

# MACHINE-VISION-ASSISTED WORKSTATIONS FOR LIGHTWAVE DEVICE MANUFACTURE

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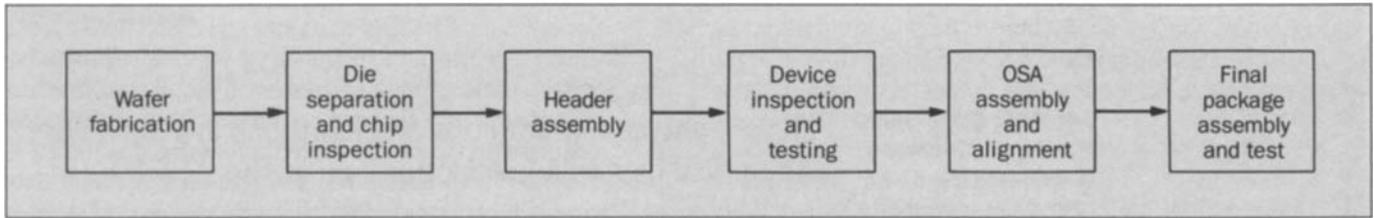
Three lightwave production workstations are a part of the optical data link production line at the AT&T Reading Works. Although they perform different production tasks, each is an example of the manufacturing advantages that can be achieved when computer-controlled robotic positioners are coupled with visual feedback. The potential benefits include reduced operator errors due to fatigue, increased product quality and consistency, and increased manufacturing efficiency.

## Introduction

Short-haul lightwave applications employ light-emitting diodes (LEDs), multimode fiber, and P-type-intrinsic-N-type (PIN) photodetectors. Systems using these devices are intended for transmission distances of less than a few kilometers.<sup>1</sup> The market for lightwave devices in short-haul systems is still in its infancy and at a relatively low point on the growth curve. However, many market analysts predict that, by the early 1990s, the growth rate in the short-haul market will be significantly greater than in any other lightwave market.

In the face of these market projections, the development of AT&T production lines for short-haul lightwave devices has proceeded with three objectives in mind. First, continue to improve device quality and reliability by refinements of the current production lines. Second, avoid adding expensive capital equipment that is not needed at the current production volumes and may put an extra burden on the cost of LED and PIN devices. Third, continue to review opportunities for automated workstations and introduce them in the production line as demand increases and cost reductions are appropriate.

The introduction of lightwave devices<sup>2</sup> to manufacturing has resulted in the need to perform reliable high-precision operations. Assembly operations have previously been performed with manual workstations, achieving the desired precision at the expense of labor-intensive operations. With the short-haul market starting to open up, price and volume become much more significant factors and the more difficult manual operations must be performed by automatic work-



**Figure 1. Optical data link production line.**

stations. However, the introduction of automatic workstations in an existing production line does not come without considerable effort. It involves extensive design work in mechanical layout, optics and lighting, and particularly software development.

The requirements of high precision and the need to handle nonstandard parts generally preclude the purchase of commercial workstations. A number of workstations have been designed and installed on the ODL<sup>®</sup> lightwave data link production lines. Each is computer-controlled, some are manually assisted, with many employing machine vision. By taking advantage of machine-vision attributes, the operations of chip placement, inspection, and chip-to-fiber alignment have replaced manual workstations to alleviate repeatability, accuracy, or throughput difficulties.

#### **Lightwave Manufacturing Line**

Lightwave devices, both transmitters and detectors, have traditionally been characterized by a significant development time followed by a relatively short manufacturing life cycle. These factors are due to the rapidly evolving technology associated with lightwave devices. The production line that supports these products, as a result, has been largely manual in nature and has processed devices in batch flow. There is, however, an ongoing effort to introduce automatic workstations in the production process in order to improve device reliability and quality and reduce device costs.

A block diagram representing an ODL production line is given in Figure 1. It is not the intent of Figure 1 to suggest that all lightwave source and detector codes are manufactured on identical production lines. Nevertheless,

it is essentially true that the diagram in Figure 1 represents the general steps required to produce transmitter and detector devices.

The wafer fabrication, die separation, and chip inspection steps for both LEDs and PINs are performed in a class 10000 clean room.<sup>3</sup> The assembly and testing operations performed in the remainder of the ODL production line are done outside a clean room. Surface-emitting LEDs, with wavelengths ranging from 0.87 to 1.3  $\mu\text{m}$ , and their corresponding PIN photodiodes are bonded to their header assemblies. Each device is then tested and inspected. Both source and detector are assembled into their optical subassembly (OSA) and aligned to a connector receptacle. Final package assembly combines an OSA with its integrated electronics in a plated die-cast housing.<sup>1</sup>

Header assembly workstations generally do not take advantage of the light-emitting capabilities of LEDs. This is primarily because of concerns over potential thermal problems with unbonded chips. However, once the device has been through header assembly, it is a working light-emitting device. Thus, subsequent workstations may take advantage of the device light-emitting capabilities in the application of automatic positioning systems.

