Ingersoll Milling Machine Company

Octahedral Hexapod Design Promises Enhanced Machine Performance

In the field of advanced machine tools, enhanced performance is seldom achieved without greater design complexity, reduced operational flexibility, and higher costs. These drawbacks have stalled innovation in the U.S. machine tool industry, where most research and development (R&D) efforts focus on incremental improvements to conventional machines. Ingersoll Milling Machine Company developed its octahedral hexapod prototype, which promised superior accuracy, stiffness, and speed, as well as lower prices, shorter delivery times, simpler assembly, and greater accessibility. Further development of the octahedral hexapod tool concept had the potential to boost U.S. status in a competitive international market and to bolster smaller manufacturing companies by meeting their need for high-precision machine tools at an affordable price. However, because the industry viewed Ingersoll's prototype as a radical design and its continued development as too high risk to fund, the company sought and received funding from the Advanced Technology Program (ATP).

Since 1996, when the project ended, sales of the octahedral hexapod machine have been limited to three laboratories. However, Ingersoll's R&D during the ATP project laid the foundation for eventually bringing the octahedral hexapod to maturity. Moreover, the company's efforts have resulted in additional research by two-dozen machine companies that are currently investigating this machine tool.

COMPOSITE PERFORMANCE SCORE
(based on a four star rating)
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Research and data for Status Report 92-01-0034 were collected during October - December 2001.

Manufacturing Industry Needs More Precise Tools

The machine tool industry depends heavily on stacked-axis computer-numerical-control (CNC) machines, which achieve a specified position and orientation of the spindle by controlling individually as many as six positioning axes (X, Y, Z, roll, pitch, and yaw). The CNC commands up to six separate movements, each performed independently, whose combined effects produce a target position. However, the stacked-axis machine architecture generates cumulative error. This occurs because inexact positioning on one axis dislocates the positioning of the spindle on the next axis, which multiplies the imprecision with each subsequent adjustment. In addition to this design shortcoming, the traditional stacked-axis machine requires a massive granite foundation for stability. This results in a cumbersome unit that takes up considerable factory floor space and is difficult to transport.

The manufacturing industry desired a more precise tool. The development of a high-precision, low-cost machine tool became imperative for small companies' ability to enhance the quality of U.S. products. Moreover, innovation was vital for the United States to improve its position in the machine tool industry (the nation lagged behind Japan and Germany in a competitive market, with domestic manufacturing companies importing $1.6 billion in machine tools in 1991).

The Octahedral Hexapod Offers Promise

In 1987, a radical concept caught the attention of engineers at Ingersoll. Eventually called the octahedral hexapod, this novel design creatively employs the Stewart platform concept, most commonly known for its application in flight simulators. The Stewart platform, a floating base supported or suspended by six actuators, is familiar to several generations of pilots (it was the basis for the design of the Link flight simulator).

The octahedron, a regular geometric shape of eight equilateral triangles, is built on an octahedral frame and a Stewart platform actuation, the hexapod. Machining operations take place within the octahedral frame, and the struts, or the pods of the hexapod, directly translate the force generated during the machining operation to the six vertices of the octahedral frame. The shape has such stiffness that when a load is applied, the frame responds by distributing the weight of the load evenly throughout the shape, eliminating much of the bending because of the shape's stiffness. Furthermore, the six axes are in simultaneous movements rather than the independent sequential movements experienced with the CNC machine. Hence, the shape of the octahedral hexapod tool would offer six times the machine stiffness and five times the position accuracy of the traditional CNC machines.

Under the ATP award, Ingersoll planned to use a laboratory prototype octahedral hexapod machine (which they had constructed prior to the ATP project with their own funding) to develop detailed baseline data on the performance of the design. Then they would try various enhancements to improve and measure machine precision. The results would be used to design a future class of commercial machines based on the octahedral hexapod concept.

ATP Provides Early Catalyst for R&D Proliferation

As indicated by the numerous predicted uses of the octahedral hexapod, this technology has the potential to substantially impact a wide range of manufacturing industries across the supply chain. However, the risk of funding research for such a radical design was too high for either machine tool companies or their manufacturing clients. Moreover, if Ingersoll absorbed the cost of the extensive R&D required to fully develop the octahedral hexapod, it would have to subsequently increase the cost of its machine tools by at least 20 percent. This cost escalation would put their products in a range that would be prohibitive for many smaller companies, such as those who provided parts for the automobile industry.

The concept demonstrated the potential to evolve into a machine tool that offered double the accuracy at a selling price and life cycle cost that was 30 percent less than that of the best existing technology. Therefore, ATP awarded cost-shared funding to Ingersoll.

Project Slowly Overcomes Technical Obstacles

With a prototype of the octahedral hexapod as a starting point, Ingersoll set out to design and develop several applications to achieve the machine tool's maximum potential for improved accuracy and precision. Though the design concept itself was in place, other components essential to achieving these performance objectives needed to be developed.

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A key step of this process was the development of a computer control system and accompanying software that were capable of processing the complex algorithmic calculations necessary to command the parallel movement of the hexapod's six struts. To direct these complicated six-axis moves in real time, the processor requires a calculation power equivalent to that of several fast PCs combined. Additionally, the software needs to compute error as well as offset data, thermal deviations, and compensation formulas. During the project, Ingersoll worked with software suppliers GE Fanuc and Siemens to incorporate software algorithms into a central control system, taking important strides toward the full computerized alignment envisioned for ideal accommodation of the octahedral hexapod. Ingersoll was able to begin the development of the system during the ATP project. However, the development and programming of such a system proved to be extensive and time-consuming, demanding R&D beyond the timeframe of the ATP project.

