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EMBEDDED BLADE MICROSYSTEM AND EVENTS RECORDER FOR DRONE STRUCTURAL HEALTH MONITORING

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ABSTRACT

Structural health monitoring is today growing challenge. A good health structure allows to assure in real-time a good performance level, to keep a high level of safety and to plan maintenance. Why drone applications? Drones are very expansive aircrafts, also referred to as UVA (unmanned air vehicle), exposed to a harsh environment due to their frequent military usage. In this context, propellers are among the key components worth health monitoring.

The purpose of our research is to develop for the drone propeller an integrated electronics combining accelerometers and signal processing, able to record damaging events for the drone: shocks, vibrations or overspeeds whereas strain gauges could not analyze all these criteria. These parameters allow concluding whether the blade is damaged or not.

This paper will present our embedded microsystem on drone propellers. Then we will show through real experiments how it is possible to monitor and detect events like stone shocks, propeller overspeeds or too strong vibrations. Specific algorithm for diagnosis will be discussed and evaluated in different environment tests conditions. Moreover the use of a wireless synchronization between several propellers will be studied too.

KEY WORDS: Accelerometer, Aircraft, Blade, Embedded, Microsystem.

1) INTRODUCTION

Structural health monitoring (SHM) is a recent domain in which scientific research is very active. It consists in a single or multiple sensors monitoring several parameters of a structure to check whether it is damaged or not [1]. This structure can be a bridge, a building, a plane or any sensitive device worth to implement SHM. The objective is trying to detect damages which could compromise performance or could initiate a failure. Damages can result from a normal fatigue or exceptional events like impacts. When a structure has been identified as damaged, it should be replaced or repaired. Moreover monitoring a structure is not only

useful to detect damages and to lead actions in consequence: it allows to better know the aging process, in order to anticipate maintenance and finally to save money [1].

Monitoring blades is part of SHM domain. Whatever blades are fitted on ships [2], wind turbines [3-5], helicopters [6, 7] or aircrafts [8], they are increasingly instrumented, because they are vital organs. This last part is also true for drone aircraft. Drones are expensive and must assure missions in harsh environment. They can be damaged either by emergency landing, during low altitude missions in urban environment and by firearms actions in military contents. They must assure service with poor weather conditions and those, all around the globe in any temperature or humidity conditions, and in addition their low mass gives them higher sensitivity to vibrations than bigger airplanes. Above all, there is no pilot on board to notice abnormal situations. Consequently, drone propeller blades are sensitive organs highly solicited during all phases of flight.

2) EMBEDDED DRONE PROPELLER RECORDING SYSTEM

Working on a real military drone presents lots of problems: availability, price... So we have decided to work on a radio controlled aircraft without military equipments (Fig. 1). This aircraft is equipped with two propellers. Its length is 95cm for a 140cm width.

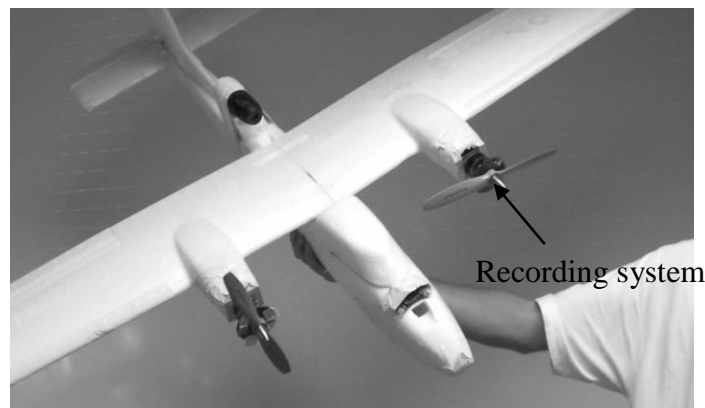


Fig. 1: Picture of the drone

Both propellers size 25 cm for a maximum width of 2 cm. They can rotate at 6 000 round per minute (RPM) powered by a brushless motor. Centrifugal acceleration can reach 5 000g at blade extremity. It results that embedding electronics onto a blade requires being careful about some issues:

- every piece must be well attached,
- most of electronics components must be placed close to the rotation centre where centrifugal acceleration is lower.
- weight must be as low as possible to avoid ejection.