Three specific workstations on the ODL production line will be described in this paper. The first is an automatic LED die bonder, which provides epoxy attachment of lightwave devices to headers. The second is a semiautomatic dark-line defect (DLD) inspection station, which is used to perform visual inspection of an LED's active area. Finally, a semiautomatic OSA alignment system is described. This machine positions the LED chip-on-header (COH) so that its emission is centered in the OSA housing connector receptacle.

Die bonding takes place in the header assembly section of the production line of Figure 1. Header assem-

bly operations are characterized by the requirement to locate and place extremely small and fragile devices within tolerances of a few mils (thousandths of an inch). This implies that both mechanical positioning accuracies and visual feature location accuracies must be less than a mil. The unique feature of the die bonder is that two parts with widely different geometries and dimensions must be visually characterized by a computer and accurately assembled. The task has a high degree of parallelism in order to achieve the desired production throughput levels. The operation of this system is totally automatic with the exception of parts loading and unloading.

Device testing and inspection is performed at a variety of places in the production line to ensure overall device quality. Previously used manual inspection and testing workstations required not only excellent operator judgment of device quality, but also hand-eye dexterity. The DLD inspection station described in this paper has an automatic and a manual component. The automatic operation prepares a given device for the critical, manual operation of visual inspection. The unique ingredient of this workstation is the high-resolution optical system, which presents an inspectable image to an operator.

In the OSA workstation, optical alignment of the OSA assembly is characterized by the need for computer-controlled positioning down to a few micrometers. Moreover, the robotic positioners have to cope with parts fixturing that introduces mechanical backlash and large impeding mechanical forces. The backlash can be an order of magnitude larger than the required positioning accuracies. The vision feedback system in this semiautomatic workstation relies on the light-emitting capability of the LED devices that are being aligned. In this case, the manual operations prepare the device for the critical automatic alignment operation.

The use of machine vision and computer controlled positioners as an aid to automating these processes helps reduce or eliminate the tediousness of the manual tasks. Although considerable development time is often needed to generate robust vision algorithms and control strategies, the potential benefits are significant. They include reduced operator errors due to fatigue, increased product quality and consistency, and increased manufactur-

ing efficiency (e.g., increased throughput and lower cost). By freeing the operator from time-consuming and tedious tasks, more attention can be paid to overall production line process control and quality.

An example of the production benefits that can result from using machine-vision feedback in workstation design is afforded by the improved performance of a lightwave detector aligner. The original semiautomatic alignment system employed no vision feedback. Instead, an estimate of the detector's active area location was obtained in a static fashion by shining a fixed-intensity light on the device via an optical fiber and monitoring its electrical output. With a machine-vision-assisted system, the detector active area is "seen" and an alignment is performed, resulting in maximum dynamic performance. With vision feedback control, alignment times have been reduced by an order of magnitude; at the same time, device yield and quality have been improved.

#### **Lightwave Production Workstations**

The three workstations presented here perform totally different tasks, yet they share some important common features. Their system architecture includes a central control computer, a machine-vision system for visual feedback and control, and robotic control mechanisms for parts presentation and positioning.

The central computer is the master controller with extensive input/output capability (RS-232C, IEEE-488, digital, analog). It monitors sensors and controls positioning stages, collects data, and can communicate with other computer systems in the factory for the exchange of manufacturing information. The vision system is a specialized computer with television camera inputs providing visual information for analysis and decision making. The motion in these systems includes linear tables, manipulators, and electrical contact mechanisms. Although the level of automation in each application is different, an extensive operator interface is provided to enhance the relationship between the workstation and its operator.

Each workstation task has required a unique manufacturing solution to which off-the-shelf assembly and inspection equipment is either not suited or not available. Vendor-supplied components and subsystems are used

when appropriate. However, these generally need additional development and modification for our specific applications. Device handlers and manipulators often need to be developed in-house. With regard to computer vision, virtually every workstation has unique lighting and optical requirements that must be met. In addition, computer-vision system algorithms must be designed and implemented by the user. Finally, connecting the peripherals requires that all of the interfaces, protocols, and responsibilities be designed and implemented. The result is that each automated workstation is a highly customized system.

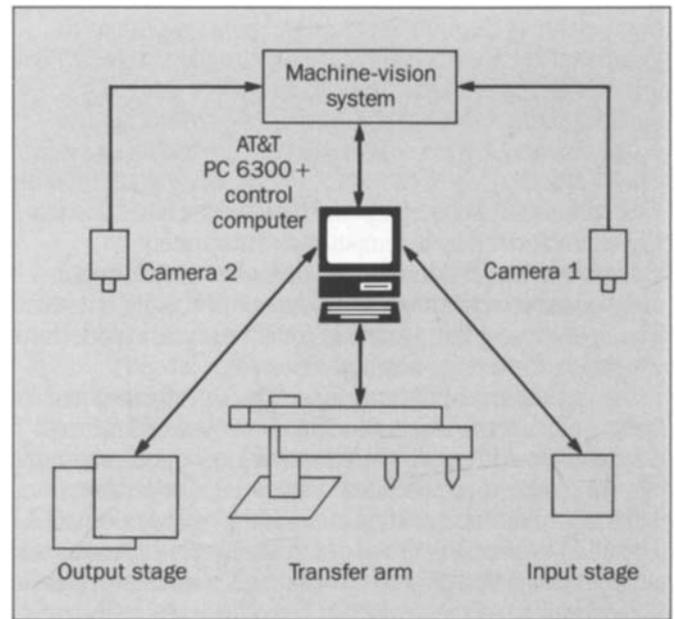
Each of the workstation applications described here requires accuracies of a few micrometers in the robotic positioning tolerances. Visual feedback from a machine-vision system has proved beneficial in each case in achieving overall positioning accuracies. The technology developed for these workstations is representative of what can be accomplished with computer-vision feedback. These solutions may be applied to other assembly, inspection, and alignment tasks in this and other lightwave production lines.

