POWERING WIRELESS SENSORS FOR ROTORCRAFT HUMS

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Abstract

Wireless sensors have been widely suggested as a technology to extend the capability of Health and Usage Monitoring Systems (HUMS) on rotorcraft. Free from the constraints of hard wiring, wireless systems not only appear to offer a cost-effective solution, but in cases of instrumenting rotating or hard to reach parts, sometimes the only solution. Wireless data connections can be implemented using a range of mature technologies, however to be a truly wireless system, power cabling must be also be eliminated. This requires either local energy storage in a battery, energy harvesting (where power is generated from the ambient conditions of the sensor node), or a form of wireless power transfer. Of these solutions, only batteries can be considered mature. In this paper the power requirements of a wireless HUMS sensor node, designed to be mounted directly on the rotor head, are described and the possible power solutions considered. The very best energy-dense batteries currently available could power this node for many 100's of flight hours (for a reasonable battery volume) but it is unlikely these chemistries would be acceptable in the high stress rotating environment; battery technologies that are proven for high g environments would power this node for just a few 10's of flight hours. A vibration-powered generator is described which can produce up to 50mW average power during flight, potentially providing the 1000+ flight hours desirable for whole lifetime monitoring of rotor head parts.

1 INTRODUCTION

The concept of a Wireless Sensor Network (WSN) is now well established, and has moved from the early blue sky visions of smart dust and intelligent structures with active sensors liberally incorporated, to the present day pragmatic implementations where small sensors nodes are based upon commercially available low power microcontrollers and communicate with a range of low-power RF protocols. The list of possible applications, and hence variety of sensor nodes (the individual remote elements of the network), is almost limitless but it does appear that industrial monitoring has come to the fore as a primary application, and Health and Usage Monitoring Systems (HUMS) as a subset which could benefit from the technology.

HUMS aim to augment or replace the periodic physical inspection of structural and drive-train components with autonomous monitoring, and they have seen a great deal of research and commercial development over the past few decades. There are several HUMS in service on rotorcraft today, and these are typically based upon conventional sensing elements and computing located in the fixed frame where they can be interfaced directly to the power and avionics systems of the rotorcraft. It is, however, highly desirable to also monitor components of the main or tail rotor[1] and to achieve this, the HUMS must straddle the fixed and rotating frames: doing this reliably requires some form of WSN, the concept is illustrated in figure 1.

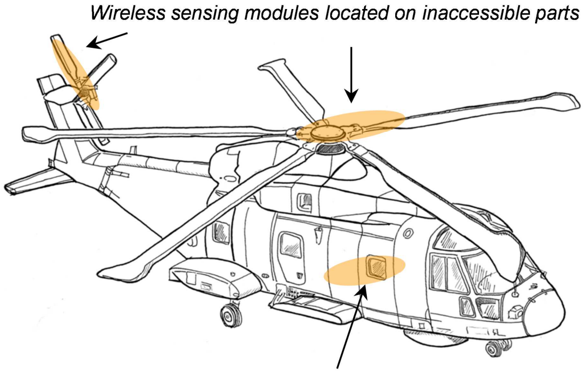


Figure 1. Illustration of wireless HUMS

Today, an engineer attempting to architect a rotorcraft HUMS based upon a WSN will find that the requirements for data acquisition, processing and wireless data transmission are all within the capability of commercial products: the ubiquitous smart phone has a surplus of processing capability and memory for the task; HD video can be streamed to and from it over WiFi. Yet the engineer will likely to conclude that the HUMS is not practicable with COTS technology, and this is because of the difficulty meeting the power supply requirements of the remote sensor node.

Contrasted with the high-performance smart phone, which will operate for just a few hours on a high capacity secondary battery, before recharging is required, the HUMS sensor node will be required to operate for 100’s or 1000’s of flight hours, with quiescent periods in between. During this time it will ideally not require intervention or maintenance. Thus the primary research challenge of implementing HUMS based on WSN today is not providing the required system performance *per-se*; it is providing the required performance within the constraints imposed by the power supply to the wireless node and the desire not to simply swap one maintenance requirement for another.

