Sensor-based Registration and Stacking of Electronic Substrate Layers

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Abstract

Substrates for most of today's electronic products contain many wiring layers which are individually fabricated, mechanically registered with one another, and laminated together. Alignment tolerances of 0.05 mm to 0.1 mm are sufficient to register the vertical connection pads or vias on each layer. More aggressive designs of the future will, however, require manufacturing accuracies of at least an order of magnitude better to accommodate much finer wire widths and pin spacings. Conventional equipment relying on mechanical "pin-in-slot" methods will likely be inadequate, and a new approach will be needed.

We describe here a sensor-based approach for registration and stacking of electronic substrate sublaminates that replaces pin-in-slot methods, yet does not require accurate automation equipment. A pilot work cell for this approach is presented, which has an IBM 7576 coarse-positioning robot, a specially-developed fine-positioning robot, optical sensors, and several routine low accuracy fixtures. A novel robot bracing method was used to minimize environmental vibration during sublaminate stacking.

Pairs of test sublaminates, each containing an identical pattern of 100 μm holes, were aligned, stacked and bonded. The accuracy of registration

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was determined by measuring the offset between the center lines of any pair of aligned holes. The results showed that the holes were consistently aligned to 2.5 μm (3σ) which surpasses our customer's 7.5 μm (3σ) requirement and is more than ten times better than the traditional mechanical method.

1 Introduction

Many electronic products use integrated circuits mounted and interconnected on substrates (circuit boards) by printed circuit wiring having widths and spacings in the range of 0.1 to 0.2 mm. Most circuit boards are multi-layer structures with internal wiring patterns interconnected vertically through contact holes (vias) to adjacent layers.

The layers are traditionally aligned with a mechanical pin-in-slot method wherein each layer has four large punched alignment slots referenced to the wiring pattern on the layer. The layers are registered and stacked by placing the alignment slots of each layer over a set of four precision guide pins which physically provide lateral and rotational constraints. The completed stack is bonded to form a rigid laminate for supporting and interconnecting the circuit components. The method is sufficiently accurate (approximately 25 μm, or 1 mil registration) to ensure via overlap for today's products.

Recently, new high density circuit layouts call for manufacturing accuracies of better than 0.1 mm with interplane via registrations of 7.5 μm (3σ) or better. That is, in a batch of products, 99.4% of the vias must register to within 7.5 μm.

Layer thicknesses for the new designs are in the range of 0.05 to 0.1 mm. The pin-in-slot method is no longer suitable as *i*) it could cause warping or bending of the sublaminate layer and thus require the slots to be somewhat larger than the pins, *ii*) the pins would have to be spaced with extreme accuracy which might be difficult to attain, and *iii*) temperature changes could alter the pin spacing. It was felt that the accumulated tolerances from these factors would easily exceed 0.025 mm.

We therefore set out to design and build a prototype system that did not rely on mechanical methods—but instead used optical sensing and fine motion to achieve the 7.5 μm registration objective. The following sections describe our efforts to produce a system using inaccurate robots, inaccurate sensors, and inaccurate fixtures, but which nevertheless succeeds in accurately aligning and stacking the sublaminate layers.

Section 2 describes the test product sublaminate layers used, Sec. 3 describes the prototype work cell and its operation, Sec. 4 presents performance measurements made on the system, and Sec. 5 presents registration results obtained using the test sublaminates.

2 Test sublaminates

The test sublaminates were molybdenum sheets of 0.05 mm thickness with dimensions shown in Fig. 1. A photolithographically generated hole and fiducial pattern was formed on the sublaminate. An array of 100 μm diameter holes spaced on 200 μm centers was fabricated at the center of each sheet to represent the wiring pattern vias.

The pattern included 750 μm diameter holes in each of the four corners which acted as accurate fiducials for optical sensing. The holes and fiducials were opened in the material by a double-sided etching process.

The fiducial shape and spacing were design options but could not vary between sublaminates to ensure minimum dimensional changes between pairs of layers. Images of each fiducial, formed by back lighting the layer, were used for optical position sensing. The rather large 750 μm circular fiducial holes were chosen to provide adequate detector output with reasonable levels of back lighting. These fiducials functionally replace the large slots needed for traditional mechanical alignment.

The sublaminates and feeder station were designed to meet two requirements:

1. The centroid of the fiducials coincided with the centroid of the outer dimensions within ordinary manufacturing tolerances of about 0.25 mm.

