A Precision Robotic Assembly Machine for Building Nuclear Fusion Ignition Targets

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Delivering unprecedented accuracy, efficiency, and repeatability for micrometer-scale laser target assembly, this machine can be adapted to build other complex miniature systems.

The primary goal of the world's largest and most energetic laser, the National Ignition Facility (NIF), is to achieve a self-sustaining nuclear fusion burn with energy gain in a laboratory setting. One of the keys to attaining this goal is the production of targets that meet extraordinarily demanding specifications in materials fabrication, machining, and assembly. As shown in Figure 1, many of the target components are designed to slip-fit together with micrometer-scale clearances, and the dimensional accuracy of a fully

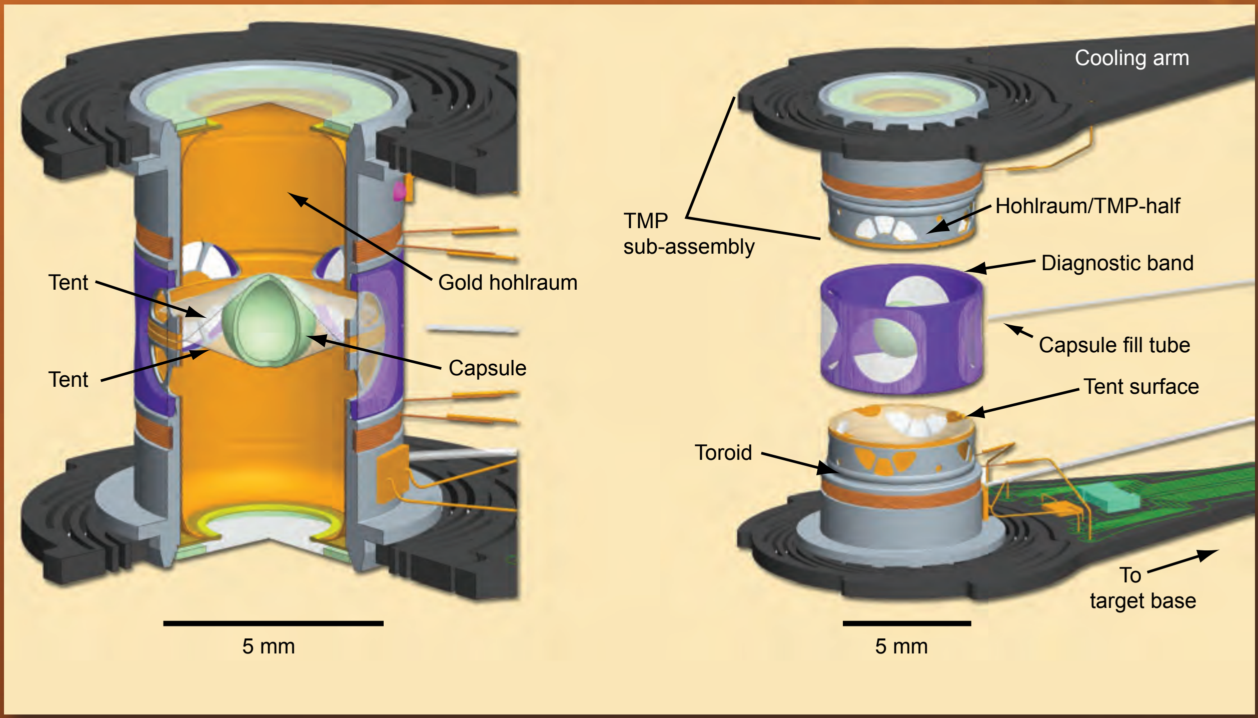

Figure 1. Model of a fusion ignition target showing the major components.

