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STRUCTURAL HEALTH MONITORING OF HELICOPTER FUSELAGE

The helicopter design is a challenging experience for fatigue concern as it is subjected to a very wide range of low- and high-frequency load cycles per flight, much more than a fixed wing aircraft. Structural Health Monitoring (SHM) seems to have capability in helping to reduce the maintenance and operational costs, which are about 25 percent of the direct operating cost of the helicopter, thus playing an important role especially in the case of the ageing helicopters. In fact, the damage tolerant design approach makes the fatigue resistance evaluation not only a safety issue but also a maintenance related concern. The work presented in this paper is a part of an international research project HECTOR (HElicopter fuselage Crack moniToring and prognosis through On-board sensoR network), founded by the European Defense Agency (EDA) and supported by 10 EDA Member States: Cyprus, France, Germany, Greece, Hungary, Italy, Poland, Slovakia, Slovenia and Spain.

Keywords: *HECTOR, Structural Health Monitoring, smart sensors, helicopter.*

1. Introduction: The HECTOR project overview

The project consortium was coordinated by Politecnico di Milano and it was comprised of universities: Politecnico di Milano, University of Zilina, AGH University of Science and Technology, non-governmental laboratories: Laboratory of Technology & Strength of Materials – University of Patras, a research entity: Consorzio Milano Ricerche, as well as from industrial partners: AgustaWestland, Vitrociset and a small-medium enterprise: Stiftelsen SINTEF. Thus, five European countries participated in the project realisation: Greece, Italy, Norway, Poland, Slovakia.

The Faculty of Electrical Engineering, University of Zilina had an important role in the project. It was included in five of six work packages (WP), while leading one of the most important WP4: Study and development of real-time SHM techniques for helicopter fuselage. Researchers from five departments of the faculty participated on R&D activities related to the project.

The aim of HECTOR was to increase the systems availability by directly monitoring the damage while it is propagating inside the structure. The concept is based on the System Health Monitoring (SHM) concept. In this way it would be possible to get real time knowledge about the damage situation, thus setting a Condition Based Maintenance (CBM) [1].

The helicopter tail structure is presented herein as a good candidate for the application and testing of the SHM system [2, 3]. The main reason is the criticality of the region, where the torque generated by the tail rotor to balance the rotation induced by the main rotor is undergone. In particular, the attention was focused over some simplified reinforced panels, well suited to indicate the general behaviour of the entire structure and particularly adapt for the safe and early application on board of the machine [4, 5]. The calculated strain distribution across an entire fuselage from finite element methods is shown in Fig. 1.

The idea was to update the scheduled maintenance intervals according to the actual condition of the structures. However, this is not an easy task, as it is governed and influenced by many variables, each one characterised by a stochastic distribution. In particular, the key factor is the disposal of detection and monitoring systems as reliable as possible, on the basis of which all the machine stops can be optimised in order to maximise the machine availability with the minimum loss of reliability, thus conjugating safety with economics [1].

2. System overview

Figure 2 shows basic structure designed for the SHM of helicopters. In general, the overall concept of the system consists of two main hardware parts, namely:

- On-board unit (helicopter side):
  - Smart Sensors' communication network placed in the helicopter's fuselage,
  - Main control unit including the communication link HW between the helicopter and the ground operator's tablet,

