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## ► To cite this version:

Christophe Paget, Roshan Patel. Damage Location in Thick Composite Material Based on Acoustic Emission and Wireless Nodes. EWSHM - 7th European Workshop on Structural Health Monitoring, IFFSTTAR, Inria, Université de Nantes, Jul 2014, Nantes, France. hal-01020358

**HAL Id: hal-01020358**

**<https://inria.hal.science/hal-01020358>**

Submitted on 8 Jul 2014

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## DAMAGE LOCATION IN THICK COMPOSITE MATERIAL BASED ON ACOUSTIC EMISSION AND WIRELESS NODES

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### ABSTRACT

This investigation is studying the behaviour of a bespoke wireless impact locator design for monitoring structures against any kinds of impacts. The device performance was evaluated against its location repeatability, its ability to last the required service life, its power consumption and its wireless range. The main variables in this investigation were the sensor sensitivity, the wireless node data repeatability and the power supply output voltage. The investigation identified which power source to be used, what is the strategy to determine the remaining power life, as well as the feasibility to use such technology for impact location.

**KEYWORDS :** *acoustic emission, composite, damage, wireless, structural health monitoring.*

### INTRODUCTION

In the era of lean principles, quality and non-quality, it is important to determine if an unscheduled event has really occurred or not, to quickly and reliably remove any non-quality or also known as waste in any manufacturing plants.

For nearly two decades now, structural health monitoring (SHM) has demonstrated great potentials in many sectors of activities, predominantly in the civil engineering and aerospace sectors [1-3]. Most of them were based on wired SHM. However, for the last 8-10 years, many investigations were focused on the wireless version of SHM [4,5], benefiting the advances in home entertainment. Other research team work on the power harvesting solution to provide complete self-sufficiency to the wireless nodes [6,7].

The present paper discusses the use of structural health monitoring for monitoring the quality of structural assembly. The main driver for this is based on the lean principles, where non-quality or waste within the manufacturing process must be removed. The aerospace sector runs a safety first protocol, meaning by that for example if a tool was dropped near a composite structure and no fitters have seen if the tool has hit the composite structure or not, then precautionary measures are taken, and NDT checks are requested in the whole area of concern. From a lean point of view, the use of SHM in this situation would have categorically indicated if that tool has actually hit the structure or not, avoiding unnecessary work by the NDT team.

Many SHM technologies are available. Such application would require the use of wireless technology to avoid broken cable by the heavy traffic around the assembled structure. Moreover, the type of damage would be mainly caused by tool dropping on an unloaded structure. Therefore the best candidate is impact detection/location by low frequency acoustic emission [5].

The equipment in question is constituted of PZT sensors [8], and its interface designed by McWade associates [9], and a wireless node designed by Airbus Group Innovation.

The paper is focussing on understanding certain parameters influencing the functioning of the wireless impact locator, such as the device power supply voltage level, the power consumption, the wireless range, the location repeatability and the selection of power source for the given application.

## 1 SET UP DESCRIPTION

This section describes how the experiments were conducted in order to measure the wireless node and sensor performance, its power consumption and wireless range. The setup section also includes the brief study on commercial one-off batteries versus rechargeable batteries.

The set of experiments were based on a composite plate containing two T-shaped stringers, six PZT transducers designed and manufactured by McWade Associates in Stockport (UK) and six wireless nodes designed by Airbus Group Innovations in Ottobrunn (Germany).

The composite plate was made of prepreg AS4 material, while the material properties and layer sequence remains undisclosed to this paper. The plate thickness was however 25mm.

The sensors were bonded with silicone RTV3140 to the composite skin (outer side) for temporary installation. The silicone thickness was similar for all sensors, using the same installation technique and weight applied on top of the sensor during room temperature curing. See Figure 1 for sensor position. Only three sensors were in-line to each other in order to measure, in a later experiment, the time of flight difference without being interfered with the changing group velocity. The fourth sensor was placed perpendicular to the acoustic emission (AE) source to be used as reference sensor for sensor performance measurement. The acoustic emission was generated by a 20mm diameter ball bearing positioned in line with the four sensors, as shown in Figure 1, on both longitudinal and transverse plate directions. This AE source is known for the rest of this study as the impactor. The longitudinal direction is parallel to the stringer direction.

Each wireless node was connected to the sensors via micro coaxial cable, as shown in Figure 2.

The impactor energy and location repeatability was ensured by the use of a guide. A simple method of capturing the ball bearing was used to avoid re-bouncing of the impactor. The impact repeatability was tested numerous times and energy level as well as sensor position was within 5%.