This last point raises the issue of volume. Our propeller is a tiny piece of 50 cm² area. So, the amount of embedded electronic devices must be as low as possible to keep total volume to a minimum.

Theses constraints imply to devise an electronic system with main functions close to propeller centre. These functions are:

- power source and supply conditioning,
- real time clock (RTC),
- microcontroller,

- memory,
- control accelerometer.

Functions are organised on a circular electronic board to meet the above constraints. Two extra deported accelerometers on different electronic boards are stuck on blades to retrieve true blade signal. These devices are piezoelectric accelerometers in order to eliminate centrifugal acceleration which is continuous and too high to be measured.

System operates as follow: a microcontroller retrieves data from deported accelerometers and converts them into digital data at a sampling frequency of 1 kHz. Then it records it into a memory together with time stamping provided by RTC. Control accelerometer is a low power device which allows detecting rotation to automatically launch data acquisition. Power supply is provided from a cylindrical cell and is conditioned to give a stable and continuous voltage to electronic devices. Overall system exhibits a diameter of 6cm with 4mm in height (Fig. 2). Deported accelerometers are on a board of 1.5cm*2cm*0.5cm (L*W*H).

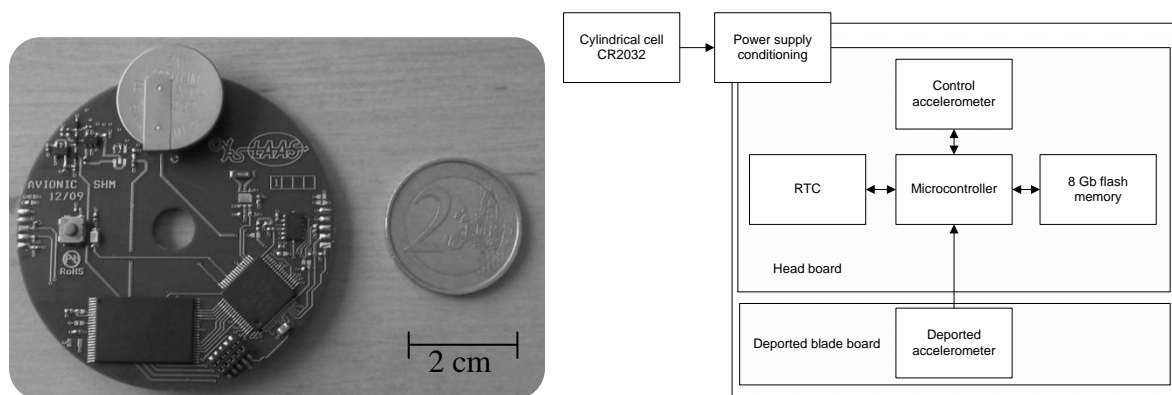


Fig. 2: Picture of the blade recorder without deported accelerometer (left) and blade recorder functional diagram (right)

3) BLADE MONITORING ALGORITHMS

Current paragraph is dedicated to detail signal processing to perform “blade monitoring” and to explain how to detect impacts, overspeeds and too strong vibrations. Processed data comes from the presented above recorder and have been collected during a drone flight or ground tests.

1.1. Impact detection

We present here blade impact detection. Data is extracted from a ground test. Propeller rotates in a horizontal plan to avoid oscillation due to earth attraction which is useless here. Illustration of this phenomenon is detailed in [9, 10].

Frequency analysis of an impact signal is shown Fig. 3. Every impact stimulates eigenfrequencies of propeller. For this propeller, a single frequency emerges from every test we lead: 246 Hz. So impact detection is done by monitoring this proper frequency. This surveillance can be done by two possible ways:

- Digital processing: a continuous FFT is continuously processed over data retrieved from accelerometer. Results are analysed to detect eigenfrequency. So, an impact has occurred.
- Analog processing: a pass-band analog filter is designed around eigenfrequency [240 Hz; 250 Hz]. If a signal is detected after this filter, an impact has occurred.

We also managed to decrease false detection probability, assuming that events happening at these frequencies and not correlated to impacts would be related to global vibrations affecting the drone. One way to get rid from these false detections could be a timed correlation between both propeller processing: a supposed impact happening simultaneously on both blades is unlikely. To design this system a wireless transmission can be established between propellers. Paragraph 4) details such a system.