In this paper the requirements for a rotor head mounted sensor node for a HUMS are described, along with the various powering options. Discussions are based upon prototype development and collaborative research over the last 9 years between Bristol University and Agusta Westland including the TSB-funded WISD (Wireless Intelligent Sensing Devices) and RTVP (Rotor Technology Validation Platform) projects.

2 OVERVIEW OF THE POWERING OPTIONS

2.1.1 Batteries

Batteries are the default power solution for wireless nodes in many applications; however, they are not always ideal for HUMS since the batteries themselves will require some charging and maintenance schedule, which becomes onerous as the number of sensors increases. When using batteries as a power source the fact they are an energy store with finite capacity is inescapable, and this makes them venerable to events and circumstances unforeseen during design.

High capacity secondary battery chemistries have proven effective in consumer applications where devices are charged daily, but this is a poor fit with the desire for HUMS to provide service for many 100’s or 1000’s of flight hours. High capacity primary chemistries have been used in wireless systems designed for extended deployments, such as smart utility meters, although as is shown later extra care needed during design for systems when low average power has been achieved by a load that is heavily duty cycled. Issues exist around the use of very high capacity batteries on aircraft due the risk of fire or explosion, and placing batteries on the rotor head additionally exposes them to extreme forces.

Notwithstanding the aforementioned drawbacks, chemical batteries are a mature technology offering a predictable power source and so battery power provides a means to de-risk developing prototype wireless sensor systems and a backstop for developing more novel power solutions.

2.2 Energy Harvesting

Energy harvesting refers to a group to technologies that can be thought of as low power ‘renewable’ power generation. Solar is the most well-known and exploited but motion, temperature gradients etc. can all be used to generate electrical power.

Rotorcraft are often held up as a good application for energy harvesting[2], especially from vibrations: the mechanical and aerodynamic components produce vibrations at frequencies and amplitudes compatible with many harvesting topologies and the frequencies are largely stationary. The infinite energy density of energy harvesters fits well with the requirements for prolonged sensor deployment without maintenance interventions. Commercial devices, such as those sold by market-leading Perpetuum[3], have extremely long design life (>100 years) illustrating the durability of the miniature mechanical components.

Energy harvesting power solutions are themselves complex systems and introduce new operating restrictions. The power density of energy harvesters is typically low compared to batteries which can make them appear physically large, and since there is no power output without the input excitation, useable electrical supply can often lag behind, preventing pre-flight operation.

Although relatively few vibration energy harvesters have made the leap from research lab to commercial product, the most commonly reported devices are based on the familiar mass/spring resonant mechanical amplifier and use electromagnetic transduction. There has been significant interest in vibration harvesters based on smart materials, such as piezoelectric materials, although reported power outputs are still some way behind those routinely achieved by electromagnetic devices.

A further consideration for energy harvesting is the strong academic community in the UK, supported by an active network, and additional support for commercial exploitation through the current TSB Special Interest Group on energy harvesting, which has coordinated a series of funding calls.

2.3 Wireless power transfer

Wireless power transfer is yet another technique that could be used to power the wireless nodes of a HUMS, and although not the main topic of this paper it is worth including discussion here for completeness. There are two approaches to wireless power transfer exploiting near field inductive coupling and a third using far-field RF

Dealing with far-field first, this technique involves the conversion of broadcast electromagnetic energy back into electrical energy. The distance between the TX and RX antennas is such that they are not coupled, hence ‘far-field’, and most systems operate at radio frequencies. The system can be parasitic (harvesting energy from ambient RF), or incorporate a transmitter. Despite high power demonstrations of wireless power transfer occurring many decades ago with highly directional microwave antennas[4], currently most proposed systems have very low power capability, stymied by the maximum broadcast power limits (and human exposure limits) and power drop off with distance due to beam spreading. In the rotorcraft environment it may also be undesirable to broadcast RF energy, which can be seen as noise or interfere with other avionic systems. The technology has found applications for very low power systems like RFID

In contrast, near field approaches use TX and RX ‘antennas’ (usually coils) that are coupled, forming something like a transformer with large air gap. Where the air gap is small (<10mm) non resonant coils are used and the system behaves like a poorly coupled transformer. There are several commercial devices that exploit this type of coupling – often marketed as inductive or non-contact slip rings. Although this technology is likely to find applications on rotor craft to transfer data and power across rotors, its suitability for HUMS is limited by the requirements for a wire harness to distribute power on the secondary side.