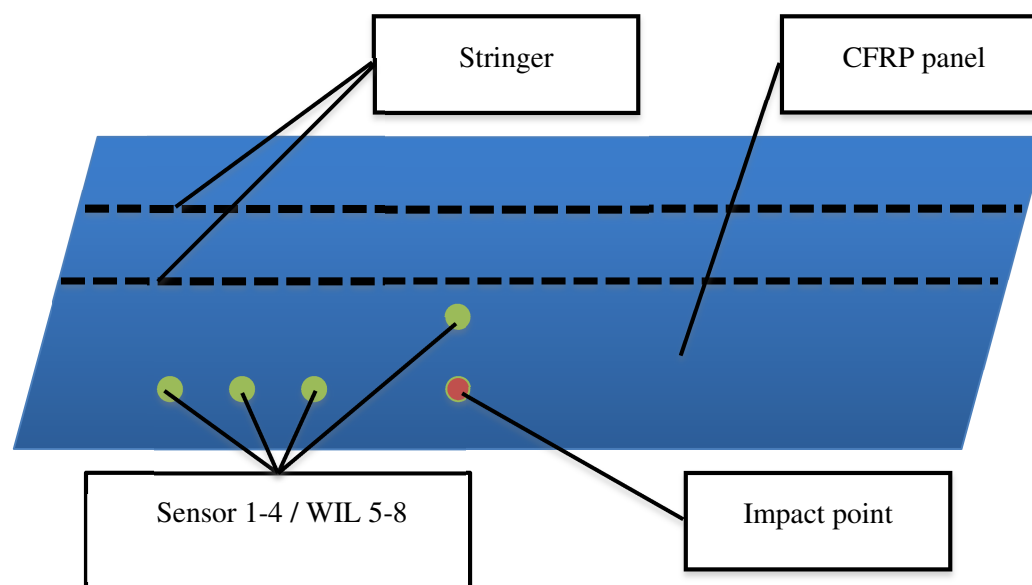


Figure 1: Composite panel with bonded stringers shown by the dotted lines.

On each experiment, 10 impacts were created per configurations to ensure robust results. The average and standard deviation was calculated to quantify the quality of the setup. In total, 17 different configurations were used to characterise as many parameters as possible.

The first set of parameters were chosen to down-select the equipment in order to have the best repeatability:

- Sensor performance
- Wireless node measurement of time of flight difference and impact amplitude

The sensor performance was measured using an oscilloscope. The wireless node performance was evaluated based on the data received wirelessly from the node to the receiver, further connected to a computer USB port, and displayed using a freeware software to read the wireless packet.

The second set of parameters was chosen to determine the equipment consumption, impact location accuracy and battery selection.

- Current and voltage
- Time of flight difference
- Battery discharge rate
- Wireless range

The power consumption was inferred by measuring both the output voltage and current. The current was in fact obtained by measuring the voltage of a resistor ( $54\ \Omega$ ) in serial, of a known value. The voltages were measured by a standard commercial off-the-shelf data logger.

The wireless range was in fact rather binary, in measuring the distance between the wireless node and its receiver, and the criteria was binary: In-Range, if wireless package received, or Out-of-Range, if otherwise. A total of 24 wireless signals were sent for each configuration, for statistical reasons.

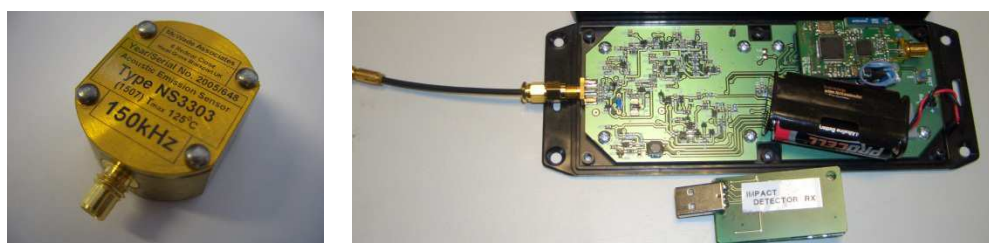


Figure 2: PZT sensor (left) and wireless node (right)

## 2 RESULTS

### 2.1 Sensor/Wireless node Downselection

A series of experiments were conducted with a large variety of variables. In order to reduce the number of variables to its minimum, the basic performance of PZT sensor and wireless node were measured in order to carry a downselection, and retain four sensors and wireless nodes with similar properties.

A total of 6 sensors and 6 wireless nodes were used to determine their basic performance as wireless impact locators.

Figure 3 shows the typical response of the 6 PZT sensors encapsulated by McWade Associates, after an impact generated by a ball bearing simulating a dropped tool. Out of 6 sensors tested, only one sensor (Sensor # 103) was relatively different from the others, in terms of amplitude but also frequency response. For the remaining of the investigation, only sensors reference # 150, 151, 154 and 155 were used.

The wireless nodes were evaluated based on their ability to locate AE events, mainly in terms of AE event amplitude and time of flight difference ( $\Delta T$ ), or also “time difference” as shown in Table 1. These two parameters were used to evaluate the performance and repeatability of the wireless nodes, with the aims of selecting the 4 devices with the least standard deviation from each other. Table 1 provides the results of 17 configurations of sensors and wireless nodes, with the  $\Delta T$  and sensor amplitude measured by the wireless node. As temperature can interfere in the results, it was measured during the experiment, and was within  $1.4^\circ\text{C}$ , therefore expected not to be influencing the results.

