Health and Usage Monitoring System

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Version 1.1.a

Limited life

Most of the components in aircraft are made of aluminum. Due to this, their operative life is limited.
In addition, it must be considered that:

- production can take a long time and an aircraft generally can be used for about 30 years, so after so much time the aircraft can be considered obsolete for its equipment
- keeping an aircraft operational involves greater wear, controls and consequently money

Aircraft Maintenance Manual (AMM)

When an aircraft is dimensioned, the Aircraft Maintenance Manual (AMM) is formalized. It details the way in which all maintenance tasks carried out on an aircraft shall be accomplished. To determine maintenance intervals it must be taken into account:

- Flight Hours (FH), for items that are in constant operation e.g. fuel pumps, electric generators
- Flight Cycles (FC), for items operated once or twice per flight e.g. landing gear, air starter, brakes
- Calendar Time (CAL), for items exposed whether operated or not e.g. fire extinguishers
- Operating hours, for items not operated every flight, or otherwise independent of FH or FC e.g. APU operation

TBM

The intervals of maintenance are parameters set within the Approved Maintenance Schedule (AMS), which is in turn based on the Maintenance Planning Document (MPD). These will be set according to different criteria, mostly depending on how well damage can be detected and failure predicted.

This kind of maintenance is called **Time-Based Maintenance (TBM)**: maintenance intervals are decided on a statistical basis and therefore through regression on previous aircraft

CBM

In **Condition-Based Maintenance (CBM)**, items are left in service on the condition that they "continue" to meet a desired physical condition and performance standards:

- The condition of an item is monitored either continuously or at specified periods.
- The item's performance is compared to an appropriate standard (e.g., cleanliness, corrosion, wear, pressure) to determine if it can continue in service.
- If item's performance is not satisfied, signals called '*potential failures*' are sent and it may result in the removal of an item before it fails in service.

It is applied to items on which a determination of their continued airworthiness can be made by visual inspection, measurements, tests or other means without disassembly inspection or overhaul.

Health and Usage Monitoring System (HUMS)

The acronym stands for:

- **Health**: is a measure of the overall flightworthiness of the aircraft
- **Usage**: is a measure of how the life of components is being expended on the life-limited parts of the aircraft as well as determining the time to overhaul of some major components such as engines and gearboxes
- **Monitoring**: is the means by which information is gathered on the aircraft on the vital systems
- **System**: indicates that there are a number of parts that must operate together towards a common objective. The system includes on-board equipment and human-implemented processes to carry out the objectives of HUMS

Health

Health monitoring is essentially a diagnostic tool capable of detecting failures well in advance with respect to other classical methods (e.g. temperature monitoring, chip detection) and therefore shall be seen not only as an additional monitoring method (not necessary to achieve the required level of safety but yielding anyhow an enhancement) but also as a special diagnostic tool (i.e., essential to achieve the *on-condition* maintenance, that is the Time Between Overhaul removal).

Aircraft Usage Monitoring

Usage monitoring is based on the principle that the life of the life-limited items is an assessment made on the assumption of a design flight envelope, that is helicopter mission profiles foreseen by the customer. In computing the lives, several pessimistic assumptions are made and lead to the application of safety (or ignorance) coefficients.

If, instead, the true flight envelope can be monitored, then the life expenditures can be computed with no need for pessimistic assumptions: the benefits in terms of Life Cycle Cost (LCC) are obvious.

Monitoring of the true flight envelope implies the capability to detect all the manoeuvres performed by the aircraft during its missions; they range from simple events, such as a take-offs and landings, up to more complex manoeuvres.

History

- Monitoring the performance of important subsystems on aircraft was first employed in the civil air transport market soon after the introduction of the wide body jet circa 1960. Civil Aviation Authority (CAA) and Federal Aviation Administration (FAA) mandated crash survivable flight data recorders.Thanks to this information, airline engineering staff was clamoring to get the information to assist them in day-to-day operations and maintenance activities. Thus, was borne the Aircraft Integrated Data System (AIDS) and the newer generation Aircraft Condition Monitoring System and Aircraft Data Acquisition System (ACMWADAS)
- HUMS came into being following a terrible accident in which nearly 50 souls lost their lives in the North Sea onboard a BV-234.

