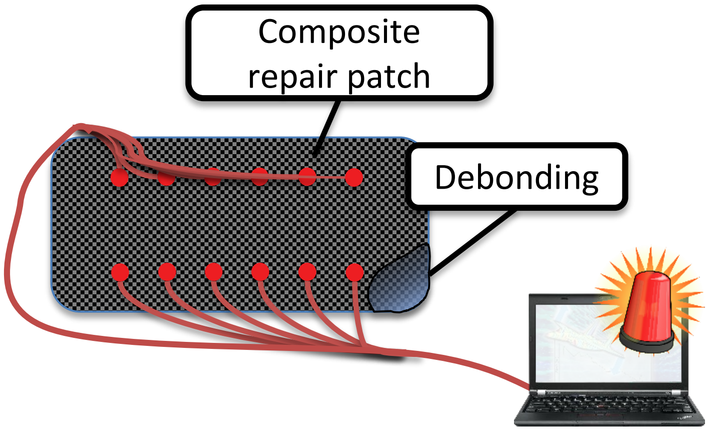


On-going projects
PATCHBOND2 - Certification of adhesive bonded repairs for Primary Aerospace composite structures

SHM system for repair PATCHES:
Strain monitoring for the identification of patch debonding

Final target is the flight test of the SHM system applied on the **horizontal stabiliser of the NH90**

Preliminary laboratory tests are scheduled for SHM system development and testing on simplifield and realistic scenarios



CONSORTIUM

- Finland (Patria, VTT, Tampere University)
- Germany (Airbus DS, WIWeB, University of Stuttgart)
- Italy (Politecnico di Milano)
- Norway(Norwegian Defence Research Establishment, Norwegian Defence Material Agency, Light Structures AS, FiReCo)
- *The Netherlands (lead)* (NLR, KVE, Fokker Services)
- Czech Republic (VZLU)

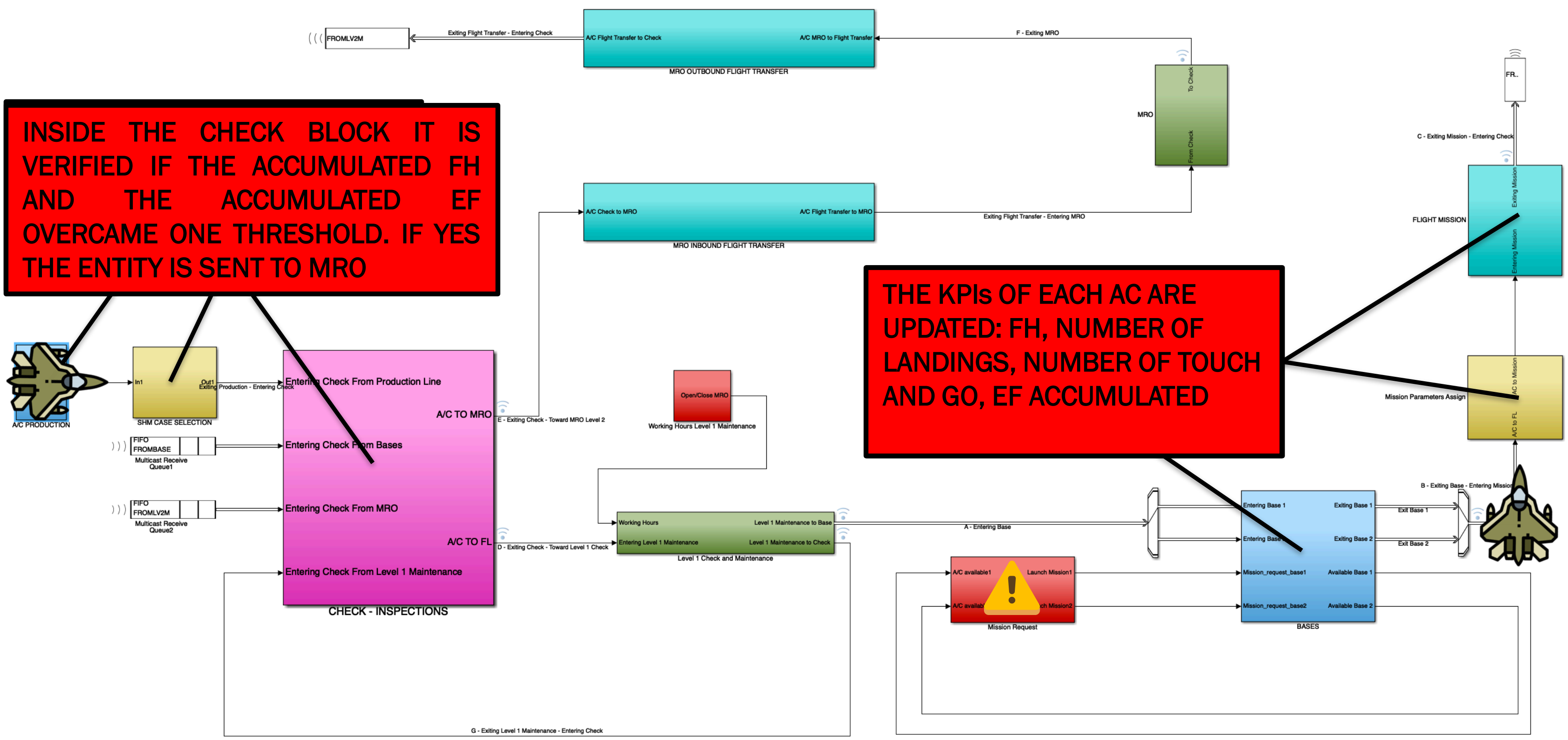
Use of a DIGITAL TWIN for Lifecycle simulation

