WIRELESS RF TELEMETRY FOR ROTATING FRAME DATA ACQUISITION AND CONTROL

J. R. Farman
Whittle Laboratory
University of Cambridge
1 JJ Thomson Avenue
Cambridge, CB3 0DY, UK
Email: jrf55@cam.ac.uk

ABSTRACT

Obtaining measurements in the rotating frame of reference requires either real-time communication between the rotating and stationary frames, or temporary data storage in the rotating frame. Rotating telemetry systems must be low-noise and high-bandwidth, which is hard to achieve using traditional slip-ring arrangements, while using temporary data storage introduces synchronisation issues. In this paper, the use of wireless telemetry for real-time data acquisition is demonstrated for two applications: tidal turbine load control and large-scale turbine pressure measurements.

Introduction

The use of wireless telemetry is an area of great interest for a wide variety of applications. The dawn of "Internet of Things" has resulted in systems developed by individuals connecting to the internet. Devices developed by companies such as Digi enable peer-to-peer messaging, broadcast messaging and ad-hoc networks. In the current work, these technologies have been used to implement data acquisition systems and control systems in the rotating frame which communicate with the stationary frame.

Two implementations of wireless telemetry will be described here: first, load control on a tidal turbine blade; and second, data acquisition from the rotating domain of a gas turbine test rig. Preliminary results will be presented along with details of the physical implementation and technical considerations. The aim in both cases was to develop a small, light and cheap data acquisition system to obtain data from or send data to the rotating domain.

Current practice is to either use slip-rings which can be prone to electrical noise, tend to be expensive and are relatively bulky; or to use optical data transfer which requires line-of-sight. In reality, obtaining data from the rotating domain is rarely attempted due to the difficulties of implementing these two methods, and so it would be of great benefit to develop a new method which is less prone to issues of data quality.

Wireless telemetry could also be used between stationary components in the gas turbine environment. This would have the added benefit of removing substantial lengths of wiring and thus reducing weight (as well as cost, through shorter installation times) [1]. The potential use of GSM, WAP, Satellite, GPRS, UMTS, Wireless Ethernet and Bluetooth communication is discussed by [1]; in terms of data speed, UMTS, Wi-Fi and Bluetooth come top. The preference is for Bluetooth in the aerospace industry due to its lower cost, although it has a shorter range.

The ICHM system developed as part of the FLEXICON project was used to assess whether electrical noise in the surrounding environment would affect wireless systems, in particular a Bluetooth position monitoring system [2, 3]. It was found that the system could be made to work despite high background noise. Rolls-Royce University Technology Centre (UTC) Sheffield have also developed MEMs technologies for measuring acceleration, temperature and pressure, as well as blade rotation monitoring technology, weighing 350g and 1000g respectively. In both cases data is transmitted using the 2.4 GHz band of communication [2] (believed to be using Bluetooth though it is not stated specifically). Power is provided to the device by a battery mounted on the blade, with a dummy system used for balance. It should be noted, however, that "Attempting to transmit RF signals within, across or through what is effectively a Faraday cage is challenging, though not completely impossible" [3].

As part of the WIDAGATE project, experimental tests were run on the Rolls-Royce Gnome engine. Seven IEEE 802.11b modules were distributed across the engine and measurements of the packet error rate (PER) and the bit error rate (BER) were used to validate a simulation model [4]. This simulation model was then used to generate insights into the performance of Wireless Sensor Networks (WSNs) for engine testing applications [5].

Though it has been shown that there is considerable interest in wireless telemetry for gas turbines, their practical implementation seems to be limited. In addition, there seems to be particular interest in ensuring that that the systems are small and light, to avoid problems with balance.

The other application of wireless telemetry discussed in this paper is tidal turbines, where wireless telemetry has not been investigated in as much detail. At the Galway bay test site, in Ireland, radio frequency (RF) communications have been set-up as a backup communication between a Wave Energy Converter (WEC) and the shore station [6]. A wireless Ethernet was considered but will only be appropriate if the WEC and the sea station are relatively close to one another. This application has potential carry over to tidal energy. In addition, other applications such as ROVs, diving communications and the oil and gas industry have considerable use for underwater RF communication. [7] showed that the antenna design has to change dependent on the medium, e.g. saline water versus air, and that the electromagnetic wave attenuation is frequency dependent. Attenuation of electromagnetic waves is a combination of the skin effect, interface loss and attenuation loss [8].