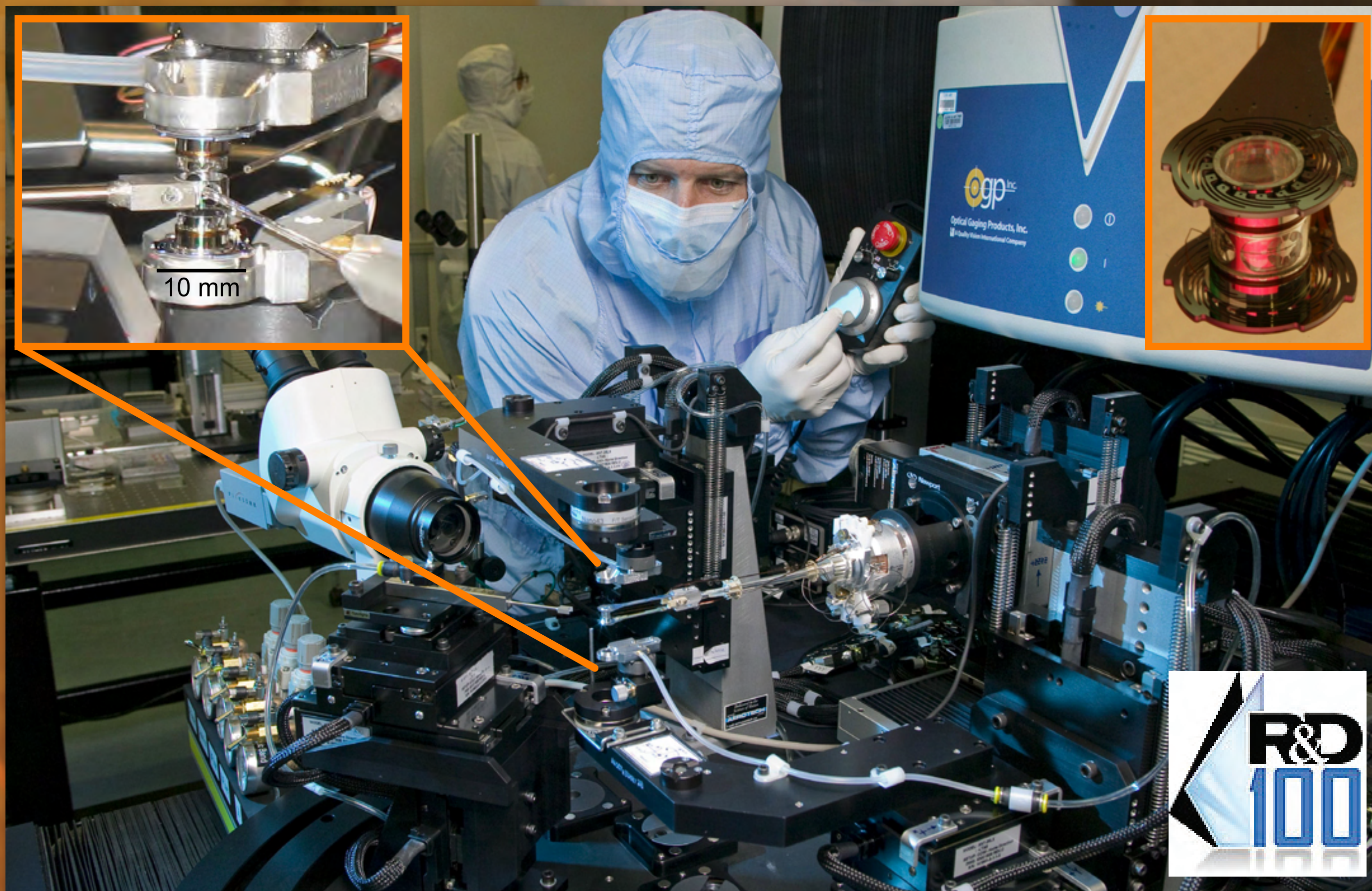

Figure 2. **The Precision Robotic Assembly Machine releasing a laser fusion target that was just assembled. Target components being assembled (left inset). A completed target (right inset).**

assembled target is in the range of 2–20 micrometers. Historically, building laser fusion targets depended on a significant amount of hand-crafting skill and technique involving microscopes and manually driven fixtures, a methodology that resulted in unacceptable variability in target quality. The Precision Robotic Assembly Machine (Figure 2) is the first fully engineered system for assembling NIF targets, and its use has removed the risk to fusion ignition experiments posed by targets of variable quality. The machine provides unprecedented accuracy and efficiency, and a ten-fold reduction in manpower needed to assemble laser fusion targets.

The Precision Robotic Assembly Machine operates in a class-1000 clean room, and consists of an

LLNL-developed manipulator system integrated with an optical coordinate-measuring machine (OCMM). Figure 3 shows a close-up view of the manipulator system, which can be reconfigured to accommodate different laser fusion target designs. Nineteen motorized and 10 manual degrees of freedom provide simultaneous manipulation of five objects in a 1-cubic-cm operating arena with 100-nm precision and micrometer accuracy. A unique attribute of the machine is its ability to stitch together multiple millimeter-scale operating arenas over distances spanning tens of centimeters with micrometer-level accuracy. Sensors embedded in the manipulator system provide 100-mg resolution force and gram-millimeter resolution torque feedback of the contact loads between components being assembled with micrometer-level or no clearance. The OCMM has a machine-vision system, laser-based distance-measuring probe, and touch-probe that provide micrometer-level accuracy measurements. Auxiliary mirrors provide the OCMM with multiple viewing directions of the target. The vision and measurement systems of the OCMM are used to guide the initial approach and alignment of the target components, and to measure the relative position and orientation of the components. The force and torque feedback is used to guide the final approach, alignment, and mating of the delicate target components.

