A novel surface temperature measurement system for industrial applications

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Abstract

There is a requirement for accurate surface temperature measurement in many industries, which has given rise to a range of sensors designed to provide such data. The integrity of surface temperature data can be adversely affected by ambient contamination, surface roughness and contact area profile, which can induce a significant uncertainty in the measurement, depending on the sensor type, design and method of application.

For precision manufacturing industries, thermal gradients cause deformity in machinery, resulting in component geometric error. In this paper, a novel sensor is proposed for surface temperature measurement in industrial environments. A unique architecture and multi-network system has been developed providing: Remote in-situ wireless temperature measurement, logic implementation, and low cost design with accuracy comparable to high-end thermistors minimisation of uncertainty in measurement. This paper provides information regarding the problem statement and the system development.

1 Introduction

One of the most significant sources of error in precision manufacturing and measurement stems from the effects of thermal error. Positional errors are due to thermal effects; for machine tools it has been estimated to be 70% of the total positional errors [1]. For a “smart” sensing system required to capture machine temperature data [2], challenges include harsh environments (damage from swarf and coolant), rough surfaces and placement on hard-to-reach surfaces inside machinery. In this paper the beta version of a novel wireless multi network smart sensing system is described which remotely reports to a central data logger. The system is shown to be robust in acquiring surface temperature data on large machining equipment in a workshop, tackling transmission challenges of data penetration and high levels of Electromagnetic

Interference (EMI), leading to losses in data integrity or availability, that are caused by separation distances and obstructions. The system is discussed and preliminary results presented, though priority is given to the robustness of communication and proven ability to incorporate intelligence through the software and hardware architecture.

2 Wireless sensor communication considerations

Selecting the wireless transmitter requires an understanding of the typical communication problems present in a manufacturing work place. Signal echo is caused by deflection from objects that are difficult to penetrate, such as cast-iron structures found in CNC machines. The signal will bounce and result in redirection back to the transmitter or off the receiver path. It is the function of the wavelength that determines the penetration depth of material, since resistivity and density are some properties that create refraction and reflection of signals. For example, short wavelengths having higher energy are not absorbed like low energy, long wavelength signals [3].

Reliable, long range wireless data transfer also requires a “transmit modulation” and a “receiver demodulation” protocol which can handle noise levels generated by operating machinery and busy shop floors. Data corruption may occur during transmission because of electromagnetic emissions generated by the various high energy systems used to perform machining operations.

The channel sharing for multi-node placement is another source of error for the receiver selecting transmission signals. It is well known that providing modulated data with a unique ID can help to distinguish between signals. This is acceptable when considering frequencies generated from designated sensor networks, but the frequency spectrum is finite and competing signals are prominent giving a crowded environment. For example, if the receiver was tuned to gather a common 2.4GHz utilizing the WiFi IEEE standards, this channel could be shared by competing devices in close proximity, resulting in the receiver fishing for the desired sensor network nodes (also sharing the bandwidth) and possibly leading to data confusion.

An additional consideration for a wireless sensor is any requirement for remote signal processing before data can be sent over the network. To eliminate this need, ‘direct to digital’ temperature sensors were selected. The DS18B20 digital thermometer by Maxim [17] is a bandgap-based digital temperature sensor, whereby variable voltage across a diode can be used to give temperature readings (diode thermometry). The attraction of this type of sensor for integrated circuit (IC) design is how cost effectively such sensors can be embedded into silicon integrated circuits. They use a 1-wire protocol which provides an additional advantage of allowing multiple sensors to be linked in series.

The DS18B20, which is a low cost digital temperature sensor, has been used to produce highly accurate readings comparable to that of a PT100 [14].

In order to determine if the DS18B20 sensor is applicable to the application proposed in this paper, a comparison was carried out with a high-end thermistor as shown in figure 1, note the repeated stutter at 28 and 52 degree, caused by freezing within digital conversion. Two DS18B20 sensors were found to be accurate to within ±0.2 °C over a 20 to 60 °C range. This accuracy can be improved by techniques such as the curvature correction method [16].

