Laser-Based Robotic Systems for Manufacturing Automation

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Although laser beam and robotics use has become widespread in areas of manufacturing, many manufacturers still do not see the urgency or necessity for their use in many manufacturing operations. Nevertheless, it is always beneficial to keep abreast of technological upgrades. This article describes laser and robotics implementation at a few manufacturing plants.

The research and development programs in manufacturing technology at Penn State emphasize automation of materials processing and inspection. Two major research projects in these areas, which are based on the application of laser technology, have recently been completed.

This article presents the background, current status, research results, and future plans for these two projects.

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The application of lasers in manufacturing has been limited because of requirements for the workpiece to be moved under a fixed beam. This process is time-consuming because extensive fixturing and alignment are required to ensure that the laser beam contacts the part at the proper position and orientation for the process involved.

Advances in sensor and control technology have made it possible to manipulate laser beams in space along a precise path using robots. This development has created a surge of interest in the application of lasers for materials processing and inspection.[1] Hence, the manufacturing science program has been established by the Applied Research Laboratory at Penn State to develop solutions to the unique problems associated with precision fabrication and inspection of components for surface and underwater vehicles.

The development of advanced welding technology for manufacturing and repair was planned to apply laser technology for materials processing, welding, and cutting thick sections and then to develop articulating robotics and associated technology for controlled high-speed manipulation of a laser beam throughout a large manufacturing cell.

The major thrust of the manufacturing science program is to develop equipment for automated materials processing and inspection. This requires the use of robots coupled with high-powered (up to 25 kW) continuous-wave CO_2 lasers for welding, cutting, heat treating, cladding, transformation hardening and glazing, and solid state lasers for measurement.[2] For laser materials processing, the Laser Articulated Robotic System (LARS) is being developed. When interfaced with a high-power laser, this large robot provides the manipulation of a beam over large distances and focuses the beam to a small spot to concentrate the energy for welding and cutting or a larger configuration for other processes.

For precision measurement, the Intelligent Robotic Inspection System (IRIS) is being developed. This is a large gantry robot equipped with laser-based vision systems for precision space location and part profiling. Both projects are funded by the US Navy Manufacturing Technology Program.

A survey to assess the applicability of high-power lasers in manufacturing for the navy and army as well as for the aerospace, electric utility, automotive, and pipeline industries was conducted in the hope that it would expand laser acceptance in these fields.[3] Copies of this survey report are available upon request. The background, current status, research results, and future plans for the LARS and IRIS are presented and organized in five main sections.

Laser Articulated Robotic System

The LARS program began in 1982 by identifying the requirements for a laser beam delivery system; they are summarized in Exhibit 1. A contract was awarded for the development of the LARS in August 1983. Upon completion, the LARS will be delivered to the Westinghouse Research and Development Center in Pittsburgh and interfaced with a 15-kW CO_2 continuous-wave laser for technology demonstration and transfer.

LARS is still in the development stage. When completed, it will consist of six major subsystems including the robot, beam transport, workhead, vision, electronic control, and software. These subsystems and their components are shown in Exhibit 2.

Exhibit 1. ***Important Parameters for LARS***

Range of Operation	11 × 11 × 3 ft 20 × 20 × 10 ft
Modes of Operation	Manual Teach Offline Program Automatic
Tracking Precision	Along Seam ± 0.005 in Vertical ± 0.015 in Angular Control ± 1°
Welding and Cutting Speeds	0–200 in/min
Tracking Device	Noncontacting 200-Hz Sampling Speed Closed Loop Real Time
Capabilities	Welding, Cutting, Heat Treating, Cladding, Surface Transformation Hardening

Robot subsystem

After considering all robot configurations, it was determined that a gantry-based system was the only practical structure for this application. Initially, the system was to be 20 feet by 20 feet by 10 feet. To reduce costs, a prototype system will be developed first and will have a working volume for welding in the down hand position of 14 feet by 14 feet by 3 feet. The gantry provides *x*, *y*, and *z* translation of the beam, and an articulated arm at the lower end of the *z* axis provides the remaining degrees of freedom for random path welding and cutting. The gantry system was designed specifically for LARS because a commercially available robot that met the requirements for this system could not be found.