History

- Industry and government sponsored research, leading to the establishment of the Helicopter Health Monitoring Advisory Group (HHMAG) that continues to meet and develop guidance material to assist in the evolution of HUMS.
- The first of hundreds of operational HUMS went into service in the North Sea in the commercial arena in 1991.
- Since 1991, there has been a major reduction in helicopter incident rates as reported by the UK CAA.
- In 1999, the CAA made HUMS mandatory for all heavy rotorcraft registered in the UK.

History

- 1982- UK Helicopter Airworthiness Review Panel (HARP) establishes need for improved condition monitoring
- 1984 - Offshore Operators Association (UKOOA) and British government sponsor HUMS research
- 1985 - V-22 Osprey development program started with onboard HUMS requirement
- 1986 - Major North Sea Accident attributed to drive train mechanical malfunction
- 1987 - US Navy procures automated gearbox mechanical fault detection system for overhaul test stands
- 1989 - North Sea Trials with sponsorship by UK Government and Industry
- 1990 - Helicopter Health Monitoring Advisory Group (HHMAG) publishes "A Guide to Health Monitoring of Helicopters"
- 1990 - UK CAA establishes mandatory date (December '91) for Flight Data Recording (FDR) on medium and large civil helicopters
- 1991 - First HUMS operational in North Sea
- 1993 - US Navy awards contract for Helicopter Integrated Diagnostic Systems (HIDS)
- 1995 - UK MOD moves forward with an operational HUM program
- 1996 – Rega Swiss Air Ambulance Modular Mini_HUMS becomes operational
- 1997 - US Navy moves forward with Integrated Monitoring Diagnostics – Health and Usage Monitoring System (IMD-HUMS) Program
- 1997 - US DOD establishes Joint Advanced Health and Usage Monitoring System (JAHUMS) Advanced Concept Technology Demonstration Program
- 1998 - US Army establishes requirement for FDR System on Helicopters – Digital Source Collector (DSC)
- 1999 - First Operational HUMS in US military becomes operational – Vibration Structural Life and Engine Diagnostic System on US Marine V-22 Osprey
- 2000 – Low Rate IMD-HUMS Initial Production on Marine Corps CH-53E Super Stallion and MH-53E Sea Dragon fleets

Benefits

HUMS were initially designed to increase safety, but it quickly became apparent that these systems, which were capable of describing the actual condition of critical dynamic component, had considerable maintenance and cost savings potential.

Most important benefits are:

- more flight safety
- less waste of resources caused by unnecessary controls and replacements with a consequent pollution reduction

Benefits

Safety benefits are:

- Accurate identification of faults prior to catastrophic failure
- Informed decision-making
- Risk mitigation and avoidance
- Lower risk of failure in flight and of emergency landings

Readiness benefits are:

- Demonstrable reduction in downtime for unscheduled maintenance events
- Proactive maintenance, allowing aircraft downtime to be a scheduled and anticipated event rather than an unexpected inconvenience
- Immediate recognition of a seemingly insignificant problem, before it turns into a significant one, allowing for better planning for the operation of an aircraft

Benefits

Maintenance benefits are:

- More efficient maintenance
- Elimination of the need for portable equipment installation and reduction of the need for additional maintenance flights due to onboard rotor track and balance capability
- Troubleshooting and diagnosis of potential faults through proper use of the system
- Deferment or elimination of certain maintenance inspection intervals as HUMS mature
- Diagnosis of problems before they cause collateral damage

Benefits

Operations and Support Cost benefits are:

