Cincinnati Lamb, a Division of UNOVA Industrial Automation Systems
(formerly Lamb Technicon)

Boring with Optimal Accuracy

Engine block bores for camshafts and crankshafts, as well as gearbox bearing houses, require precise cylindrical holes up to 30 inches long. In 1995, all line-boring operations to ensure precision specifications on these cylindrical holes were performed by a machine tool that was dedicated to a specific engine model. Lamb Technicon and its research partner, the University of Michigan's College of Engineering, proposed to develop an agile, flexible precision line-boring machine tool for engine manufacturing. This single machine tool, called Boring with Optimal Accuracy (BOA), would provide line-boring operations for six or more different engine models. The project involved developing a complex piece of equipment that must be able to manufacture accurate parts and operate reliably for 16 hours a day. If successful, the precision advancements could potentially reduce auto production costs by up to $750 million annually, based on the domestic production of 15 million vehicles.

The Advanced Technology Program (ATP) awarded Lamb Technicon cost-shared funding in 1995 as part of the focused program, "Motor Vehicle Manufacturing Technology." By the ATP-funded project's conclusion in 1998, the BOA team had successfully developed an award-winning prototype machine, had received three patents, and had published its project results. They succeeded in incorporating innovative laser measurement, software control methods, and sophisticated hardware to achieve quick changeovers between engine models, while improving the required ultra-high precision. These innovations gave Lamb Technicon considerable recognition as a leader among U.S. machine tool manufacturers. However, in recent years auto manufacturers have developed new processes using standard flexible machining centers and have decided not to purchase the more specialized BOA.

Soon after the conclusion of the ATP-funded project, manufacturers of large-scale engines (such as heavy diesel and tractor engines) expressed interest in the technology; however, it was too costly to scale up BOA's dimensions compared with using new standard machining centers and new processing techniques. The BOA technology (e.g., software control and laser measurement methods) is being applied in new engineering developments at the University of Michigan's Engineering Research Center. In 2003, Lamb's parent company, UNOVA Industrial Automation Systems, merged Lamb's operations with Cincinnati Machine and renamed the combined organization Cincinnati Lamb. This merger has enhanced Lamb Technicon's ability to supply standard flexible machining center systems, which incorporate some of the knowledge gained from BOA.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 95-02-0019 were collected during November 2003.

Existing Dedicated Boring Machines Were Precise but Inflexible

Line boring, a critical and expensive operation in industrial engine production, involves first drilling a hole in a metal part. Then a boring tool smoothes the inside a boring bar (like blades on a fan) to ensure a smooth finish and to meet precise diameter and concentricity (roundness) tolerances (see illustration below). A number of products (e.g., engine block camshaft and crankshaft bores and gearbox bearing houses) require narrow holes up to 30 inches long.

In 1995, boring had to be performed by machine tools and stations on the assembly line that were dedicated to one engine model. This situation prevented the engine manufacturing industry from achieving the economic benefits that accrue with fully flexible, agile systems. A typical boring station is part of a factory assembly line that has dozens of machine tools lined up sequentially to perform many specific operations, such as milling surfaces flat, drilling holes, and cutting cylinder bores. The boring blades move horizontally along the cylindrical opening. The conventional method for boring in high-volume production was to make multiple passes to produce a finished bore. At the time, the engine manufacturing industry was producing 400,000 to 500,000 components per year, and the machine tools had to work quickly and achieve precise tolerances.