the real fleet lifecycle is an **highly complicated** concept and it is modeled as a **sequence** of **discrete events**

fleet not equipped with SHM		**fleet equipped with SHM**
traditional mainteinance logics		CBM mainteinance logics
other variables	=	other variables
↔ KPIs		KPIs ↔

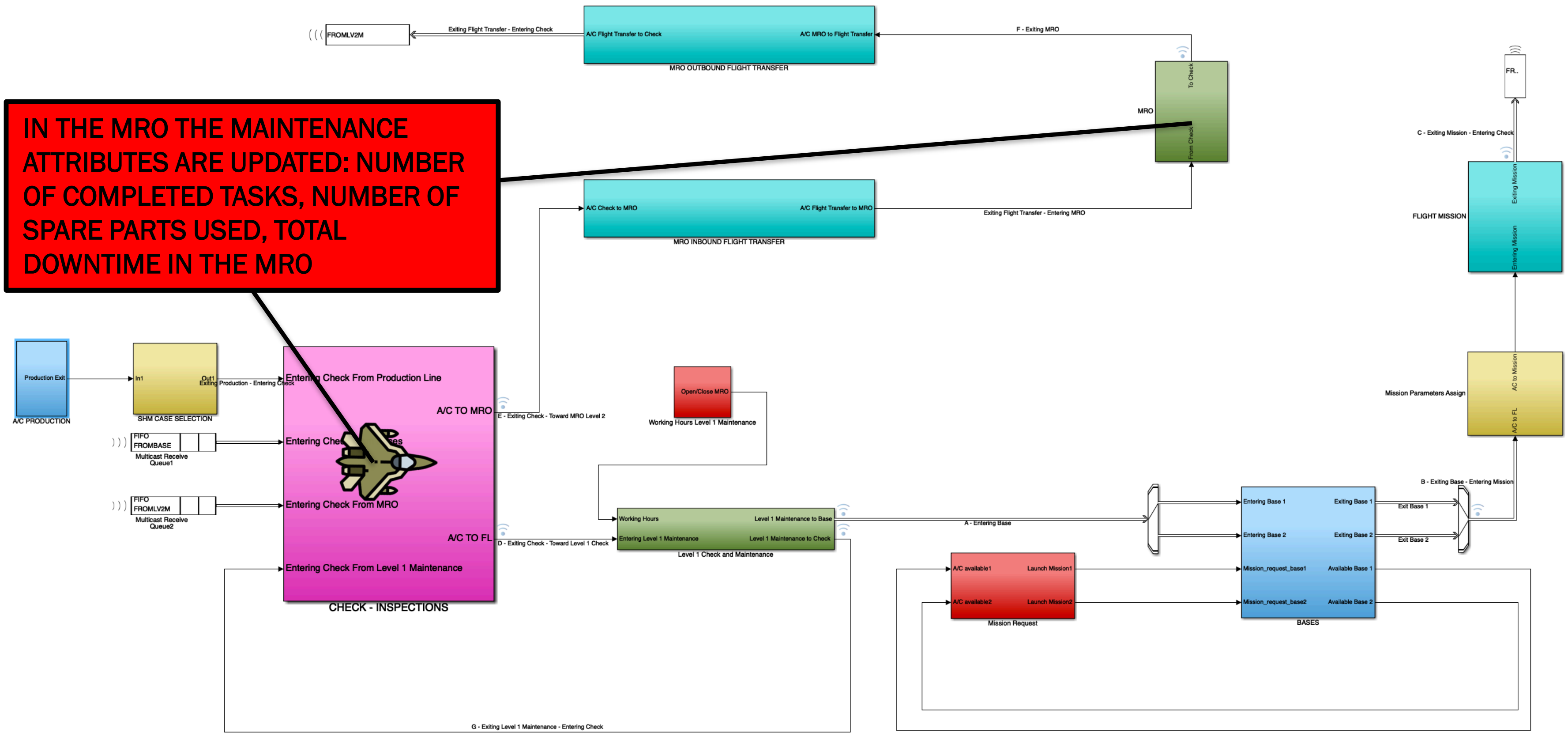
↳ COST BENEFIT ANALYSIS ↲

Simulation scheme



Simulation scheme

IN THE MRO THE MAINTENANCE ATTRIBUTES ARE UPDATED: NUMBER OF COMPLETED TASKS, NUMBER OF SPARE PARTS USED, TOTAL DOWNTIME IN THE MRO



Simulation outputs

KPIs after a lifecycle simulation

Fleet configuration	No HUMS		Partial HUMS		With HUMS	