Workstations being developed for the ODL production line share additional features beyond those of improved device quality and reliability. Each workstation can be used as an off-line tool to assess the quality of the task the system was designed to perform. For example, the die bonder may be operated in a mode where it can determine how well it has bonded a chip to its header. Moreover, a workstation may be used to perform failure analysis on previously processed parts.

The OSA aligner is a good example of this capability. The recovered OSA housing is placed in the alignment station and the position of the light-emitting area is determined. When the serial number of that OSA housing is available, the current active area position can be compared with records of the original position to see if any movement has occurred.

#### Chip-on-Header Assembly

The header assembly portion of the ODL production line in Figure 1 performs three major tasks: header preparation, die bonding, and wire bonding. Header preparation consists of loading device headers into mass-



**Figure 2. Die bonder system block diagram.**

handling carriers and attaching lead frames and chip heat sinks with epoxy. Once the lead frames have been trimmed, the LED and PIN devices are then bonded to their respective headers. Sample testing of bonded devices for die-attachment strength and thermal impedance allows tracking of product quality. Finally, an automated workstation for wire bonding completes the header assembly operations.

The most critical part of this assembly sequence is die bonding, which is the attachment of lightwave chips to headers. Automatic die bonding of LED devices requires a computer-vision system to characterize two independent parts, the LED and its header, which are more than an order of magnitude different in physical dimensions. A computer-vision-located feature on the LED chip must be overlaid on a computer-vision-located feature on its header to within a few mils. The performance of the die bonder, in terms of chip-positioning accuracy, has a direct impact on the task performed at the OSA aligner. The more accurate the match between the chip and its header, the faster the

speed and better the quality of alignment that will be obtained later in the production process.

Machine-vision feedback is an essential element in this automated workstation, and sets this machine apart from most commercially available epoxy die bonders. The die bonder was designed to improve the bonding task in at least three respects:

1. Better quality and repeatability of the die bond. Programmable and adjustable features result in substantially greater control over bond quality.
2. Dramatically increased product throughput. The automatic bonder has an instantaneous throughput more than an order of magnitude greater than that of the manual workstation it replaces. Moreover, four different codes of LED chips are handled by the same automated system.
3. Greater chip placement accuracy. The die bonder accurately bonds an LED chip to its header so that the emitting area is positioned at the center of the circular header. The chip is also oriented with respect to the header so that subsequent wire bonding can be accomplished.

A block diagram of the automatic die bonder is shown in Figure 2. There are three principal elements in this automated die-bonding system. First, there is a dual-camera machine-vision system. One camera is mounted over the input table for locating the two essential features of an LED chip (i.e., the chip center and the chip active area). A second camera is mounted over the output table for locating the center of the header. Second, the AT&T PC 6300+ system control computer orchestrates the operation of all peripherals. Third, the input table, output table, and transfer arm are precision, computer-controlled, programmable positioning systems which perform all the mechanical operations required to get the LED chip, its header, and its epoxy dot where they must be for accurate bonding.

The system is accessed by an operator via menu-driven system software on the PC 6300+ control computer. An operator loads a wafer pack of inspected chips on the bonder input fixture. Each pocket in the input tray contains a single LED chip that is N-contact up, but is randomly oriented. The operator then loads a

plate of 200 headers onto the bonder output stage fixture. System operation is initiated by the operator via the main menu.