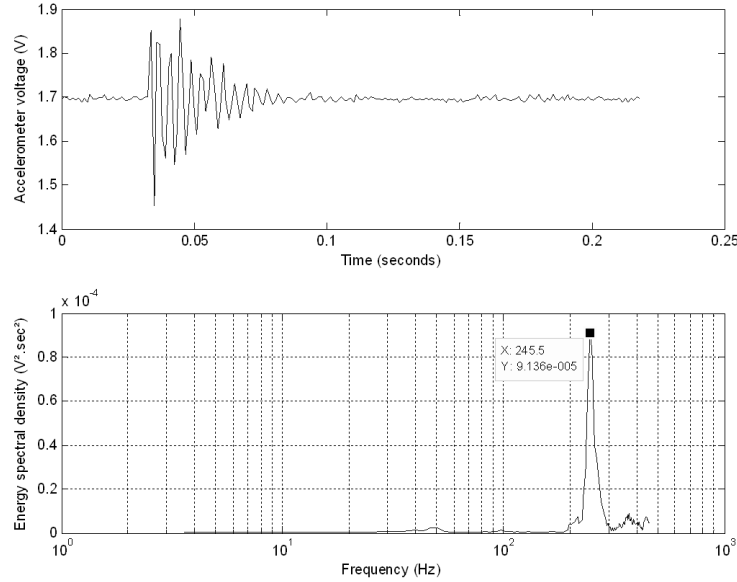


Fig. 3: Time and frequency response to an impact

1.2. Overspeeds monitoring

Another damaging event for propeller is overspeed. This paragraph explains how to detect through an instrumented blade. During our tests, we noticed that one frequency was correlated to blade rotating speed as shown on Fig. 4. On this figure blade rotates at 63.44 Hz that is 3806 rounds per minute. The other visible frequency has an unknown origin. It is supposed to originate from electrical motor or from airplane structure. It ranges from 150 Hz to 240 Hz depending upon rotating speed. We can notice that when this frequency is close to 240 Hz, i.e. the blade eigenfrequency (see 1.1. Impact detection), plane cannot be controlled anymore. It probably happens because then propeller loses its efficiency. Whatever the precise origin of this phenomenon, it can be avoided by monitoring the rotating speed of the propeller, that is by measuring the low frequency peak of Fig. 4.

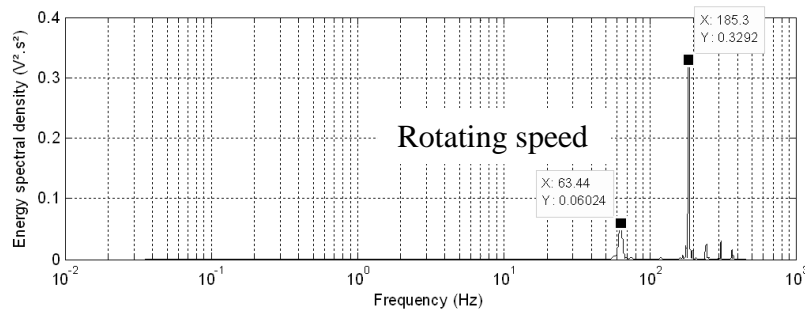


Fig. 4: Blade Frequency analysis showing rotating speed.

1.3. Vibrations surveillance

Too high vibrations can damage blade, that's why monitoring them is vital. These vibrations can originate from too important aerodynamic charges or from a damaged structure. Accelerometer stuck on blade vibrates as much as structure does. So "over-vibrations" will directly be transmitted to the accelerometer. An embedded system is able to detect these "over-vibrations" by checking that vibrations amplitude does not exceed a threshold (Fig. 5): if exceeded, it means "over-vibrations" are happening. This procedure may also be sued for impact detection.

Determining the right threshold requires a large amount of data. At this point, we are still not able to determine it. Multiple tests have still to be run in various conditions to check if a vibration is too important or not.

