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Original Citation

Tansley, Dean, Fletcher, Simon and Longstaff, Andrew P. (2013) Smart sensor for surface temperature measurement on manufacturing machines. In: Proceedings of Computing and Engineering Annual Researchers' Conference 2013 : CEARC'13. University of Huddersfield, Huddersfield, pp. 55-60. ISBN 9781862181212

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Smart sensor for surface temperature measurement on manufacturing machines

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ABSTRACT

The requirement for accurate milling machinery gives rise to a host of controllers capable of data handling from sensors. Accurate measurement of temperature is important since thermal gradients cause deformity in machinery. The development of a temperature-measuring instrumentation system is proposed to improve surface temperature reading accuracy on machinery. The use of digital temperature sensors are combination with a 32-bit ARM cortex M4 processor enabling data handling and averaging is presented.

Keywords Machine tool embedded systems sensor

1. INTRODUCTION

Embedded system design for sensorisation of advanced manufacturing machines is a key part for existing and emerging engineering companies; the add-on sensor market is especially attractive to establishments wishing to optimise the performance of reliable and functional equipment. The challenge of upgrading such machinery can make manufacturers look for cost effective solutions, thereby keeping these machines in operation and saving expensive replacement. One solution would be to add sensors to gain higher levels of accuracy. One advantage of implementing such designs would allow an old machine to produce parts outside of its normal capability; such improvements increase quality and potentially open up new market areas.

One of the most significant sources of error in machine tools stems from heat, the effects of thermal error has been estimated to be approximately 70% of the total positional errors [2]. Some modern machine controllers would compensate for inaccuracies caused by thermal expansion over the operation time; only a very few can account for other distortion due to bending/bulging. The use of a sensor capable of accurately measuring the surface temperature of the machine is critical for such solutions.

This paper describes the benefits of using a *smart* sensor for machine tool surface temperature measurement. First a brief description of what a smart sensor is and the benefits that can be gained from implementing such devices in surface temperature measurement. Following this, a description of work carried out in developing a smart temperature sensor with a high accuracy thermistor. Finally, there is a discussion on the direction for further work on smart sensors and surface temperature measurement.

2. SURFACE MEASUREMENT

Following on from the introduction, the issues surrounding the sensors used to measure temperature on machine surfaces are discussed. By reading the surface temperature of a machine it informs the operator of its state resulting in possible diagnosis and/or compensation if the response behaviour is repeatable.

2.1. Thermocouple

Measuring surface temperature can be achieved in two ways. The first by infrared temperature detectors that use non-contact means of measuring the surface that work by sensing the infrared radiation emitted by the surface. Secondly are the sensors that attach directly and measure by physical contact. The typical sensors used in industry are thermocouples and resistance dependent devices particularly Platinum Resistance Thermometers (PT100). Thermocouples are inexpensive costing a few pounds but typically have insufficient accuracy for metrology applications. PT100 type sensors are extremely accurate but tend to be quite expensive which could affect the number placed on any given piece of machinery. An inexpensive digital sensor commonly used is called DS18B20 which has a standard accuracy of +/-0.5°C, typically lower than the PT100.

2.2. Bandgap temperature sensor and controller

The DS18B20 is a bandgap-based digital temperature sensor, whereby variable voltage across a diode can be used to give temperature readings (diode thermometry). The attraction to this type of sensor for IC design is how cost effective such sensors can be embedded into silicon integrated circuits. The equation for achieving this is [7]:

$$\Delta V_{BE} = \frac{kT}{q} . In(\frac{I_c}{I_s}) \qquad (1)$$

Where:

V_{BE} = The 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.
I_c = Current .
I_s = Saturation current.

The DS18B20 has a variable saturation current I_s which is process dependant; this is also known as the turn ON current. This is what makes V_{BE} less stable because it is sensitive to process spread. However the spread can be normalised by using a trimming current I_c[7][4].