The attraction of this type of sensor for IC design is how cost-effective such sensors can be embedded into silicon integrated circuits. The equation describing the response of the sensor is [7]:

$$\Delta V_{BE} = \frac{kT}{q} \, . In(\frac{I_c}{I_s})$$

Where:

V_{BE} = Voltage between the base and emitter for a bipolar junction transistor.
k = Boltzmann's constant.
T = Temperature measured in kelvin.
q = Charge on an electron.
l_c = Current.
l_s = Saturation current.

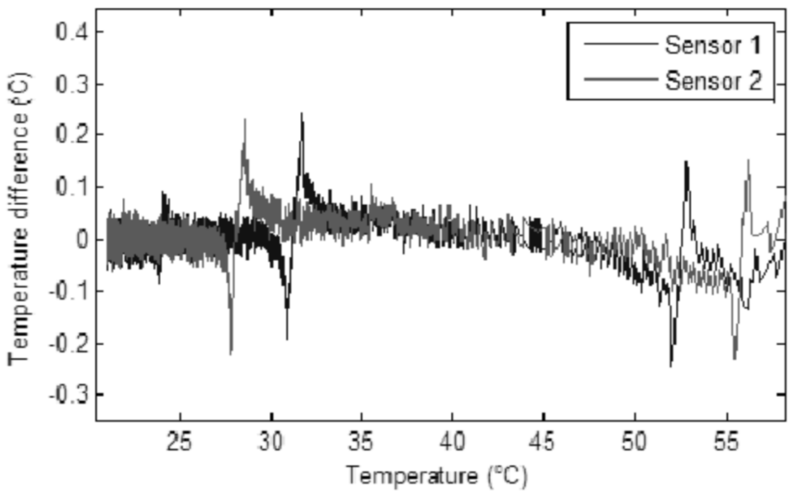

Figure 1: Error in the readings of two DS18B20 sensors when compared to a standards level thermistor (FLUKE CHUB E4 1529 controller and 4-Wire thermistor)

2.1 Wireless data transfer using ZigBee

ZigBee devices, based on the IEEE 802.15.4 standard, were selected for the required wireless communication, due in part to extensive supporting literature;

evidence of robust and stable performance was first established in 2004. In particular, successful fully duplexed data transfer from multiple nodes in applications in harsh environments shows the suitability for manufacturing trials [4-9]. It was highlighted by the ZigBee Alliance that the ease of use and low cost purchasing price has seen extensive use of the ZigBee protocol in the scientific community [10].

ZigBee devices have previously been used in successful projects that required measurement of temperature, in a broad range of challenging conditions [11, 12]. Similarly, a multi-node temperature acquisition system, based on ZigBee has been successfully implemented [13]. For the proposed system, a multi-node and temperature sensor is required therefore supporting the use of ZigBee architecture for wireless communication. ZigBee is designed as a low-cost, low-power, low-data rate wireless mesh technology. The ZigBee specification identifies three kinds of devices that incorporate ZigBee radios, with all three found in a typical ZigBee network shown as:

- A coordinator, which organizes the network and maintains routing tables
- Routers, which can talk to the coordinator, to other routers, and to reduced function end devices
- End devices, which can talk to routers and the coordinator, but not to each other.

2.2 Putting intelligence into temperature sensor instrumentation

Smith *et al* define a smart sensor as, “one where some or the entire signal conditioning functions are carried out by a microprocessor within the sensor package’ [15]. At the simplest level, the proposed smart temperature sensor has three main capabilities: measuring the temperature sensor quality with a large weighting on accuracy; computing processes, algorithms used to enhance the raw data, increasing accuracy and showing estimation based on trends; and communication with the end user, via industry standard protocols or in this instance a LabVIEW interface. To cover a suitable area of a machines surface, 9 sensors have been arranged in a 3x3 matrices, the distribution offers an 8 sensor comparison against a given surface temperature reading, providing higher resolution on a relatively mobile platform suitable for required placement.

2.3 Implementation of smart sensor wireless setup.

The setup of the system is shown in the figure 2. A remote unit consists of an array of temperature sensors and a coordinator unit used for reporting to the central PC. An XBee is used which is an embedded wireless end-point connector to the smart sensor unit that uses the ZigBee protocol. The FRDM is the ARM cortex microcontroller which performs the logic operation, whilst the IC7407 and FTDI are used for XBee to function and communicate serially with the central PC.

