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Robotic System for Precision Assembly of NIF Ignition Targets

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ROBOTIC SYSTEM FOR PRECISION ASSEMBLY OF NIF IGNITION TARGETS

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INTRODUCTION

This paper provides an overview of the design and testing of a robotic system developed for assembling the inertial confinement fusion ignition targets (depicted in Figures 1 and 2) that will be fielded on the National Ignition Facility (NIF) laser [1]. The system, referred to as the Final Assembly Machine and shown in Figure 3, consists of six groups of stacked axes that allow manipulating millimeter-sized components with sub-micron precision, integrated with an optical coordinate measuring machine (OCMM) that provides in-situ metrology. Nineteen motorized axes and ten manual axes are used to control the position and orientation of five objects that are predominantly assembled together in a cubic centimeter work zone. An operator-in-the-loop provides top-level control of the system, making it more similar to a surgical robot than to a programmed computer-controlled machine tool. The operator is provided visual feedback by the vision system of the OCMM, and tactile feedback by force and torque sensors embedded in the tooling that holds the major components being assembled. The vision system is augmented with auxiliary mirrors providing multiple viewing directions, and is used to guide the approach and alignment of the components, and to measure the relative position and orientation of the components. The force and torque sensors are used to guide the final approach, alignment, and mating of the components that are designed to slip–fit together, and to monitor that mating while adhesively bonding those components and attaching the target base.

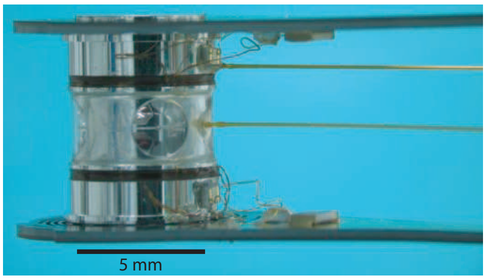

FIGURE 1. A prototype NIF ignition target.

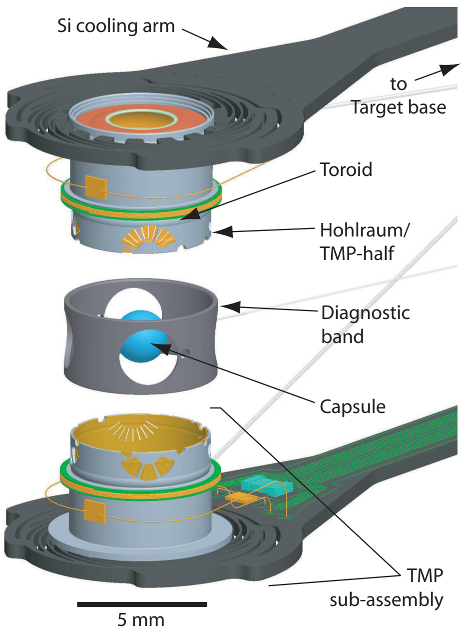

FIGURE 2. Model of a NIF target (exploded).

MOTIVATION FOR DEVELOPING THE FINAL ASSEMBLY MACHINE

The National Ignition Campaign [2] goal of achieving thermonuclear fusion burn and gain with the NIF laser requires building at least one target per day while maintaining flexibility to accommodate changes in target parameters governed by the evolving physics requirements expected during the campaign. Referring to Figure 2, the target is designed so that the physics package (hohlraum inner-liner, fuel-filled capsule, and the gas between them) can be tailored somewhat independently of the thermal–mechanical package that holds it (the TMP-halves, diagnostic band, and cooling arms). The required position accuracy of the assembled target components is in the range of $\pm$ 2–20 μm. Historically, building

FIGURE 3. The NIF Ignition Target Final Assembly Machine: Manipulation System integrated with an optical coordinate measuring machine (left); operator console and display for the OCMM (center); and operator console and displays for the Manipulation System (right).

inertial confinement fusion targets depends on a significant amount of hand-crafting skill and technique involving manually-driven fixtures for guiding components together. Using that method, building a target like the one shown in Figure 1 used to require a one week effort by a team of two to three people; increases in efficiency and incremental gains in equipment roughly halved that time. The Final Assembly Machine provides the needed transformation in how the targets are assembled: the motorized slides in the Manipulation System provide the precise and repeatable motion needed for assembling a target, the force and torque feedback allows an operator to more deterministically engage the components being assembled, and the in-situ metrology enables the requisite alignment of components during the assembly process and provides an immediate verification of the accuracy of the as-assembled target. The Final Assembly Machine is on track for meeting its major goal of allowing one person to build a target in one day while improving the quality of the target and the repeatability of that quality.