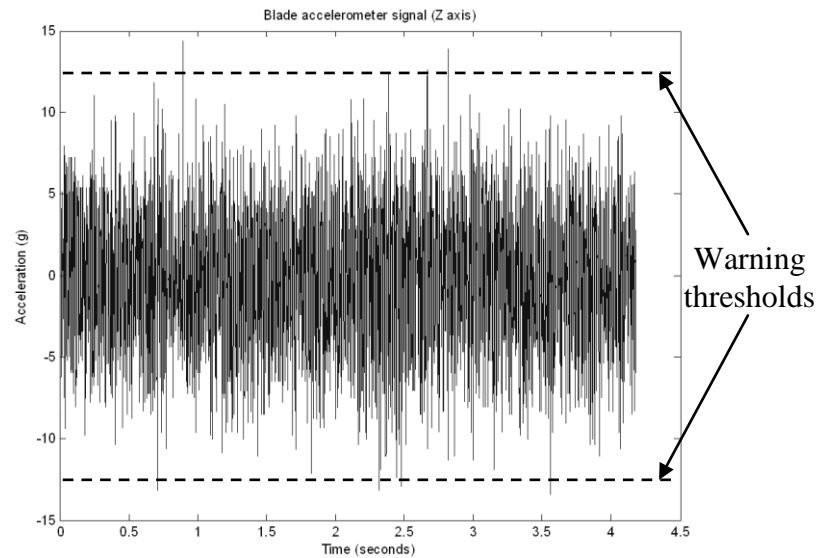


Fig. 5: Vibrations on a blade during a flight and possible warning threshold

1.4. Generic algorithm for blade parameters monitoring

Based on previous considerations, we suggest an algorithm (Fig. 6) ready to be computed and embedded into a blade monitoring system. First the system stores 120 samples (sampling is performed at 600 Hz) in memory to obtain a 200 ms window. Consequently previously studied events can be monitored: impacts can reach 250 Hz and lasts less than 200 ms. Minima and maxima of signal window are analysed and compared to previously adjusted thresholds.

If a threshold is exceeded, we supposed it can provide from an impact or from an overvibration. Monitoring blade eigenfrequency at 245 Hz gives the answer: if power is detected (as seen in 1.1. Impact detection), an impact happened on blade. Otherwise an overvibration occurred. Then these events are recorded in a memory.

In addition to threshold crossing, software looks after overspeeds. They are monitored by watching frequencies between 100 Hz and 110 Hz, that is between 6000 rpm and 6600 rpm. When these frequencies are observed, the event occurrence together with the measured speed is electronically recorded.

Of course these numerical values are blade dependant. Values presented here in this algorithm are linked to the blade we test. Storing events in embedded memory goes with a time stamping. To save memory capacity, events are classified by level: for example an event

for overspeed is stored like “overspeed category 1”, “category 2”, etc... rather than storing the exact value of overspeed.

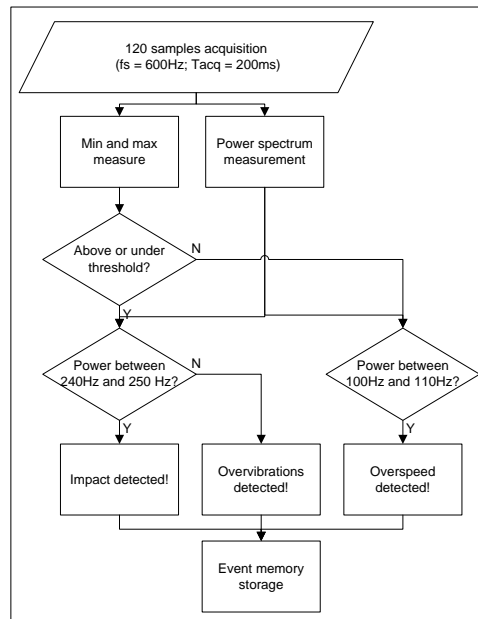


Fig. 6: Algorithm to monitor a drone blade

4) MONITORING BOTH PROPELLERS IN REAL TIME

We discuss here the feasibility of implementing a real time dual propeller monitoring. It consists in a wireless architecture based on two blade sensors and a single controller (Fig. 7). This structure would allow reducing volume and weight on each blade whereas main system will be inside drone. The challenge here is about time synchronisation between emissions, to avoid excessive energy consumption due to reemission of packets when collisions take place. Timing between signals is also very important to adequately process data and conclude on a right diagnosis.