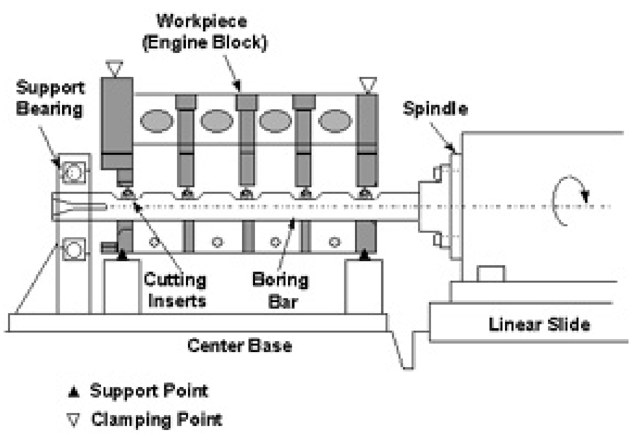


Diagram of a conventional boring tool of 1995, placed to the right of a workpiece (engine block). The boring bar enters the engine block from the right and is supported by a bearing at the left. The boring bar, with many cutting inserts, is attached to the spindle and machines that bore through the entire length of the engine casting. It requires multiple passes to complete the boring process.

Dedicated machine tools, such as boring tools, can produce high volumes of precision parts, but are limited to performing a specific repeated task on a particular engine model. This constrains the introduction of flexible manufacturing systems that are necessary in order to compete in the automobile market. High-precision machining of long bores for automobile engine crankshafts and camshafts ranked among the most inflexible processes of all. Increasing flexibility, so that one machine could bore holes in blocks for multiple engine models, resulted in less accuracy and precision. To enable quick changes of boring bars, for example, the end support bearing could be eliminated. However, then the bar would be subjected to excessive vibrations and cutting insert deflections (droop at the end of the bar), which would decrease the precision.

ATP Funding Stimulates Research

Lamb Technicon Machining Systems was a leading U.S. manufacturer of machine tools for the worldwide automotive, truck, and off-road vehicle industries. Prior to 1995, the University of Michigan's College of Engineering had conducted conceptual and exploratory research into auto manufacturing technology and solution concepts with the "Big 3" U.S. auto manufacturers (Chrysler [later DaimlerChrysler], Ford, and General Motors). Their research results showed that line boring was the least flexible process in the production system and should be redesigned.

Together, Lamb Technicon and the University of Michigan approached ATP for funding under ATP's focused program, "Motor Vehicle Manufacturing Technology," which aimed to stimulate manufacturing innovations and develop more versatile equipment with greater operational flexibility. They proposed to pioneer an agile (truly flexible) line-boring system with intelligent tooling and controls that would correct for known causes of inaccuracy and would quickly identify errors. Those capabilities would eliminate the need for support bushings and, along with innovative machine and tooling designs, would enable quick changeovers from one engine design to another. The team called the machine tool concept Boring with Optimal Accuracy (BOA). The BOA machine tool would bore distinct parts with varying sizes and locations for at least six different engine models without the need for changeover or retooling. The primary risk lay in embedding intelligence in the control electronics and in the mechanical components to achieve ultra-high precision. ATP awarded funding to Lamb Technicon for three years, beginning in 1995.

In 1995, boring had to be performed by machine tools and stations on the assembly line that were dedicated to one engine model.

Boring flexibility would enhance auto manufacturers' ability to participate in the manufacturing trend toward mass customization and would accelerate the made-to-order process. Existing technology required at least six dedicated boring machines to bore the different sizes and locations of six different engine models. A flexible line-boring station would enable high-level capacity utilization, thereby providing the potential to trim U.S. automotive production costs by up to $750 million annually using BOA (based on the domestic production of 15 million vehicles). Chrysler, Ford, and General Motors initially stated that they would cooperate on the work. In 1995, it was estimated that by 2005 domestic car companies alone would invest several billion dollars in new engine-machining systems, with each system costing more than $50 million. Machine tool technology that enabled both flexibility and high precision in boring would provide speed and agility to U.S. automotive manufacturers. In addition, spillover applications would include other manufacturing needs for precision-bored and aligned holes, such as heavy diesel and aircraft manufacturing.