2. Sublaminates loosely placed in a feeder station had their centroids within about 0.50 mm of each other, which was straightforward to achieve.

Meeting these requirements ensured that the fiducials and the fine positioner movements would be in the view of the optical sensors when the laminate was placed at the alignment/stacking site.

3 Aligner system

The prototype work cell (Fig. 2) was developed to demonstrate accurate registration and stacking of thin sublaminates at production line rates. Rather than developing highly accurate equipment for this task, a sensor-based approach was taken which made it possible to use inaccurate equipment. Major components included the feeder station, an IBM 7576 robot manipulator (CM) for coarse motions, a specially developed fine positioning manipulator (FM) for fine motions, optical sensors for sensing the sublaminate fiducial holes, and the alignment/stacking station.

Coarse and fine manipulators

The system used a standard IBM 7576 robot coarse positioning manipulator (CM) with a specially developed IBM fine positioning manipulator (FM) [1], fastened to its tooling end (Fig. 3). Optical sensors, feeder stations and an IBM PC-AT industrial computer complete the system. The CM moves the FM to locations in a 0.5 m $\times$ 1 m $\times$ 2 m work envelope with roughly 0.1 mm (100 μm) accuracy and somewhat better resolution and repeatability.

The FM is a precision air-bearing supported planar manipulator with a programmable translation range of $\pm$1.000 mm in the x,y plane and $\pm 1.75°$ in rotation about the z axis. It can be programmed to move in 0.03 μm steps with 0.2 μm (3σ) resolution and repeatability in both axes. Small rotations θ_z of 0.0003° can be commanded about the z axis. A no-load frequency response of 50 Hz is attainable. The absolute accuracy of the FM was only about 10 μm, but does not matter in this situation. The FM was the critical component of the aligner system as it provided precision fine motions for the alignment process as well as acting as a calibrator for the optical sensors. The CM+FM combination with endpoint optical sensing [2] makes possible very small moves anywhere within the CM's workspace. A similar strategy has been used successfully for mounting fine-pitch components on circuit boards [3]. A program-actuated vacuum chuck attached to the FM carries sublaminates from the feeder station to the alignment and stacking area.

Optical sensors

The optical sensors located a set of fiducials in each sublaminate and registered their coordinates to the alignment system. As noted previously, the fiducials are part of the wiring pattern lithography and are accurately referenced to it.

Each optical sensor consisted of a set of microscope lenses to focus the back lit fiducial image on a position sensing detector (PSD) [5]. Each image generates two sets of currents from which the x,y coordinates of its centroid are derived with analog-to-digital conversion circuits. Although these sensors are inherently inaccurate and there are lens distortions, it was found that a positional sensing resolution of 0.12 μm (3σ) could be achieved after A/D conversion. The computed image centroids were stored as the sublaminate location.

The use of PSDs rather than video cameras allowed for much faster data acquisition, higher resolution, and lower cost.

Feeder and alignment/stacking station

The feeder station shown schematically in Fig. 2 was designed to constrain the sublaminate supply to a square area of dimensions 226.854 mm with tolerances of -0.00 mm, +0.02 mm on a side.

At the alignment/stacking station, a vacuum chuck secured the stacked laminates after alignment. A transport mechanism moved the back-lighting illuminator into the alignment site to project the fiducial images onto the optical sensors and is later removed when the optical sensing is complete. Mechanical grounds are provided for both the FM and the CM. Vibrations occur at the unrestrained end of the CM with amplitudes of about 10 μm in the frequency range of 1-50 Hz, typical of environmental noise. Various means of bracing to reduce vibration are described by Book [4]. A unique bracing method used in this system [5] is shown in Fig. 2. It uses two mechanical grounds or "V" blocks. The lower block braces the stationary part of the FM, the upper block braces the CM arm during the alignment operation.

[5] made by United Detector Technology.

Alignment process

A simplified drawing of the prototype system is shown in Fig. 3 and the procedure to align and bond a pair of sublaminates is described below.

1. The CM+FM picks up a sublaminate from the feeder station and transports it to the alignment site beneath the optical sensors.

2. The FM is pushed into a mechanical "V" groove grounding block just prior to the grounding of the CM robot with its block. (The CM z-axis bends slightly.)