- Increased useful life and efficiency by recommending changes to system components such as shaft alignment or gearbox design. Frequently, one damaged part will go unnoticed, eventually resulting in a severe malfunction and the need to replace an entire gearbox.
- Identification of certain problems that warrant grounding the aircraft immediately, thereby preventing further damage, and resulting in a cost savings through averting damage to components other than the root cause
- Extension of the life of an aircraft's avionics and airframe by reducing overall vibration on the aircraft

Benefits

Other benefits are:

- Increased pilot confidence
- Ability to more effectively plan maintenance actions over the long-term
- Ability to monitor health of an entire fleet, regardless of physical location
- As the program matures, the potential to predict when certain faults will occur, based on historical data and specific aircraft data

Evidence of Benefits of HUMS

- The US Joint Helicopter Safety Analysis Team (JHSAT) found that part/system failures caused approximately 26 per cent of the helicopter accidents in 2000 and that 24 of those (47 per cent) might have been mitigated by the use of HUMS or equivalent systems. HUMS is not just a maintenance tool: it has the potential to prevent accidents and save lives.

- The US Army recently performed a detailed study of the benefits associated with HUMS for US Army helicopter platforms, covering more than 500 aircraft and several hundred thousand flight hours.

Evidence of Benefits of HUMS

- The US Army developed six operating metrics, including readiness, Maintenance Test Flight (MTF) hours, mission abort rate, Maintenance Man Hours (MMH), parts cost per flying hour, and combat power.

It was discovered that:

- Non-mission capable for maintenance (NMCM) rates were reduced by 5.3 per cent
- reduction of 1.44 MTF (maintenance test flight) hours per 100 flight hours
- 5-8 per cent increases in readiness across various platforms
- over 125 maintenance procedures have been improved or eliminated

HUMS Components

The basic **components** in all HUMS systems are very similar, differing only in the location, quantity, type of sensors, and the complexity of the particular system requirements. Systems are made up of a combination of accelerometers of various designs and function, velocimeters, magnetic pickups, photocells, some type of acquisition unit and a ground station for analysis.

We will now consider the example of the Agusta-Westland AW139 HUMS Kit.

Flight Data Monitoring

Initially, the principal use of flight recorders was to assist accident/incident investigators, especially in those accidents with no surviving crew members. It was recognized that analysis of the recorded data was also useful for better understanding of safe operations

To capitalize on these benefits, several operators set up systems to routinely analyze recorded flight data. This program is called:

- **Flight Data Analysis (Program)**: Flight Data Analysis (FDA) or Flight Data Analysis Program (FDAP)
- **Flight Data Monitoring (Program)**: Flight Data Monitoring (FDM) or Flight Data Monitoring Program (FDMP)
- **Flight Operations Quality Assurance**: Flight Operations Quality Assurance (FOQA)

Flight Data Monitoring

A Flight Data Monitoring program could be defined as:

'*the routine collection and analysis of flight data to develop objective and predictive information for advancing safety*' (EASA definition)

'*A proactive and non-punitive program for gathering and analyzing data recorded during routine flights to improve flight crew performance, operating procedures, flight training, air traffic control procedures, air navigation services or aircraft maintenance and design*' (ATR definition)

In general, a Flight Data Monitoring Program assists an operator to identify, quantify, assess and address operational risks.

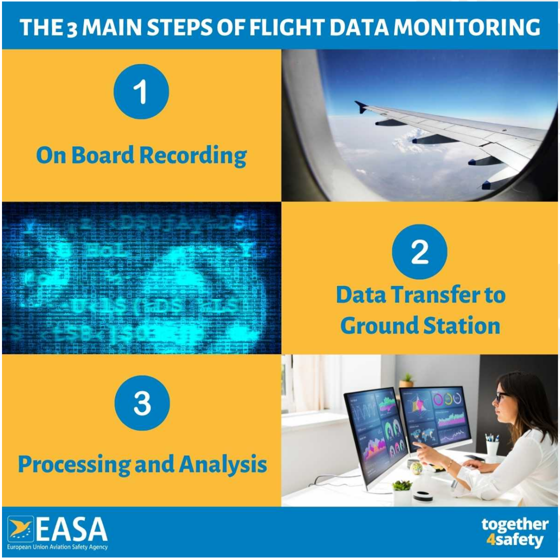
Flight Data Monitoring

FDM involves capturing and analyzing flight data to determine if **exceedances** (or **events**) happened, identifying trends and promoting action to correct potential problems.