Table 1 shows that wireless nodes # 5,6, 7 and 8 have the most consistent  $\Delta T$  results as first, second and third AE events, and in line with the expected results within 6  $\mu$ s. These 4 wireless nodes were used for the remaining of the investigation.

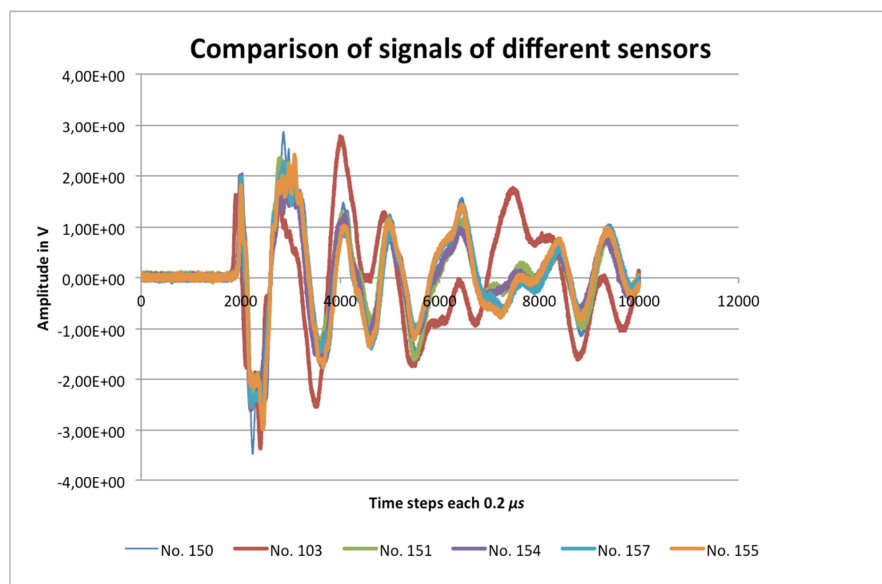


Figure 3: Sensor check showing the response from identical ball bearing drops at the same distance away.

Table 1:  $\Delta T$  for three hit sensors in various configurations (in  $\mu$ s).

Configuration	Reference Sensor	Temp. (°C)	Time Difference 1	Time Difference 2	Time Difference 3
2-4-5	6-154	23.30	61.556	128.047	182.648
2-5-4	6-154	23.00	62.301	105.351	224.313
2-5-8	6-154	23.60	58.188	105.087	181.075
4-2-5	6-154	23.30	62.835	131.124	183.925
4-5-2	6-154	23.30	62.374	105.070	225.097
5-2-4	6-154	23.00	47.701	130.414	224.514
5-4-2	6-154	22.80	46.847	127.420	223.977
6-2-4	7-154	23.90	43.998	127.424	220.586
6-5-4	7-154	23.80	42.620	100.024	219.188
6-5-8	7-154	23.60	46.143	103.570	183.141
7-2-8	6-154	23.70	44.111	126.726	181.576
7-8-2	6-154	23.60	43.501	119.876	220.892
8-2-7	6-154	23.20	43.813	128.565	181.426
8-5-4	7-154	23.90	43.587	102.389	221.362
8-7-2	6-154	23.30	45.688	105.628	224.000
8-5-7	6-154	22.50	49.958	105.648	184.980
5-8-7	6-154	22.50	46.676	123.355	183.194

## 2.2 Impact location performance

In order to assess the performance of the wireless impact locator in locating an impact, a sensor and wireless node selection has been carried out in the previous section. This in turns has reduced the number of variables in the results discussed herein.

The location accuracy is measured in terms of time-of-flight different ( $\Delta T$ ) rather location coordinates themselves, since the main interest of this investigation is to evaluate the performance of a network of wireless impact locators, constituted of a PZT sensor and a wireless node, each within a network of 4. The  $\Delta T$  is measured based on the time at which the signal reaches its maximum value (peak amplitude). The peak amplitude is also recorded as shown in Table 2.

Table 2 shows the  $\Delta T$  for 4 wireless impact locators after ten impacts located at the same place, as shown in Figure 1. Table 2 column 4 provides the hit order of the wireless impact locator (reference number between 5 and 8) following a single impact, numbered from the first to the last hit wireless impact locator. Table 2 columns 5-7 shows the  $\Delta T$  for the corresponding hit order of column 4. Table 2 columns 8-11 provide the wireless impact locator amplitude of the corresponding hit order of column 4.

The average  $\Delta T$  for all wireless impact locators was in line with the theoretical data. Its standard deviation was low, below 2.8%. The average amplitudes for all wireless impact locators were of similar values, with a standard deviation below 0.9%. The level of amplitude is typical amplitudes for AE events, rather than impact events. However, for reducing the power consumption of the wireless node, no amplifiers were used and therefore the amplitudes expected are low, as shown in Table 2.

Table 2 also reinforces the repeatability of the impactor used in this investigation. Figure 4 further demonstrates that not only the peak amplitude is repeatable, but also the whole signal. In turns, the behaviour of the wireless impact locator is repeatable, which is key for structural health monitoring.