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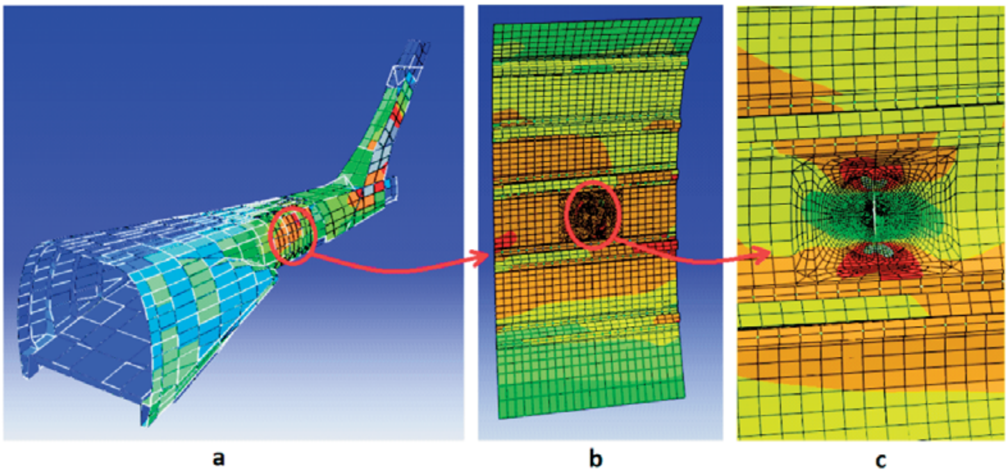


Fig. 1 Calculated strain distribution across an entire fuselage from finite element methods a) General model of the entire rear fuselage b) Submodel for the most stressed zone, with crack modelled inside c) Crack model

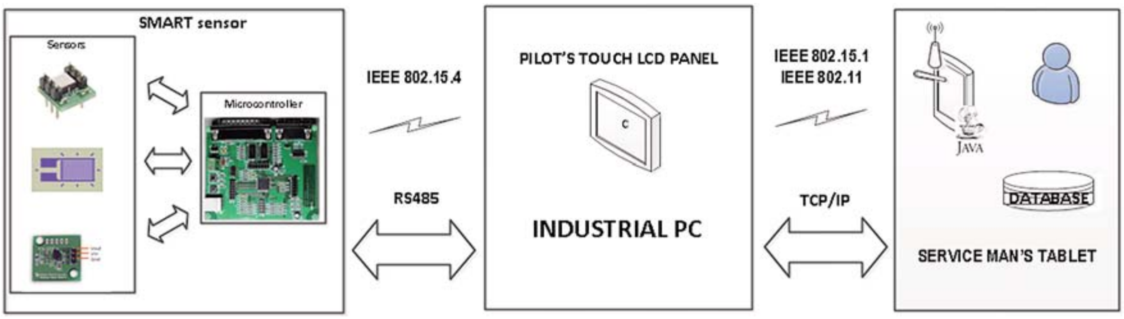


Fig. 2 Designed SHM system structure

- Maintenance unit (service side):
  - Serviceman's tablet or other kinds of handheld devices.

And two main software parts:
- GUI (Graphic User Interface) at helicopter side:
  - signal pre-processing, enhancement and feature extraction block,
  - simple crack prognosis block,
- GUI at the service side:
  - feature extraction and signal classification block,
  - detailed crack prognosis block,
  - database block.

3. The Sensor Network definition

The basic premise of most damage detection methods is that damage modifies the stiffness, mass, or energy dissipation properties of a system, which in turn alter the measured dynamic response of the system. Environmental and operational variations, such as varying temperature, moisture, and loading conditions affecting the dynamic response of the structures again will complicate the interpretation of possible damages.

The ideal sensor for the purpose of damage detection should have the following properties:
- be sensitive to the measured property,
- be insensitive to any other property,
- does not influence the measured property,
- be linear over the expected range of the measured property.

There are several available sensing principles for reading mechanical properties. These range from the well-established strain gauges to innovative and so far unproven technologies like, for example, sensing devices based on nano-technologies. Based on available knowledge, literature and information from vendors the following sensor candidates were evaluated in this study: strain gauges, crack gauges, eddy current sensors, fibre-optic sensors, potential drop, MEMS devices and mechanical wave-based sensors including general piezoelectric sensor systems, ultrasonic, Lamb waves and acoustic emission. Three among the most innovative and relevant for the current purposes are described hereafter.