As the distance between TX and RX coils becomes larger, the reducing coupling between coils causes losses to become more significant (generally speaking in transduction systems it is the ratio of transduction coefficient to loss that defines ‘goodness’). To overcome this, electrically resonant coils are used. The resonant action allows much higher field strengths to be generated, and although this is accompanied by greater primary-side losses, generally power is not limited on the input. Several commercial examples are available, perhaps the most well-known company being Witricity[5] and also recently the UK-based company Drayson Wireless[6]. Currently, popular applications of inductive power transfer are in consumer goods and electric vehicle charging.

3 POWER REQUIREMENTS FOR WIRELESS HUMS

3.1 System-Level influences

The power demand of a wireless sensor node is heavily dependent upon the functionality demanded by the application; however, as observed in section 1, the node is almost always power limited: by the size of energy harvester; the desire to use smaller batteries; etc. Fixed-frame HUMS may consume many watts of power without consequence yet in comparison, the sensor node of a wireless system will be trying to perform many of the same operations with average powers of just milliwatts – three orders of magnitude less.

One approach to reduce power consumption is to do the same operation less often. By interspersing periods of activity with quiescent periods, average power consumption can be reduced. Since the time constants of wear and some failures are long, it may be sufficient to be active for one second in ten, or a few seconds every minute. The challenge for the power supply of a heavily duty-cycled electrical system is that the specification will be largely defined by the higher peak level, not the average level. Batteries will often need to be larger, and in energy harvesting solutions energy storage may have to be added.

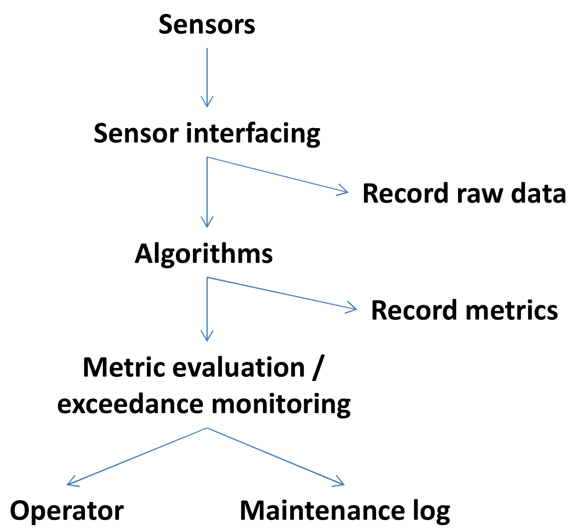


Figure 2. A generic HUMS process

Another system-level approach to minimise power consumption of the wireless node is to carefully consider how HUMS functionality maps onto the overall wireless system. The stages of a generic HUMS architecture are shown in figure 2, and it has been observed that it may be more power efficient to store or process data rather than transmit it, e.g. Arms et al.[7]. As a consequence, running damage detection algorithms on the wireless node and transmitting just the derived metrics has been a running theme of wireless HUMS development. A practical downside of this approach is that low power processing is almost always inferior to what can be done without power constraint; however, a more significant drawback becomes apparent if it is necessary to have access to the raw sensor data, perhaps for regulatory reasons.

In the remainder of this section, subsystems of a prototype HUMS are described and representative figures given for power consumption.

3.2 Sensing

HUMS are often based around sensing stress waves within a structure or accelerations at particular locations. The sensors to detect stress include metal strain gauges and piezoelectric elements bonded to the structure. Accelerometers are principally either ‘instrumentation’ types using piezo elements (configured with charge output) and a seismic mass, or more recently developed MEMS (Micro Electro-Mechanical Systems) devices. Typically HUMS require high fidelity sensor data, often with a wide bandwidth.

Figure 3. Prototype sensor interface board.

To illustrate, a bench prototype ultra-low power sensor interface is shown in figure 3. This sensor interface board has four channels, briefly: 1) A charge amplifier for a commercial piezo accelerometer with bandwidth from 2.4 Hz to 50 kHz; 2) A charge amplifier for a custom piezoelectric strain gauge with response from 0.06 Hz to 5 kHz; 3) a PT1000 temperature measurement, +/-50 °C; 4) A rotor position measurement device.