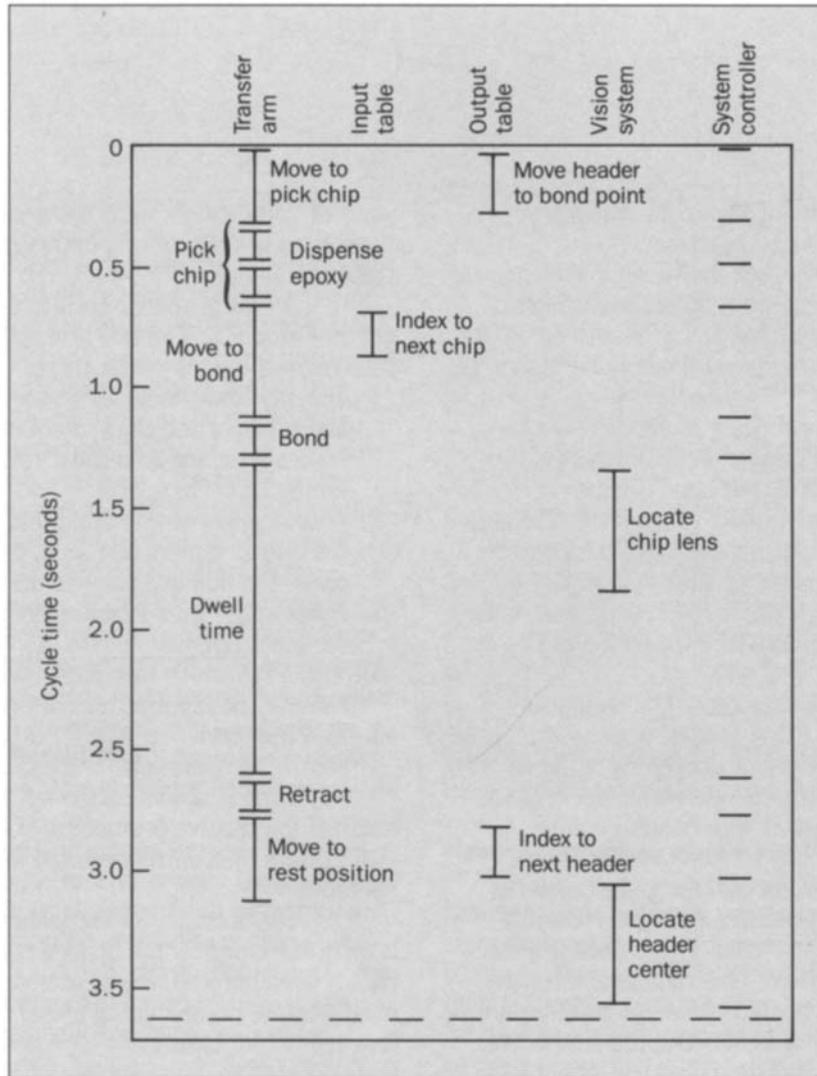
A typical bonder cycle is depicted in the Gantt chart of Figure 3. The five principal system elements are listed across the top of the chart:

1. *Transfer arm*—includes a vacuum collet for picking up and transporting chips, a collet for depositing epoxy on headers, and an angular rotation mechanism for orienting LED chips.
2. *Output stage*—an  $x$ - $y$  table that indexes headers under the output camera and accurately positions the header under the bonding point of the transfer arm.
3. *Input stage*—an  $x$ - $y$  table that indexes LED chips under the input camera.
4. *Vision system*—a machine-vision system used to locate chips at the input and headers at the output.
5. *Host computer*—an AT&T PC 6300+ computer used to control all operations of the die bonder.

Time is shown on the left side of the chart. A study of the relative positioning of individual events in the chart shows the control required for one cycle of system operation.

The accuracy and repeatability of the die bonder is a critical aspect of the bonder task. The vision algorithms used to locate the header center and chip features must tolerate normal visual noise. In addition, the transfer arm and output table must have positioning resolution and accuracy that are compatible with the overall task requirements. An essential element in achieving the bonder accuracies is the calibration of the coordinate systems representing the two cameras and the three positioning systems. This is achieved by positioning fiducials, which have been attached to the transfer arm and output table, at several locations within each camera's field of view. Data on the fiducial centroid and positioner motor coordinates are collected and processed to compute a transformation matrix from the given camera to the specific positioner. The vision system is also used to determine the offset distances from the transfer-arm fiducial to the vacuum pickup collet and the offset from the vacuum collet to the epoxy dispenser. Calibration accuracies on the order of several micrometers are achieved by these means.