**Table 2: Measurements of the delta T and amplitude using multiple drops of the ball bearing using the drop tool.**

Sensor Hit Order	Time Differences			Amplitudes			
8:7:6:5	70.25	135.25	202.50	111.14	111.14	109.99	108.17
8:7:6:5	74.12	137.00	200.38	111.63	110.43	110.43	108.81
8:7:6:5	69.00	134.25	202.63	111.00	109.84	107.97	107.97
8:7:6:5	72.63	137.50	204.75	111.10	111.10	109.78	108.13
8:7:5	68.38		199.50	111.33	111.33		110.34
8:7:6:5	68.88	134.00	202.75	110.86	109.98	107.96	107.96
8:7:6:5	69.75	134.75	201.75	110.23	110.18	108.27	108.27
8:7:6:5	72.25	136.87	201.25	111.29	109.95	108.33	108.33
8:7:6:5	71.25	136.50	203.62	110.71	109.75	109.10	108.42
8:7:6:5	72.88	137.88	201.38	110.17	109.42	108.60	108.44
Average		136.000	202.051	110.946	110.312	108.937	108.484
Standard Deviation	1.97195	1.456829	1.536739	0.468549	0.662467	0.928143	0.69835
% Standard Deviation	2.779783	1.071198	0.76057	0.422321	0.600539	0.852003	0.643736

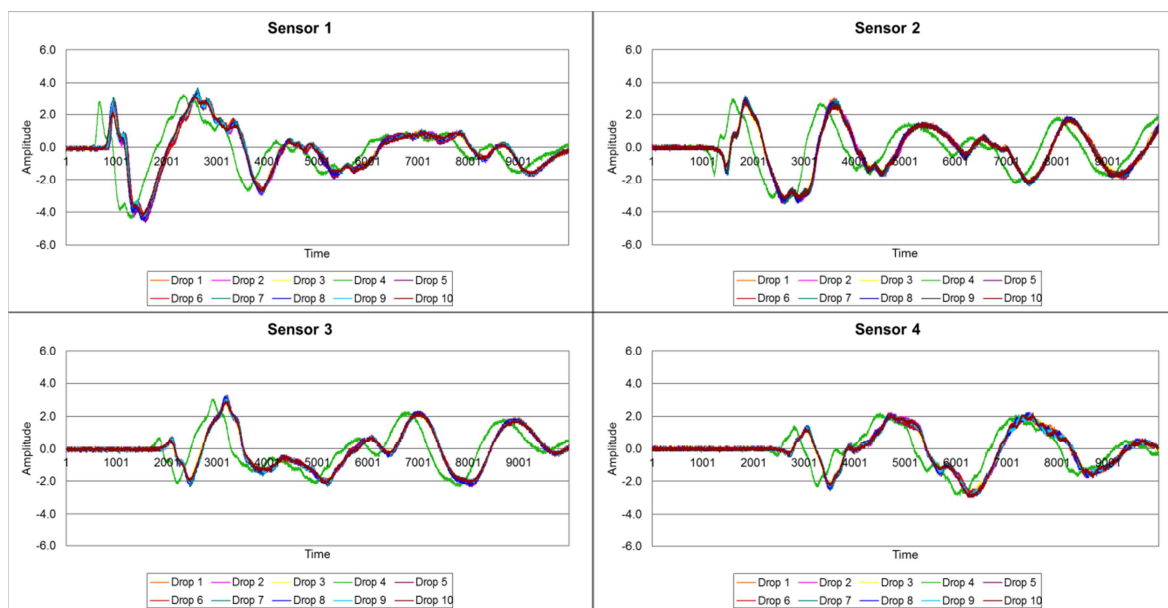


Figure 4: Oscilloscope plots of each drop from the four wireless impact locators.

### 2.3 Energy consumption

A data logger was measuring the voltage and through a resistor, the current was inferred in order to determine the power consumption of the wireless impact locator. The variables used in this investigation are the power supplier voltage, as well as the wireless impact locator running mode, namely the standby mode or the wireless RF data transfer mode. This work was carried out for periods of 500hrs at a time to mimic some assembly line application scenarios.

Figure 5 shows the typical power consumption of the wireless impact location in standby mode is between 6 and 8mW and is relatively constant throughout the power supply voltage range of 0.5V till 3.7V. The current consumption is however not linear, as expected, and is ranging from 2mA at 3.7V to 14mA at 0.5V. The wireless impact location device was working as expected during the power supply voltage range from 0.5V till 3.7V. The device however ceased working below 0.5V, as expected by the ship manufacturer data sheets.