The power consumption of this sensor interface is just over 1.2 mW, rising to approximately 2 mW when the temperature channel is energised.

3.3 Data processing and storage

The data processing and requirements of a HUMS generally dictate that a microprocessor is incorporated into the wireless node. Only the very lowest power architectures are suitable and along with this will be reduced processing performance compared to power-hungry devices. Even where limited processing is required, a microcontroller will still be required to handle sampling, data storage and for the communications. Writing data to memory can in itself be a power-consuming process.

The prototype microcontroller board, constructed from current commercially available components is shown in figure 4. It is based around one of the well known TI (Texas Instruments) MSP430 family, and using SD card to supplement memory. During sample and storage operations power consumption of the micro controller board is in excess of 60 mW. Duration of this sampling period is defined by the specification application; when monitoring rotor head components this maybe several rotor revolutions so that TSA (Time Synchronous Averaging) can be applied as a first processing step.

Figure 4. Prototype micro controller board with RF daughter board (on right hand side)

Processing power requirements can vary widely with simple metrics, like RMS, consuming little power, but frequency domain operations such as an FFT more power hungry.

Careful selection of the microcontroller and accompanying hardware in view of the of expected algorithms is required to minimise power consumption.

3.4 Wireless Data Transmission

Today, standards for wireless protocols tend to be defined for mass-market consumer applications, and despite recent attempts to define a low power protocol for aircraft (TSB-funded WITNESSS project), emerging systems are normally based around one of the well-known options, for example IEEE 802.15.4.

The prototype described here featured a TI radio module (seen as a daughter board on the right in figure 4) implementing the 802.15.4 compliant, but reduced capability, TI basicRF protocol. When transmitting the wireless link consumed a little over 100mW of power and achieved speeds of up to 192 kbps.

3.5 System power profile

The operation to derive a reference power profile for the WSN is as follows: the node remains in a low power state, periodically waking to listen for an instruction to sample from the network. When an instruction to sample is received, a little under 4 seconds of sensor data from the four inputs is sampled and stored in memory. Some basic metrics are then calculated and the raw data transmitted back. The measured current consumption (for a 3.3V supply) is given in figure 5.

With reference to figure 5, spikes in the current profile can be seen every 2 seconds between 0-6 seconds as the node wakes briefly to ‘listen’ for a command from the network. In this region the average power consumption is ~ 3 mW. Sample and store operations run for a little under 4 seconds, consuming ~ 70 mW as data is captured from the four sensor channels over multiple blade rotations. Transmission of all the raw data takes approximately 6 seconds, with the node consuming ~ 100 mW.

In this example basic time domain metrics were calculated which executed rapidly and since the power demand for processing is comparable to that during sampling, the corresponding power consumption (occurring between sample and transmit regions) is not identifiable on the time scale of figure 5

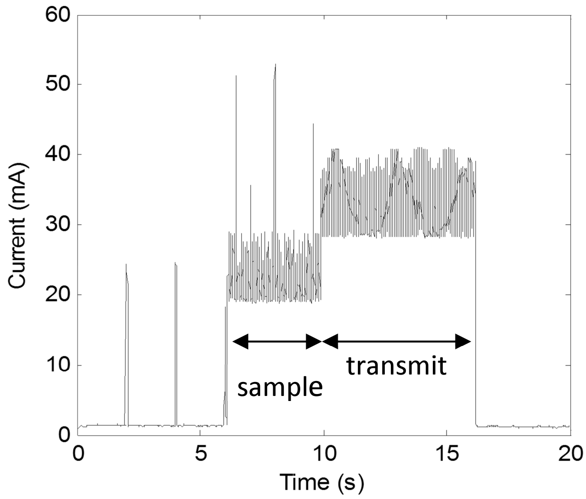


Figure 5. Current consumption profile of node over a sample and transmit cycle.

The power profile of figure 5 represents a worse case sampling/transmission event, since all data is returned to the network wirelessly. The frequency of repetition of the sampling event will be determined by the specific requirements of the application. Hence it is possible to conceive a number of differing operational approaches, for instance the sampling event occurring every few minutes of flight, and metrics calculated but raw data is only transmitted every 10th sampling event, etc.