In summary, the objective of a FDMP is to:

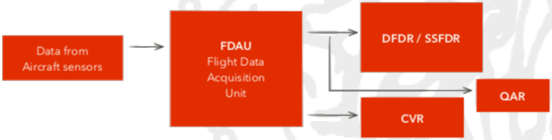
- Determine operating norms
- Identify potential and actual hazards in operating procedures, fleets, aerodromes, ATC procedures, etc.
- Identify trends
- Monitor the effectiveness of corrective actions taken
- Provide data to conduct cost-benefit analyses
- Optimize training procedures
- Provide actual rather than presumed performance measurement for risk management purposes

FDM Main Steps



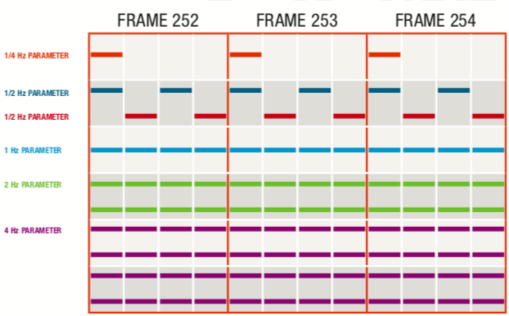
Data Collection

Flight Data Recorder (FDR) system has the purpose to collect and record data from airplane sensors onto a media designed to survive an accident.
To ease data recovery, **Quick Access Recorder** (Quick Access Recorder (QAR)) systems have been developed: they record a copy of the FDR data but on a media that is *easily accessible and interchangeable*, but they are *non-crash protected*.
Wireless data transfer solutions exist too.



Sampling Rate

The QARs also allow for increasing the *sampling rate* (frequency) or the *recording resolution* of specific flight parameters to values appropriate for advanced flight data analysis.



Data Analysis

Data is processed by software that provides a corresponding series of flights and flight events to the end user.
Analysis is the heart of the FDM process. Much of the benefit of FDM comes from analysing very large numbers of flights and flight datas.

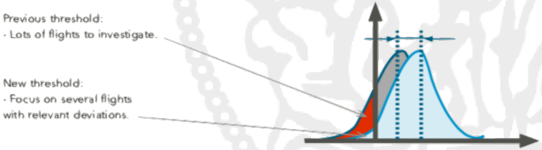
When working with large amounts of data, statistical analysis methods are beneficial to highlight useful information. By its nature, any FDM program involves working with large amount of data, thus using correct statistical analysis methods is important to look for trends and emerging operational risk areas.
Basic measures based on FDM events are:

- FDM event count
- FDM event rate
- Trends over time

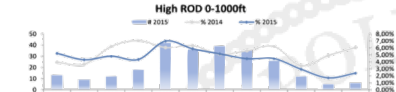
Fine Tuning

FDM events can be grouped by severity level: an FDM event may correspond to a more severe or less severe event.

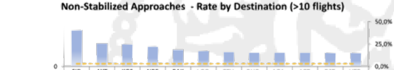
Fine tuning is the process with which the airline modifies the logics or the thresholds of one or several events.
Without this event threshold tuning, a lot of events will be triggered without any relevant information and they will pollute the flight database, not producing relevant statistics.
With the modified threshold, the event dispatch will show:



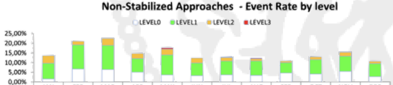
Examples



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
# 2015	13	9	12	18	42	36	39	35	26	12	5	6
% 2014	3,93%	3,64%	6,19%	7,04%	6,05%	6,31%	5,08%	5,59%	6,19%	3,45%	4,91%	6,05%
% 2015	5,22%	4,31%	4,82%	4,35%	6,98%	5,87%	5,15%	4,46%	4,48%	2,94%	1,71%	2,38%



