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Automated Adaptive Control of the Reflow Soldering of Electronic Assemblies

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Abstract

This paper describes a new technique for the monitoring and automated control of the reflow soldering process. The new technique combines state of the art infra-red (IR) sensor technology, coupled with application specific process control software, to provide a unique capability to both monitor actual product temperatures during the soldering process and to use this information to modify the process settings.

The development of techniques to allow rapid variation of the heat transfer from the oven to the in-process Printed Circuit Assemblies (PCAs) allows the system to automatically adjust the soldering oven's process settings for each individual PCA passing through it. This product-by-product profiling facilitates the assurance of consistent thermal histories and also allows the oven to optimise its energy consumption to the demands of each product. Archiving of the reflow temperature profiles also provides full traceability to the reflow process. The incorporation of IR sensing technology also aids in determining/verifying the oven profile at the introduction of new PCA designs.

This paper presents an overview of the construction and operation of the system and outlines the technical challenges that have been met and overcome.

1. Introduction and rationale

Successful reflow soldering of electronics assemblies involves operator skill, experience and time in process set up. Typical procedures require the use of sacrificial product to profile the process for a number of user selected critical points on the PCA. Thermocouples are attached to these points and the

PCA processed using a profile for the oven based on previous experience of similar PCAs. The data logged from such a procedure is used to guide the adjustment of the set points for the oven zones and/or the through-process conveyance speed (the combination of which is commonly called the 'process recipe'). Such techniques do not allow for either variations between notionally identical PCAs [1] nor for any drift in the efficiency of the process to deliver the required thermal energy. They also do not guarantee that all components on the assembly fall within the acceptable process window, as only a small number of locations may be monitored. While advances in modelling of the soldering process [1] will also provide assistance with process set up and thermocouple attachment location, a modelling approach is reliant on access to detailed CAD models of the product.

The processes currently available are also open loop in their control, as the control of the process is not governed by its effect on the products passing through it. Other process monitoring tools, such as the KIC system, whilst aiding in long term monitoring of oven temperature stability, do not provide information on the actual PCA temperature achieved. With the high proportion of convective heat transfer in most modern soldering ovens, changes in air velocity, e.g. due to flux build up in the system, may go undetected until process defects occur.

A process monitoring and control system for reflow soldering, known as Adaptive Intelligent Reflow (AIR), is under development at Loughborough which builds upon the groups experience in reflow soldering processing and modelling [1] and process control research and application [2]. AIR is designed to tackle the inherent problems with current oven

control paradigms by closing the control loop for the process. The AIR system will adapt the oven process recipe automatically, in response to the effects the reflow recipe has on each PCA. Additionally the system has been designed to provide Statistical Process Control (SPC) information for each and every PCA passing through the oven.

The design and development of the system has required a number of enabling technologies to be sourced or developed in-house and has also seen a number of significant technical challenges met and overcome. The rest of this paper reviews these and presents an overview of the final system.

2. Enabling technologies

Two key enabling developments in process and sensor technology have allowed the construction of the AIR system. These key developments have been:

- High performance, non-contact temperature measurement using affordable IR sensors;
- Dynamically responsive reflow processes which allow the heat transfer to any PCA to be rapidly increased or decreased.

2.1 Infra red sensors

Infra red sensors with suitable spatial resolution and sensitivity to the required temperature ranges have only recently become available at prices appropriate to commercial exploitation in this application.

Given the nature of the reflow process, where the product is conveyed at a constant speed through the oven, a two dimensional thermal images of PCAs may be readily created from the compilation of successive lines of temperature measurements scanned at 90° to the conveyor direction. The use of line scanning has the additional benefits that the temperature of the whole of the PCA is measured at the same point within the process and it minimises the aperture size required for the sensor to view the product.

All of the sensors evaluated for the application were of a mechanical scanning variety, where movement of the measuring spot is achieved by a continuously rotating mirror reflecting the IR incident energy onto a stationary IR receptor. This enables higher optical resolution (i.e. more points per scan line) than sensors arrays (e.g. CCD line arrays) and also avoids the pixel to pixel sensitivity variations

typical of array detectors.

The specifications of the sensor finally selected are summarised in Table 1 below.