Lamb Technicon Develops Challenging Milestones

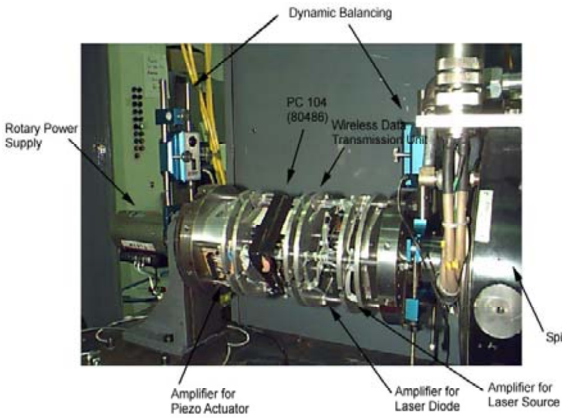
The team's primary challenge was, "How do we add precision to the line-boring process without sacrificing rigidity?" Their research plan was organized into six tasks:

1. **Process and tool modeling.** Design rigid tools without supports to enhance precision; design smart cutting tools to improve process performance and reduce downtime by 50 percent. The goal was to increase accuracy and precision of the boring process by compensating for boring bar deflections (droop at the end of the bar), vibrations, and thermal distortions, which were caused by components heating and expanding at different rates.
   Results: The team developed algorithms to accurately predict the tool deflection (droop) and allow compensation. They built two prototype cutting tools that take into account tool rotation and optimize the stiffness and frequency of the boring bar in order to increase the precision of the process. The cutting tools allow bores with lengths up to 30 inches and diameters of 1 to 3 inches to be machined in various locations.

2. **Machine Design.** Design mechanical hardware to enable precision machining of at least six different engine block models on the same machine tool station with short changeover time (less than 10 seconds, which is the time necessary to unload/load an engine block).
   Results: Rather than use solid metal for the body of the machine, the team arranged the metal in layers that resembled a honeycomb to increase strength without adding substantial mass. They designed a unique machine that provides both flexibility and precision in the line-boring process. The team was able to move the boring bar's location and allow for quickly changing the horizontal, 30-inch-long tool for different size bores (less than 10-second changeover time for 6 or more different engine models).

3. **Smart tool development.** Develop a personal computer (PC)-based control and laser-positioning sensor to allow early detection of process failures (to enhance reliability) and to identify the engine being processed (to store the information). The goal was to gain active control of the precision line-boring process, isolating vibration and disturbance. The housing for the instrumentation was designed to work with multiple boring bars, allowing for fast changes. Adding precision was the aspect of the project that had the highest risk.
   Results: The team met all of the objectives: early corrective action eliminated failures and engine specifications were stored to speed changeovers. The team developed a "smart tool" a PC-based control, and achieved precision levels of about 0.1 micrometer (µm), a hundredfold improvement. They increased the precision of the boring process by adding sensors and actuators inside the boring bar to allow nearly instant, minute adjustments (see illustration below). BOA responded to operator position adjustments in about 0.6 milliseconds. Ultimately, the laser tracking and navigation system

was able to adjust the cutting insert location 1,000 times per second, approximately 30 times per revolution.



Lamb Technicon's prototype "Smart Tool" Signal Processor and Controller. Laser sensors and piezo (pressure) actuators (to compensate for errors) are located inside the boring bar to make adjustments. Results are transmitted to the operator's PC at a rate of 1,000 results per second, or 30 times per revolution. This allows for virtually instant recognition and correction of a potential problem. Patented electronics compensate for droop during the boring operation.

4. **Intelligent control and compensation.** Add a predictive controller to (a) shorten the time to change over to a new engine model and maintain precision despite environmental changes; and (b) enhance both precision and production speed by monitoring process and tool performance. Thermal effects (distortion caused by ambient temperature changes and heat created during operation) needed to be incorporated into the compensation predictions. Error compensation must allow the boring bar to maintain an entering angle that was perpendicular to the workpiece.
   Results: The team developed non-proprietary software (called open-architecture control) that uses 18 error components as major input parameters in order to compensate for the geometric error at the tool tip. Sensors and actuators account for geometric and thermal compensation. A machine controller accepts input from machine sensors and computes axis offsets for added precision.

5. **Integration into experimental prototypes.** Integrate the four previous tasks into one machine.
   Results: The tool was still under construction when the ATP-funded project concluded in September 1998, but all engineering for the system, including all subsystems to accomplish agile and precise line boring, was complete.