Makinwa [4] describes the use of a typical Bandgap temperature sensor having an accuracy of only a few degrees. The DS18B20 is rated to have an accuracy of ±0.5°C from -10°C to +85°C [5]. The accuracy can be improved by applying error compensation, Dallas Semiconductor created a bath tub curve based on the DS1631 which shares similar architecture to the DS18B20. In order to determine if the sensor is applicable to be used in the proposed accurate smart sensor, the use of a curvature correction coefficient and a comparable high end temperature sensor was used to implement a compensation factor for use in the controller algorithm. A range of temperatures were recorded to give the best fit error correction curve [6]. Figure 2 shows a residual error for two sensors of less than +/- 0.2°C after compensation compared to an accurate reference which is suitable for this application. The reference was a FLUKE CHUB E4 1529 controller with a four wire thermistor with an accuracy better than 0.01°C..

Bohorquex [1] correctly identified the use of low cost digital temperature sensor DS18B20 as a means of producing accurate readings comparable to a PT100 which is a popular resistance sensor used on machinery. For such a low cost sensor, precision, ease of connection and immunity to noise seem unlikely. However by interfacing the DS18B20 with additional material as shown by Miguel, it's possible to produce reliable readings. The sensor and controller can form a novel integrated system leading to a new application in the field of smart sensors.

Temperature sensors can be constructed in many different ways, the thermostatic sensor known as PT100 gives excellent accuracy and gives readings based upon changes of resistance.

A typical PT100 controller unit would handle and convert the data based on the relationship between temperature and resistance; this tends to be linear over a small temperature range of a couple degrees. However over a greater range a non-linear algorithm would be required to manage appropriate compensation to give a similar level of precision in measurements. A controller used would abide to the International Temperature Standard 90 (ITS-90)[10] which defines the relationship between resistance and temperature. Another drawback to consider for the PT100 is that one reading is taken from the whole region of the element and if the sensor is standalone then self-servicing for malfunctions cannot be achieved. Also, generally, the self-heating problem caused by the current passing through the element P=I2 * R, isn't handled by the controller.
A PT100 can have an accuracy of up to 0.001°C (depending heavily on the class of sensor)but typically this is only for the sensor, and does not consider the losses in accuracy from the controller handling the data and in some cases the effect of resistance drop in the wires. Sensors working towards the accuracy standards BS1904 Class A can go to 0.15°C [9].

This sensor is widely used in manufacturing processes and on inspection equipment such as Coordinate Measuring Machines (CMMs), however there are some drawbacks; the PT100 controller tends to be expensive and gives an average reading from the large contacting surface of the sensor. The PT100 sensor cannot detect contamination from poor contact or other environmental factors resulting in the potential for unreliable data or data with a high level of uncertainty to be recorded.

Many different types of machine tool's exist and have varying capabilities, Some are able to produce higher quality components than others, due to various reasons including the materials selected based upon the cost factor of manufacturing the machine. Another point is that some machines predate milestones in technological advancement, so they basically were not created with functionality built into them to handle and process such as thermal changes on surfaces. To allow error monitoring in machine tool, a transducer can be used to aid in further development upon the basic original system. New models with compensation built into the controller of the machines are very expensive and therefore a cheaper solution would be adding functionality and feeding this data back into the machines controller.

The equation used to find the temperature gradient is as follows [11]:

$$H = kA\frac{T_{High} - T_{Low}}{L} \quad (2)$$

The model as shown in figure 1 simply doesn't take account of the roughness and imperfections in the material, but can offer a guide to accurate measurement of the surface. The surface temperature is lower since heat is applied from beneath the surface of the machine. A is the area of the surface and L is the length. k is the thermal coefficient of one type of material used, for example aluminium $k = 240\ W/m\ K$ [8]. The advantage of taking the gradient, allows for defects and errors to be passed to a soft comparator by the system. Machinery that does not have temperature calibration cannot account for movement in the chassis caused by the heating process when operated. The expanding and contracting movements that occur in the machine result in deviations finally resulting in a reduction in the quality of the work piece.

3. Smart Sensor

3.1. Smart sensor design

On the simplest level a smart sensor has three main capabilities: sensing, in this case temperature; computing processes, the data handling algorithms and general husbandry duties and communicating with the end user, via industry standard protocols. One definition has been 'A smart sensor is one where some or all of the signal conditioning functions are carried out by a microprocessor within the sensor package' [3].