Irrespective of the application, an advantage of amplifying and processing signals close to their measurement location is that digital signals are more robust to EMI than low-voltage analogue ones. Slip-rings require regular maintenance and tip replacement, while using wireless telemetry also removes the need for complex and heavy wiring harnesses. Wireless telemetry gives the option for retrofitting or upgrading instrumentation with much greater ease and (though not covered in this paper), the potential to have self repairing networks. The ability to be adaptable to changing requirements for instrumentation is highly advantageous for research facilities.

The approach detailed in this paper utilises cheap, light-weight, off-the-shelf components for developing wireless telemetry units. For underwater telemetry, using the correct transmission frequency and careful selection of antenna position were crucial for reliable data transfer. It was necessary to choose high frequency (2.4 GHz) transmission for the gas turbine test rig in order to achieve the required data rates.

Method

In the Whittle Laboratory at Cambridge University there are currently two activities which involve the application of wireless telemetry for turbomachinery research.

The first of these is the control of load alleviation mechanisms in tidal turbines. The purpose of the load alleviation mechanism is to mitigate fatigue issues due to high levels of flow unsteadiness.

The second is the acquisition of pressure measurements from the rotating frame on the Peregrine low speed gas turbine test facility, in particular to investigate the stator blade passing effects.

Tidal rotating domain load alleviation

A small scale tidal turbine, see Figure 1, with a diameter of 700 mm was modified to test a variety of different load alleviation mechanism designs.

In the first instance, communication was required between the operator (above the water surface) and the actuation system (in the rotating hub) to set the mechanism position without having to lift the turbine out of the water and adjust it manually. In the second instance, communication was required between the torque and thrust sensors (both in the stationary nacelle) and the actuation system (mounted in the rotating blade and hub) for the purpose of closed loop control. It was not possible to use slip rings without increasing the risk of water ingress, and so, despite the low electromagnetic permittivity of water, wireless telemetry was chosen as an alternative means of data transmission. The arrangement of the data acquisition, communication and control system can be seen in Figure 2.

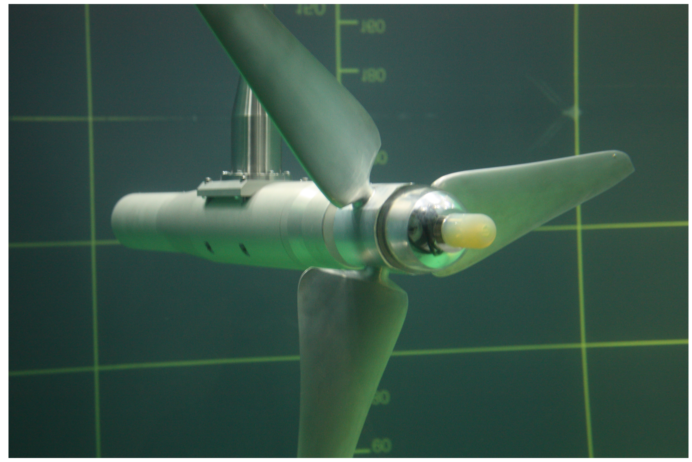

FIGURE 1: Tidal turbine in the flume tank at Ifremer, Boulogne

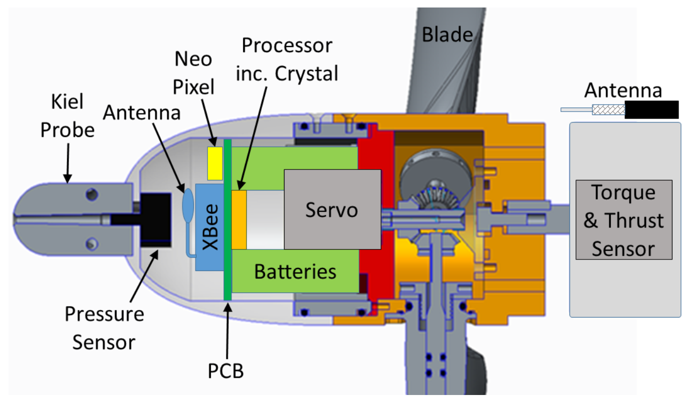

FIGURE 2: Tidal turbine hub schematic with control hardware

The processor actuated the load alleviation mechanisms through a servo (a MG959 towerpro with a stall torque of 28 kgfcm [9]), connected to a gearing arrangement. Visual feedback was achieved employing a Neo Pixel which can be controlled via an analogue output pin to display any RGB colour. The configuration of the electrical hardware can be seen in Figure 3. The front half of the hub was manufactured from Perspex to prevent it from acting as a Faraday cage.