Feature	Requirement
Measurement accuracy	+/- 2°C
Measurement repeatability	+/- 1°C
Spatial resolution	< 1mm ²
Scan speed stability	< +/-0.1% deviation
Measurement range	100 - 300°C

Table 1: IR Sensor specifications

2.1.1 Signal acquisition from the IR sensor

The sensor output is an analogue signal which is converted into 12 bit digital data. The 12 bit analogue to digital conversion is required on account of the sensor not providing a signal directly proportional to the temperature of the object.

The total radiated power, Q , from a black object, i.e. with an emissivity of 1, at a temperature T is given by the Stefan-Boltzmann equation:

$$Q = T^4 \times b \text{ W/m}^2$$

where b is the Boltzmann constant.

However, the radiation sensors (PbSe) used in the line scanner are only sensitive to a limited bandwidth (3 - 5µm), their detected signal, U , from a body of temperature T , follows the function below:

$$U = \frac{a}{e^{(T + 273.2)} - 1} - c$$

where a , b and c are constants.

The data has therefore to be linearised and also corrected to take account of emissivity before an accurate measure of temperature is provided. Many of the materials used in the construction of electronics assemblies have emissivities of less than 1 and will therefore radiate less heat than given by both equations above. Accurate temperature measurement therefore requires emissivity correction for every point being observed.

2.2 Responsive processes

Whereas the availability of IR sensors facilitates

process monitoring and ultimately automated process control, the process itself has also to be sufficiently responsive to changes in the process recipe. This requires a rapid change of thermal energy transfer to the target PCAs whilst in process. The alternative strategies for this are as follows:

- Change the through oven conveyance speed;
- Change the thermal energy source temperatures for increased IR radiation;
- Change the temperature of the fluid in a forced convection process, or,
- Change the flow rate of the fluid in a forced convection process.

Any of these strategies on their own or in combination could be used, however there are some disadvantages associated with each. Changing the through oven conveyance speed will change the shape of the temperature profile and has implications for the production rate of the oven, and perhaps the whole production line. Changing source temperatures and consequently the level of radiative heat transfer has two potential drawbacks. Firstly typical heat sources have a large thermal mass and take too long to reach a new stable set point and secondly, there is the possibility of imparting too much thermal energy to low thermal mass areas of the PCA, causing thermal damage. Similarly, changing the temperature of the fluid in a forced convection process may take too long and have similar problems with low thermal mass areas. The fourth option, changing the volumetric fluid flow rate, offers a means of rapid process modification and also reduces the risk of thermal damage to the PCA. This option provides the most promising strategy for process actuation and has been the focus of the AIR system development.

Figure 1 is derived from a thermal process model of a mixed IR and convection based reflow soldering oven [1]. This demonstrates the effect on a point in a PCA of varying the heat transfer coefficient due to forced convection. Implementation will require calibration of a forced convection oven, mapping heat transfer coefficient against fluid flow.

3. Technical challenges

Implementation of a process monitoring and process control system requires the following major system components in addition to the IR sensor:

Figure 1: Effect of varying convection coefficient in final zone of a reflow soldering process.

- Acquisition and process synchronisation;
- Data acquisition;
- Data pre-processing;
- Data presentation and analysis;
- Archival routines (for SPC etc.);
- Derivation of a robust control algorithm, and
- Process actuation to affect control.

The following sub sections review the technical challenges and solutions implemented in construction of the system.

3.1 Data acquisition

The data acquisition system provides 1200 12 bit measurements of the sensor output voltage during the time the sensor scans across the full width of the oven conveyor (600mm) giving an average pixel pitch of 0.5mm. The scan rate of the sensor would ideally be set so that the pixel pitch along the conveyor belt is equal to that across the belt width, but this would require a variable scan rate to compensate for changes in the belt speed. The machine being used for system development has a typical belt speed for conventional PCAs of 500-600mm/minute which at a line rate of 20Hz gives a line pitch of 0.42 - 0.5mm.