4 PERFORMANCE OF POWERING OPTIONS

4.1 Reference profile and deployment lifetime

In order to compare the differing power supply options it is necessary to fix a power profile. In this paper we shall assume the node consumes 3mW of power when active, waiting to sample and that this is the normal mode during flight. A single sample event will be a sample/store and transmit cycle as outlined in figure 5, and this will be repeated regularly throughout the flight.

Target lifetime of the node before any maintenance intervention is greater than 1000 flight hours.

4.2 Battery power

4.2.1 Sensor node energy usage

First, assume a sampling event occurs once every 60 seconds. Considering the active quiescent operation, 3 mW would be consumed over 5/6th of the target 1000 hrs flight time resulting in 2.5 Wh of energy usage. If the consumption over the sampling period is approximated to 88 mW for 10 seconds, then the average consumption is 14.6 mW, and over 1000 flight hours results in 14.6 Wh of energy usage. A total consumption of 17.1 Wh for a 1000 hrs lifetime of the node. If an allowance is made for power conditioning and/or regulation circuitry of 85% efficiency then the energy to be supplied by the battery is approximately 20 Wh.

4.2.2 High capacity lithium primary cells

The highest capacity batteries widely available are lithium thionyl chloride, a primary chemistry which has proved effective at powering other wireless sensor nodes. Taking data from data sheets on the Tadiran website[8], model TL-5920, a 'C' sized cell, has sufficient nominal capacity (8.5 Ah @ 3.6 V). However closer inspection of the data sheet reveals two limiting issues for the proposed application, namely: capacity reduction due to low temperature, and capacity reduction due to the high peak current level. The worse-case temperature for which data is supplied is -30° and with a current draw of 30mA the capacity of battery falls to around 1.9 Ah @ 2.8 V, less than a 1/5th of the nominal capacity.

The rotor-head mounting of the sensor node exposes the battery to the full range of ambient operating temperatures. Lithium thionyl chloride (and other chemistries) display reduced capacities at both extremes of temperatures, due to electrochemical effects within the cell, and so batteries must be sized accordingly.

The effect of reduced capacity with increased current is particularly unwelcome as duty cycled operation is one of the primary mechanisms used to achieve a low average power consumption of sensor node. The effect is caused by mechanisms within the cell that appear as an output impedance and with lithium thionyl chloride this is impedance relatively high. Data sheet values for TL-5920 give a capacity of 8.5 Ah @ 3.5 V for a discharge rate of 3 mA, falling off to 2.2 Ah @ 2.9 V for a rate of 100 mA, a reduction of nearly 80%.

Designing a battery for the worse case temperature, pulsed current, and to exceed the 1000 flight hours with sampling/transmit every 60 seconds, requires 4 TL5920 'C' size cells or 2 TL5930 'D' cells. Each 'D' cell is 93g, 62 mm long and 33 mm diameter.

4.2.3 Other environmental factors

Because the head is rotating and the sensor node is likely located off-axis, the battery cells will experience continuous centrifugal forces during flight. The accelerations are determined by the displacement from the axis of rotation and angular velocity, and can result in accelerations of 10's of g at the node. The Tadiran batteries used for calculations in section 4.2.2 are not rated for shock load. In addition lithium thionyl chloride batteries have fire risk if mechanically or electrically damaged.

Tadiran primary lithium metal oxide cells[9] are rated for Aerospace and military applications, including high 'g' loads and to be robust to failure. However this chemistry has an energy density around ¼ that of thionyl chloride, hence the battery pack required for the sensor node would be prohibitively large.

4.2.4 Battery Summary

Assuming the mechanical and safety issues around high capacity chemistries can be addressed, batteries can provide a viable power option for a wireless node; however, the power requirements dictated by the rotor HUMS application result in a significant volume and mass.

The reader will no doubt note that altering the frequency of sampling and the number and amount of data in each transmit event can help to reduce the battery size further, although this should be balanced against the inevitable pressures to offer increased performance and extend the lifetime beyond 1000 hrs.