When measuring the surface of machinery structures, data integrity is of great importance so that accurate modelling can be achieved. Such surfaces are not always compatible with accurate measurement due to surface irregularities and contamination from the harsh environment often found in manufacturing processes such as oil, grease and swarf . A smart sensor needs to be autonomous and capable of carrying out specific tasks whilst maintaining reliable data communication with the machine operator therefore in this case capable of maintaining accurate measurement on such surfaces.

3.2. Hardware design

The system uses 9 DS18B20 sensors connected to an ARM processor using the FreeScale FDRM-KL25Z development board. An external 32MHz oscillator is used along with an RGB LED; the controller is connected to a PC via RS232. The housing of the sensor has a copper body for good contact with the surface. A schematic, including representation of surface irregularities, is shown in figure 3.

3.3. Communication Design

The DS18B20 sensor can be connected in a network which allows for easy data transfer and handling which is ideal via the one-wire protocol. These sensors are then connected to a Freescale semiconductor FRDM-KL25Z development board, which uses a 32 bit ARM processor. The unit is aimed at being portable and free standing with minimal connectivity. The following prerequisites were

considered for the system to be a viable solution: (1) stable communication between sensors and ARM processor. (2) Low signal to noise ratio, minimal interference to stop data being corrupted; (3) Accurate timing analyses for data handling, allows for each sensor signal to be handled on the one wire bus. (4) Following serial communication protocol, RS232 for logging the data onto a PC.
The flow chart in figure 4 shows how the program operates when running. The use of CodeWarrior 10.4 IDE was used to develop the code, the general functionality of the program was written in C whereas for the time critical parts, typically requiring 15µS delays, were written in Assembly.
In figure 5 an oscilloscope was used to show the binary signals used for communication between the sensors and controller

3.4. Preliminary performance evaluation

The comparison test between a thermistor (connected to a FLUKE Chub-E4) and the Smart Sensor was carried out. A block of aluminium with the dimension of 230x230x40mm was used. The block has a hole 115mm across and 20mm from surface where the Fluke thermistor is fully inserted. The prototype smart sensor is fixed into place on the surface using thermal heat paste to ensure good contact. A heat gun was used to raise the temperature of the aluminium. A thermal image is shown in figure 6, which shows the metal being heated. As the test was running the sensors were checked for self-heating which could contaminate the results.

The aim of the test was to compare the sensor stability over a period of time and over a typical operating machine temperature range. For this preliminary evaluation, the sensor network carried out simple averaging. The test involved applying constant heat to the underside of the aluminium until the sensors measured approximately. 40°C, the data was collected via serial port on both the FLUKE and smart sensor. This test was repeated several times and the results in figure 7 which show the offset between the sensors and figure 8 shows the temperature decreasing with potential ambient contamination.

Due to the positioning of the sensors, a temperature increase lag for the sensor network is seen. This time lag is a result of the thermistor being embedded into the aluminium. There is also a noticeable lower temperature on the surface which is expected since heating is from underneath the aluminium. The tests show reliable readings over a period of a few hours.

4. Conclusions and future development

The raw concept is shown to be viable, that a low cost controller using relatively low rated digital sensors can produce readings that can be used for surface temperature measurement. A comparison between the Fluke thermistor confirms the reliability and accuracy of the sensor. Sensor data credibility is a major problem and without confidence in the processed data, models are devalued. Reported malfunctions can arise from poor sensor positioning and built quality.

Future work involves improving the accuracy of the smart sensor bycalibrating the sensors in non-ideal conditions, the parameters of which are stored and applied intelligently.. Development of the smart controller that handles the sensor can involve the following improvements: better self-diagnoses capabilities, accurate estimator algorithm for predicted behaviour, cross correlation with ambient temperature for poor ambient conditions, irregular contact and contaminated surface compensation.

