Multi-Sensor Fusion to Provide Quantitative Process Characterisation*

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Abstract

This paper describes the design, specification and implementation of a machine vision system. The system integrates structured light, coherent light, and X-ray imaging techniques to provide component coverage. The integration of the multiple sensor systems is facilitated by the object oriented design.

1 Project Overview

This paper describes the design and construction of an open, automated, visual inspection machine for the electronics manufacturing industry, under the auspices of VERBONDS. It is being under taken by a consortium of partners, comprising Trinity College, Dublin; Lucas Engineering and Systems Ltd.; Digital Electronics Corporation; Liverpool John Moore's University; Sopelem-Sofretec; and LETI (CEA - Technologies Avancees), DSYS-CENG. The prime target area in the industry is fine pitch, Surface Mount components, with care being taken to address the more advanced technologies of the future. The design goal is to provide the industry with an inspection system capable of accurately measuring the quality of product, in a realistic time scale and to sufficient accuracy to serve as a process calibration tool. The ideal objective of the project is to develop a system capable of 100% inspection of Printed Circuit Boards (PCBs). In practice, operating as a calibration tool, it is not envisaged that this would be the typical mode of operation.

The inspection platform is expected to be an integral part of the production process providing a product characterisation function. This characterisation function contributes directly in the short term to effective process control, allowing production process trends to be identified. The long term benefit will be in providing a direct relationship between product quality and production standards. The production standards can be improved over time as the quantitative inspection measurements are correlated with the performance of the product in the field.

The machine will be constrained to operate within the time constraints imposed by the product cycle time. It is envisaged that dynamic analysis of the inspection results will provide information to allow on-line modification of production parameters thereby closing the production/inspection loop. To this end, the operator will interact with an expert system through a Graphical User Interface, (GUI). This will enable both flexible and in-line re-configuration of the inspection machine on the production line as process trends are detected, and inspection priorities change.

In closing the process control loop in a quantitative rather than a subjective manner (as is the current practice in the electronics industry), the VERBONDS system will make a significant contribution to the industry. The scalability and flexibility of its system architecture should allow it to benefit from advances in computer technology and maintain its performance in its application domain.

2 Application Domain

Both SMT and PTH components (particularly Pin Grid Arrays, (PGAs)), are developing apace, with decreases in pitch, and diversification in functionality. The trends within the industry are to shy away from extremely small pitch devices, but there is continuing innovation in component package types. With the penetration that dedicated silicon is making into the marketplace, it is envisaged that this latter trend will continue. This will place additional strain on the current inspection processes, and to meet these demands a radical upgrade in inspection techniques is need.

2.1 Visual Mechanical Inspection (VMI) Standards

The fundamental problem with current VMI standards is that they are subjective. Such standards as [Denman, 1988], MIL-STD-2000, or WS-6536, are undermined by the inability of the subjective inspector to provide objective quality assessments, and do not provide quantitative data on the manufacturing process. The motivation for the VERBONDS project is to obviate this subjective assessment, which precludes the automation of process control.

To meet the demands of the industry across the full spectrum of today's technologies, the approach taken is to design an open system, fusing multiple sensing subsystems into an integrated process instrument. This will facilitate the flexibility of the system in dealing with a range of product types, as well as providing sufficient coverage of component and package types.

With the diversity of components currently in the industry, the imaging requirements for 100% coverage are complex. These can be met, by providing a comprehensive configuration, but begins to be prohibitively expensive. The ability to dynamically configure the inspection routines and to incrementally upgrade the sensing subsystems means that the VERBONDS system can provide a cost effective solution to automating process control.

3 Addressing the Sensor Modality Issues

The broad range of component and fault types leads to extremely diverse imaging requirements. The functionality of the machine meets these requirements by its multi-sensor design. The VERBONDS System may be configured with one or more Sensor Subsystems, allowing minimal, cost effective, solutions to be provided and comprehensive functionality for critical applications.

Illumination sources in the differing sensor modules include point source LEDs, coherent light, and X-rays. The

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sensors being utilised include standard CCIR cameras, and high-specification CCD arrays producing digital output. The optics used in the imaging systems provide for a variety of resolutions, thus enabling the optimum combination of data throughput and analysis speed to be chosen per application.

The analysis of the images varies with the type of sensor, so in addition to a parametric model of the solder joint, an analytic model of the sensor's imaging capacity is required. The burden of the development work will be to integrate successfully the sensor dependent prepossessing, with subsequent stages of solder joint analysis.

4 System Architecture Overview

The VERBONDS system architecture supports the requirements for differing sensing modalities and resolutions while maintaining a modularity of design which provides for the independence of each sensor system. Each sensor system generally requires specialist hardware and low level software. In facilitating this need, the VERBONDS system architecture provides each sensor subsystem with the flexibility to operate independently. In addition, once the sensor subsystem ascribes to the modular interface specification, it can be easily configured to cooperate with other sensor subsystems.