	SID	AYT	KGS	NBE	RAK	LGG	CFU	RHO	AGA	ACE	DJE	HER
Rate	40,0%	25,3%	24,5%	21,7%	18,1%	17,0%	15,8%	15,2%	15,2%	15,1%	14,9%	14,7%
Occurrences	24	48	26	15	17	24	16	12	15	16	10	25
# Flights	60	190	106	69	94	141	101	79	99	106	67	170
3% Reference	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%	3%



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
LEVEL3	0,00%	0,00%	0,00%	0,00%	0,66%	0,00%	0,26%	0,38%	0,00%	0,00%	0,00%	0,00%
LEVEL2	4,02%	1,91%	3,61%	2,66%	2,99%	2,61%	1,85%	1,15%	0,86%	1,47%	2,05%	1,19%
LEVEL1	8,03%	12,44%	12,45%	7,00%	10,30%	6,53%	7,12%	7,39%	5,34%	7,35%	7,85%	6,75%
LEVEL0	1,61%	6,70%	6,43%	5,07%	3,65%	3,26%	3,69%	3,44%	4,65%	4,17%	5,46%	2,78%

FDM Insights

For more information about the FDMPs you can check the EASA site and the European Operators Flight Data Monitoring (EOFDM) three working groups publications.
The **European Operators Flight Data Monitoring forum** (EOFDM) is a voluntary partnership between European Operators and the European Union Aviation Safety Agency (EASA) in order to:

- Facilitate the implementation of Flight Data Monitoring (FDM) by Operators
- Help operators draw the maximum safety benefits from an FDM Programme

Depending on the working groups (WGs), operators, operators associations, aircraft manufacturers, FDM software vendors, research and educational institutions and regulators (national aviation authorities and international aviation regulators) may participate.

HUMS practical applications

The US Army has launched an aggressive program to implement CBM on its rotary wing assets. CBM takes advantage of technology developments in the areas of machinery monitoring, signal processing and fault modeling to reduce the cost of ownership through improved maintenance procedures.
Before proceeding, let's make a distinction clear:

- Fault: undesired anomaly in an item or system
- Failure: loss of function of a part, component or system caused by the presence of a fault

An optimized HUMS detects incipient faults, determines their severity and provides feedback to maintenance personnel to indicate when a fault has become a failure (many components have fault-tolerant designs).

Case study 1: gear fault detection (1)

This case, which dates back to 2009, consists in the identification of an AH-64 nose gearbox gear fault, which is equipped with a Modernized Signal Processing Unit (MSPU) to collect vibration data.

Boeing AH-64 Apache nose gear boxes

Case study 1: gear fault detection (2)

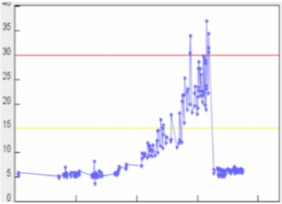
The nose gearbox is equipped with a three times redundant diagnostic system, which includes:

1. A chip detector, for the detection of metal shavings that may indicate wear and therefore give an indication of the need for maintenance or a timely warning of an imminent failure

2. A temperature sensor, to reduce the overheating risk
3. An accelerometer, tied to the MSPU

Case study 1: gear fault detection (3)

The gearbox was removed from service following the analysis of HUMS data, which detected a *red indicator condition*:



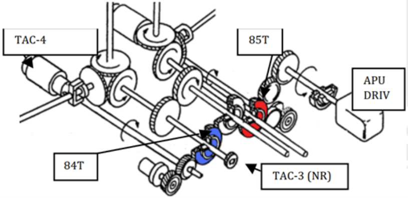
As a matter of fact, a *teardown analysis* of the gearbox revealed severe damage to both the input pinion and output bevel gears:

Case study 2: sprag clutch monitoring (1)