3. Light reflected from removable 45° mirrors passes through the fiducials to produce an image on the optical sensors (Fig. 3). The centroid of the fiducial image is computed from the sensor output and stored as a reference for all subsequent sublaminates of the stack. This constitutes a set of "virtual" pins, analogous to the mechanical pins used in the traditional method.

4. The sublaminate is lowered by the CM, transferred and secured with a vacuum chuck at the aligner/assembly station without disturbing its lateral position.

5. The location of a second laminate is determined using the same sequence (1-3) above.

6. Fine x, y, θ_z motions are made by the FM using an iterative process to minimize the error between the first and second sublaminate locations.

7. The second sublaminate is lowered and glued to the first laminate to complete a bonded pair.

8. Subsequent laminates are aligned and glued in the same way to form a multi-layer stack.

9. The stack is processed to form a rigid laminate ready for later component mounting.

4 System performance measurements

System registration accuracy is a function of electrical noise, mechanical vibrations and the repeatability of mechanical positioning. Each source was isolated and classified as follows:

Sources of noise

- Random noise sources
  1. analog to digital converter noise
  2. optical detector and circuit noise
  3. mechanical vibrations seen by optical sensor
  4. FM servo noise
- Mechanical repeatability
  1. illuminator transport repeatability
  2. robot z-axis repeatability

Measurements of output voltages were made on each source to observe the distributions. The 3σ values were obtained and converted to equivalent dimensional errors at the end of the 7576 robot. These values were placed at their respective sources and are shown schematically as a graph in Fig. 4.

Combined effect of error contributors

An estimate of the sum of the three major uncorrelated contributors to alignment error *i.e.*, random noise (vibration, converter noise), illuminator stage repeatability and z-axis repeatability, was made by taking the square root of the sum of their squares, where $N_r = 1.2$ μm, $N_{op} = 0.65$ μm, and $N_z = 2.3$ μm:

$$N_t = \sqrt{{N_r}^2 + {N_{op}}^2 + {N_z}^2} = 2.7\ \mu\text{m}.$$

Thus we were able to predict that the system would be capable of registering sublaminate layers to with 2.7 μm (3σ). This result was encouraging, as it was well under our customer's 7.5 μm (3σ) requirement. Moreover, the error appeared to be dominated by the z-axis repeatability, pointing to a specific area which could be improved by future work.

5 Registration results

The alignment process described above relies on good short-term repeatability rather than absolute accuracy and is particularly important in two phases of the stacking process:

- lowering of a sublaminate from the sensor area to the bottommost vacuum holder
- preventing translational or rotational "squirm" of a sublaminate when contacting the bottommost laminate.

Two tests were performed: one to characterize system repeatability at the stacking station and the second to measure the misalignment of two holes on a bonded pair of sublaminates.

Sublaminate placement repeatability

Repeatability was measured using a single alignment sequence consisting of picking up a sublaminate at the feeder and aligning its fiducials to an artificial target at the sensor site. The sublaminate was lowered to make contact with the vacuum holder at the stacking area and the fiducial locations were remeasured. The laminate was placed back into the feeder station and the cycle repeated. All the system uncertainties are included in this test cycle including randomly replacing the sublaminate into the feeder. A short-term repeatability test was done for 24 alignment cycles with the results shown in Fig. 5.

The radial registration errors were smaller than 2 μm and are well within the 7.5 μm specification, in agreement with prediction.

Ideally, all the registration errors should have been less than 1.0 μm which was the threshold setting of the iterative alignment algorithm. However the sublaminate was lowered several centimeters from the sensing elevation to the stacking area by the (constrained) z axis of the CM. The sublaminate position could not be monitored during this excursion since the back light illuminator was withdrawn at this point. Repeatability of motion during this operation depended on details of mechanical sliding along the "V" braces described earlier, and accounted for most of the error.

A long-term repeatability test was run for 1500 cycles over a 26 hour period. The absolute position of the sublaminates during this time varied over perhaps 100 μm due to thermal effects, but the layer-to-layer registration results were similar to the short-term repeatability test. Most of the misalignment errors were within 1 μm and 98% less than 2.5 μm [5].

Sublaminate registration accuracy

It is not straightforward to directly measure the registration accuracy of many pairs of aligned, stacked and bonded sublaminates. However, x ray and scanning electron microscopy (SEM) were investigated. A representative SEM of two 100 μm via holes with 2.7 μm misalignment is shown in Fig. 6 at a view normal to the surface. From similar SEM images taken of other aligned and bonded sublaminate pairs it was verified that the registration capability of the system was approximately 2.8 μm with the worst sample at 5 μm. These results were consistent with the repeatability tests.