**Figure 3. Die bonder cycle of operation (Gantt chart).**



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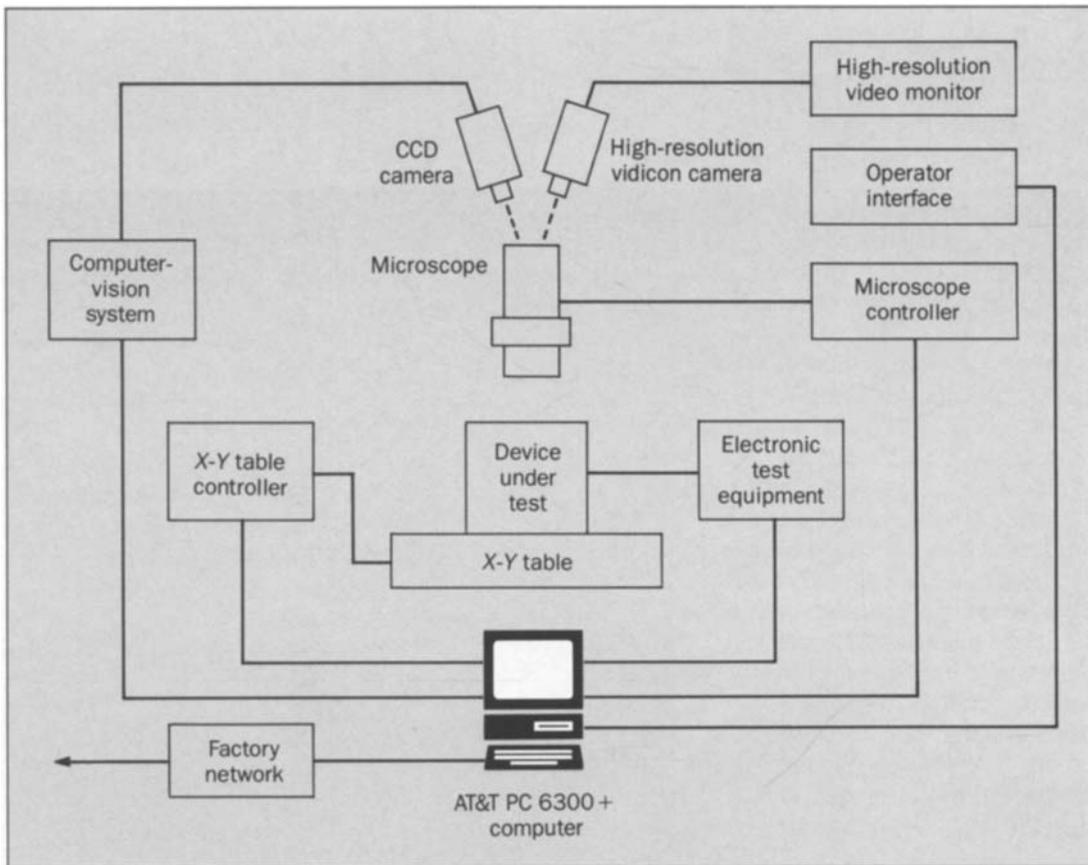
### Testing and Inspection

After header assembly, devices are tested and inspected. To achieve high reliability in the ODL-50 transmitter, every chip-on-header device is electrically tested both before and after a burn-in period and then visually inspected. The electrical tests involve measuring voltages and optical power output while the device is activated. The visual inspection is also performed while the device is activated. The ODL-50 transmitter radiates light from its top surface at a wavelength of  $0.87 \mu\text{m}$ , the near-infrared region of the optical spectrum. The luminous region is gauged for size and searched for defects.

There are several requirements for inspection.

The area to be inspected is approximately  $100 \mu\text{m}$  (4 mils) in diameter. This should completely fill the viewing screen. Defects as small as  $2 \mu\text{m}$  must be detected. The image must be sharp, requiring an optical system with relatively high resolution. The device should be presented to the operator in a consistent manner to improve accuracy of inspection.

There are several problems with inspection. One set of problems has to do with the variations that exist from device to device, requiring that every device must be individually set up, on the basis of its own unique characteristics, for inspection. Horizontal device positioning by dead reckoning to the center of a  $100\text{-}\mu\text{m}$  field of view is



**Figure 4. Architecture for visual inspection system.**

difficult because of inexactness of assembly and fixturing. Two different fields of view are used. First, a device is located within a wide field of view and moved so that it will be seen within the 100- $\mu\text{m}$ -wide inspection field of view. Second, the device is viewed in the inspection field of view, where it is centered precisely and presented for inspection.

Resolution requirements demand a relatively large numerical aperture for the microscope objective lens, resulting in small depth of focus. Again, because of inexactness of assembly and fixturing, the device must be vertically positioned so that its image is optimally focused on the camera sensor. Variations in optical power efficiency from device to device make it impossible to use a fixed bias current for performing inspections. The bias current for each device is automatically adjusted to achieve the optimum intensity level for inspection.

A second set of problems involves people performing visual inspections. Human inspection accuracies depend on many factors.<sup>4,5</sup> Of all the potential reasons for

inspection inaccuracies, two classes are worth mentioning here. One class has to do with less-than-optimum presentation, which causes inspection quality to fluctuate randomly. A second class includes all the reasons that inspection quality degrades over time, such as fatigue and boredom.

A solution to these problems has resulted in a semiautomated, intelligent workstation that automates much of the setup and record-keeping tasks in addition to measuring physical dimensions needed for process-control feedback. The operator is freed to devote more attention to the critical job of defect inspection.

A diagram of the system architecture appears in Figure 4. The controlling processor for the workstation is an AT&T PC 6300+, programmed in the C language. The machine-vision system is a vendor-supplied computer with dedicated image-processing hardware programmed in the C language running under an operating system similar to the UNIX<sup>®</sup> system. Electronic test equipment is connected to an IEEE-488 bus controller attached to the