Several assumptions have been made when attempting to size the battery. In particular that the wireless node is able to determine when to be in the active quiescent state and at other times it is hibernated with negligible power consumption: if node was consuming even a small amount of power when the aircraft was parked, the energy used would exceed that in active operation. RF transceivers often consume as much power when receiving as they do transmitting; hence 'listening' for a command from the network can consume considerable energy over time. To avoid this, ultra-low power 'Wake Up Receivers' (WUR) have been proposed in the literature which act as a secondary RF system solely for waking up the node. Whilst this appears a technical solution to the problem it is at the expense of additional complexity and duplicating the RF system.

4.3 Energy Harvesting

4.2.5 Vibration on rotorcraft

Helicopters have been suggested as suitable applications for vibration energy harvesting due to the presence of significant vibrations at fixed frequency. Figure 6, adapted from Lester et al.[1] shows typical vibration spectra on the body of a helicopter at three differing locations. Magnitudes are omitted for commercial reasons; however, magnitude in excess of 1 g can often be encountered, variable with the flight condition.

Experience has indicated that most often the blade pass frequency has the most consistent vibration signature, and conveniently this is typically at a frequency compatible with established harvester meso-scale construction techniques. Devices featuring a resonant mass/spring system with electromagnetic damping for power extraction are suitable for the input vibration and electrical output demands of the application[2].

Harvesting from on the rotor head has the additional complication of exposing the harvester to centrifugal forces. Since these forces are large careful mechanical design is required to prevent deformation causing fretting in the narrow air gap of the electromagnetic transducer or detuning the resonant frequency of the harvester.

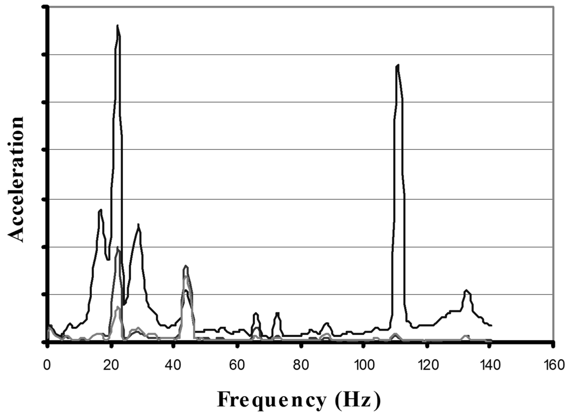


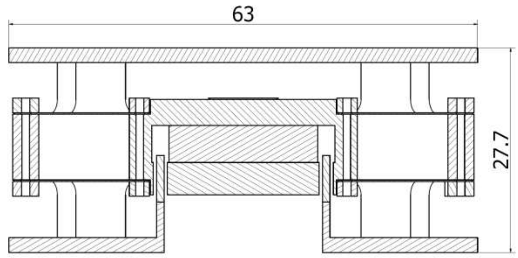
Figure 5. Vibration spectra measured at 3 locations on the fuselage[1]

Energy harvesters are typically designed to give a continuous output, since designing to cope with the peak demand of a load would result in a device prohibitively large and wasteful of energy harvested during quiescent period of the load. In this respect harvesters are less flexible than batteries. To enable a harvester to efficiently supply a load with a duty cycled power demand, it is necessary to interface the harvester and load with some power electronics. Their function is to harvest maximum power throughout the flight, and store the energy, often in a super-capacitor, then provide further power conditioning such that the energy can be extracted as required by the load. In some cases an electronic 'flag' raised by the power conditioning system can indicate enough energy has been stored to power an active cycle.

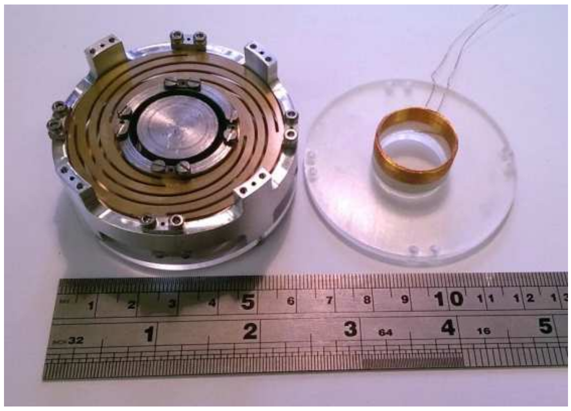
4.2.6 Prototype harvester

Figure 6 shows a prototype vibration energy harvester with voice-coil type electromagnetic transduction which has been designed for the HUMS application. The design was computer optimised for minimum mass and to provide a target power output, using linear models of the mechanical and transduction elements. Additionally the suspension was designed to be stiff to resist centrifugal forces experienced by the proof mass.