The goal of an extended smart sensor system should be to provide an early warning that material fatigue is under development. The focus is thus on strain sensors since formation of cracks usually follows from excess strains. While there are several methods for measuring strains, the most common is to use a strain gauge, a device whose electrical resistance varies in proportion to the amount of strain in the device. The most widely used gauge is the bonded metallic strain gauge. The implementation of strain gauge sensors is shown in Fig. 3.

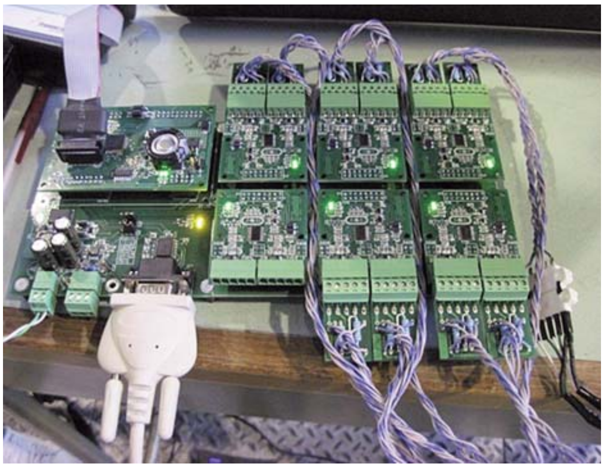


Fig. 3 HECTOR Smart Sensor, Base board, DSC board, 6x ADC modules

A system based on fibre Bragg gratings (FBGs) is again a strain sensing system which can be made capable of displaying a strain map in the structure. These sensors, easily and economically embeddable into the laminates without significantly affecting the mechanical properties of the hosting material, have several advantages such as: light weight, low power consumption (less than 1W is required to power the filter and the SLED optical source), immunity to electromagnetic interference, long lifetimes and high sensitivity. They don't need initial and in-service calibrations and are affected by very low signal drop. From an economic point of view, because of their diffusion and industrialisation, also the costs are by far reduced. Last but not least, comes the multiplexing option, or the possibility to photowrite more FBGs inside one optical fibre, thus becoming particularly attractive for damage location identification through the analysis of the whole FBG network reflected spectrum. The continuous improvements concerning the operating range of such sensors [6], would make possible their utilisation also in the harsh environments typical for the helicopters. It is also possible to correlate the effects of various damages (mainly cracks and delaminations) on the reflection spectrum of the embedded FBG sensor [7]. However, there are some challenges that must be addressed in order to construct a system based on FBG sensors from a practical point of view. First of all, an optical fibre for sensor purpose in which a Bragg grating is inscribed consists of the circular glass fibre surrounded by a thin and hard protective coating like, for instance, polyamide.

The SMART Layer® developed by Acellent Technologies, Inc. is also presented as a valid alternative for monitoring the structural integrity of composite and metal structures. It consists of an array of networked piezoelectric sensors embedded in a thin dielectric film, eliminating the need for each sensor to be installed individually. A pre-defined diagnostic signal can be transmitted by one of these sensors. It then travels through the structure under investigation as surface acoustic waves and is picked up by the neighbouring sensors. Each sensor can function both as an actuator and as a detector, creating a multitude of actuator-sensor pairs. By looking at the modulation of the transmitted signal, information about the structural health of the object can be extracted. Information about parameters such as loading, delamination, crack initiation and growth as well as corrosion can be deduced. The SMART Layer technology has been tested in monitoring the health and condition of diverse structures ranging from aircraft and rotorcraft to pipelines, bridges, wind turbines, automobiles etc. This technology seems to be a very promising candidate for helicopter SHM, but further tests are needed in order to prove the long term stability and airworthiness of the sensors.

4. The communication system

The main objective of the designed SHM system was to develop the hardware and software solutions for the real-time monitoring of the structural integrity of helicopter fuselage.

The communication system is capable to deliver measured data from the sensors to the access points for further processing. The problem related to communication systems was classified as follows.