Synchronisation with the oven and PCAs alleviates potential problems such a volume of data per second presents. Two techniques are used to minimise the amount of data handled per PCA. The first involves the set up of data acquisition to acquire for

the field of view occupied by a PCA. Secondly, the acquisition is only active whilst the PCA passes, the active time calculated from conveyor speed of the oven and the length of the PCA. These metrics are currently entered manually, i.e. the width and length of the PCA and oven speed. The acquisition process is triggered by a signal from a fibre optic proximity sensor, located in the oven at a fixed distance from the IR sensor.

It is possible to derive the above metrics in data acquisition by interrogating the oven controller for conveyor width and speed and by using the signal from the proximity sensor (which provides a signal whilst a PCA passes). However, trials have indicated that the positioning and speed control capabilities of oven conveyors are somewhat less than ideal, primarily due to mechanical inaccuracies when operated at reflow soldering temperatures. The reflectance trigger has also proven to be more reliable for only detecting the leading edge of PCAs. This is on account of the variabilities in the reflectance properties of the PCA materials and PCA designs that include cut out sections which result in a loss of signal. The strategy adopted therefore assumes the worst case scenario and includes an allowance by acquiring data for slightly wider than the PCAs for a longer period of time than required.

3.2 Data processing, handling and analysis

Whilst data linearisation is straight forward, the correction for emissivity is more problematic. There are no simple means to automatically correct for emissivity across the whole PCA, without having fore knowledge of the materials in PCA. A predetermined template of emissivity values for a whole PCA would still be problematic for applying to the thermal data, on account of the pixel by pixel alignment accuracy required. Consequently the system has been developed to acquire and initially process all the data with a single value of emissivity. Points on the PCA required for process monitoring and/or process control functions are individually corrected for emissivity when the user selects these points. The consequences of this strategy are twofold:

- i. Only points of interest are processed, affording computation efficiencies as compared to template matching techniques;

(a) Non emissivity corrected

(b) Emissivity corrected

Figure 2: Effects of emissivity correction on thermograph of a PCA.

- ii. A non-emissivity corrected thermal image is provided during operation and set up. Such images have greater contrast between features, allowing easier identification of monitoring/control points.

The difference emissivity correction makes is evident in Figure 2, which presents two thermal images of the same PCA design, one of which is emissivity corrected.

4. System architecture overview

The AIR system has been created with a number of off-the-shelf components that have been integrated with substantial software engineering. The following subsections deal with the physical and software architecture of the system.

4.1 Physical system

Standard components have been sourced to keep costs low, with the only customisation required being the calibration and operation of the sensor and

the construction of the interconnecting cabling.

Integration of the system into a production oven requires provision of a line of sight for the sensor and a suitable operational environment. The optics of the sensor are sapphire and as such are robust enough to withstand the fluids and abrasive materials that may be used remove flux condensates. Fume extraction prevents build up of material that may impact on the optical performance of the sensor. In addition to providing the space and environmental conditions for the sensor, the stand-off from the PCAs is required for sensor calibration, as this calibration is tuned to the distance the sensor is from the PCAs.

The sensor output is captured using a commercial 12 bit digital to analogue capable acquisition card, sampling at 250 kS (kilo Samples). This also has a number of other I/O capabilities, one of which is a digital input which acts as the trigger to the data acquisition process. This is provided by the proximity sensor located within the oven. The acquisition hardware is built into a host Personal Computer (PC) upon which the AIR software resides. For the purpose of monitoring and control functions, this PC has to be integrated with other hardware. For instance, a bar code scanning device is located at the entrance to the oven to provide traceability of data to individual PCAs. For the purpose of control, the AIR system actuates control of the oven through the oven controller PC. This requires the AIR PC to interface with the oven PC, which in turn interfaces to the hardware controlling the oven. There are different strategies to achieving this. If the oven controller and the AIR system are to reside on the same PC, then an inter-process DDE (Dynamic Data Exchange) can be used. Alternatively an inter-application interface between two PCs is required, using an RS232 serial link. The current state of the art with oven controllers dictates that the second of these two options is the only viable technique at present.

Figure 3 illustrates the current physical connectivity between the major operational hardware components of the system

4.2 Software architecture

The AIR system has been developed using object oriented methods (Visual C++) coupled to an interface builder (Zapp) and exploiting the drivers

Figure 3: Physical connectivity of AIR system.

provided with the data acquisition card. The system has been developed on Windows NT 4.0, utilising the advantages afforded by this operating system with respect to low level control of system resources and the ability to assign critical portions of the application to prioritised individual threads.