6 Conclusions

We have demonstrated that accurately-made electronic substrate sublaminates can be accurately aligned, stacked, and bonded using inaccurate optical sensors and inaccurate robots. The new method eliminates the need for mechanically-punched slots in the sublaminate, substituting photolithographically etched fiducial holes. Results show layer-to-layer registration accuracies that are at least an order of magnitude improvement over the traditional pin-in-slot methods.

The accuracy improvement was achieved by augmenting a standard industrial robot coarse manipulator (CM) with a high-resolution fine manipulator (FM), using high-resolution optical sensing of the fiducial holes, and providing mechanical bracing. These considerations lead to a highly repeatable system in which none of the components need be accurate. The system successfully produced assemblies (stacked and bonded sublaminates) with accuracies of 2.5 μm (3σ), which are much higher than those normally associated with industrial robots.

It seems likely that this approach can be used for many other precision robotic assembly tasks.

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References

[1] R. L. Hollis and R. Hammer, "The fine positioner: a robotic tool for precise planar motion," *Industrial Robot*, vol. 19, no. 5, pp. 22–25, 1992.

[2] R. H. Taylor, R. L. Hollis, and M. A. Lavin, "Precise manipulation with endpoint sensing," *IBM Jour. of Res. and Develop.*, vol. 29, pp. 363–376, July 1985.

[3] J. P. Baartman, A. E. Brennemann, S. J. Buckley, and M. C. Moed, "Placing surface mount components using coarse-fine positioning and vi-

sion," *IEEE Trans. on Components, Hybrids, and Manufacturing Technology*, vol. 13, pp. 559–564, September 1990.

[4] W. J. Book, S. Le, and V. Sangveraphunsiri, "The bracing strategy for robot operation," in *Proc. 5th Symposium on Theory and Practice of Robots and Manipulators*, (Udine, Italy), sponsored by CISM-IFToMM, 1984.

[5] R. L. Hollis and R. Hammer, "Real and virtual coarse-fine bracing strategies for precision assembly," in *Proc. IEEE Int'l. Conf. on Robotics and Automation*, (Nice, France), May 12-14 1992.

Figure captions

Figure 1: Test Sublaminate. The test vehicle is a thin metal sheet with 750 μm diameter hole fiducials accurately registered to the wiring pattern. The centroid of the fiducials is registered to the sublaminate edge centroid within a tolerance of 0.25 mm.

Figure 2: Aligner/Stacker Hardware. (a) Photograph of the aligner system, (b) schematic drawing of the aligner system.

Figure 3: Aligner/Stacker System Concept. A coarse-fine positioning strategy is used to accurately align and stack sublaminates with an IBM 7576 robot, a fine positioner and optical sensing.

Figure 4: Alignment Error Contributors. The total alignment error is the vector sum of the individual noise parameters. All the 3σ values were obtained from distributions measured at each noise contribution source.

Figure 5: Short Term Repeatability Experiment. The alignment errors for 24 placements are less than 2.0 μm overall and well under the 7.5 μm specification.

Figure 6: A Pair of Aligned 100 μm holes. (a) Micro-photograph of an SEM view along the vertical axis of an aligned pair, the alignment offset appearing as a small dark arc with a white horizontal line at the center of the view; (b) cross section of the the cusps of the holes are formed as result of the double-sided etching process, one is seen as a broad white arc in (a).

Author information

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Andrew Brennemann was employed as an electrical engineer with the IBM Research Division, Thomas J. Watson Research Center, Yorktown Heights, NY until his retirement in 1993. He worked on various computer related technologies throughout his IBM career. His latest assignment was with the Advanced Robotics group in the Manufacturing Research Department where the focus of the work was integrating robotic technology to manufacturing tasks.

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He has authored a number of papers in these fields and holds patents in thin-film masking, circuit connectors, linear actuators and combined linear-rotary stepping motors. While at IBM, Mr. Hammer received five Invention Achievement Awards.

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Dr. Hollis is a member of the American Physical Society and a Senior Member of IEEE. He has served on several government panels, and the editorial boards of the Journal of Micromechanics and Microengineering: Structures, Devices, and Systems, and the IEEE Transactions on Robotics and Automation. At IBM, he received five Invention Achievement Awards and an Outstanding Technical Achievement Award for work in precision robotic positioning.