- Which technology (wired or wireless) would be convenient for data transport? Wired technology seems to be a good choice, but there are problems to be solved (e.g. reliability of physical connection among sensors, lots of wires, etc.). Besides, there is a possibility to enhance the connectivity reliability by using both technologies (wired – main, wireless – secondary).
- There were problems in the wireless solution to be solved.
  - Radio wave propagation in closed metal environment concerning signal attenuation, time dispersion of the signal.
  - Signal frequency selection in other to avoid mutual interference to/from other communication systems.
  - Communication technology selection based on wireless standard for indoor and outdoor communication.
  - Network topology selection, etc.

The communication technology and the standards selection for communication infrastructure are pointed out in Fig. 4. There are two main technologies to be used for indoor communication – CAN bus for wired solution and IEEE 802.15.4 (ZigBee) for wireless communication. To deliver collected data to service side, the IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (ZigBee) or IEEE 802.11a, g, b (WiFi) were taken as possible candidates.

Problem connected with radio wave propagation in closed metal environment is due to the almost ideal wave reflection from a con-

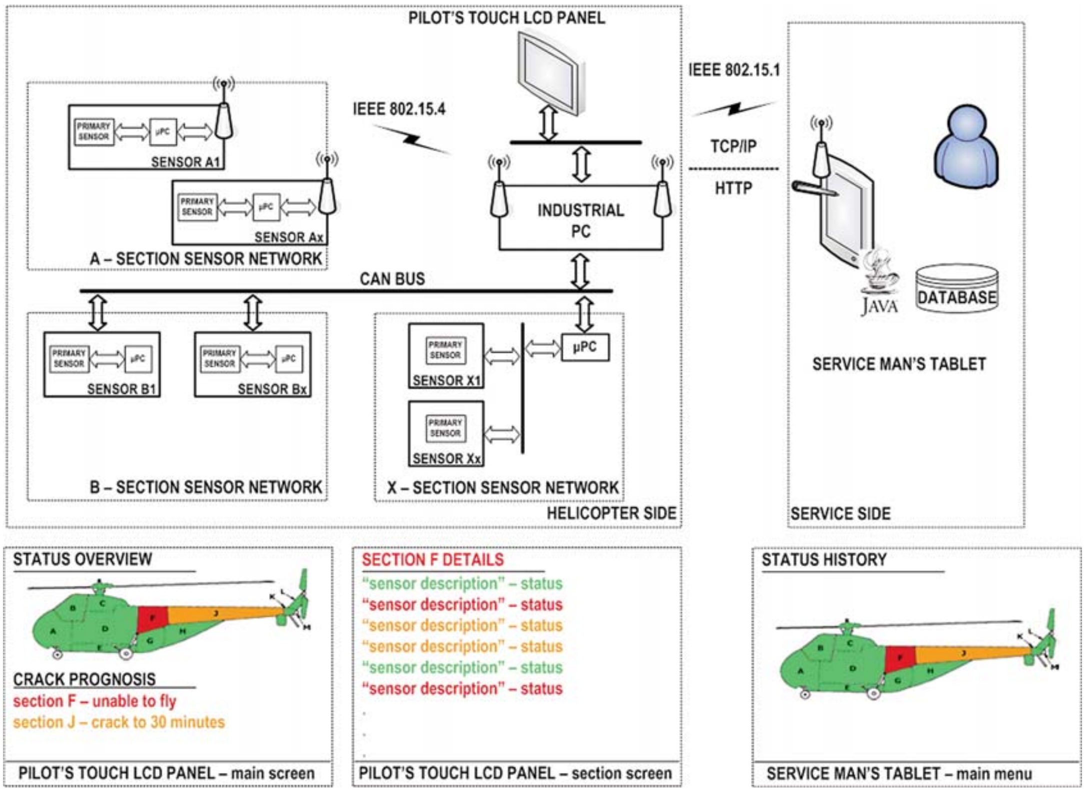


Fig.4 The principal block diagram of communication concept

ductive plate. The result is the signal propagation only through holes or apertures in metal plates as shown in Fig. 5.