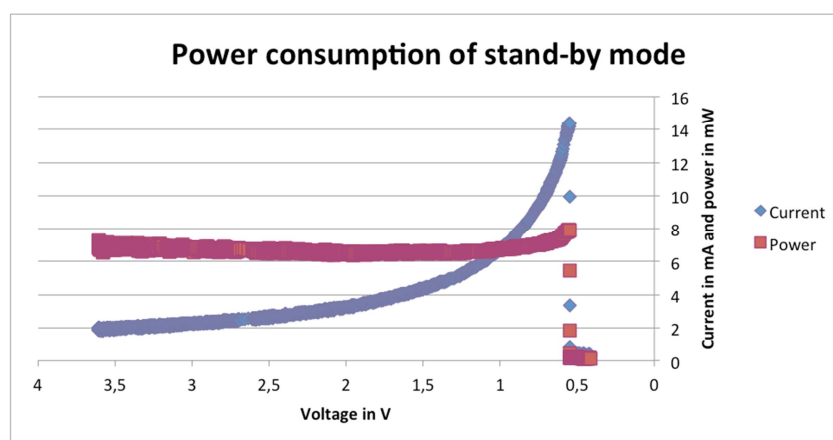
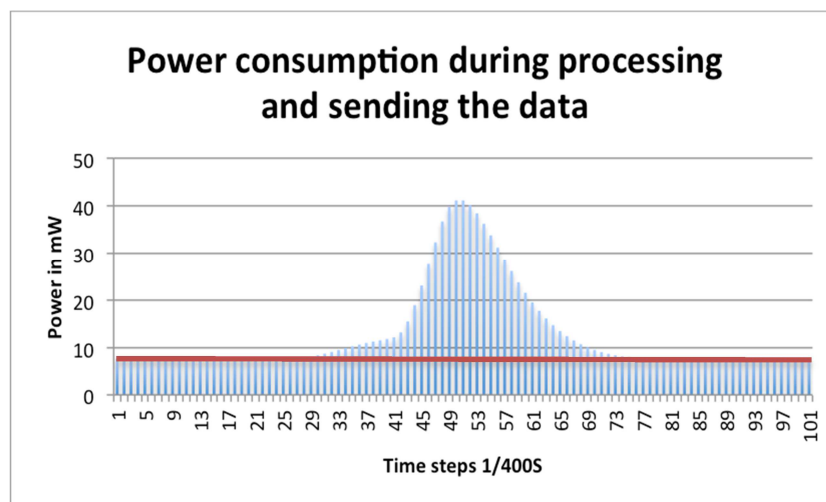


Figure 5: Stand-by power and current consumption versus wireless node power supply voltage

As soon as a valid hit was detected by the wireless impact location, the device sends the relevant data by RF wave, which unsurprisingly consumes more power than the standby mode.

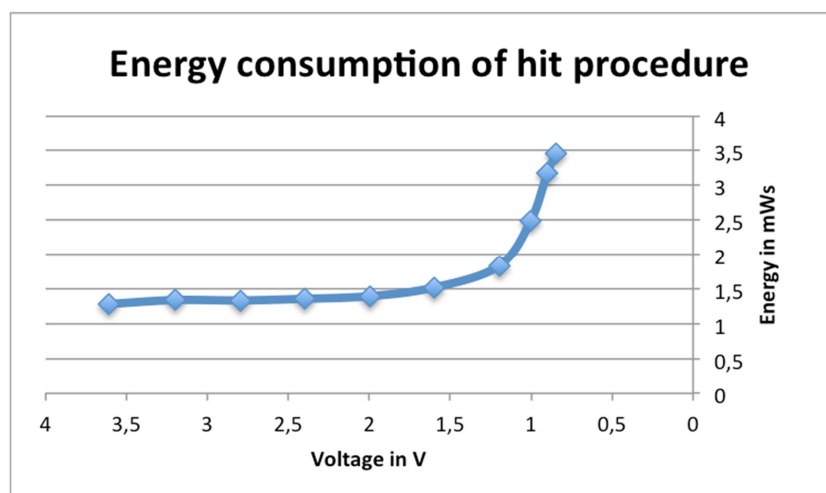
Figure 6 is providing the typical power consumption of a single RF wave transmission after reception of a valid impact hit. The power consumption rises up to 42mW peak, corresponding to around 1.4mWs.



**Figure 6: Power consumption versus during the hit procedure of the WIL**

The second part of the power consumption study is to understand the effect of the power supply voltage to the power consumption of the wireless impact location during RF wave transmission.

Figure 7 shows the energy consumption rather than the power consumption to take into account the power consumption envelop (width). The figure clearly shown the relatively constant energy consumption between 1.5V and 3.7V, at around 1.4mWs. However as the power supply voltage decreased down to 0.5V, the energy consumption increased drastically to above 3.5mWs.



**Figure 7: Energy consumption during RF wave transmission versus power supply voltage**



From these results an empirical equation can be derived, governing the energy consumption as a function of the power supply voltage, the time and the number of RF wave transmitted by the wireless impact location, as shown in (1). It consists out of a constant part which represents the stand-by power consumption and the energy which is needed for processing the impact information.

$$E = ((0.5942 \cdot U + 5.7285) \cdot t + 1.4) \cdot n \quad (1)$$

where  $E$  stands for the energy consumption,  $U$  for the power supply voltage, supplied to the wireless impact location, and  $n$  for the number of RF transmissions. It is therefore recommended to monitor the power supply voltage of the wireless impact location to ensure that it remains above 1.5V.