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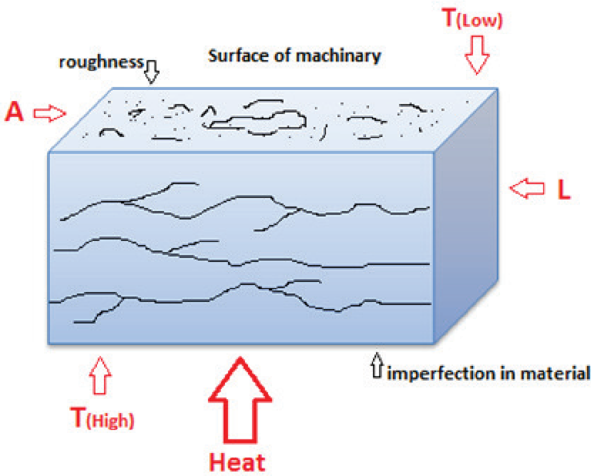


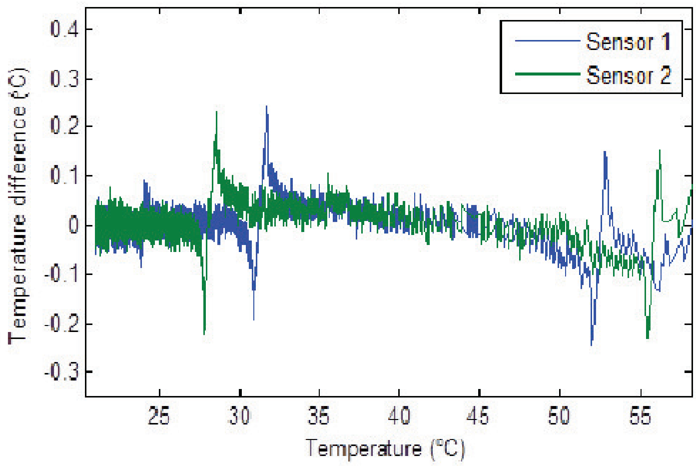


Figure 1: Surface gradient calculation

Figure 2: DS18B20 Calibration

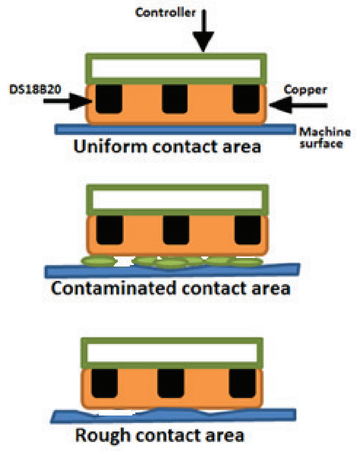


Figure 3: Sensor contact region

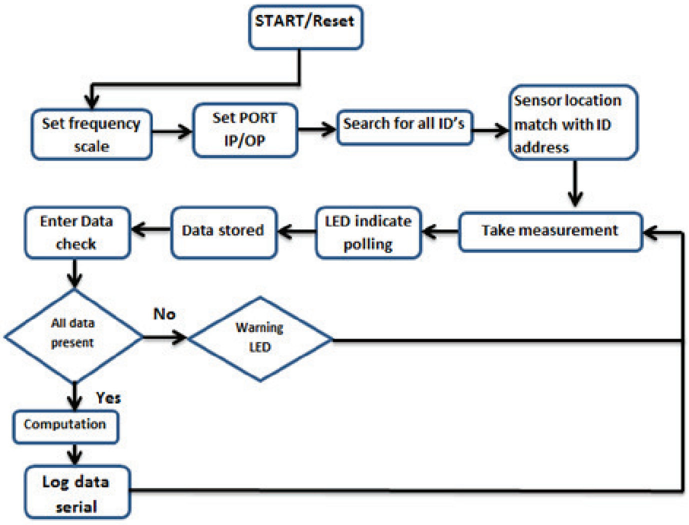