Tests were conducted on two different wireless telemetry cards: the XBee S1 Pro and the XBee S5 Pro. In both cases the telemetry card was connected over a serial communication bus to the processor (a Teensy 3.1, a device similar to an Arduino manufactured by PJRC [10]). The Teensy employs an M4 Cortex processor with a nominal frequency of 72 MHz, but can be over-clocked to 96 MHz. It has 256 kB Flash memory and 64kB RAM. A real-time clock was implemented using a 32.768 kHz crystal oscillator powered by a cell battery.

Size was critical due to the lack of space within the hub. A bespoke PCB designed to fit in the turbine blade hub was developed. The diameter of the PCB was 62 mm, the board was double sided and the thickness with mounted components was less than 25 mm. The weight of the electronic sub-assembly without the batteries was 101 g of which the servo made up 68g, and the XBee module and pressure sensor 4 g each.

The PCB was used to connect the Teensy to the XBee module, as well as to a 32 GB SD card and a set of AA batteries (It was decided that due to the high risk of water ingress that it would be

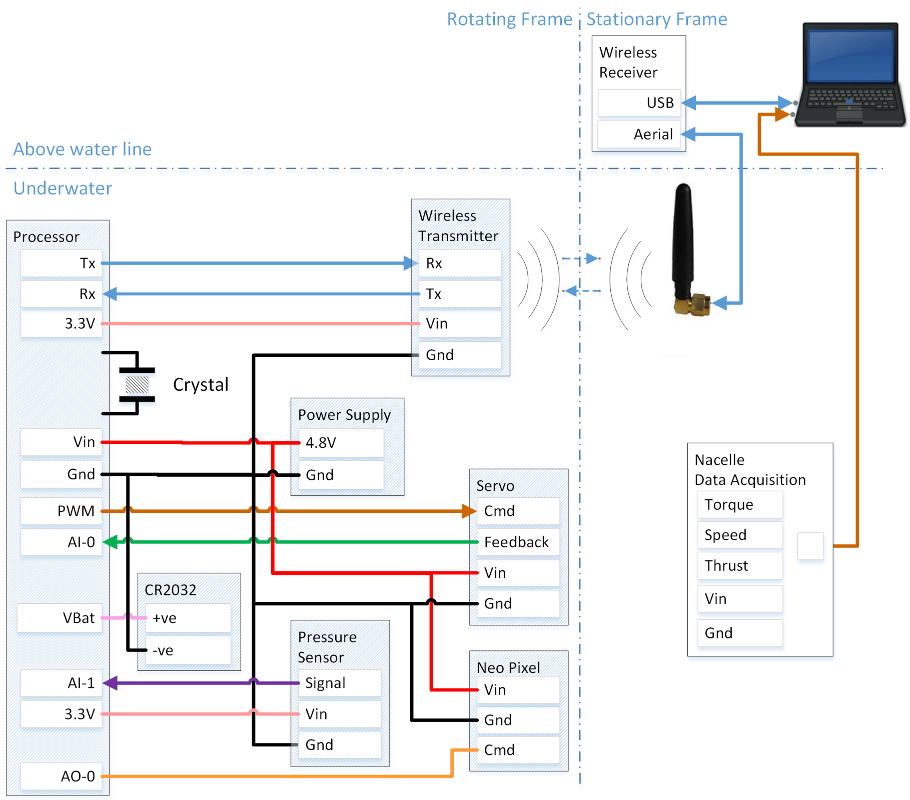

FIGURE 3: Tidal turbine telemetry wiring

unwise to use lithium-ion or lithium-polymer batteries despite their increased power density. The Teensy can tolerate a maximum supply of 5 V, so 4 rechargeable AA batteries were used because of their lower voltage compared to their non-rechargeable counterparts.)

The rotating XBee module, housed within the hub, was fitted with a standard whip antenna, as it transmits directly into air. The stationary XBee module was positioned above the water line next to the control computer and was connected to a RG172 50 ohm coaxial cable of 15 m length, which transmitted directly into water. It was not feasible to use an off the shelf antenna under the water line of the turbine as it would affect the hydrodynamics of the turbine as well as the design being incorrect for transmitting in water. This is an important area for the future development of the tidal turbine underwater communication system as the ideal length of an antenna for underwater use differs to that required for use in air. Indeed [11] have developed a new antenna for underwater communication at the 2.4GHz frequency band for increasing the achievable data rates, however, size is critical and a trade-off has to be made between physical size, achievable data rates and transmission distance.