## 2.4 Battery type selection

The power consumption discussed in the previous section is vitally important to understand what power source solution to use. However, in this case, since the use of wireless technology is for ground base application, with full access to the wireless node, and a relatively short service time, without constraints such as the aeronautics grey list for chemicals, then the natural candidate for powering the wireless impact locator is straightforward batteries.

Two main families of batteries are commercially available: the rechargeable and non-rechargeable batteries. For the purpose of this investigation, only 1 type of rechargeable and non-rechargeable batteries was used, Uniross (1.2V, 1300mAh) and Duracell (1.5V), respectively.

The aim of this section is to understand how long can these batteries last, and understand their typical behaviour to further select the family of batteries to choose from for this application scenario.

### 2.4.1 Battery evaluation

Figure 8 shows the typical rate of discharge of two non-rechargeable Duracell Power Plus (1.5V each) in a 54Ω resistor load. The voltage loss is relatively linear down to 2V, where the discharge rate is rapidly increasing. In the previous section, the recommendation was to have the minimum voltage of 1.5V. It therefore means that such battery pair can provide up to 7Wh. This type of battery is showing the possibility of predicting the remaining life of the battery thanks to the quasi-linear discharge characteristics up to 2V, and again up to 1.5V. It is therefore recommended to warn the user of the wireless impact locator when the battery output voltage reaches 2V, and request for changing them for new ones.

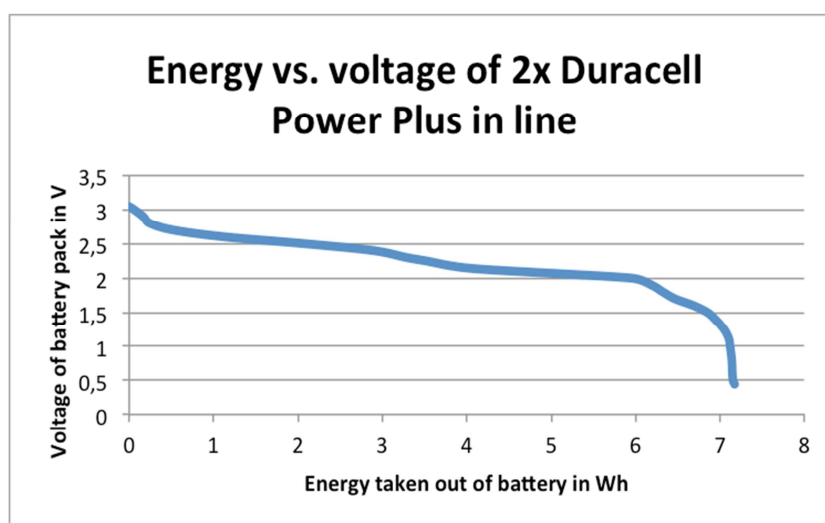
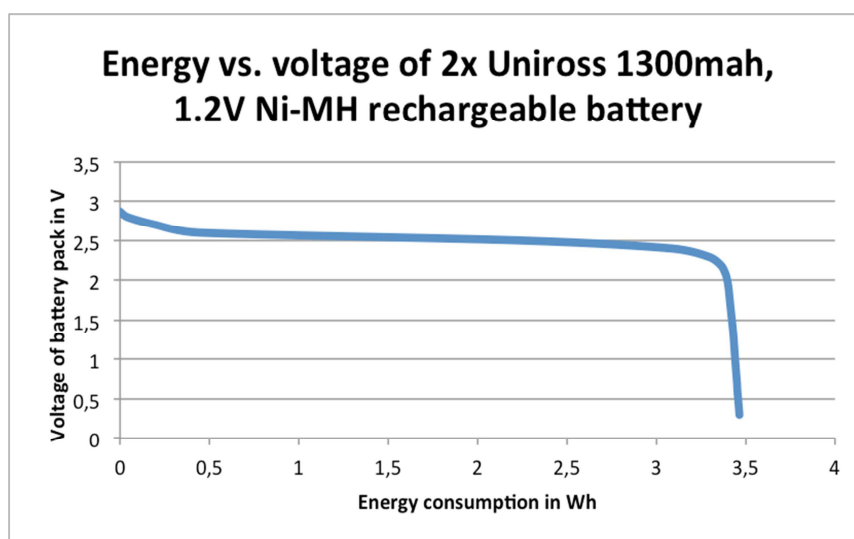


Figure 8: Available output voltage versus Energy drawn for a battery pack of 2 Duracell Power Plus batteries



**Figure 9: Available output voltage versus energy drawn for a battery pack of 2 Uniross 1300mAh Ni-MH batteries**

Figure 9 shows the typical rate of discharge of two rechargeable Uniross 1.2V, 1300mAh in a 54Ω resistor load. The voltage quickly stabilises at 2.5V up to 3.4Wh, where it subsequently loses voltage rapidly shortly after. With this type of battery, it is rather difficult to predict the remaining life of the battery, since the voltage stays at 2.5V for a significant period of discharge, and discharges drastically shortly after. In the previous section, the recommendation was to have the minimum voltage of 1.5V. It therefore means that such battery pair can provide up to 3.4Wh, about half what the Duracell could.