Figure 4: Flow chart for controller

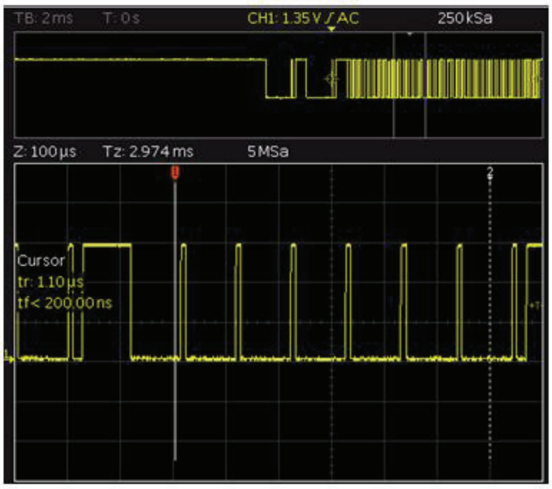


Figure 5: Controller and sensor talk

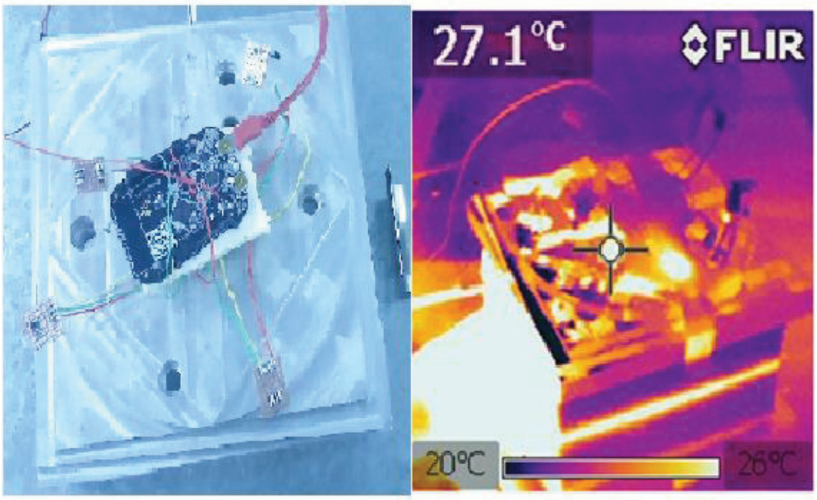


Figure 6: Visible and Thermal image of test

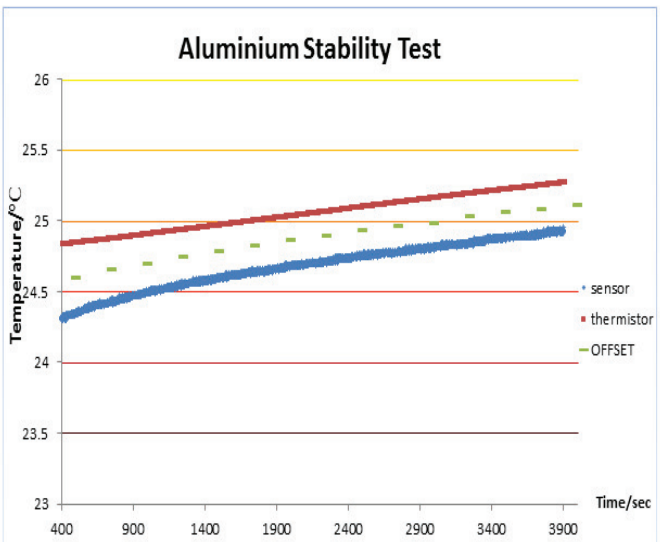
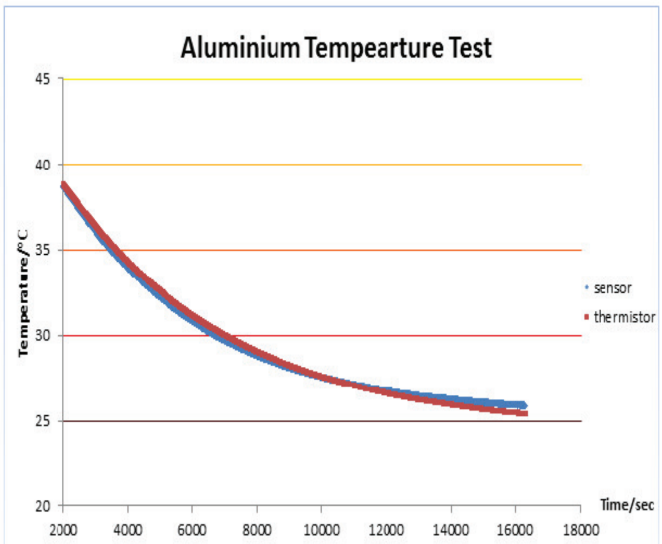


Figure 7: Stability test



8: Heating test