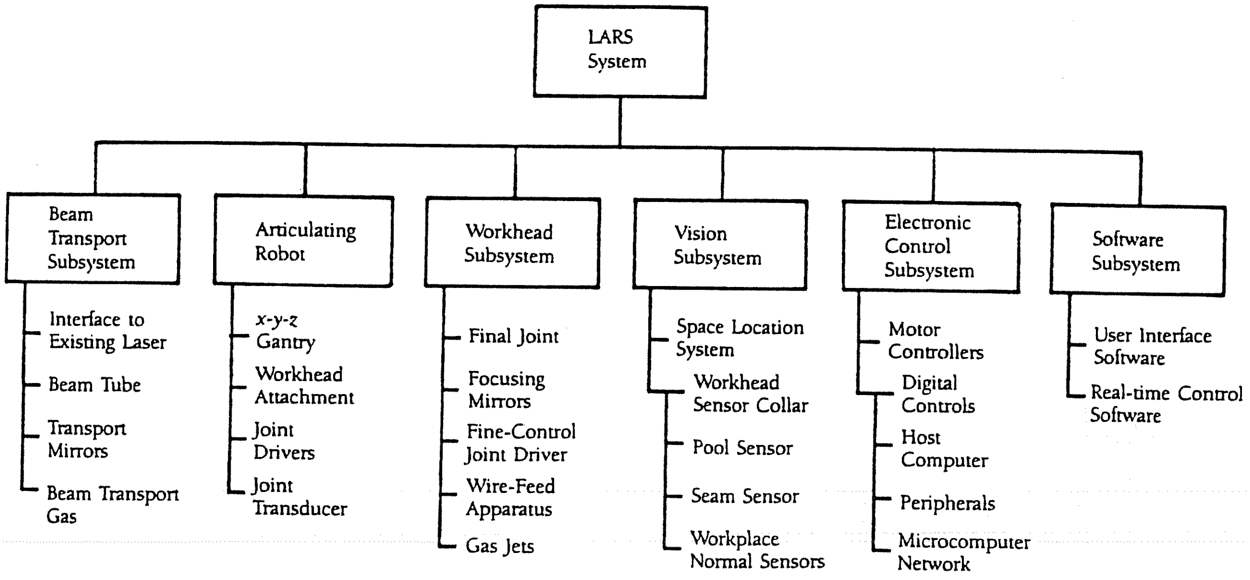
The robot is designed to be extremely accurate; however, the accuracy requirements shown in Exhibit 1 are dynamic rather than point to point and relate to the position of the focused beam instead of the robot position. As a result, the beam-positioning accuracy is achieved by a carefully controlled positioning mirror with a high-speed vision system located in the workhead.

Workhead subsystem

The workhead is attached to the gantry's lower end of the *z* axis. The workhead shown in Exhibit 3 is an integrated system of mechanical and electromechanical components that focuses the laser beam and provides final positioning of the laser beam and process hardware at the workpiece. The workhead focuses the laser beam to a 0.040-inch-diameter spot for welding and cutting using f/7 optics.

In addition to focusing and beam positioning optics, the workhead contains a gas shield for

Exhibit 2. ***LARS Subsystem Breakdown***



plasma suppression, a wire feeder and positioner, seam tracking vision components, and a gas cutting jet.

Vision system

The positioning requirements for the LARS include tracking the center of a butt joint, maintaining the desired standoff distance, and controlling the angle of the incident beam with respect to the workpiece. This tracking requirement must be met for random path welds throughout the working envelope without preprogramming and must operate at speeds of 200 inches per minute. For metalworking processes other than welding in which there is no seam to follow, LARS must follow a preprogrammed path to the same accuracies as that stated for welding.

The A sensor. The LARS vision system has four vision subsystems for space location and seam following, the latter of which uses the two independent closed-loop systems: fine loop and coarse loop. The sensors and their function are shown schematically in Exhibit 4. The A sensor uses three linear charged coupled devices (CCDs) to monitor the *x*, *y*, and *z* coordinates of the laser spot at the surface of the workpiece and measures the workpiece surface angle. The output of Sensor A, combined with the fine-control mirror drives, provides the precision positioning of the focused laser beam.