Aircraft role	training	operative	training	operative	training	operative
HUMS	✗	✗	✓	✗	✓	✓
Tot FH mission	8019	8007	8147	7930	8077	7968
Tot FH transfer	33	30	16	29	16	15
Tot H maintenance	7150	5632	4978	5608	4978	4370
Tot H level 1 maintenance	890	832	29	414	58	50
Total spare parts - LG	4	3	4	3	4	3

THE DOWNTIME IN MAINTENANCE IS MUCH LOWER IF HUMS IS INSTALLED

CBA: total balance

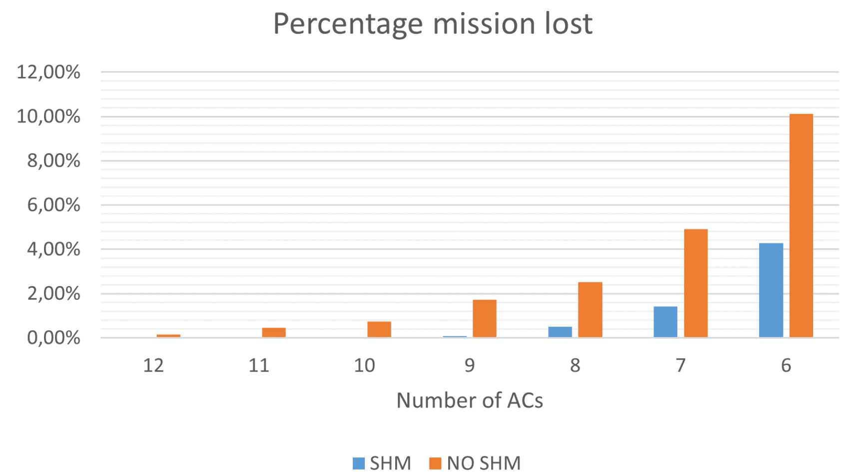
Cost of A/C (LG) maintenance

Cost due to reliability

Cost of SHM system

Cost of SHM maintenance

TOTAL COST OF THE LIFECYCLE



Fleet configuration	No HUMS	Partial HUMS	With HUMS
SHM	✗	✓ / ✗	✓
DIFFERENCE WRT CONFIG. 1	-	-6.9%	-10.8%