The harvester produces an average of 50mW when excited with vibrations previously recorded on a helicopter rotor during a particular flight condition. The instantaneous electrical power output over a 20 second window is shown in figure 7, indicating some of the variability that occurs with real excitation even at a fixed flight condition.



a) Device in section



b) Photograph of device with coil removed

Figure 6. Prototype vibration harvesting device.

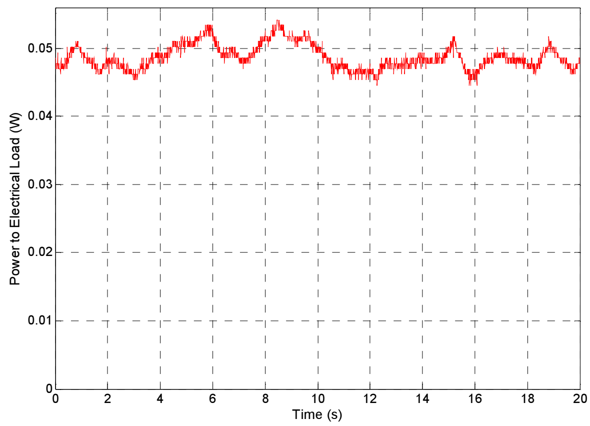


Figure 7. Harvester power output over a 20 second window of recorded real excitation.

4.2.7 Power conditioning system

Obtaining the maximum power requires the harvester to be loaded with a particular optimum load. Simple interface circuits, such as peak rectifiers deviate from this optimum and so are not suitable where the power budget is particularly tight. A range of interface circuits based on switched mode technology are available to maximise harvested power, for the interested reader more detail can be found in Szarka et al[10].

In addition to maximising power extracted from the harvester, the power conditioning system must provide a temporal match between the constant or slowly varying (with flight condition) input power and the heavily duty cycled power demand of the sensor node. To achieve this along with optimum harvester loading an architecture illustrated in figure 8 is adopted.

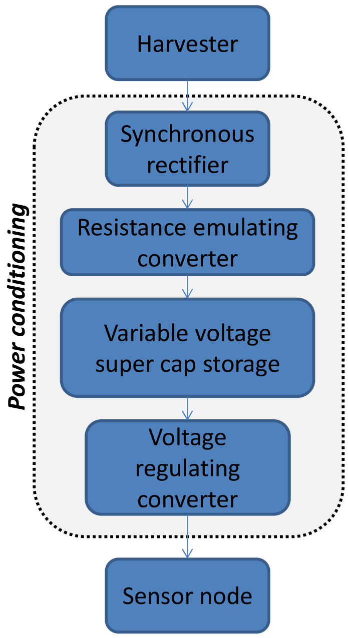


Figure 8. Block diagram of the power conditioning system.

The first stage in the power conditioning system is a synchronous (active) rectifier. The synchronous topology is preferred in harvesting applications of this power level due to the much reduced losses over a passive arrangement. The rectifier feeds a resistance emulating converter (not a stiff DC link as with the peak rectifier) and this ensures the harvester is always optimally loaded. The output of the resistance emulator feeds a super capacitor, used as the main energy storage element. The subsequent voltage regulator provides both a clamping function to prevent over voltage on the super capacitor and regulation for the 3.3 VDC supply to the sensor node.

An implementation of the power conditioning system is shown in figure 9.

Figure 9. Photograph of the prototype power conditioning system .

4.2.8 Powering the WSN with a harvester

Unlike the battery example in section 4.2, where *stored energy* determined system lifetime, when designing a harvester powered system it is matching the powers of load and source that is important.

The harvester can generate up to 50 mW in the most energetic flight condition, which should be rounded down to 40mW over a complete flight. Assuming the power conditioning circuit is 80% efficient, then an average power output of 32 mW gives a good first approximation.