6. **Evaluation of experimental prototypes.** Build and test the final lab prototype.
   Results: This was 75-percent complete upon project conclusion. The target completion date was January 1999, and the team planned to start testing immediately following completion of the prototype.

BOA Achieves Technical Success

After ATP funding ended, the BOA team completed testing of the prototype with very favorable results. Lamb Technicon used internal funds to continue the project. The BOA machine tool design is more flexible and cost effective than previous conventional dedicated designs. It allows small-batch processing of multiple parts that would otherwise need to be produced on separate boring machine tools. Compared with dedicated boring stations, manufacturers would save time and money and would gain increased precision and accuracy using the computer-controlled Smart Tool System.

They proposed to pioneer an agile (truly flexible) line-boring system with intelligent tooling and controls.

The BOA machine tool achieved significant technical advances: the spindle and feed axis allows the bore size to be changed quickly (less than 10 seconds) and ranges from 1 to 3 inches in diameter and up to 30 inches in length; the rotation speed and bore depth are programmable; and the Smart Tool contains patented electronics to compensate for droop during the boring operation (maintaining precision, while increasing flexibility).

Even today, the University of Michigan's Engineering Research Center continues to develop the BOA project technology. "The technology advancements represent a quantum leap over the technology of the time," said Professor Zbigniew Pasek. The business partnership established during this project also became a model for the university's further collaboration with industry. Ongoing research from the BOA project in 2003 included open architecture (non-proprietary software, so that additional applications can use the system), smart tool concepts, laser measurement techniques, miniaturized electronics, and improvements in stiffness.

The university is monitoring machine tool performance online by connecting with machines over the Internet. These research results are being applied to improve the life of machine tooling.

Product Fails to Reach Commercialization

While the BOA machine tool was intended to improve the auto engine manufacturing process at an anticipated price of $700,000 to $800,000, auto manufacturers developed a new process that would allow the use of standard flexible machining centers. They found that they could perform half of a boring operation and then rotate the engine block to complete the task. Precision and flexibility are somewhat lower with this process, but still meet specifications. This allows manufacturers to use less expensive machine tools (priced at $400,000 to $500,000) to meet their needs. Therefore, Lamb Technicon has been unable to find a manufacturer to buy and implement its technically successful ATP-funded specialized BOA machine. Soon after the project was completed, several large-scale diesel manufacturers expressed interest in using the BOA technology; however, the tool would need to be twice as big. Further development to scale up would be difficult and expensive. The machine tool industry has been hit hard by the transfer of manufacturing jobs overseas and by the downturn in the U.S. manufacturing economy. Manufacturers must limit capital investments and keep costs down.

The BOA machine tool achieved significant technical advances.

The BOA technology received three patents and won a “Top 25 Technology and Innovation Award” from *Industry Week* magazine in 1999, the first ever for a machine tool. The researchers published their findings in trade journals. The success of the BOA project’s process innovations led Lamb Technicon to increase its research and development group and earned it a reputation as an innovative leader among U.S. machine tool manufacturers. Much of the processing knowledge from BOA was incorporated into Cincinnati Lamb’s new process techniques in standard flexible machining centers.

In 2003, Lamb Technicon’s parent company, UNOVA Industrial Automation Systems, merged its Cincinnati Machine operations, a machine tool manufacturer that served the aerospace, heavy equipment, and defense industries with the business operations of Lamb Technicon to form Cincinnati Lamb. This organization is now the largest machine tool maker in the United States and one of the largest in the world.

Conclusion

Lamb Technicon and the University of Michigan proposed the Boring with Optimal Accuracy (BOA) project in response to an automotive industry need for increased agility in manufacturing. An industry survey determined that line boring of long, cylindrical holes (e.g., for camshafts) was the single most inflexible operation performed in the factory assembly line. The BOA team achieved all of its technical goals and developed a prototype flexible boring machine. However, Lamb Technicon was unable to commercialize the BOA tool, because other flexible less expensive standard flexible machining centers and manufacturing processes were developed during the same time period. Technology advancements, such as open architecture, laser-guided measurements, and smart tool concepts, from the BOA project continue to be developed and applied in machine tool and precision manufacturing.