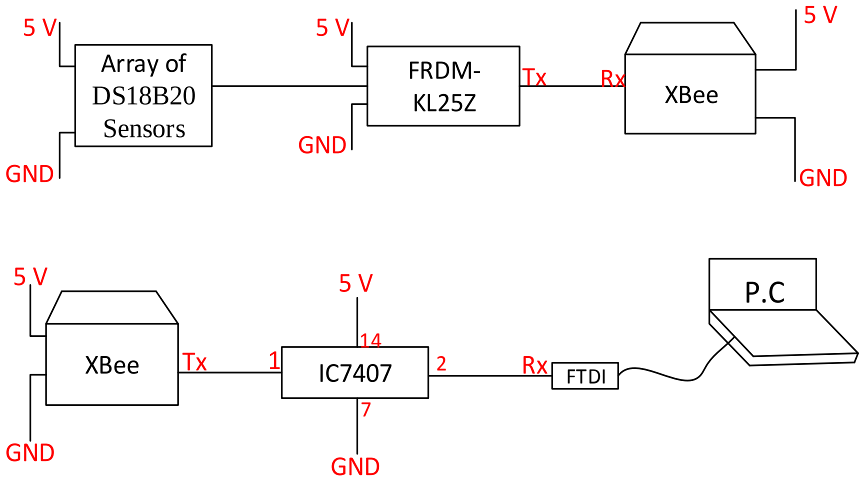

Figure 2: showing the wireless sensor setup

The ZigBee transceiver is used to allow for the ARM cortex processor to pass the DS18B20 temperature values (T_i) directly to the transmitter module in a serial form which in turn is packaged and sent to the receiver.

The data is then acquired via a central PC running a front end control panel created in LabVIEW. The DS18B20 polynomial CRC-8-Dallas/Maxim check is conducted for a 1-wire bus, such as the function f*(x)* provides the binary check for the data byte being sent between the sensors and the ARM cortex microcontroller, providing data integrity to the system as shown in the form:

$$\boldsymbol{F(x) = x^8 + x^5 + x^4 + 1}$$

The surface temperature is calculated by passing the 9 individual sensor values to the central computer which then produces an average. A tolerance limit is used for each DS18B20 sensor reading to ensure integrity of data such as ($x_{threshold} < T_i < x_{threshold}$) and giving a gradient of temperature change for sensor readings that drop-out of the tolerance.

In figure 3, one in the nine sensors is heated beyond the acceptable tolerance to simulate an erroneous reading or misapplied node. The two signals show averaging with and without the pre-processing of the heated sensor. Inclusion of this functionality to improve robustness could have a negative impact in the event that one sensor is actually affected by a physical phenomenon. Therefore, the protocol has been constructed to add a check-bit indicating which elements of the node have been filtered.