Based on the previous figures, the sensor node consumes 3 mW when active but quiescent and then 88 mW during a sample and transmit operation of 10 seconds duration. To achieve an average power consumption matching the output of the power conditioning system the sample transmit cycle can occur with a frequency approximately once every 30 seconds.

In addition to the maximum repetition rate caused by the average powers, the capacitor voltage must build up before the first sampling event can occur imposing a start-up delay on the system.

An illustrative plot of voltage across the super capacitor is shown in figure 10, indicating the start-up, sampling event and re-charge periods. The super capacitor can be sized to provide optimum performance for a range of differing operating regimes.

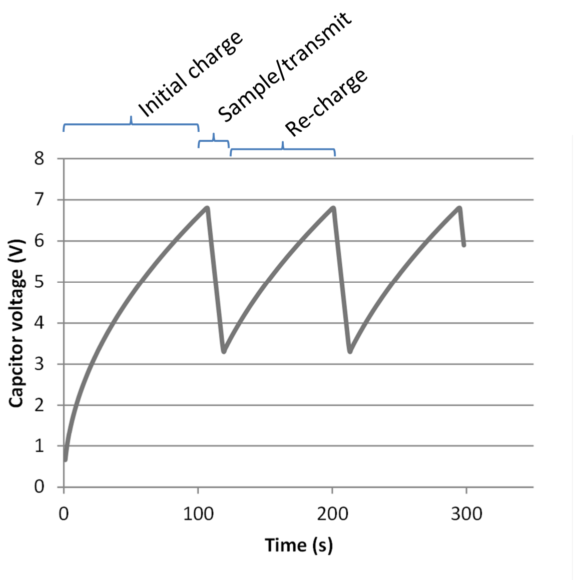


Figure 10. Variation of super capacitor voltage illustrating different phases of operation.

4.2.9 Harvester summary

Unlike the battery example, the energy density of the harvester power solution is infinite – the harvester will power the wireless sensor node indefinitely as long as vibration is present. However; because of the need to store energy in the power conditioning system, there will always be a delay, after the onset of vibration, before an operation of the WSN can take place. As the duty cycle of a WSN becomes smaller, it is difficult to take advantage of the reducing average power consumption because relatively more energy must be stored and the start-up time can become prohibitive.

Allied to the start-up delay, the harvester power solution has limited capacity to alter the frequency of sampling/transmission events, for instance performing extra operation in response to some external system input, whereas a battery solution has more flexibility in this respect.

Another factor not commonly considered in the harvesting literature is the influence of sporadic or intermittent vibrations. Since the harvester and power conditioning system combination are typically inefficient during start-up periods then repeatedly entering this condition can yield useable power very much lower than predicted. Although the helicopter application is often considered to have consistent vibration, it will still contain a degree of variability that cannot be predicted and it has been shown in recent research work[11] that the effects of input variability can be amplified by interactions with load schedule, and the system forced into a non-operational state even though average load and source power appear to suggest operation is possible.

The requirement for a power conditioning board adds extra complexity to the harvester power solution over that of a battery; however it maybe advantageous to architect a battery power system with an additional power averaging circuitry so that the improved capacity of batteries at lower discharge rates could be exploited.

5 CONCLUSIONS

The power demand profile of the prototype wireless node described in this paper is determined by functionality in the application and the capability of current hardware. Consuming an average of 14 mW with peaks of 100 mW, it is not ‘ultra-low power’ in the context of wireless systems, but nevertheless it has been shown it is be feasible to power the system with batteries or energy harvesting.

Both powering options take up a similar volume, but the biggest difference being that the ‘energy-source’ battery is designed for a number of sample/transmit operations, whereas the ‘power-source’ harvester is designed for maximum rate of sample/transmit operations.

There are concerns regarding the use of the highest energy density batteries on aircraft, and in the exposed position of the rotor-head, which leaves energy harvesting as a key technology for the further development of wireless HUMS.

Between the two extremes of a 'battery only' or 'harvesting only' system there are of course many possible combined systems that may offer the best of both options, at the cost of complexity.

As electronic hardware progresses and knowledge of the minimum fidelity of HUMS sensing and processing improves it is likely the reduced power consumption will further strengthen energy harvesting as a viable power source.

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