This case focuses on the sprag clutches of the main transmission of the Apache AH-64D, that are:

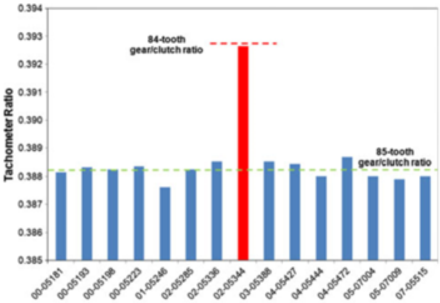
- A 85-tooth spur gear, powered by the Auxiliar Power Unit (APU)
- An 84-tooth spur gear, powered by the engines

During the transition from APU power to engine power, the primary clutch on the 85-tooth gear is engaged while the secondary clutch on the 84-tooth gear continues to overrun. If, for some reason, the primary clutch does not engage, the secondary clutch will engage and drive the accessory section.



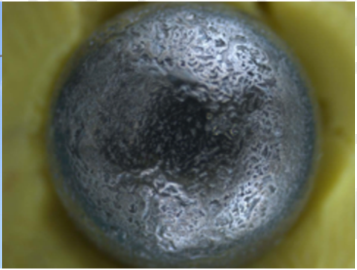
Case study 2: sprag clutch monitoring (2)

A failure of both clutches would leave the aircraft without AC power. The flight crew originally had no methods for determining if the primary clutch had failed and the aircraft was operating on the secondary clutch. To solve this, the AH-64D fleet was equipped with a MSPU that, interfacing with the pre-existing sensors, measures the speed of the AC generators, that is dependent upon which gear/clutch combination is engaged, determining it.



Case study 3: gearbox generator bearing fault (1)

This case involves the ability of the HUMS to predict the Remaining Useful Life (RUL) of the Sikorsky UH-60L accessory module generator bearings. Although they can continue to operate for a certain period of time even after their wear, they would produce iron shavings which would cause the illumination of the chip light. Excessive chip events require the replacement of the gearbox, meaning the RUL of a bearing that "makes metal" is effectively zero hours, and prompts a precautionary landing.



Case study 3: gearbox generator bearing fault (2)

In order to develop improved mechanical diagnostics and refined thresholds, HUMS analysts followed a six-step methodology:

1. Physics of the failure analysis
2. Development of detection algorithms
3. Fault correlation data mining
4. Fault validation
5. Inspection/*teardown* analysis
6. Electronic and embedded diagnostics.

Three *teardown* analyses were performed to confirm the presence of the bearing fault and correlate it to existing condition indicators. New thresholds were developed and, when applied to the fleet, a faulted gearbox was immediately identified. Upon its removal, the unit noted metal shavings in the oil. Early identification of this fault likely prevented a precautionary landing.

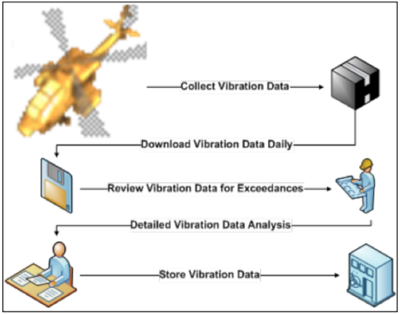
HUMS processes (1)

All basic processes are very similar in operation, the major difference is the way the data is managed and analyzed. When beginning a HUMS program, it may be helpful to create or reference a HUMS manual or guidance document with defined processes that also describes well-known faults and prescribed maintenance action for well-known faults.