PROJECT HIGHLIGHTS
Cincinnati Lamb, a division of UNOVA Industrial Automation Systems (formerly Lamb Technicon)

Project Title: Boring with Optimal Accuracy (Agile Precision Line Boring)

Project: To develop an experimental prototype of a flexible line-boring station with intelligent tooling and controls.

Duration: 9/15/1995 – 9/14/1998
ATP Number: 95-02-0019

Funding (in thousands):

ATP Final Cost	$1,997	82%
Participant Final Cost	448	18%
Total	$2,455	

Accomplishments: The success of this project helped elevate Lamb Technicon to the forefront of U.S. machine tool manufacturing. Lamb and the University of Michigan met or exceeded all of their technical goals. They successfully constructed a prototype Boring with Optimal Accuracy (BOA) machine tool with all of the desired qualities:

- Innovative laser measurement
- Open-architecture control methods (using non-proprietary software)
- Sophisticated hardware to allow quick (10-second) changeovers between engine models (for bores with lengths up to 30 inches and diameters of 1 to 3 inches), while maintaining the required ultra-high precision
- Smart tool concept, which allows compensation for errors
- Electronic rather than mechanical control
- Improved stiffness
- Improved cutting-tool process

Lamb Technicon received three patents for technology developed during the BOA project:

- "Precision positioner for a cutting tool insert" (No. 6,062,778: filed August 7, 1998; granted May 16, 2000)
- "Machine and method for flexible line boring" (No. 6,149,561: filed March 16, 1999; granted November 21, 2000)
- "Method of error compensation for angular errors in machining (droop compensation)" (No. 6,325,578: filed August 17, 1999; granted December 4, 2001)

Lamb Techicon won an innovation award for the BOA project, the first ever for a machine tool:

- "Top 25 Technology and Innovation Award," from Industry Week magazine, 1999

Commercialization Status: The BOA technology was not commercialized because auto manufacturers found less expensive machine tools to meet their specifications.

Outlook: The outlook for the BOA product is uncertain. The BOA technology advances established the company as an innovator among U.S. manufacturers. Machine tool productivity continues to rise at approximately 12 percent annually, while machine tool prices continue to drop. However, the BOA technology has not been commercialized. Some aspects of the technology such as open architecture (non-proprietary software) control, droop compensation, and laser-precision measurements, are still being developed and applied to multiple forms of research at Cincinnati Lamb and the University of Michigan's Engineering Research Center. Cincinnati Lamb is expanding its offerings in flexible machining center systems.

Composite Performance Score: * *

Focused Program: Motor Vehicle Manufacturing Technology, 1995

Company:
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Contact: Richard Curless
Phone: (800) 521-0166

Subcontractor:
University of Michigan
College of Engineering
Ann Arbor, MI

Publications and Presentations:
The team's publications include the following:

- Li, C.-J. and A.G. Ulsoy. "High-precision measurement of tool-tip displacement using strain gauges in precision flexible line boring." Mechanical Systems and Signal Processing, vol. 13, no. 4, pp. 531-546, July 1999.

PROJECT HIGHLIGHTS
Cincinnati Lamb, a division of UNOVA Industrial Automation Systems (formerly Lamb Technicon)

- Koren, Y., Z. Pasek, and P. Szuba. “Design of a Precision, Agile Line Boring Station.” Annals of the CIRP, 48/1, pp. 313-316, 1999.

- Li, C.-J. and A.G. Ulsoy. “Precision measurement of tool-tip displacement using strain gages in precision flexible line boring.” American Society of Mechanical Engineers, Dynamic Systems and Control Division, DSC, vol. 67, pp. 743-751, 1999.