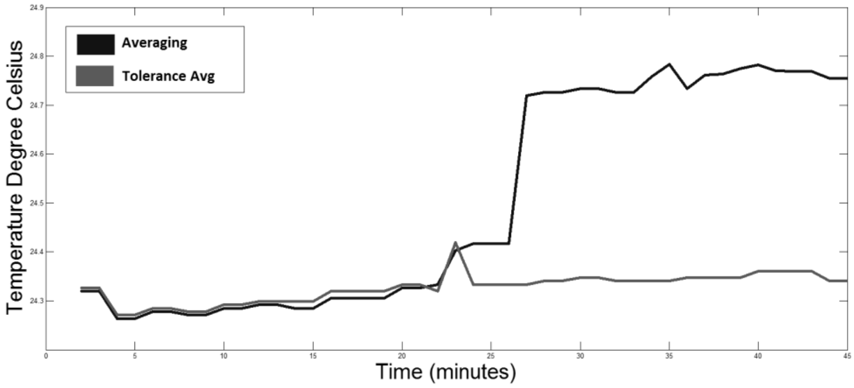

Figure 3: Shows the average tolerance effect with 1 sensor heated

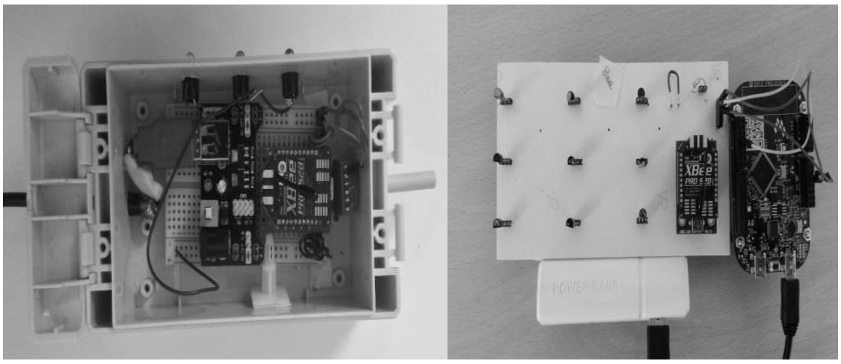

Figure 4 Left: ZigBee coordinator. Right: transmitter to system.

3 Result

In this section the results are shown from the data logging trails. The wireless capability of the smart sensor data acquisition system shown in figure 4 was trialled on a small CNC machine tool situated in a workshop, having 5 other CNC machines in close proximity. This arrangement, coupled with an unstabilised electricity supply provided a reasonable representation of a typical small industrial environment in which to validate the robustness test of the XBee Modules. Previous experience of applying sensors on the machine had shown that the door interlock could generate significant interference even using wired sensors with shielded cabling. Therefore one trial was conducted to see whether the magnetic field generated by the interlock would corrupt the data transmitted. The wireless transmitter was located next to the interlock as shown in figure 5. Other tests had the sensor in the control cabinet of the machine where all the transformers, PLC and drive systems are mounted, on the column of the machine near one of the axis servo motors (see figure 6) and then finally inside the machine on the table whilst the main spindle was running at different speeds (1000 and 5000RPM). The system was place relatively near to the spindle as shown in figure 7.