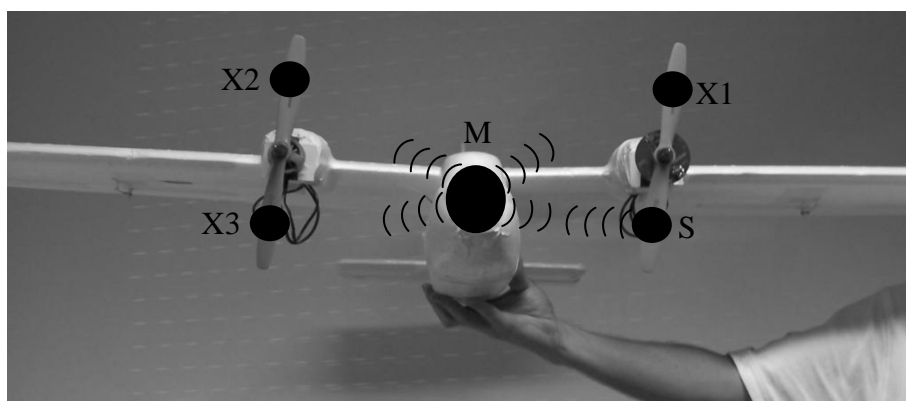


Fig. 7: Functional diagram of wireless system

One of the most important issues in Wireless Sensor Networks (WSN) is related to their energy consumption. On the other hand, another important application requirement is to ensure data sensing synchronization, which leads to additional energy consumption (to ensure the synchronization performance a high number of messages is sent and received at each

node). Our idea is to take advantage of the performance, in terms of synchronization accuracy, of the IEEE1588 standard [11] that was designed for wired networks and then of the energy saving capability of the PBS [12] (Pairwise Broadcast Synchronization) protocol that was designed for sensor networks. The main goals of our new synchronization protocol are: to ensure the accuracy of local clocks up to a tenth of a microsecond and to provide an important energy saving.

In the following we present our energy-efficient extension of the clock synchronization protocol IEEE 1588 and how it works for a group reduced to only 3 nodes (Fig. 8). In such a group, the master (M) and the slave (S) nodes will synchronize using the IEEE1588 standard; the third node (X) will use the already existing synchronization (with high accuracy) between master and slave. This is done as in PBS with the assumption that node X is in the communication range of nodes M and S. Just by listening to the transmissions, X will synchronize its internal clock with that of node M with the help of the received messages.

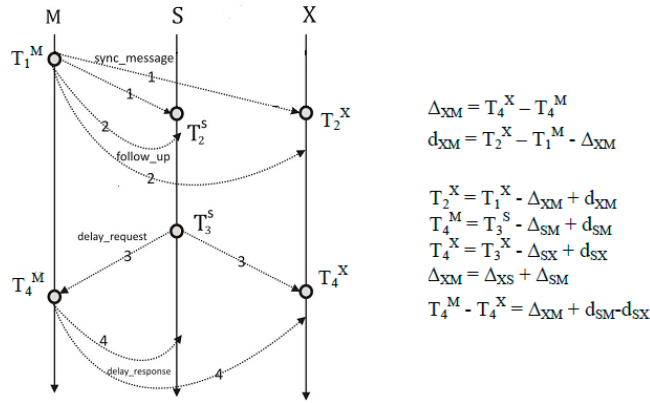


Fig. 8: Exchanging messages and the calculations performed to synchronize the nodes in 1588-PBS protocol

Let Δ_{XM} be the clock offset between X and M and d_{XM} the propagation delay between X and M. We assume that the messages sent by S arrive at the master and at the PBS node at the same time, which implies that $d_{SM} - d_{SX} = 0$. This hypothesis can be taken due to low distance between nodes.

Next we present our results in terms of timing and energy consumption, obtained by implementing our solution in the NS-2 Simulator. We mention that for the application presented in this paper, the number of nodes X is 3.

Our simulations were performed for one fixed concentrator and 4 mobile nodes. It is shown in Fig. 9 that the accuracy of the synchronization is around tens of nanoseconds for the Master-Node1588 (S) pair and varies between $1\mu s$ and hundreds of ns for the Master-NodePBS (X_i) pair. We notice a degradation of the synchronization accuracy in the order of 10^{-1} over the same system with no moving.