- O'Neal, G., B.-K. Min, Z.J. Pasek, and Y. Koren. “Integrated Structure/Control Design of Micro-Positioner for Boring Bar Tool Insert.” Journal of Smart Material Systems and Structures, vol. 12, no. 9, pp. 617-628, 2001

- O'Neal, G., B.-K. Min, Z. J. Pasek, and Y. Koren. “Cutting Process Diagnostics Utilizing a Smart Cutting Tool.” Mechanical System and Signal Processing, vol. 16, no. 2-3, p. 475-486, 2002.

- Min, B.-K., G. O’Neal, Y. Koren, and Z. Pasek. “A Smart Boring Tool for Process Control.” Mechatronics, vol. 12, pp. 1097-1114, 2002.

- Mehrabi, M. G., P. Szuba, G. O'Neal, B. Min, Z. Pasek, and Y. Koren. “Geometric Error Compensation in Line Boring Process.” Journal of Intelligent Manufacturing, 13/5, pp. 379-389, 2002.

- Li, C.-J., W. Endres, and A.G. Ulsoy. “The effect of flexible-tool rotation on regenerative instability in machining.” Journal of Manufacturing Science and Engineering, Transactions of the American Society of Mechanical Engineers (ASME), vol. 125, no. 1, pp. 39-47, February 2003.

Four Ph.D. dissertations resulted from this project:

- Szuba, P. Improving Part Accuracy in Machining Operations that Employ Cantilevered Boring Tools. Ph.D. Thesis, Oakland University, Auburn Hills, MI, 1998.

- Li, C.-J. Tool-Tip Displacement Measurement, Process Modeling, and Chatter Avoidance in Agile Precision Line Boring. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 1999.

- Min, B.-K. Modular Diagnostics of Computer-Controlled Machine Tools and Mechatronic Systems. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 1999.

- O’Neal, G. An Analytical Approach to Integrated Structural and Control Design. Ph.D. Thesis, University of Michigan, Ann Arbor, MI, 2001.

The team shared the project’s technology advances through numerous presentations

- O’Neal, G., B.-K. Min, Z. J. Pasek, Y. Koren, and P. Szuba. “The Development of a Precision Piezoelectric Micro-Positioner for Line Boring Bar Tool Insert.” ATP Motor Vehicle Manufacturing Technology (MVMT) Public Workshop, Ann Arbor, MI, Oct. 1997.

- Pasek, Z. J. and P. Szuba. “Development of a ‘Smart’ Tool and Machine for Precision, Agile Line Boring.” AC ’98 V Intl. Conference on Monitoring and Automatic Supervision in Manufacturing, Warsaw, Poland, Aug. 20–21, 1998.

- Pasek, Z. J. and P. Szuba. “Intelligent Agile Line Boring Station.” Proceedings of Dynamic Systems and Control Division, ASME International Mechanical Engineering Congress and Exposition, DSC, Vol. 64, pp. 439-446, Anaheim, CA, 1998.

- O’Neal, G., B.-K. Min, C.-J. Li, Z.J. Pasek, Y. Koren, and P. Szuba. “Precision Piezoelectric Micro-Positioner for Line Boring Bar Tool Insert.” Symposium on Active Control of Vibration and Noise, ASME IMECE, DE-Vol. 97/DCS-Vol. 65, pp. 99-106, 1998.

- O’Neal G., Z. Pasek, B.-K. Min, and Y. Koren. “Integrated Structure/Control Design of Micro-Positioner for Boring Bar Tool Insert.” Proceedings of SPIE’s 7th International Symposium on Smart Structures and Materials, Conference on Smart Structures and Integrated Systems, Atlanta, GA, 2000.

- Pasek, Z. J., B.-K. Min, Y. Koren, A.G. Ulsoy, and P. Szuba. “Strategies to Enhance Agility and Machining Accuracy in Line Boring.” 2nd IFAC Conference on Mechatronic Systems, pp. 601-606, Berkeley, CA, Dec. 9–11, 2002.

- Li, C.-J., W. Endres, and A.G. Ulsoy. “The effect of flexible-tool rotation on regenerative chatter in line boring.” ASME IMECE Symposium on Dynamics Acoustics and Simulations, DE-98, pp. 235-243, 2003.

Research and data for Status Report 95-02-0019 were collected during November 2003.