The VERBONDS system is divided into two primary subsystems, the Measurement System and the Supervisory System. The Measurement System's main function is to perform data acquisition and calculate solder joint parameters on the Printed Circuit Board Assembly (PCBA) being inspected. The Supervisory System provides the overall management of the work cell providing such things as load/unload mechanical handling, interfaces to both users and the on-line production management system.

4.1 The Supervisory System

The Supervisory System is responsible for overall work cell management. The Supervisory System constructs the Inspection Request by interfacing with the product CAD database and production process requirements. The process requirements can be dynamically determined by the production engineer, or by statistical analysis of past inspections. The Inspection Request is sent to the Measurement System which returns the parameters which were requested. The Supervisory System analyses the data, reports on the analysis from a quality standpoint, in addition to performing statistical analysis over a period of time to identify trends in the production process. It is this information that can be used as online feedback to production control.

The Supervisory System is further subdivided into the following sections.

Inspection Request Generator (IRG) This determines the Inspection Events necessary to fulfil an inspection request. These events constitute an Inspection Request (IR) that should be carried out for a particular subject PCBA. Possible inspection strategies range from a statistically driven sampling routine to a full 100% inspection of all bonds. The IR details the locations where inspection events should be carried out and the particular measurements required from each inspection event. It is loaded to the Measurement System which performs the actual inspection events, returning the measurements requested.

Material Handling Subsystem (MHS) The Material Handling Subsystem identifies PCBA's as they are loaded into the work cell. The distinction between new product, which requires the building of a new IR and new PCBA, which entails execution of the configured IR, is signalled by the MHS to the Supervisory System. When the inspection has completed the MHS is informed and, depending on whether bottom side inspection is required, inverts or inverts the PCBA.

Data Analysis (DA) This module receives the information from the Measurement System in the form of either parametric measurements or in the form of pass/fail results. For quantitative measurements the DA sub-system processes the information with respect to the current quality criterion to develop an overall strength/reliability measurement for the joint. Selected algorithms to generate the quality measurement from the criteria are being developed using a Finite Element Modelling (FEM) package. The quality measurements are returned, linked with the CAD data for the PCBA, providing precision logging of process performance and product quality.

Process Control Information (PCI) The PCI module is responsible for results dissemination both directly to an on-line Process Control System and to the system operators via a GUI. There are several GUIs for the different types of operator, including a different interface for production engineers, machine operators and system developers. The PCI system will use the current information to update process control charts (for variables or attributes) which can be used to monitor the process. When development work is complete, the process information will be available via a standard interface, to process management systems such as Apple's ProAct.

4.2 The Measurement System

The Measurement System is responsible for the production of information about the product under examination. The Measurement System is itself divided up into four main components, Inspection Control, Acquisition Control, Image Management and Image Processing.

Inspection Control Module
The Inspection Control Module drives the real-time measurement functions of the Measurement system. It generates the configuration requirements for the Image Management and Image Processing modules. However, it's primary function is to drive Acquisition Control through the imaging requirements of the Inspection Request. It drives the Acquisition System through the sequence of inspection events in the IR, in order to acquire the necessary images and pass them to the Image Management module. To perform these functions it uses the processed PCBA CAD files to generate routing and configuration information for the sensor subsystems within the Acquisition Control module. Critical issues in synchronisation, timing, and mechanical control are the within province of this module.

Acquisition Control Acquisition Control primarily manages the acquisition of the images from the different sensors subsystems. It takes the Inspection Request from the Inspection Control module and executes the inspection events, moving the PCB and passing the relevant configuration information to the sensor. The resulting images are passed to the Image Management module. The modular specification of this component of the VERBONDS workcell provides for the flexibility of configuration that will guarantee the viability of the project. Each project partner is enabled to develop one or more sensing systems, which can be readily integrated on account of the Sensor Subsystem interface specification. Sensor Subsystem configuration time is projected at 15 minutes, thus enabling rapid re-configuration.

Image Management The Image Management module manages the system resources and distributes sub-images to the relevant image processing algorithms in the Image Processing module. This provides for the possible parallel operation of sensor systems within the Acquisition Control Module and the multi-processor distribution of the image processing algorithms within the Image Processing module. For speed sensitive applications a processor farm architecture will be implemented. The resource managment issues in such a system would be encapsulated within the Image Management module precluding any integration problems with the other components of the system.

Image Processing The Image Processing module converts the raw sensor data into parametric solder joint measurements or pass/fail measurements. These measurements are then passed to the Supervisory System.