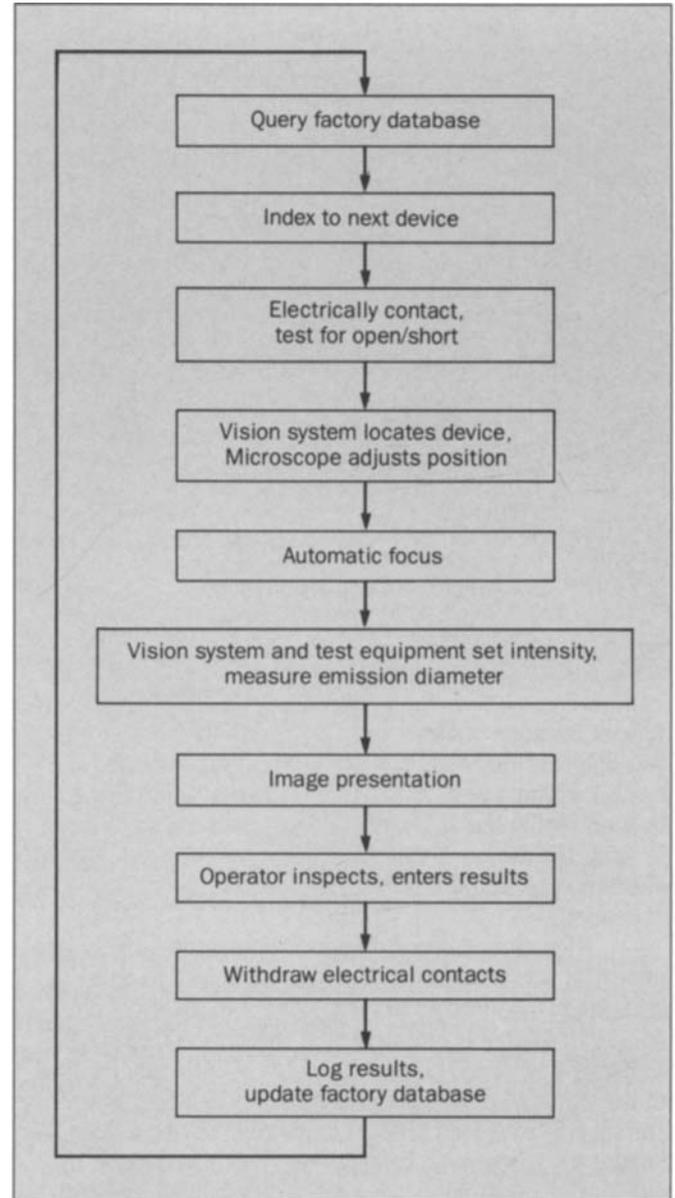
control computer's internal bus. An operator interface control panel is the main channel of interaction between the human operator and the workstation. A vendor-supplied, computer-controlled microscope with automatic focusing completes the system equipment.

As can be seen in Figure 5, during routine production operation on the factory floor, the computer control and vision systems execute all but the inspection process itself. Beginning with querying the factory database, the device is indexed nominally within a wide field of view. It is electrically contacted and biased so that it emits light. The origin of the light, the area that needs to be inspected, is located by the vision system. Updated coordinates are transmitted to the positioning mechanism controller, which moves the device to a specific target location for inspection. The device is brought into vertical position with a laser autofocus subsystem. With the device viewed by the computer-vision system under high magnification, a software feedback loop between the vision system and a programmable current source is used to bias the device at a brightness level optimum for automatic gauging and inspection.

The operator views the device with a high-resolution vidicon camera, sensitive to 0.87- $\mu\text{m}$ -wavelength light, and a high-resolution video monitor, as depicted in Figure 6. If the operator desires, manual controls on the operator interface can be used to adjust the position, focus, and brightness of the device. If any defects are found, the defect categories are entered via push buttons on the operator's panel.

The results are recorded on the computer's disk and also transmitted to the factory network database computer, completing the entire inspection sequence.

The benefits resulting from the introduction of the semiautomated inspection workstation are several. Inspection accuracies have increased because the quality of the image is better and because the operator's efforts are directed to the inspection only. Workstation throughput has been improved by a reduction in the setup time interval from 30 to 10 seconds. In addition, bookkeeping and data-entry errors have been reduced because the operator



**Figure 5. Sequence of steps for a device under test on the dark-line-defect inspection workstation.**



**Figure 6. An operator at a visual inspection workstation.**

needs only to indicate the inspection decision by pushing a button on the interface panel. This eliminates writing results on paper and keeping track of the identity of the particular device under examination.