The B sensor. Sensor B measures the *y* coordinate of the seam at three locations, finds the seam position by scanning an intense beam of light across the weld seam, and monitors the reflected light pattern. By controlling the RF drive frequency of the device, the angular position of the scanning laser beam and the beam position on the workpiece can be determined with precision. The solid-state light deflector can create a complex pattern of light. Another benefit of this approach is its flexibility. An acousto-optic deflector can be programmed to generate any sequence of light patterns within the range of operation. Sensors A and B acquire data at a 1-kHz rate and update the fine-position mirror controller at 200 Hz for seam tracking. By comparison, current seam-tracking systems for arc welding operate at up to 30 Hz.

The information from these two sensor systems is obtained synchronously. The desired weld-pool location determined by Sensor B is compared to the actual weld-pool location from Sensor A. If these positions differ, an error signal is sent to the fine-position mirror controller and a correction is made.

Exhibit 3. ***LARS Workhead***

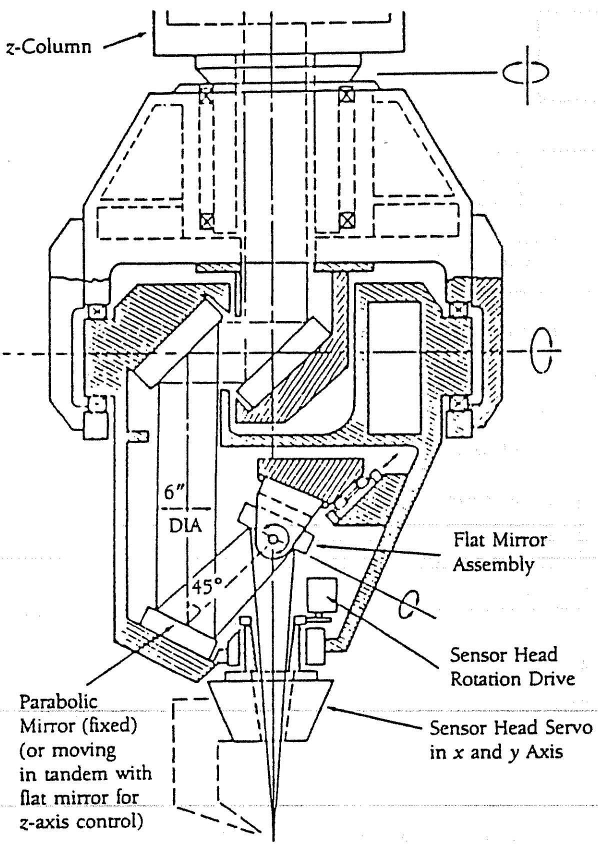
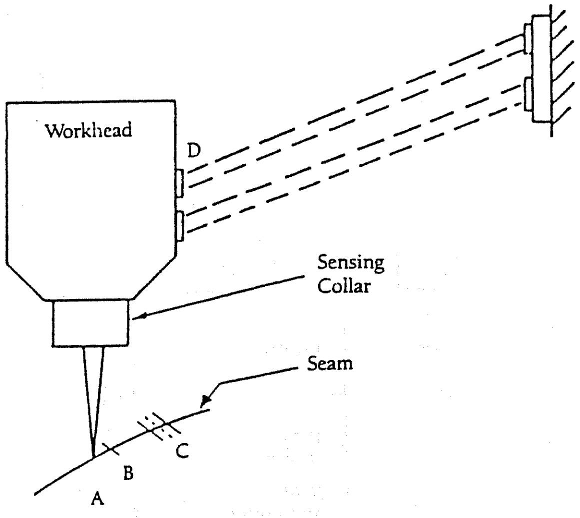


Exhibit 4. ***LARS Sensor Systems***



Name	Function
A. Beam Sensor	Locates puddle center in x, y, z
B. In-Close Seam Tracker	Locates seam (y) position directly in front of puddle
C. Look-Ahead Seam Tracker	Locates seam coordinates and angles about 2 inches in front of puddle
D. Space Location System	Locates position of workhead in world coordinate system

The C sensor. Sensor C is the workpiece profile sensor that measures the angular orientation of the workpiece surfaces and deduces the shape and orientation of the part ahead of the welding area. It then informs the robot controller at a 50-Hz rate for course robot position control and develops data to be used during the fine-position control.