The Image Processing module receives the images from the Image Management module and processes these images into quantitative or pass/fail measurements of solder joints. The site of the processing is not predetermined, specialised hardware, DSP chips or multiprocessing networks may be incorporated to provide for realistic measurement times.

The Image Processing system can provide pass/fail measurements from pre-determined critical bounds on the prime variables of the particular assembly technology. The quality criteria within the industry remain subject to the production process and manufacturer, principally determined by the application demands, and hence the financial constraints imposed on producing cost effective product.

5 Imaging — From the Subjective to the Objective

To remedy the lack of quantitative standards for solder joints, a theoretical model of the quality of a solder joint has been developed. Thus irrespective of the sensor modality, the information being measured provides input to a unifying model of the joint. In addition to facilitating integration of multiple sensing modalities, this enables the VERBONDS system to be configured for a variety of products, with differing technologies, pitches and inspection requirements.

The theoretical model of the solder joint, coupled with a sophisticated model of each sensor system's imaging, allows *quantitative measurement of the solder joint*. The validity of the model of the physical properties of the solder joint and the accuracy of the sensor system determine the validity of the quality assessment.

The model of a solder joint effectively parameterises the geometry of the solder. Some recent work in this area[Heinrich *et al.* 1992] identifies the prime variable in the SMT process as fillet formation. However, due to imaging difficulties, the heel fillet requires much more expensive sensing equipment, e.g. X-rays, and so to provide a cost effective yet comprehensive solution, several secondary variables are taken into consideration in the model. The surface profile, both longitudinally and laterally, coupled with both the toe and heel fillet curvatures, leads to a geometric representation of the solder volume. This, coupled with a FEM of the properties of solder under thermal cycling, provides a solid reference for the parametric measurements from the Imaging Systems.

Illumination	Structured Light	Structured Light	Structured Light
Physical Property	Specular Reflections	Specular Reflections	Intensity
No. Images	4	4	1
Resolution μ per pixel	4μ	10μ	13μ
Size	1260x1152	768x512	768x512
Depth	8	8	8
Acq Time	0.04s	0.04s	0.04s
Data	BYTE	BYTE	BYTE
Memory	1.3MB	0.8MB	0.8MB

Table 1: Structured light Sensing Systems tabulated by Source, Acquisition (Acq.) Time, Resolution and Image Depth.

5.1 Quality Assessment

There are many different quality assessment criteria in the PCB assembly industry. Typical criteria include resistance after temperature cycling, pull test strength after temperature cycling and temperature cycling to failure. Any quality measure must be demonstrated to correlate with the Mean Time Before Failure (MTBF) in the marketplace of the PCBAs.

The underlying quality criterion on which the VERBONDS system is based is the residual mechanical stress after temperature cycling. The relationship between Tensile Pull Strength and temperature cycled product was demonstrated to be linear by [Brady 1991]. It is this result motivates the choice of mechanical stress after temperature cycling as the physical measure of solder joint quality at this stage in the system development.

By building a comprehensive three dimensional model of the solder geometry and incorporating the solder flux density, the residual Mises stress can be calculated by FEM. The quality measurement of a solder joint is thus based on the physical properties of the material. The detailed nature of the physical model of the solder joint will enable other quality criteria based on differing physical properties of solder under mechanical, thermal or electrical conditions to be utilised.

The quality assessment is therefor customisable and can be initial based on the manufacturer's in-house standards. But more significant is that standards may be upgraded to meet quality implications arising from advances in solder technology or the identification of correlations between production parameters and product reliability.

6 Sensor Systems and Multi-Sensor Fusion

There are a number of modular sensing heads under development. The physical imaging systems are tabulated in Table 1 and 2, and the optimum measurement parameters for each system are described in the following section. The specification for Sensor System fusion is outlined in the last section.

6.1 Sensor Systems

The following table depicts the relative capabilities of the differing systems. The physical properties under measurement are indicated in the third column. The specular reflections are used to determine geometric parameters of the solder using a technique based on a model of the joint geometry and the imaging system (Waldron *et al.* in preparation).

The calibration of the sensing system is incomplete, as the mechanical structures of the sensing systems are under manufacture. The figures are based on the design trials, and so do not reflect the finished system calibration figures.

Source	Coherent Light	X-ray
Physical Property	Surface Profile	Thickness
No. Images	1	1
Resolution μ per pixel	20μ	20μ
Size	739x484	1024x1024
Depth	32	32
Acq Time	0.12s	1.5s
Data	REAL	REAL
Memory	3.2MB	12MB

Table 2: Laser and X-ray Sensor Systems tabulated by Source, Acquisition (Acq.) Time, Resolution and Image Depth.