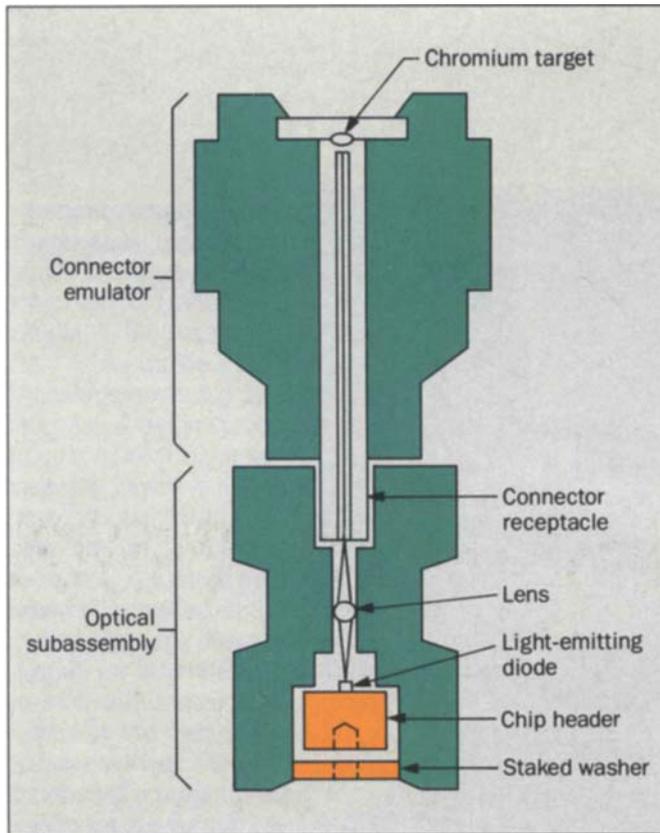
#### **OSA Alignment**

An ODL transmitter OSA consists of an LED bonded on a header and a spherical lens pressed into a housing, as shown in Figure 7. The housing has either an ST® connector or a biconic connector® built into it. The header assembly is mounted in the OSA and held in position by a washer staked behind it. This staked washer supplies a retention force to hold the header in position until epoxy is applied and cured after alignment. The OSA alignment operation positions the header such that the LED emission is centered in the OSA housing connector receptacle. This results in peak coupled power into the fiber.

Previous alignment systems on the ODL produc-

tion line attempted to align transmitters by plugging a fiber into the device and monitoring the resultant light output. Then, by moving the header to attain the maximum output power, the system aligned the device. Difficulty in returning to peak power was experienced because of fixture backlash (about 7 mils), complicated by the forces (about 20 pounds) required to overcome the retention force of the staking washer. Alignment times ranged from several minutes for a 15- $\mu\text{m}$  tolerance to hours for trying to attain 2  $\mu\text{m}$ . With machine vision, however, smart workstations reduce alignment times to 5 seconds for a 15- $\mu\text{m}$ -tolerance alignment and to 60 seconds for a 2- $\mu\text{m}$  alignment.

By viewing the transmitted image with machine vision, the exact center of emission can be calculated and the header moved to the optimum position. This has the desired result of providing maximum coupling of light to a fiber, as was attempted in previous alignment systems. In addition, since the coupled power variation for a given lat-

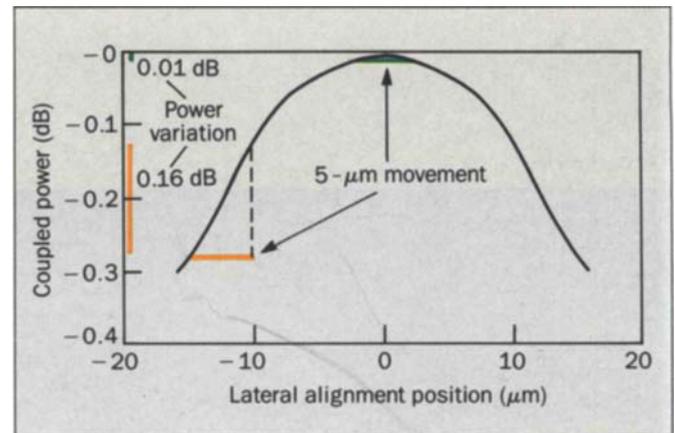


**Figure 7. Connector emulator for the ODL-50/200 transmitter optical subassembly.**

eral movement is highly dependent on alignment position, fiber connector stability and insertion repeatability are greatly improved. This is illustrated in Figure 8.

A key component in this system is the connector emulator inserted into the device in lieu of a fiber during alignment. The connector emulator transmits the focused emission to the focal plane of the vision system microscope and provides a chromium target referenced to the connector center. Thus, a transmitter image may be viewed through a microscope and camera and referenced for optimum alignment. Machine vision handles the tasks of acquiring an image, extracting features, and relaying data to the control computer, which handles all other system operations. A system block diagram is provided in Figure 9.

During the alignment operation, two types of images are processed by the vision system: the chromium target, which is illuminated by external light sources, and the transmitter emission itself. The chromium target



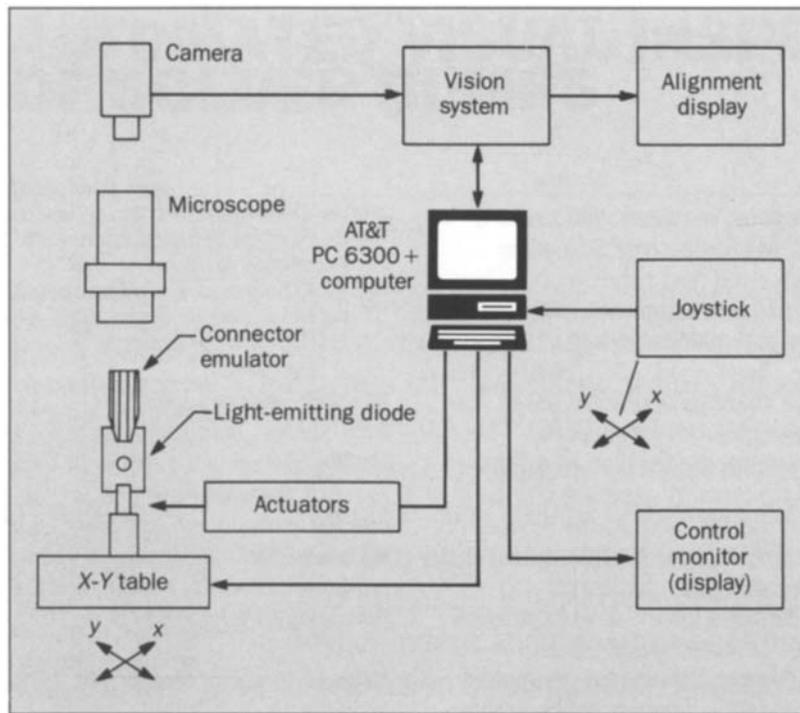
**Figure 8. Coupled power as a function of alignment position.**