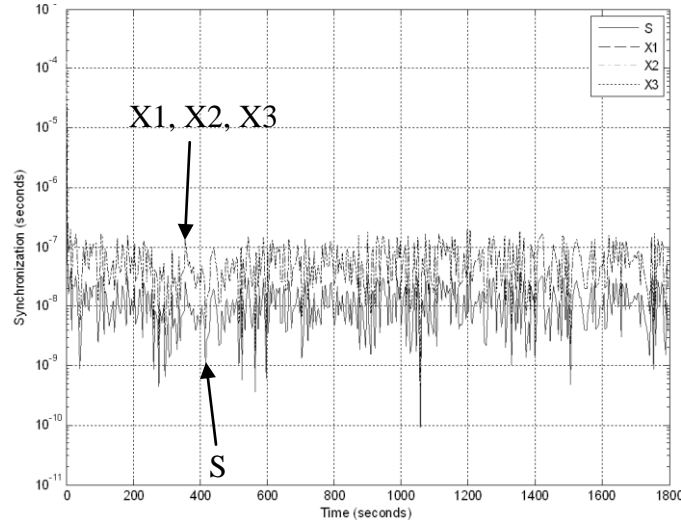


Fig. 9: IEEE1588-PBS C<->Ns synchronization

Network wide synchronization is achieved in about 20 seconds after the beginning of the simulation. So it is clearly shown by these results that the achieved accuracy is very good.

We also assessed the energy consumption of our system, but especially the consumption in the nodes. We decided to use the energy consumption parameters of a Berkeley mote [13] in order to simulate real life conditions (the power consumption of sending a message is evaluated by NS-2 as 7 mW and that of receiving a message as 4.5 mW). Total initial energy is 2700J, which matches a CR2032 cell (3V, 250 mAh). Fig. 10 shows that the difference in energy consumption between a PBS node and a 1588 node is in the order of 5.26 J. In other words, a PBS node consumes 79% less than a 1588 node. This is directly related to the number of messages required to achieve synchronization.

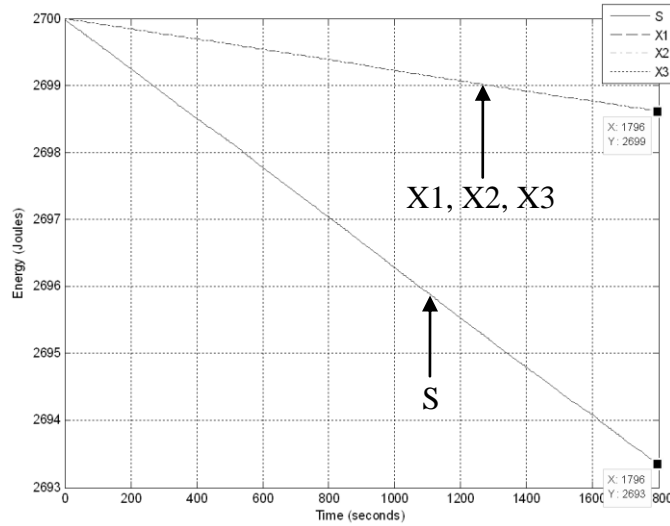


Fig. 10: Energy Consumption for PBS and 1588 Nodes

With good synchronization accuracy our solution offers a valuable energy saving. The advantage of this solution is that, depending on the type of node (S or X_i), battery can be matched with node function. This implies an increase in the lifetime of the system and a reduction in production costs.

5) CONCLUSION

This study is a first step for designing a blade real time monitoring system. In this paper we present an embedded recording system we devised. This autonomous electronic board allows retrieving sufficient data to develop a first version of real time monitoring algorithm. For future work, we will devise system that will perform signal processing to detect impacts on the blade, overspeeds and overvibrations. A wireless transmission will be implemented to increase quality of diagnosis. A focus will be given on power considerations. For our tests, a single cell is sufficient. But for an embedded system which will get longer operational time, new solutions has to be studied. Main problem about this point is the weight we can afford on such a little blade.

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