Gas turbine telemetry

The aerodynamic portion of the Peregrine low speed turbine test facility, which can be seen in Figure 4, consists of an inlet duct, two stages each of stator and rotor blades, a turbine output shaft and a centrifugal fan which draws air through the test facility. The power from the output shaft is absorbed via an eddy current brake and a 300 kW inverter is used to power the centrifugal fan. The turbine

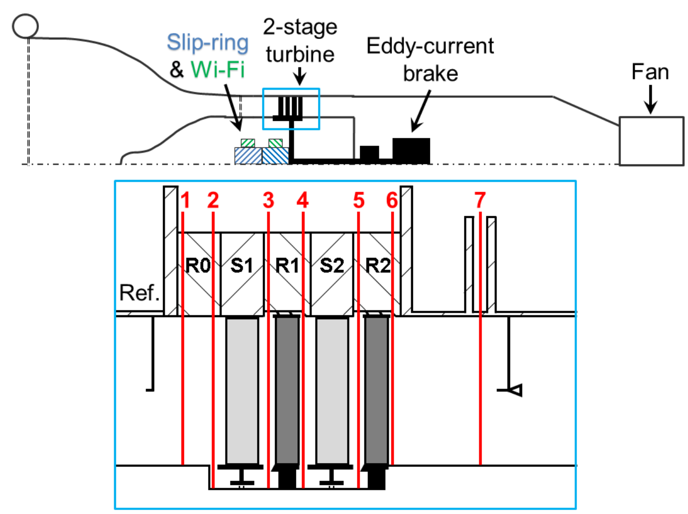

FIGURE 4: Peregrine test facility schematic

rotates up to 415 rpm with 84 stator blades, if ten measurements were required per stator blade passing then 5.8 kS/s are required.

Detailed measurements have been taken using stepper motors to traverse a probe at seven locations in the stationary frame, and a similar standard of data acquisition is required in the rotating frame. The turbine was previously equipped with slip-rings to transfer this data from the rotating frame, but tests confirmed that the noise from the stepper motor and the main turbine inverter was too great.

The end goal of using wireless telemetry in this application is therefore the transmission of pressure measurement data from

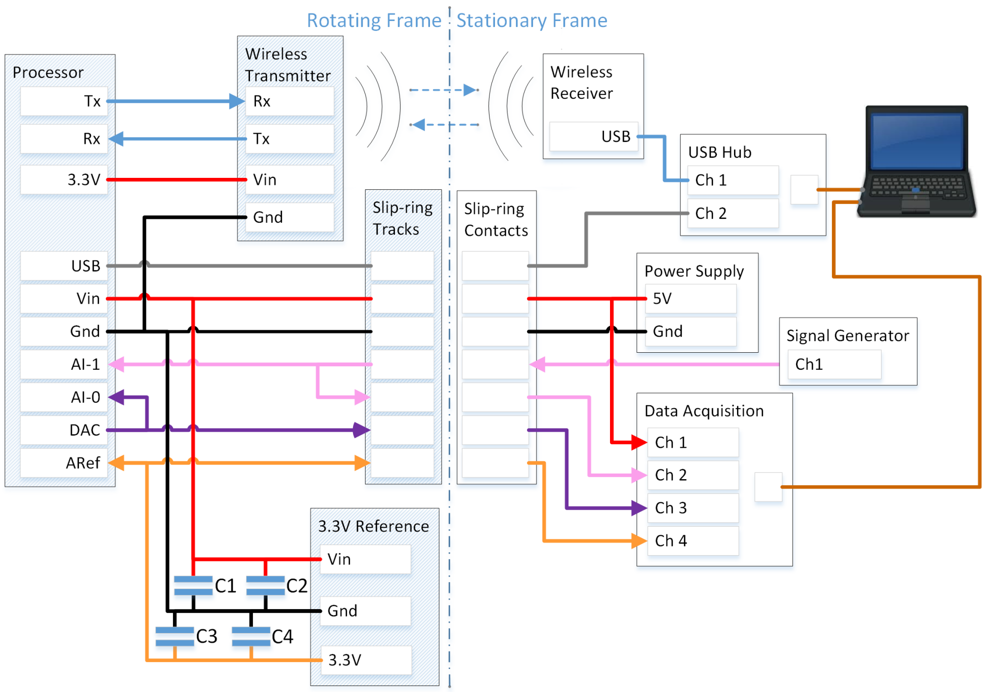

FIGURE 5: Peregrine telemetry wiring

the rotating domain. As a precursor to this goal, a system has been developed to test the achievable data rates of the Wi-Fi sub-system as well as the accuracy of the rotating data acquisition sub-system.