#### 2.4.2 Battery Use Strategy

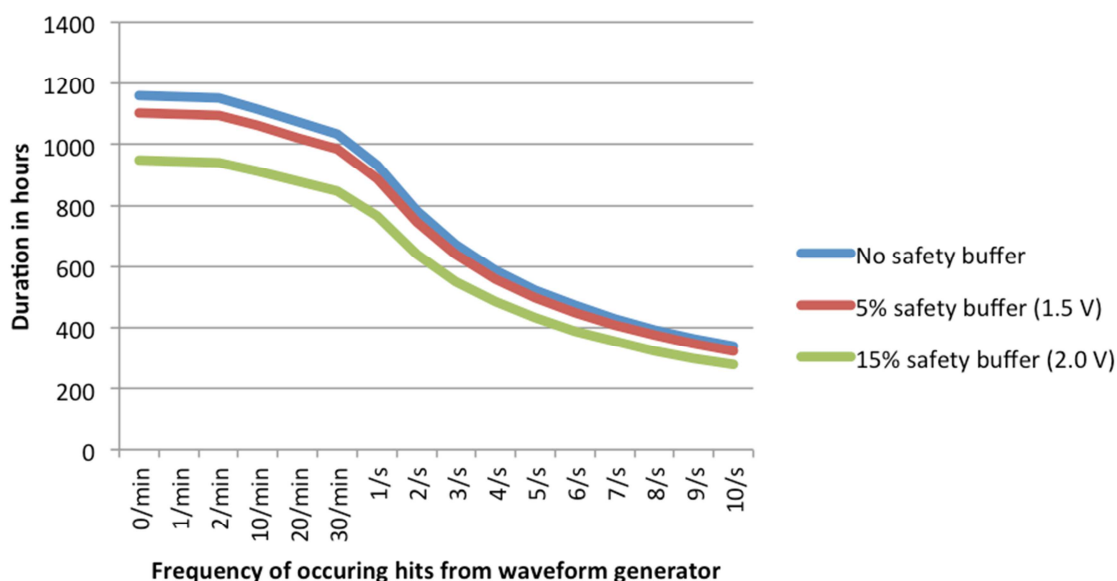
The previous section showed the main characteristics of both battery families in use. This section is defining the strategy to cope with the battery shortfalls for the given application.

This section is discussing the likely duration of the wireless impact locator connected to the studied batteries, based on Equation 1 and data from Figures 8 and 9.

Figure 10 provides how long the wireless impact locator would last as a function of the RF wave transmission frequency.

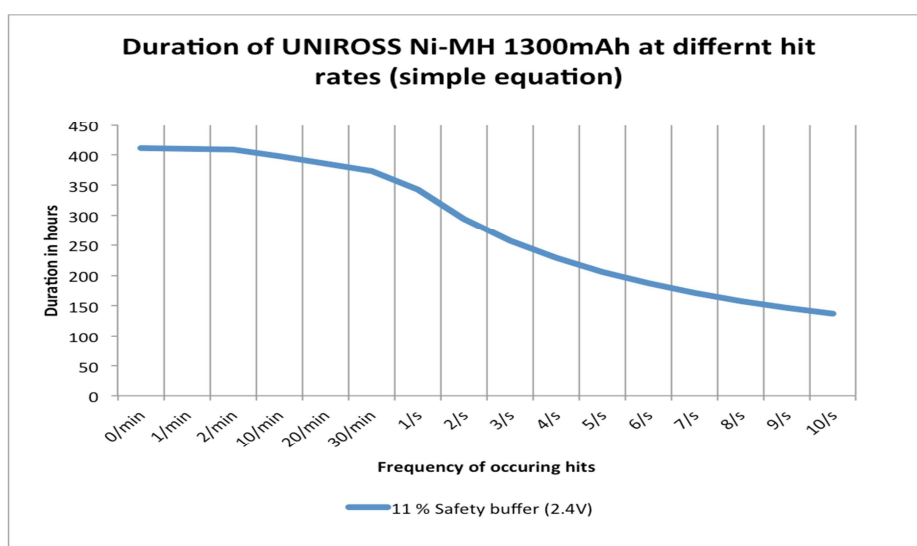
Although the impact event would rarely occur, Figures 10 & 11 show the expected duration of functioning of the wireless impact locator, which is mainly driven by the standby mode, given such low frequency of events.

With Duracell batteries, the wireless impact locator is expected to last up to 1150 hours, until the battery would be reaching 0.5V. However, Section 2.4.1 recommended changing the batteries shortly after the Battery output voltage reaches 2V. This corresponds to what is call herein “battery safety buffer” of 15%. In other words, the user of the wireless impact locator, would be warned when the battery life reaches 15% of its full life to replace them. Figure 10 shows that with such safety buffer, the user of the wireless impact locator can operate the device up to 950 hours, just under 40 days. Typical assembly lines would take much less than the 40 days, leaving such device a perfect candidate to monitor the assembly for potential impact from tool drops or similar.