The Precision Robotic Assembly Machine transforms the way laser-driven fusion ignition targets are built so that one person can assemble a high-quality target in one day, and repeat that quality every time. The vision was to create a system that would allow a target assembly technician to build a target in a manner similar to how a surgeon uses a surgical robot to perform a delicate operation: the operator provides top-level control of the machine, initiating and controlling the movement of the motorized precision instruments. Hand movements that are precise in the millimeter-scale realm are scaled to precision in the 100-nanometer realm, and innovative use of force feedback with 100-mg resolution allows the operator to “feel” the delicate components being assembled and adjust accordingly. The machine has enabled every operator to build fusion targets with an equally high level of finesse and repeatability. This accomplishment is more remarkable considering it was achieved, from early concepts to a working machine that assembled targets that met specification, in only 14 months.

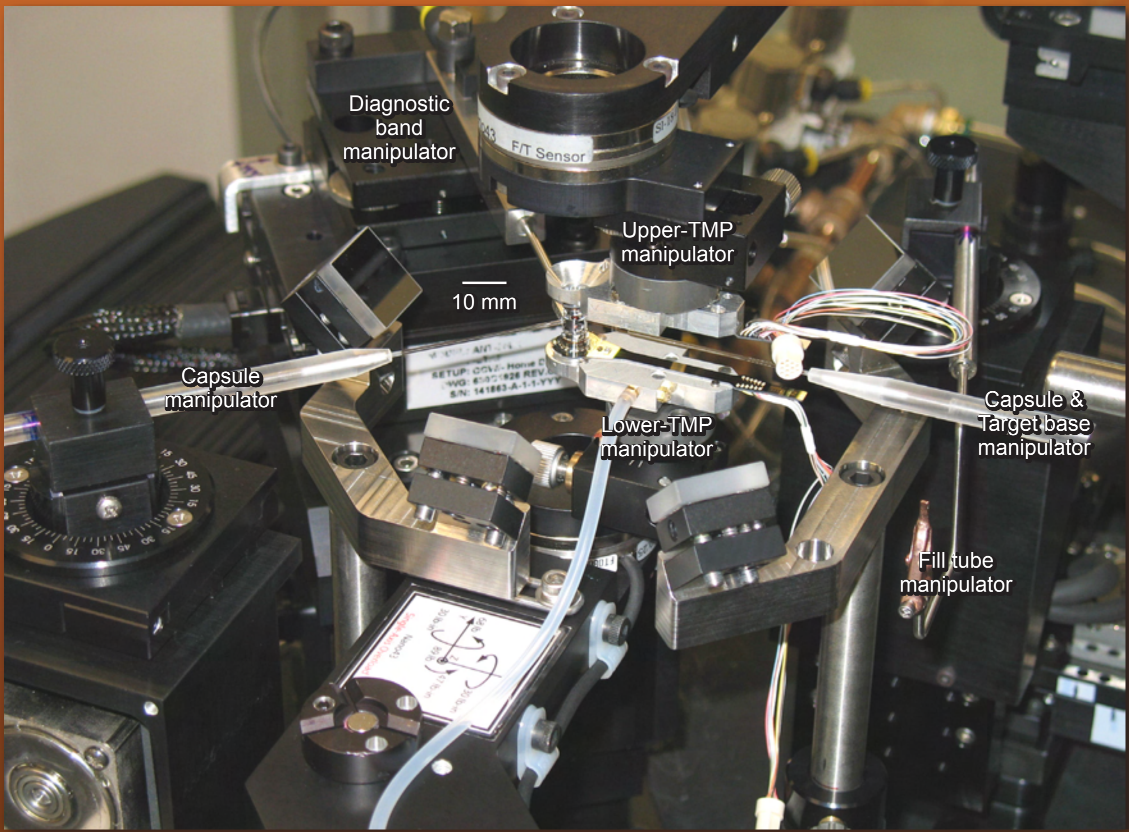

Figure 3. **Close-up view of the manipulator system, with a target being assembled.**