Surveys of existing products showed that a wireless sensor network (WSN) could be created using the WLS-9163 or the cDAQ-9191 equipment, both manufactured by National Instruments. They communicate using the IEEE 802.11g protocol. Bench tests were conducted using the WLS-9163 module in conjunction with the NI 9215 4 channel analogue input card with a sample rate of 100 kS/s. The configuration is described in [12]. The required data rate of 5.8 kS/s is therefore well within the capability of the WLS-9163 card which will be used as the benchmark.

The WLS-9163 chassis [13] with the NI 9215 card [14] weighs a total of 415 g with dimensions of 182 mm **x** 95 mm **x** 37 mm. The newer cDAQ 9191 [15] weighs 481 g with dimensions of 203 mm **x** 89 mm **x** 34 mm. Space and weight constraints in the gas turbine mean that the off-the-shelf equipment discussed above were deemed unsuitable for this application, so a more compact, in-house system was developed instead.

The new in-house Wi-Fi system uses an XBee S6B Wi-Fi module which communicates using the IEEE 802.11b/g protocol. It was selected due to its high transmission data rates (up to 72 Mbps [16]). However, communication to the XBee module from the processor is limited by the hard-wire Universal Asynchronous Receiver/Transmitter (UART) communication data rate of 1 Mbps or the Serial Peripheral Interface (SPI) data rate of 6 Mbps. The firmware within the XBee transmits messages multiple times to protect against the loss of individual messages, thereby utilising some of the available transmission bandwidth. Initial tests to confirm transmission in a gas turbine environment have used UART communication between the XBee module and the processor. The receiving XBee module, positioned within the turbine in the stationary frame, is connected to the operator's laptop through an active USB repeater cable which has a length of 15 m.

As with the tidal turbine, the Teensy processor was selected, due to its large amount of memory, the ease of programming (using the Arduino integrated development environment) and its high clock frequency. In addition, the Teensy has an in-built 16 bit analogue-to-digital converter (ADC) and a 12 bit digital-to-analogue converter (DAC). The data-sheet recommends only using 13 bits of the ADC due to electrical noise.

The Teensy has an inbuilt 3.3 V regulator in the Cortex M4 chip (accuracy of +/-10 % [17]) so to improve measurement accuracy it was decided to add a 3.3 V reference chip to the system. The unit used was a ADR4533BRZ which has an accuracy of +/-0.02 % and is manufactured by Analog Devices [18]. This chip was connected to the reference input on the ADC and DAC with the intention of increasing the number of bits that could be used. In line with the manufacturer's recommendation [18] capacitors were added between the voltage input and ground, as well as between the reference output connections and ground.

The slip-rings, originally intended for instrumentation, were used to provide power to the Wi-Fi data acquisition system and to allow reprogramming. This allows updates to be made to the software without dismantling the test facility. The arrangement of the hardware can be seen in Figure 5. In this figure a data acquisition system and signal generator can be seen in the stationary frame. The purpose of these additional components is to enable an assessment to be made of the accuracy achievable using the slip-rings compared to that achieved using the Teensy processor and Wi-Fi module.

Interrupts have been used to ensure the reliable, repeatable capture of the turbine pressure data at the required data rate. However, due to the potential latency of sending the messages over Wi-Fi and to reduce the message overhead bandwidth, data measurements are grouped together in memory in the rotating frame and sent whenever the processor is free. Further code development is required to synchronise the time stamps of the stationary and rotating frames. Both currently use the international internet clock.