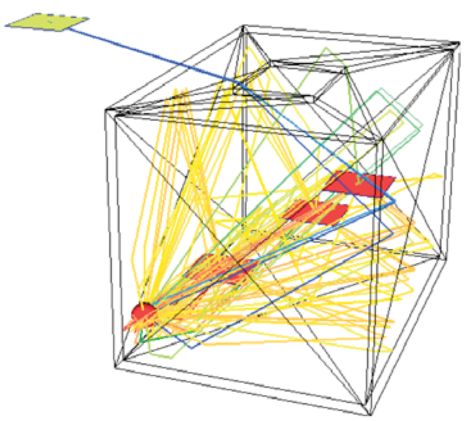


Fig. 5 Signal propagation through aperture in a conductive material

Signal propagation in such an environment may be roughly described through the following formula:

$$L(d) = L(d_0) + 10 \cdot \alpha_0 \cdot \log(d) + n_w \cdot L_w$$

where $L(d)$ is the signal attenuation (in dB) in distance d, $L(d_0)$ is signal attenuation in a reference distance (1 m), α_0 is the path-loss exponent, n_w represents the number of obstacles, L_w is the obstacle attenuation. This expression doesn't take into account the signal reflection from walls. For precise evaluation of signal attenuation it is commonly used the ray tracing method [8], which was also used for the investigated simulation (Fig. 5).

From Fig. 5 (red ball is transmitter, red squares and green square indicate receivers) it is obvious that the signal transmitted by transmitter is able to propagate outside the cube only following one path through the aperture (blue line), while other paths (yellow and green lines) are blocked. Signal attenuation becomes high outside the cube (changing squares colour from red to green). In conclusion, to deliver radio signals in metal conducting materials with barriers it is possible only by convenient arrangement of transmitters and receivers.

Indoor wireless communication system was proposed to be based on the IEEE 802.15.4 standard. Two different device types can participate in an IEEE 802.15.4 network; a full-function device (FFD) and a reduced-function device (RFD). The FFD can operate in three modes serving as a personal area network (PAN) coordinator, a coordinator, or a device. An FFD can talk to RFDs or other FFDs, while an RFD can talk only to an FFD. An RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor; they do not have the need to send large amounts of data and may only associate with a single FFD at a time. Consequently, the RFD can be implemented using minimal resources and memory capacity. Depending on the application requirements, an IEEE 802.15.4 network may operate in either two topologies: the star topology or the peer-to-peer topology.

In the star topology the communication is established between some devices and a single central controller, called the PAN coordinator. A device typically has some associated application and is either the initiation point or the termination point for network communications. A PAN coordinator may also have a specific application, but it can be used to initiate, terminate, or route communication around the network. The PAN coordinator is the primary controller of the PAN. All devices operating on a network of either topology shall have uniquely 64- bit addresses. The PAN coordinator might often be mains powered, while the devices will most likely be battery powered. Applications that benefit from a star topology include home automation, personal computer (PC) peripherals, toys and games, and personal health care.