The **Minimum Requirements** in equipment design for data management concern:

- The ground station
- The history of indicators and thresholds data
- The ability to trend data and facilitate comparison with data from other aircraft

HUMS processes (2)



Data Acquisition and Transfer

- Capture, extraction, processing, and analysis of HUMS data can be done through manual methods, automated methods or a combination of both
- It is important to download HUMS data regularly at a predetermined download interval

HUMS processes (3)

Data Analysis

- After download, the data should be reviewed by the maintainer on the flight line for advisories and threshold exceedances, followed by detailed analysis by a trained HUMS analyst or engineer
- There are two types of thresholds: *fixed* and *learned*

Data Validating

- Verification of the correctness of the detection
- Supporting evidence
- Removal of the component, documentation (with pictures) of any noticeable fault and sending to an overhaul/*teardown* facility

Note

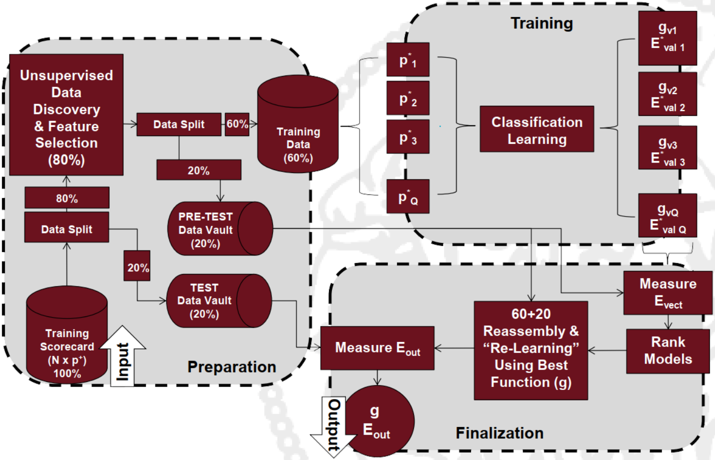
Communication about the status of removed components is crucial for the enhancement of the HUMS.

A hint on Machine Learning

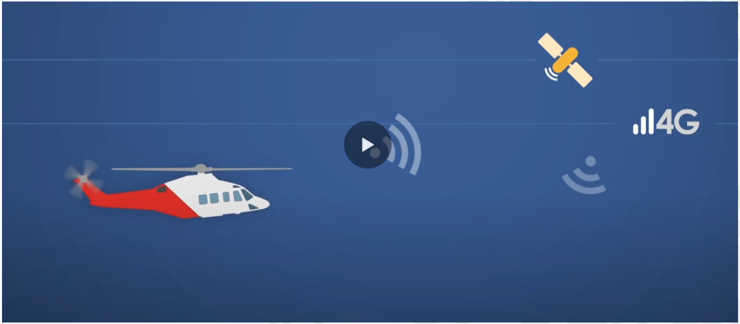
Machine Learning (subset of Artificial Intelligence) is the study of computer algorithms that can improve automatically through experience and by the use of data.

Its employment is crucial, also because data are collected from different sources (HUMS, Flight Data Recorders, Maintenance Records and Reliability Databases) which are not integrated, but decisions regarding the health of aircraft components are dependent upon the information stored within them.

A Machine Learning algorithm example



HUMS: summary video



Credit where credit is due

The present material has been prepared as part of the contribution to the *Flipped Class-innovative didactic* initiative during academic year 2021/2022 by the following students:

- Rebecca Pedron
- Davide Pio Loco Zanet
- Laura Silvetti

List of Acronyms

AMM	Aircraft Maintenance Manual
AMS	Approved Maintenance Schedule
APU	Auxiliar Power Unit
CAA	Civil Aviation Authority
CAL	Calendar Time
CBM	Condition-Based Maintenance
EOFDM	European Operators Flight Data Monitoring
FAA	Federal Aviation Administration
FC	Flight Cycles
FDA	Flight Data Analysis
FDAP	Flight Data Analysis Program
FDM	Flight Data Monitoring
FDMP	Flight Data Monitoring Program
FDR	Flight Data Recorder
FH	Flight Hours
FOQA	Flight Operations Quality Assurance
HUMS	Health and Usage Monitoring System
LCC	Life Cycle Cost
MPD	Maintenance Planning Document
MSPU	Modernized Signal Processing Unit
QAR	Quick Access Recorder
RUL	Remaining Useful Life
TBM	Time-Based Maintenance