appears as a very stable image, since it was selected for maximum contrast and lighting levels are maintained for this purpose. As a result, vision-related problems associated with the target have been minimal. Transmitter emission images are another matter. Two major factors affect an emission image: chip output power and alignment position.

Output power varies from chip to chip and may be further affected by the OSA lens. As a result, the image presented to the vision system for a given transmitter drive current varies from device to device. The vision system analyzes each acquired image for brightness via the image gray-level content. Based on this analysis, one of two actions is taken. If the image is satisfactory, coordinate information is generated and transmitted to the control computer. If not, bias correction information is returned to the control computer.

Because of assembly tolerances and procedures, initial device alignment position is random. Therefore, a given drive current does not produce the same image intensity when devices are first biased on. Image intensity also changes as the device is aligned. A vision algorithm measures the intensity and provides feedback to the control computer, which dynamically adjusts the drive current. This routine is employed throughout the alignment cycle, resulting in very stable images.

To date, three generic transmitter systems have been installed. These include an aligner for the ODL-40 transmitter, one for the combined ODL-50/ODX transmitters, and a third for ODL-200 transmitters. In addition, the ODL-40 and ODL-50 systems are used to align their corresponding detector devices. The performance of these systems is outlined in Table I.



**Figure 9. Block diagram of optical alignment system.**

**Table I. Alignment System Performance**

Device	Alignment tolerance, $\mu\text{m}$	Average time, seconds
ODL-40	15	5
ODL-50/ODX	10	40
ODL-200	2	60

The alignment time difference between the ODL-40 system and the ODL-50/200 systems is due to differences in transmitter device design. With machine vision, these devices are aligned in a cost-effective operation. Incurred-cost analysis shows that the visual alignment cost for a device is very similar to other operations performed during device assembly.

In addition to the transmitter aligners, machine vision has been used in an ODL-200 detector-alignment system and a laser-alignment-measurement system. For the detector, a back-illuminated indium gallium arsenide PIN, light is transmitted through the chip and viewed by the vision system. The detector active area is then moved via the control computer to cover the emission to within 6  $\mu\text{m}$ . This ensures that all light strikes the active area and maximum dynamic sensitivity is achieved. The laser align-

ment measurement system measures how well a laser chip has been aligned to a feature on the device package. This system relies on a round package in a V groove. The package is rotated and emission measurements are made at 90° points. The center of these points is the alignment target, and the distance to the center of any point is the alignment error.

The implementation of these alignment systems requires development expertise not apparent from this discussion. Machine vision requires development activities in optics, lighting, mechanics, software, and computers. Approximately 2500 lines of code, in addition to that supplied by the vision-computer manufacturer, are required to perform the task and provide robust operation. Each system employs a microscope, lighting systems, and mechanical fixturing. Controlling all this is a computer with over 2000 lines of code and an array of electronic instrumentation, stepping motors, and sensors. Finally, a fixture is required to hold the devices and accommodate the sensors and mechanisms associated with systems of this nature.

#### Summary

Three computer-vision-assisted workstation applications have been described. These systems exploit the power of robotics combined with vision feedback. These three examples are representative of the nearly dozen

intelligent workstations designed, installed, and successfully operating on the AT&T Microelectronics Reading Works ODL production line for the past three years. Their combined performance is providing significant improvements in both device quality and manufacturing consistency and efficiency.

These workstations share an additional set of features beyond improved device quality and reliability. These include the ability of the system to be used as an off-line tool for failure analysis and task quality assessment, the flexibility of a system design that accommodates device evolution, and the fact that system operation does not depend on expensive or precision parts fixturing.

The technology developed for these workstations is representative of what can be accomplished with machine-vision feedback. These solutions may be applied to other assembly, inspection, and alignment tasks in this and other lightwave production lines.

#### Acknowledgments

The authors gratefully acknowledge the work of the members of the Robotic Systems Development and Engineering Groups whose efforts made these workstations a reality, and particularly the help of L. A. Daniels and R. J. Radner for their comments on the manuscript. We also acknowledge the members of the Optical Data Links and Test Set Development Organization at the AT&T Reading Works for their technical involvement in these projects and their continued support of these activities.

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#### Biographies (continued)

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