**Figure 10: Duration of the Duracell battery versus the frequency of possible impacts**

For the Uniross batteries, the only warning we can get is around 10% of battery life left. However, the rest of the 10% gets discharged at an incredibly fast rate, rendering the warning to the user very difficult. The user therefore has to recharge the batteries at regular intervals. Indeed, Figure 11 shows that such batteries would allow the wireless impact locator to function for only 400 hours, just over 16 days, which does not provide much margin to the user. Therefore, this Uniross battery option could only be viable if a third battery was added to the wireless impact locator. In the interest of space availability, this option will not be retained as it is, and only the non-rechargeable batteries like the Duracell will be used for final concept. However, it is envisaged in a future investigation to complement the re-chargeable batteries with solar cells, which is expected to compete with the power levels of the non-rechargeable batteries for the same space availability.



**Figure 11: Duration of the Uniross battery versus the frequency of possible impacts, with a 11% safety buffer**

## 2.5 Wireless range

In the previous sections, the paper discusses the performance of the wireless impact locator in locating impact as well as its power consumption. It also discussed the power supply options. This section however discusses an important parameter, the wireless transmission distance between the wireless node and the wireless hub. Today off-the-shelf wireless devices propagates for over 50m, but are powered by large power sources, and are using redundant transmission protocol until the data is received successfully. This is common practice in IT, however, it is not power efficient, especially when the devices such as the wireless impact locator have limited power sources, it is vital that the redundancy transmission is reduced to its minimum.

This section discusses the first prototype attempt of optimised redundancy transmission protocol to be as power efficient as possible.

Figure 12 shows the results of the investigation of the effect of the power supply voltage to the functioning of the wireless impact locator in terms of RF propagation. This investigation is by far a thorough study of the RF propagation, but was expected at least to identify if the power supply voltage was directly affecting the wireless impact locator function.

The setup was not taking into account any potential interference to the RF waves. Nevertheless, all measurements were carried out with the same conditions to ensure that comparative results can be done. To simplify the study, only two power supply voltages were used: 3V which corresponds to a “healthy” voltage, and 1V which is well below the recommended 1.5V in previous sections, to emulate a worst case scenario. The evaluation was also limited to 17m which is the maximum distance possible for the given application.

Paradoxically, the results of Figure 12 show that when powered with 1V only, the average successful RF transmission rate was around 97%. With 3V power supply, the average successful RF transmission rate was around 92%. However, the wireless impact locator cannot afford to have any misses of RF transmission, and 100% is the expected success rate here. Further investigations are ongoing to resolve that deficiency, with the most power efficient solution possible.

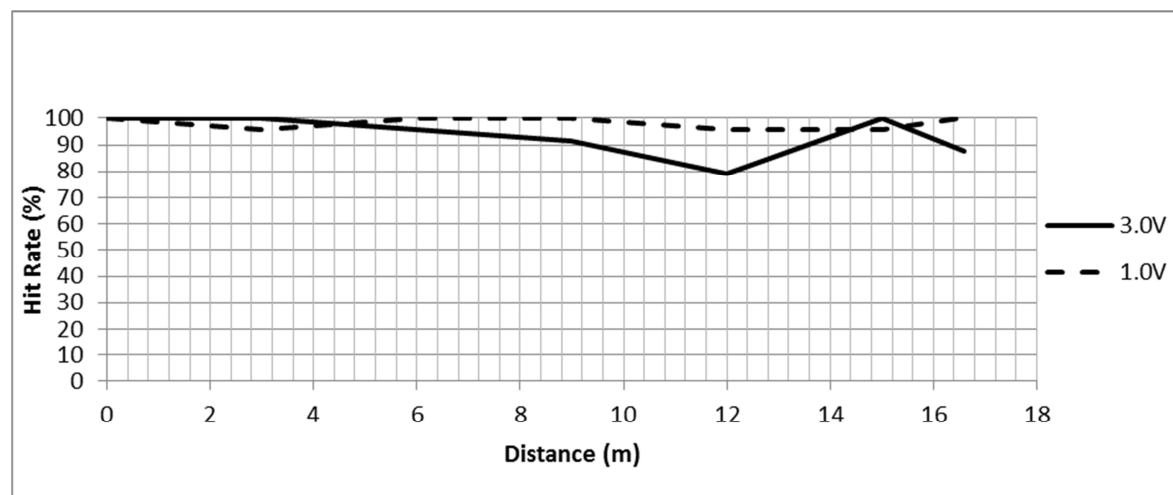


Figure 12: Hit transmission success rate versus RF propagation distance for given power supply voltages

## 3 CONCLUSIONS

The investigation of the bespoke wireless impact locator has demonstrated that the influence of the power supply voltage was little influence of the power consumption of the device, down to 0.5V for the standby mode, and down to 1.5V for the RF wave transmission. The study on the influence of

power supply voltage to the wireless range has not provided enough conclusive data probably due to a series of variables not well understood, and would require further investigations. The battery evaluation strengthens the need of using non-rechargeable batteries for their efficiency versus size, and their ability to forecast their expected end of life. The battery option and the power consumption study has emphasised that such device would be able to run for about 40 days, which is more than sufficient for such application scenario. Other power harvestors, such as solar cells could also be used to extend that cycle time.

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