The D sensor. The space location system, Sensor D, locates and tracks the position of the workhead in world coordinates for those preprogrammed metalworking operations in which no seam is available for guidance. This system must know the position of the robot workhead to within 0.005 inches. Because it is not possible to obtain such accuracy using robot joint encoders, a tracking interferometric system, mounted on the workhead, was selected.

Control system

The control system and precision digital interface hardware must be capable of the following:

- Providing control accuracy over extreme control ranges.
- Coordinating online the motion of a complex robot.
- Providing online compensation for variations in control that occur during operation.

To accomplish these tasks, a hierarchical multiprocessor control system must be used. The LARS control system tasks are divided into six subsections:

- Operator interface and system management.
- Coarse loop control.
- Coordinate conversion and servo control.
- Fine loop control.
- Safety.
- Task support.

The tasks in each subsection are accomplished by either a computer system or a cluster of microcomputers. A particular computer or special-purpose hardware and software modules can be specified to perform the critical tasks of a particular subsection.

Intelligent Robotic Inspection System

The Applied Research Laboratory has been involved in the design and inspection of multiblade propulsors for underwater vehicles for many years. Unfortunately, because of the complex shape and limited space between blades, the inspection equipment can only measure to an accuracy of ±0.003 inches. As a result, it's been impossible to establish a relationship between manufacturing accuracy and performance. Recognizing this need, the navy developed IRIS, which will use the enhanced vision and control technology already developed for the LARS project. The contract was awarded for IRIS in January 1985.

The LARS is designed for precise manipulation of high-power (up to 25 kW) laser beams

The IRIS is essentially a robotic, laser-based measuring system capable of accurately comparing actual part dimensions with design requirements. The major technology issues to be addressed include world coordinate and orientation measurement, noncontact part sensing, advanced robot control development, advanced user interface capabilities, and dynamic accuracy.

The IRIS is shown schematically in Exhibit 5. The system consists of three major components including the mechanical, sensor, and control subsystems.

Mechanical subsystem

The primary mechanical components of the IRIS include the robot, a two-degree-of-freedom wrist assembly, the retroreflector, a granite base, a rotary table, and the robot end effector.

In contrast to the LARS, the IRIS robot provides x, y, and z translation. A highly repeatable, two-degree-of-freedom wrist assembly is located at the end of the z-axis column of the robot and is almost identical to the ones found on the more accurate coordinate-measuring machines except that the measuring component has been replaced with an end effector for part profiling.

The retroreflector is also located on the z-axis column. It is part of the space location system and consists of three mirror assemblies that return the beam back to its source along a parallel path. The base of the IRIS is constructed of granite to ensure dimensional stability during the inspection process. A precision rotary table is also mounted on the granite base.

Sensor subsystem

In conventional systems, measurement accuracy is functionally connected to the control accuracy which determines the accuracy of the robot or manipulation device. The equipment can only be as accurate as the manipulation device for dynamic measurements. In the design of the IRIS, the measurement accuracy and the control accuracy are functionally separated; therefore, overall accuracy can be obtained in the dynamic mode.

To meet accuracy requirements, two sensor subsystems, as shown in Exhibit 6, were developed for IRIS: the space location system (SLS) and the part sensor. The part sensor determines the surface position of the part with respect to the retroreflectors. The part sensor shown schematically in Exhibit 7 consists of a solid state laser, optics, mirror, and a 3,000-element linear array. The laser beam is focused by the optics and reflected to and from the part surface by the mirror. Distance measurements are determined by the position that the reflected laser beam strikes the linear array, and data is collected at a speed of 1000 Hz.

Control subsystem

The IRIS control system has two major requirements. It must be able to position precisely the end effector within the work envelope, and the part sensor feedback must be used to monitor the location of the measured part. To meet these requirements, the control system uses two position-locating devices—the SLS and the motor resolvers. The sum of these signals form a composite feedback signal: one from the SLS at low frequencies