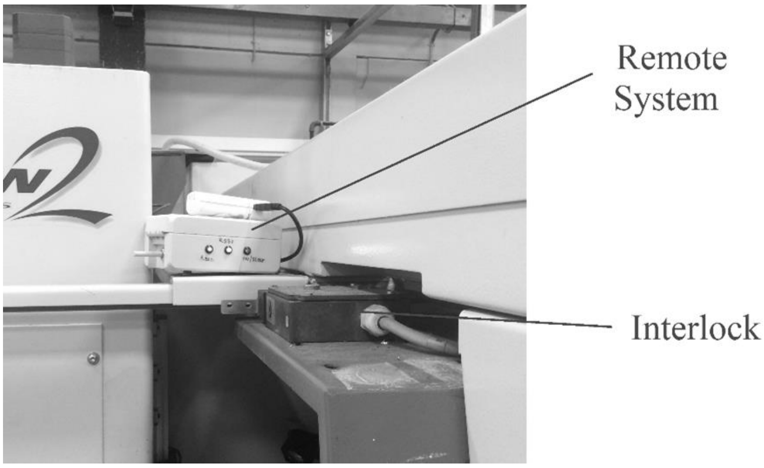

Figure 5: A Picture of the Remote System on the Interlock

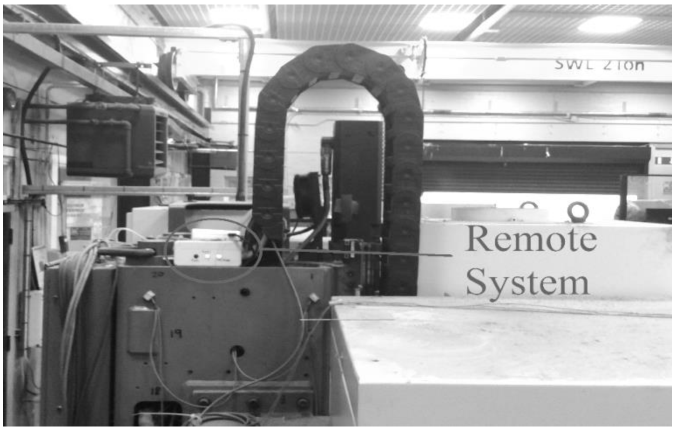

Figure 6: Picture of the Remote System at the Back of The CNC Machine

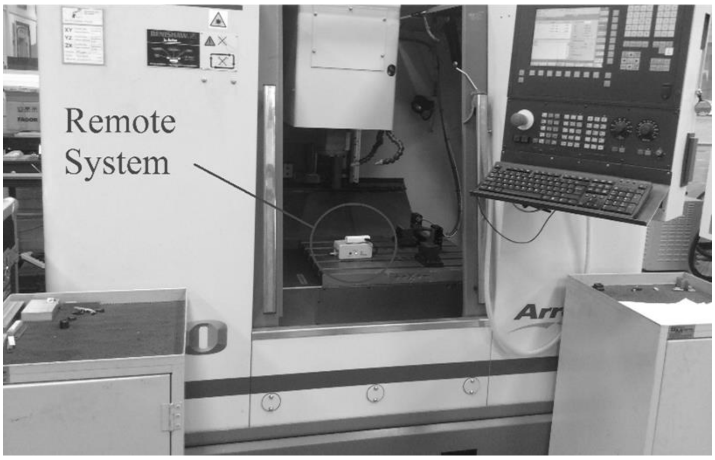

Figure 7: A Picture of the Remote System on the Work Table of one CNC machine.

The results from the trail tests are provided, mainly showing whether the environmental effects of an operating machine would induce data corruption on the multi node smart sensor network. The output of the coordinator system which consists of the receiver collecting the data from the sensor nodes transmitting the temperature data is monitored and compared with the output when the CNC machine when turned off.

It was noticed that no change in the transmitted data, in terms of corruption caused by machine operation was present when the router was being used. This means that the electromagnetic field generated by the induction motor has no significant effect on the transmission of data when using XBee modules.

The smart temperature sensor was placed around the CNC machine at the various locations described above for duration of 240 minutes. Figure 8 provides the results from different location placement of the smart sensor. The main peaks in the graph are from the sensor placement within the control cabinet, whilst the valleys are caused from placement on large metal surfaces. The average ambient temperature throughout the test was 22.17°C. It shows the sensors are capable of transmitting accurate data before, during and after the machine was in operation, if one of the sensors was to drop-out of the tolerance level during surface temperature acquisition the data would show little change since it would be identified as an invalid reading.

No interference was experienced when the CNC machine was initially switched on or during variations in operating conditions.

A distance test was also carried out, which showed successful communication between the smart temperature sensor node and the coordinator unit up to 15 metres in the workshop conditions. Whilst not implemented for this testing, a repeater unit could be produced to extend this range. However, in normal practice, it is intended to have a data capture unit located close to the machine which can then transfer the data management tasks onto a network system.

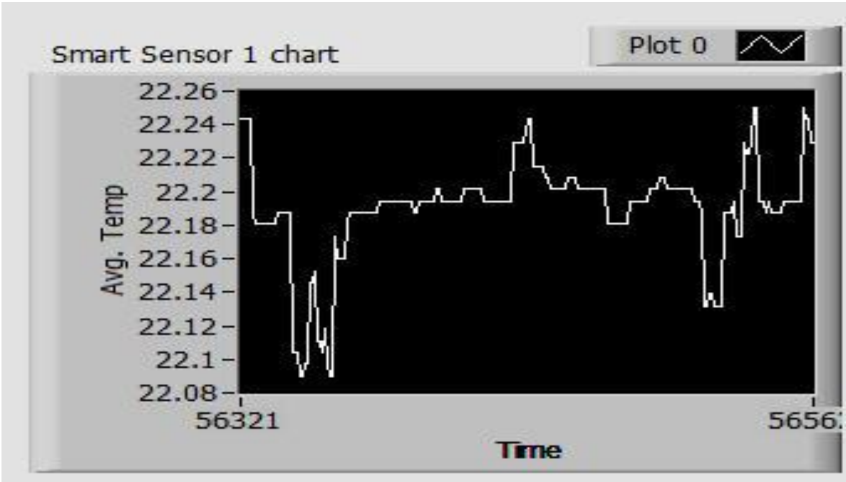

Figure 8: Average resultant graphs from LabVIEW central system from smart Sensor node 1.

5 Conclusion

The use of wireless data transmission for the smart temperature sensor application within a workshop has been demonstrated. The integrity of the transmitted data was maintained despite the introduction of a variety of environmental influences and machine operating conditions. Furthermore, the system was shown to be robust up to a distance of 15 metres in these conditions, making it suitable for monitoring the moving elements of even very large machine tools. The benefit of applying logic to surface temperature sensors, can lead to better thermal modelling of machinery, improving accuracy with in-situ measurement.

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