Results

Tidal Turbine

The tidal turbine turbine has been tested in the water flume at the Ifremer test facility in Boulogne, France. Preliminary underwater tests were conducted using the XBee S1 Pro (International version) which transmits at 2.5 GHz, has a power output of 10 mW (+10 dBm), a data rate of 250 kbps and communicates using IEEE 802.15.4. In water, the maximum transmission distance was found to be 20 mm, so wave guides were required to facilitate the transmission of the signal from the stationary nacelle to the rotating hub across a gap of 100 mm. Even with the wave guides, transmission was poor. Whilst transmission was possible with any rotor position with the rotor stationary, with the turbine spinning packets were dropped before connection was re-established at the new fixed position. The system was extremely sensitive to antenna position. To minimise this, the rotating antenna was placed on the axis of rotation.The ability to send messages to the hub whilst the turbine was stationary but under water was useful for changing between operation points but would not allow closed-loop control of torque or thrust using the load alleviation mechanism, because this requires constant communication between the stationary and rotating components.

In order to overcome the transmission issues, the XBee S1 Pro telemetry card was replaced with a XBee S5 Pro, which transmits at 868 MHz, has a data rate of 24 kbps and a maximum transmission power of 315 mW (+25 dBm) [19]. The higher power and lower frequency between the XBee cards enabled an increased transmission distance. The specification for the XBee S5 Pro states that it has an RF line-of-sight range of 40 km in air. Tests are required to determine the maximum transmission distance in water; nevertheless, communication between the nacelle and the hub was successful over the 100 mm distance required in the model tidal turbine whilst spinning at 290 rpm. This was only possible with a change in the transmission frequency from 2.5 GHz to 868 MHz which also decreased the quoted data rate from 250 kbps using the XBee S1 Pro to 24 kbps using the XBee S5 Pro. In addition, the XBee S5 Pro is limited to a 10% duty cycle (calculated on an hourly average) due to thermal constraints [19]. This limit affects the duration for which fast data transfer can be used. A review of alternative equipment is required to see if this is a fundamental limit of using the 868 MHz transmission frequency or whether it could be avoided by choosing alternative hardware.

The wireless telemetry system for the tidal turbine using the XBee S5 Pro module has been tested under water, and control signals were transmitted successfully over a distance of 100 mm. Given the high electromagnetic permittivity of water, this is a significant success. The use of wireless telemetry removed the need for slip-rings, which would have presented significant issues with sealing (especially as the system was being retrofitted to an existing development turbine). The next stage in the validation of the telemetry system is to test the maximum transmission distance of the XBee S5 Pro module in water.

It is believed by the author that telemetry systems using even lower frequencies will transmit further with a deterioration in the potential data rates. Manufacturer variability exists for data rates at a given transmission frequency and so it should be possible to optimise the selection of hardware for an appropriate combination of frequency and data rate for a given application.

Gas Turbine

Preliminary bench tests were conducted using the National Instruments WLS-9163 module and the quoted data rates were achieved. However, the size and weight of this device were too large for the application. An in-house system was therefore developed employing an XBee S6B WI-FI module and a Teensy processor. This system has been installed in the Peregrine gas turbine test rig next to the stator and rotor blades. Successful tests have been conducted up to 1 kHz whilst rotating at 410 rpm and further tests up to 5 kHz will be conducted shortly employing SPI communication rather than UART to achieve the higher data rates required in this application.

The plan going forward is to employ a fast response pressure sensor to measure at 5.8 kHz. It will be connected to the Teensy processor module via an external low-noise amplifier. Due to the expected low voltage signal from the pressure sensor it may be that the 13 bit “useful” resolution of the built-in ADC on the Teensy is inadequate for the accuracy required in this application and therefore an ADC separate from the Teensy (but still mounted in the rotating domain) will be added. The power for the system will continue to be provided via existing slip rings.

Conclusions

This paper has shown that it is possible to use wireless telemetry in applications where data collection was previously impractical. Particular attention has been paid to the transmission of data from the rotating to stationary frame, because the traditional techniques, involving slip rings, tend to give poor quality data with high noise content. The following conclusions can be drawn from the work:

1. Underwater wireless telemetry is possible, despite the high attenuation of radio waves in water. In order to achieve communication over longer distances in water (over 50 mm), a lower transmission frequency must be used. This leads to a reduction in the maximum data rate.
2. Wireless telemetry has also been demonstrated in a large-scale gas turbine test rig. In this case, a high transmission frequency chip has been selected due to the fast data acquisition rate required.
3. For both water and air applications, antenna placement is important. Further research is required to investigate the effects of placing the antenna within a metal case and to establish whether this results in dropped data packages.
4. It has been shown that power can be supplied to the rotating frame either by using batteries or through slip-rings, and neither approach has a negative effect on the quality of the data acquired.

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