Exhibit 5. *The IRIS and Its Major Components*

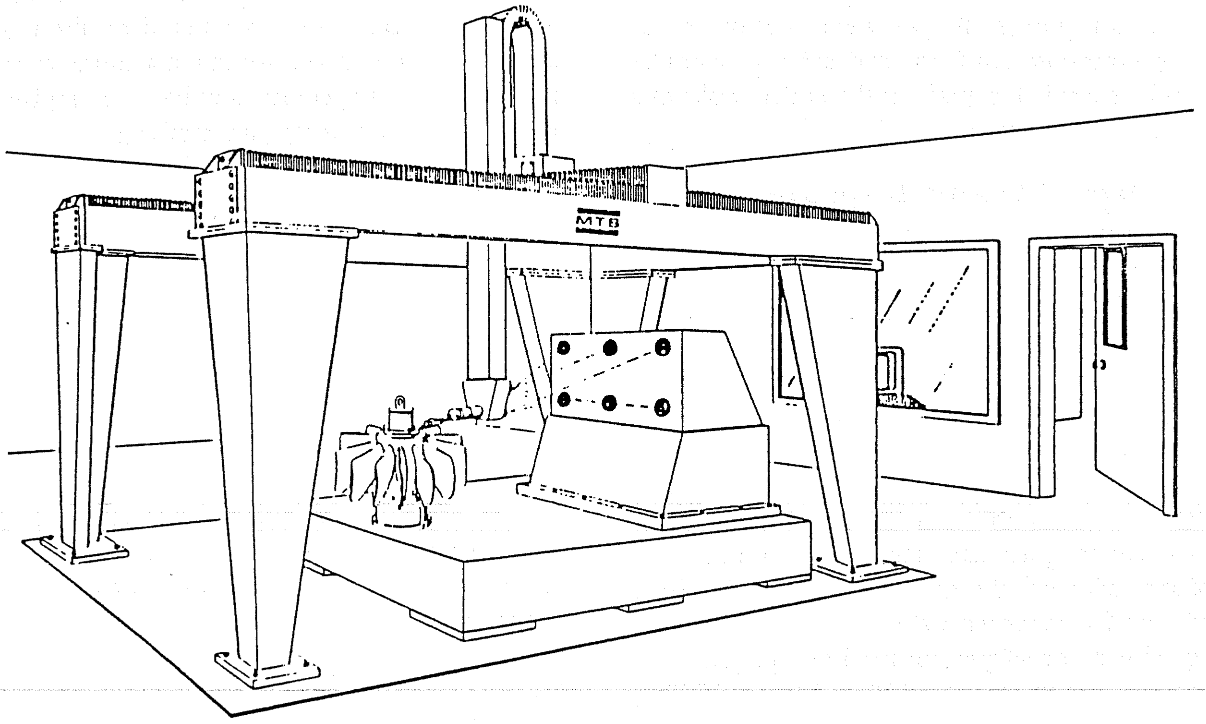
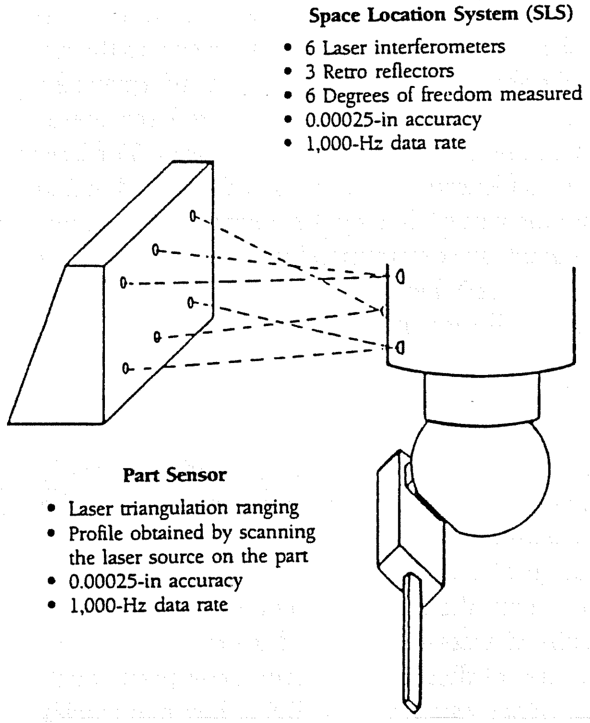


Exhibit 6. *The IRIS Sensor Subsystem*

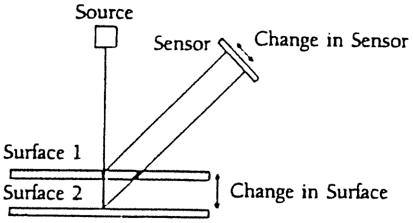


and one from the motor resolver at higher frequencies. This provides the control system with a broad range of frequency response, thereby extending the usable bandwidth of the position control loop and improving the measurement speed and accuracy (i.e., dynamic response).