Initial efforts concentrated on creating a “friendly” user interface for the monitoring and control system. Zapp classes and objects are utilised, providing a fully menu controlled windowing system to display the thermal images, SPC graphs, process data and alarms. Edit dialogues have been produced for editing process initialisation data and system configuration data. Menus and toolbars have been designed around Windows standards and made to match those on the oven control PC. Data Analysis functionality is integrated into the user interface to analyse data acquired from the scanner, and to calculate and display SPC trends.

Data acquisition is made transparent to the User Interface, so that changes in acquisition hardware and software can be made in the future, if necessary, without effecting the user interface and data analysis functions. The acquisition software is coded in a separate thread to enable real time operation incorporating libraries provided with the hardware. Similarly, closed loop control algorithms are to be coded in separate, real-time threads. The structure of the system is presented in Figure 4, which illustrates the overall architecture of the application.

5. Operation of the AIR system

The AIR system can be used in either Process Monitoring, Process Control, or both modes simulta

Figure 4: Overview of AIR software components.

neously. The difference to the user is in the details of initiating the system and in operation additional algorithms are used for control decisions, the requisite I/O and process actuation functions.

5.1 AIR system initiation

The AIR system requires initiation for every PCA design that is to be processed. The initiation information is determined in a two step process. In the first step the following information is required:

- PCA identifier;
- Date;
- Option to start a new archive or open previous records;
- PCA length and width;
- Oven conveyor speed;
- Indication as to whether a barcode is to be used.

Following this the user has to define which points/locations are required for process monitoring or as control points, or both. These are selected from a reference image which may have been previously acquired or alternatively a new thermograph may be acquired. In both cases the following is required:

- Identifiers for each location/point on the PCA;
- Emissivity for each point (selectable from a database provided for common PCA materials).
- Indication as to whether each point is for monitoring, control or both.

A new reference image is acquired by processing a PCA through the oven with the acquisition function enabled. Once acquired, this reference image is presented to the user for selection of the nec-

essary points as above.

5.2 Operation of AIR system during PCA production

Having initialised the AIR system with the prerequisite information, PCA production can begin. Figure 5 illustrates a screen snapshot during a production run and shows the area into which the most recently acquired image is presented and the SPC control charts for each of the user selected points.

As PCAs enter the oven, and if they are barcoded, the barcodes are scanned for cross referencing the data acquired to individual PCAs. At the peak of the process the proximity sensor is triggered and data acquisition activated. The data is acquired until just after the PCA has passed out of the line of sight of the sensor. The latest image is presented as in Figure 5 overleaf, with the data linearised and emissivity corrected to update the SPC charts and archived in a comma delimited (CDL) text file.

If the automated AIR control function is activated, the linearised, emissivity corrected data is input to a control algorithm, currently under development at Loughborough. Based the inputs, this algorithm may, or may not, output new set points for the fans driving the forced convection heat transfer in the final zones of the oven. The control outputs update the process recipe file and the oven controller application acts on these to actuate the required fan speeds.

The operation of the system is presented diagrammatically in Figure 6.

6. Discussion and conclusions

This paper has presented an overview of a system that promises for the first time a true closed-loop control paradigm for reflow soldering. This level of potential control offers the ability to optimise oven performance for every PCA, allowing a tuned process for each PCA design. Other benefits include: the tailoring of energy consumption to each PCA design; reductions in process setup times; more informed instrumentation of PCAs for initial process recipe determination; reduced risk of thermal damage to the PCAs and the possibility of successful processing of products requiring tighter process windows, such as those utilising lead free solder alloys.

The system currently provides a means to log

Figure 5: Snapshot of AIR application in operation

Figure 6: Overview of AIR system operation

substantial amounts of information from the peak of the reflow process for each and every PCA passing through an oven, with full traceability down to each data point. The system therefore provides the first means by which manufacturers can produce the quantity and quality of data required for SPC and quality assurance for every PCA processed.

Current work on the system is in progress in the development more empirically tried and tested process control algorithms with future avenues exploring intelligent control algorithms and the expansion of AIR's applicability to a wider range of ovens.

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