Not just for aerospace…

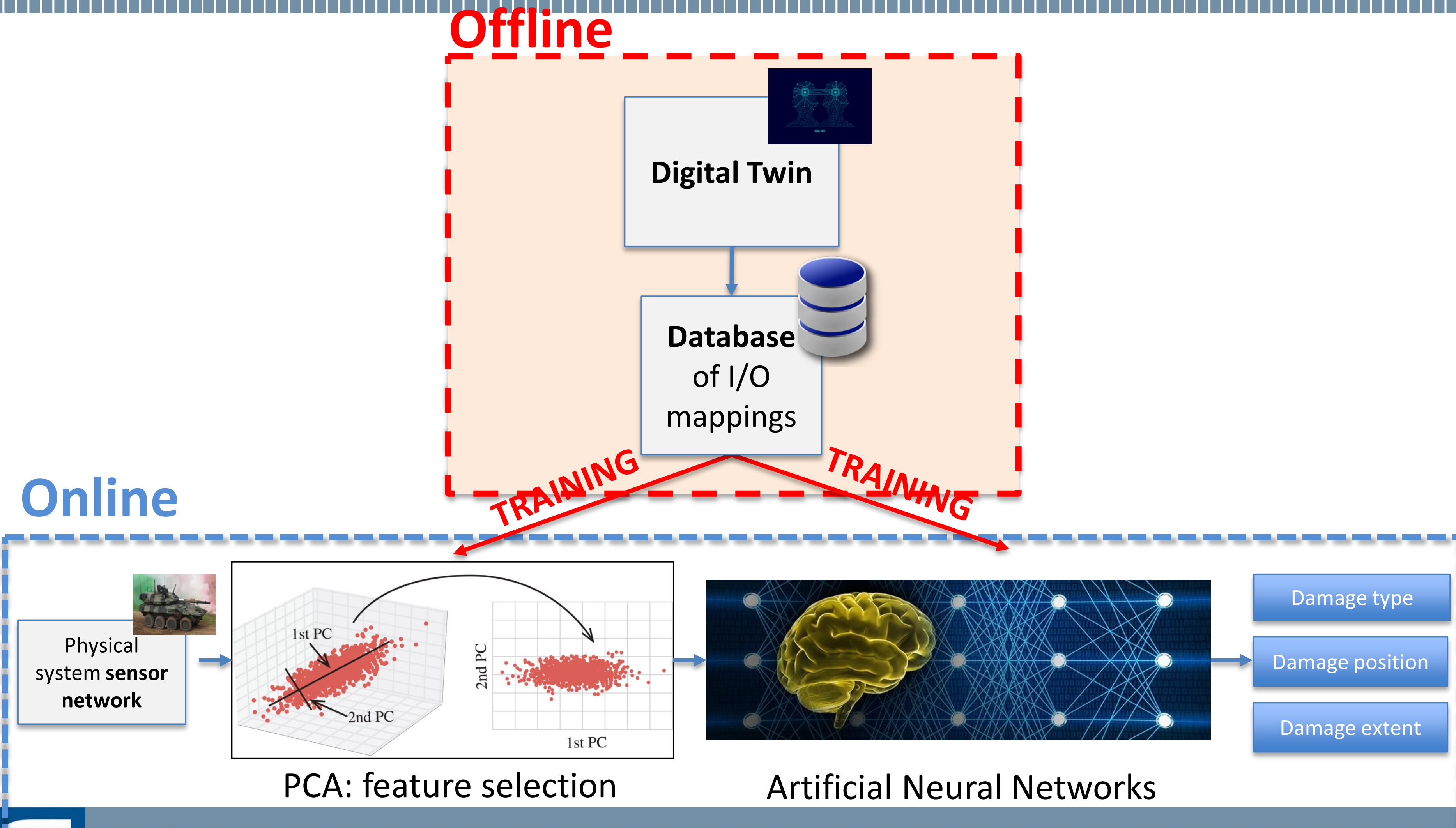
Demonstration of HUMS applicability with reference to three important Centauro II mechanical sub-systems

Tower rotation

Cannon elevation

Bullet management system

Diagnosis: machine learning-based approaches



SIGMALab

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