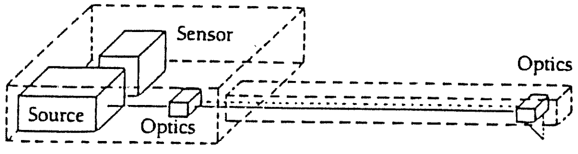
Future Directions

LARS-related activities will continue even after installation with system refinement and process development. Equipment must be developed and integrated with the LARS to permit coordinated control of the process parameters as well as the real-time determination of weld quality. To improve LARS, its control system should be integrated with a knowledge-based system capable of decision making in real time for high-speed laser welding.[4] New applications of laser technology must be developed for the military and the private sectors. Westinghouse and Penn State have been developing the process requirements for other materials that are difficult to weld (e.g., high-strength steels, copper, and aluminum).

Exhibit 7. ***The Part Sensor for IRIS***



a. Triangulation



b. Look-to-the-Side Triangulation Part Sensor

Future plans for the IRIS include hardware enhancement and applications of advanced inspection technology; higher accuracy extends precision engineering to efficiency and manufacturing cost. The knowledge-based system could autonomously determine the location of inspection points and the amount of data required for the desired inspection accuracy.

Although the IRIS addresses the navy's problem with multiblade propulsor design and inspection, it is considered a generic system capable of inspecting any part that fits within the work envelope and has a measurement data base.

Summary

This article summarizes the background, current status, results, and future plans for two laser technology–based research projects at the Applied Research Laboratory of Penn State. Both projects are supported by the US Navy Manufacturing Technology Program.

The LARS is designed for precise manipulation of high-power (up to 25 kW) laser beams for welding, cutting, heat treating, cladding, and surface transformation for materials such as aluminum, high-strength alloy steels, ceramics, and composites. The initial thrust of the LARS project was on applying laser technology to materials processing and related technologies such as seam tracking, real-time control of welding parameters, and CAD/CAM interface development. Human factors will be applied to arc welding in the future[5].

The first application of the LARS is scheduled to be the welding of catapult-paunch rail trough covers and rails to produce one-piece assemblies for aircraft carriers. The first application of the IRIS is scheduled to be the design and certification of components for underwater vehicles. ▲

Notes

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2. J.S. Eckersley, "Laser Applications in Metal Surface Hardening," *SME Laser Welding and Surface Treatment Clinic* (Plymouth MI, October 29–31, 1985); J.H.P.C. Megaw et al, "Surface Cladding by Multi-kilowatt Laser," *Proceedings of 3rd International Colloquium on Welding & Melting by Electron and Laser Beams* (Lyon, France, September 1983); C.J. Dawes, "Laser Welding of Sheet Metal Fabrication," *The International Congress on Applications of Lasers and Electro-Optics* (San Francisco, November 11–14, 1985); D.R. Martyr, "The Application of High Power Laser Technology to Ship Production," *Transactions of the North East Coast Institution of Engineers and Shipbuilders* 101, no. 3 (June 1985), pp 127–141; W.C. Ball and C.M. Banas, "Welding with a High Power CO_2 Laser," *Society of Automotive Engineers at National Aerospace Engineering and Manufacturing Meeting* (ASE No. 740863) (San Diego CA, October 1–3, 1974); A. Gukelberger, "New Developments of CO_2 Higher Power Lasers in the Multi-kilowatt Range and Their Use in Industrial Production," *Proceedings of SPIE Conference on Industrial Applications of High Power Lasers. SPIE* 455 (Linz, Austria, September 1983), pp 24–28.
3. J.S. Foley, "Survey of Applications of High Power Lasers in Manufacturing," *Report No R86-917261-1 of the United Technologies Research Center* (East Hartford CT, January 1986).
4. D.R. Thompson et al, "A Hierarchically Structured Knowledge-Based System for Welding Automation and Control," *ASME Journal of Engineering for Industry* 110 (February 1988), pp 71–76.
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