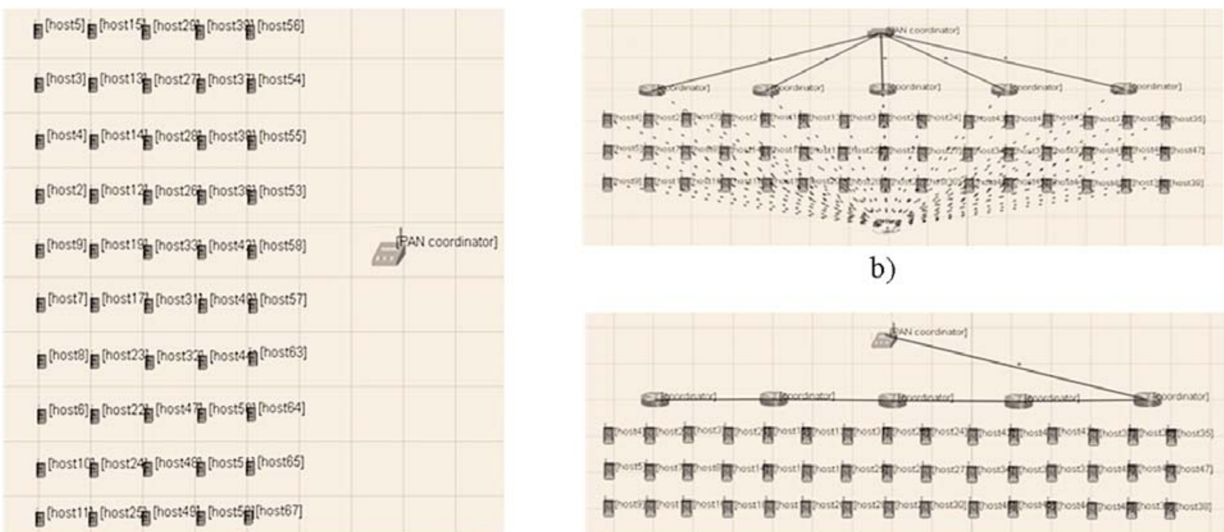
The peer-to-peer topology also has a PAN coordinator; however, it differs from the star topology in that any device may communicate with any other device as long as they are in range of one another. Peer-to-peer topology allows more complex network formations to be implemented, such as mesh networking topology. Applications such as industrial control and monitoring, wireless sensor networks, asset and inventory tracking, intelligent agriculture, and security would benefit from such a network topology. A peer-to-peer network can be ad hoc, self-organizing, and self-healing. It may also allow multiple hops to route messages from any device to any other device on the network.

Up to now some proposals and simulations were prepared with IEEE 802.15.4 (ZigBee) standard as solution for indoor wireless propagation. Several topologies for wireless networks have been compared – Star, Clustered star and Clustered star bus shown in Fig. 6, discarding Peer-to-Peer topology because of problems with radio signal transmission through apertures in structures. Instead, star topology was simulated with hybrid link connection – wired solution for connection among coordinators and PAN coordinator and wireless connection for individual networks belonged to coordinators. The division of the whole network to several sub-networks helped to avoid problems with propagation of radio signal through metal apertures in indoor environment.

5. SHM implementation

In this section the On-Board and the Maintenance Units software applications are presented. These software applications cover on the one hand visualisation of crack detections and propagation and on the other hand they prepare basic database structures for storage of all data from sensors which can be downloaded whenever it is necessary.

The On-Board Unit interface allows data acquisition from various Smart Sensor Units and stores them in a database. Collection and storage is going on at regular intervals. Communication with sensor networks is done through MODBUS protocol over RS485 network. The time intervals are adjustable, however, there are some theoretical limits. For demonstration purposes a period of 1 second was selected. It is obvious that this value is far above the real possibilities of the used network and the database subsystem. This is the main task of this application. Another task of the



a) c)

Fig. 6 Sensor network topology scenarios: Star (a), Clustered star (b), Clustered star bus (c) application is a visual representation of the state of a helicopter tail. The visual representation is for simplicity done using three states. These three states are presented as a change of colour of the helicopter tail in the picture inside the application GUI, depending on whether the part is intact or not. The green colour means that it is not damaged. The orange colour represents that there is already some damage in the part, however, the operation is still safe as shown in Fig. 7. The red colour means that the damage is already serious and the helicopter should land as soon as possible.

The Maintenance Unit provides deeper diagnosis and prognosis in the SHM system. The communication is managed by a standalone application and provides full access to establishing and closing communication channels between the On-Board Unit and the Maintenance Unit. The data transfer is made of stream of pre-processed readings from sensors. Connection is established and communication executed after successful mutual authentication and authorization. After terminal connection, the sensor data are transferred only in one way with continuous depositing in the database.