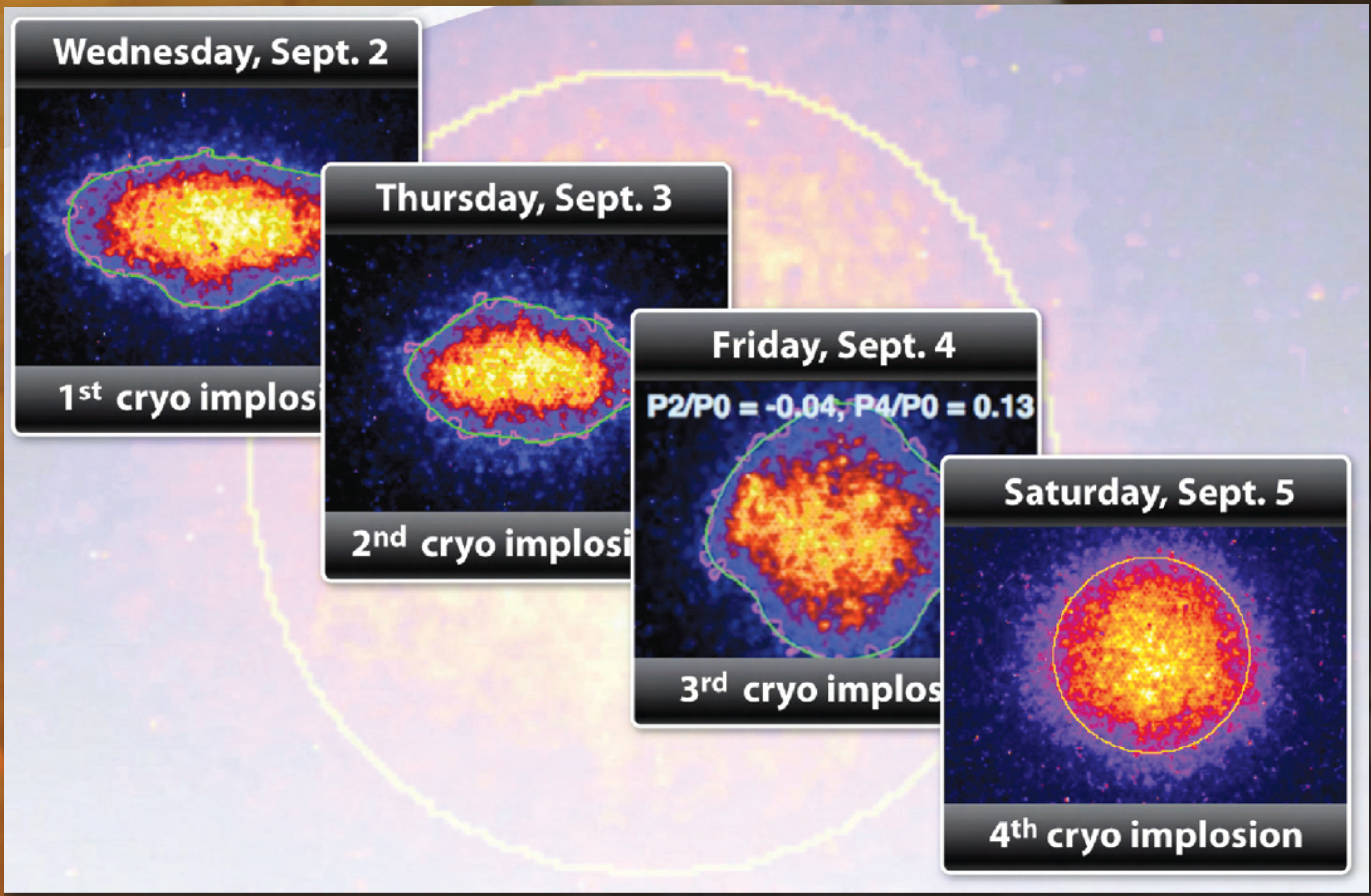

Figure 4. X-ray images of the imploding fuel capsule for four sequential cryogenic target shots at the NIF in September 2009.

The value of reliable, repeatable, and consistent production of high-quality, precision ignition targets for the National Ignition Campaign was demonstrated recently. Figure 4 shows the x-ray images of the imploding fuel capsule in four different targets built with the machine. The desired spherical shape of the fourth shot was achieved by using data from the previous three shots to incrementally adjust the laser beams. This use of the NIF to step-wise converge on a desired symmetrical capsule implosion was a momentous accomplishment for the National Ignition Campaign, and was made possible in large part because of the repeatable, high-accuracy targets built with the Precision Robotic Assembly Machine.

The Precision Robotic Assembly Machine provides a balance between the earlier method of manually assembling a target and a fully automated system. Certain aspects of the target assembly process, such as alignment of components and measurements of that alignment, are being automated. To the extent that each target is slightly different from the ones before it—just as each person undergoing the same surgical procedure is slightly different—the operator stays in the loop as the top-level controller. As targets for a sustained campaign converge on being identical to each other, the level of target assembly automation can be increased by adding a machine-based, top-level control system.

Laser-driven fusion targets for the NIF program are a first application for the Precision Robotic Assembly Machine, which can be adapted to build other complex miniature systems. The multiple technologies integrated into the machine bridge the gap between building miniature- and man-sized machines. The machine could provide a key enabling platform for significant advances in the discovery and manufacture of centimeter-scale systems that integrate millimeter- and micrometer-scale optical, electrical, mechanical, and biological subsystems.