Ingersoll also faced the challenge to develop a calibration system that would guarantee high-level accuracy, enabling the machine tool to manufacture parts repeatedly within specified tolerances. Because of its design, the octahedral hexapod concept did not lend itself to conventional inspection techniques. Therefore, before it could be commercialized, Ingersoll needed to develop a turnkey calibration method that could be performed more quickly and efficiently than the existing labor-intensive procedure. To this end, the company worked to implement a self-calibration system that would allow machines to check their own performance and correct any detected inaccuracies.

In addition to these tasks to install control and calibration systems, Ingersoll encountered obstacles in developing the supporting electronic and mechanical components of the octahedral hexapod machine tool. However, the company maintained steady and productive R&D efforts throughout the ATP project, continuing to demonstrate promise for eventual commercialization and revealing more and more possible applications.

Sustained R&D Points to Commercialization on the Horizon

At the conclusion of the project in 1996, the technology components of the octahedral hexapod were well understood; however, six years later, the machine tool was still in development. While several fully functional hexapods exist, researchers must improve their accuracy, streamline the production process, develop standards, and solve small but important mechanical problems before pursuing full-fledged commercialization. Based on the interest generated by Ingersoll's original prototype, there are currently about two-dozen companies that have invested R&D funds in hopes of bringing the Ingersoll hexapod to market.

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Ingersoll has sold three octahedral hexapods, one each to the National Institute of Standards and Technology (NIST), Lockheed-Martin's research facility, and Aachen University. Because Ingersoll's current goal is the evaluation of production techniques rather than sales, only a national laboratory, a large corporate research facility, and a university have purchased hexapods. Octahedral hexapods are custom-made because Ingersoll has not developed a protocol for high-volume, quick, and affordable manufacturing. Future research will address production problem areas, such as computer control systems and struts, which together account for 75 percent of the machine tool's cost. Other research will focus on simplifying the hexapod's design, since reducing the number of machine parts could lower costs by an estimated 40 percent.

Calibration, control, and thermal compensation issues persist as roadblocks to commercialization, reducing the octahedral hexapod's ability to repeatedly manufacture parts within specified tolerances. Using an octahedral hexapod purchased from Ingersoll, a project at NIST's Manufacturing Engineering Laboratory, supported in part by ATP intramural funds, is addressing these problems by setting common performance-evaluation procedures and developing measurement methods to achieve high positioning accuracy.

Scientists at NIST have focused on implementing a built-in metrology system and an enhanced machine controller that simplifies performance-enhancing modifications in software or hardware. Ingersoll has improved thermal compensation techniques by using laser feedback that senses and eliminates deviant length changes of the hexapod's struts. Additional post-project research will determine the optimal machine configuration and the most advantageous strut length given a particular working envelope size (the work area).

Researchers Identify Multiple Uses for the Octahedral Hexapod

As researchers assessed the mechanical and electronic specifications for the octahedral hexapod, they discovered the versatility and flexibility of this machine tool. Engineers at Ingersoll predict that the hexapod could become a general manipulator for various tasks or a universal carrier for several end effectors, such as milling heads, coordinate measuring machine probes, and turning tools. These engineers anticipate that current R&D efforts will lead to the octahedral hexapod's role in numerous applications, including the following:

- Mold and die industry uses, such as contouring large surfaces and machining dies for precision sheet-metal forming
- The machining of high-value, low-volume, high-complexity components, such as titanium for use in military aircrafts
- The machining of lighter metals and materials

- Precision assembly technology; for example, delicate welding in an automotive assembly line and in aerospace and aircraft production

Conclusion

Dennis Bray, vice president of engineering at Ingersoll, reports that the current configuration of the octahedral hexapod would not have been designed without ATP funding. The ATP project allowed Ingersoll to tackle a number of the deficiencies identified in the original prototype and to bring the hexapod closer to full-scale development. Additionally, ATP funding helped to validate the unconventional concept and design of the octahedral hexapod, convincing other machine tool companies of its worth and generating further investment in its R&D. Although commercialization of the octahedral hexapod machine tool has stalled, Ingersoll continues to research methods to improve accuracy, streamline the production process, and develop the ability to manufacture parts repeatedly within specified tolerances, with reasonable production costs.

PROJECT HIGHLIGHTS
Ingersoll Milling Machine Company

Project Title: Octahedral Hexapod Design Promises Enhanced Machine Performance (Octahedral Hexapod Machine Development Program)

Project: To demonstrate a revolutionary new design for high-precision, multi-axis machine tools based on an octahedron frame and a Stewart platform actuator.

Duration: 3/1/1993-2/28/1996
ATP Number: 92-01-0034

Funding (in thousands):

ATP Final Cost	$ 1,864	53%
Participant Final Cost	1,635	47%
Total	$ 3,499	

Accomplishments: Ingersoll has sold three octahedral hexapod machine tools, one each to NIST, Aachen University, and Lockheed-Martin's research facility, to be used for further R&D. The company performed several demonstrations of its prototypes to potential clients such as Boeing Corporation and the U.S. Air Force. These demonstrations created interest and generated constructive feedback.

Ingersoll received the following patent for its work:

- "Octahedral machine tool frame"
  (No. 5,392,663: filed November 9, 1993, granted February 28, 1995)

Commercialization Status: Due to the need for additional research, Ingersoll has not been able to fully commercialize the octahedral hexapod. However, the company has sold three of these machine tools, generating $6 million in revenue.

Outlook: The outlook for the octahedral hexapod is clouded. At this point, researchers at Ingersoll have been unable to combine accuracy and the ability to manufacture parts repeatedly within specified tolerances with reasonable production costs. This has stalled the commercialization of the octahedral hexapod machine tool. However, several companies continue to research the octahedral hexapod tool concept.

Composite Performance Score: *

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