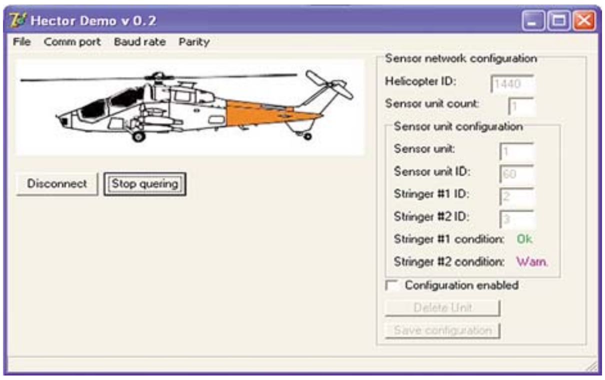


Fig. 7 Graphic user interface for On-Board Unit

The JAVA platform was chosen for this application. The main advantage of this programming language is multiplatform use (the application is runnable on all operating systems with Java runtime) [9]. The communication with SQL database is also provided by standard library the Java Database Connectivity (JDBC). The system contains four function blocks; the graphical interface for data visualisation and application control, the communication unit for the communication with On-Board Unit, the database unit for data storing and access control and data processing unit for the diagnosis and prognosis. The Maintenance interface is shown in Fig. 8.

6. Conclusion

The System Health Monitoring is the next future key factor of all the cutting edge structures, in particular concerning helicopters and going ahead tiltrotors. The raw instruments such as sensors, algorithms and stress analysis implemented into a compact functioning SHM system were studied and laboratory tested in this project. In this paper, the short system overview was presented. Analyses of sensor network definition and network communication were described. Finally, the visualisations for the On-Board and the Maintenance Units were shown. The future task is to improve analytical and laboratory based studies to set-up innovative SHM technology for helicopter applications, taking into consideration the main characteristics such as high frequency vibratory loads, different load manoeuvres, missing of pressurisation in the fuselage, etc. of this very complex machine.

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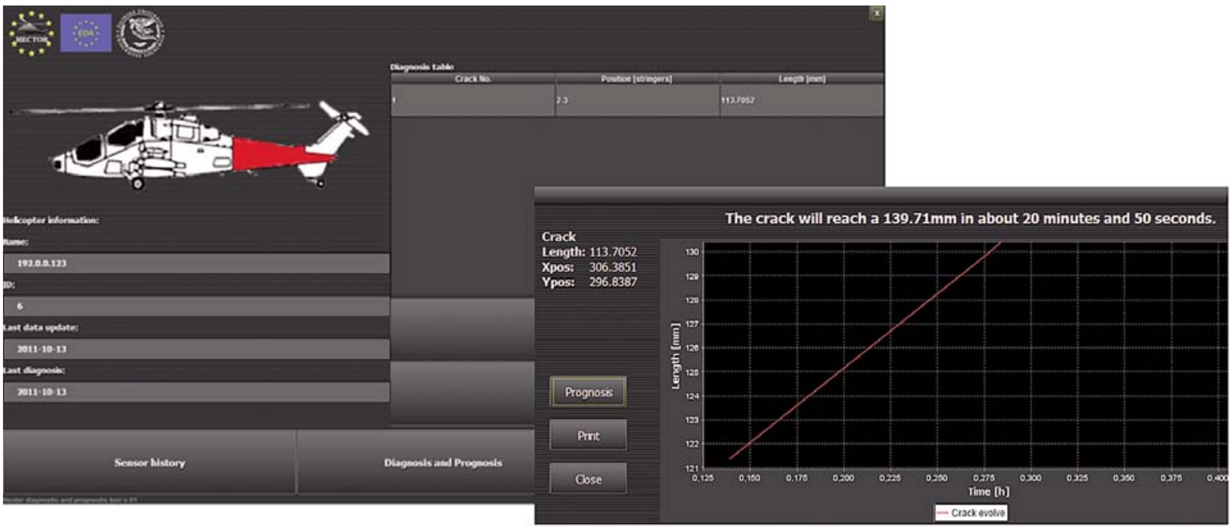

Fig. 8 Graphic user interface for Maintenance Unit

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