6.2 Parametric Measurement

The prime variable under consideration is the fillet angle. The high resolution structured light sensors are specifically designed to image the toe fillets. The measurement of width and length of gull wing joints are relatively tractable with any sensor. To measure the surface profile a laser diffraction pattern is projected across the joints. Finally, the X-ray system, using a micro-focus source, is capable of imaging solder features to $\sim 4\mu$. The *thickness* of the solder in the joint is readily calculated from the Radon transform of the absorption function. The principle requirement on sensor fusion is to couple the information from the structured light, laser light and X-ray sensors to provide an integral measure of the geometry of the joint from the separate measurements.

The model of the imaging system allows calibration of the images, in microns per pixel. This is the essential prerequisite for turning a machine vision system into a measurement device.

6.3 Fusing Sensor Modalities

The integration of multiple sensor modalities is facilitated by the use of a *Open Object Oriented* design philosophy. The object oriented (OO) features such as encapsulation using inheritance and operator overloading provide a robust and simple method of avoiding many of the complexities common to multi-sensor fusion. Other OO features such as message passing allow the parallel execution of tasks to be facilitated. The open design philosophy involves making the design as independent as possible of both hardware and operating systems. This involves managing the hardware dependencies of the component systems at the lowest possible level within the system. The OO paradigm provides a structure within which alternative implementations of system functions can be dynamically linked into the system.

Image analysis occurs in two distinct stages. The different sensors provide different types of information, and encapsulate image data in different ways. For example the X-ray image represents the absorption of the X-rays as they pass through the PCB, this data is encoded in images with pixels 32 bits deep. The structured light sensors produce images of the specular reflections from the solder on the PCBAs and encode these in 8 bit pixels.

The system is being implemented in the *Object Oriented* language C++. The *Object Oriented* (OO) features of C++ facilitate the integration of the different sensing modalities, image data types, and processing functions. The physical difference between the data captured by the different sensor systems requires that sensor specific algorithms be used to extract the sensor independent data.

Inheritance The data abstraction, or *inheritance*, that is implicitly available in the OO methodology allows for the sensor subsystems to be treated at the appropriate level of abstraction, to wit, the level of image acquisition, irrespective of illumination, and hardware issues. Thus sensor fusion is achieved through inheritance.

Polymorphism Polymorphism, or the ability to treat data processing at the requisite level of abstraction *dynamically*, provides for the dynamic re-configuration of the sensor systems, without the need to rebuild the software from scratch.

Operator Overloading The ability to overload operators allows particular implementations of image processing algorithms operating on the differing image data types to be treated as single algorithms.

After sensor specific pre-processing the sensor independent information extracted provides input to generic image processing algorithms. After the pre-processing of the images several sensor independent algorithms may be shared by the different sensor systems. Typical image processing algorithms at this level will include texture measurement, geometric parameter extraction, and morphological operations to determine connectivity.

The subsequent extraction of solder depth, height and surface features in the sensor independent processing provides the physical dimensions to the geometric solder joint model. The sensor independent data will have tolerances which relate directly to the original sensor modality and to the sensor dependent algorithms. These tolerances will determine the overall accuracy of the inspection.

7 Machine Vision Sensor Systems

The machine vision sensor system incorporates high accuracy imaging without losing the flexibility to image at several different resolutions. The imaging of highly specular surfaces such as solder provide particular problems for image processing. To over come this difficulty the lighting technique used provides highly controllable, directed lighting allowing the use of structured highlight image processing techniques [Nayar et. al., 1990, Sanderson, 1988, Lacey *et al* in preparation].

7.1 Fault analysis

The sensor independent processing provides supervisory system with values for the various solder joint parameters. The monitoring of the solder joint properties may be utilised in several ways. The manufacturer may define a quality measure as a function of the parameters, enabling pass/fail inspection. Process monitoring may enable the detection of detrimental trends in the process, thus improving overall quality, and preempting future faults. The process model under development will enable the parameters to be used as feedback for on-line process configuration.

8 Future Vision Systems For Inspection and Control

The trends in vision systems at present point to the use of future systems with auto calibration, and dynamic configuration. The minimum amount of operator expertise is favoured in the industrial marketplace. Machine vision is becoming an integral part of the production process, rather than a separate workcell inspecting product. It is in this vein that the VERBONDS system is being developed. It is seen as an integral part of the production system, providing the information to aid automatic control of the entire process. The flexibility and configurability of the VERBONDS system is designed to enable the system to be used in controlling the any PCBA assembly process rather than as simply an inspection machine.

The success or failure of any machine vision system in the final analysis depends on the robustness and repeatability of its measurements. The robustness and repeatability of results of each of the individual systems is maximised as in any vision system through a rigorous test and development cycle. The VERBONDS system also benefits from the ability to compare the measurements of multiple sensor systems. This sensor redundancy provides a means of highly accurate tuning of the algorithms of all different sensor systems. However the final configuration will really be decided on the cost/benefit analysis for particular applications.

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