OVERVIEW OF THE SYSTEM

Designed to operate in a class 1000 clean room, the Final Assembly Machine (Figure 3) consists of an LLNL-developed Manipulation System, a commercial optical coordinate measuring machine (OCMM), and an operator station comprising controllers, displays, joysticks, and a handwheel-pendant. A close-up view of the Manipulation System is shown in Figure 4. Each stage–stack provides its target component with the requisite translational and rotational degrees of freedom. Target components are held by a vacuum chuck at the distal end of the tooling that attaches that component to its stage–stack. Incorporated in the proximal ends of the tooling are kinematic or semi–kinematic mounts that provide accurate remove–and–replace orientation of the tooling. One of the more significant challenges during the design phase for the Manipulation System was maintaining a relatively open assembly arena (the zone where the target components come together) while providing the total of twenty-nine degrees of freedom for the five objects being assembled (nineteen motorized and ten manual).

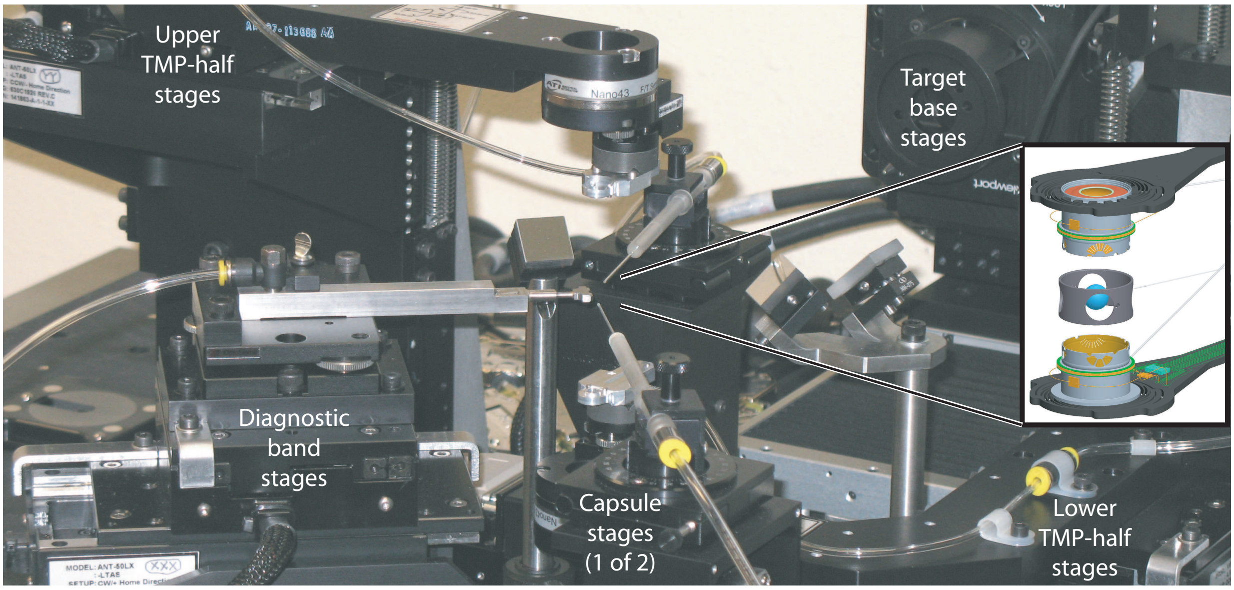

FIGURE 4. Manipulation System for assembling the NIF ignition targets, with model of a target.

Kinematic mounts allow accurate remove–and–replace of the auxiliary mirrors that provide the OCMM with multiple viewing directions into the assembly arena, and of the capsule stage–stacks that occupy the same region as some of those mirrors and the target base, albeit during different times during the assembly process. Commercial linear motor–driven crossed–roller bearing slides were selected for the majority of the actuated degrees of freedom because their compactness allowed integrating them into tightly–packed stage–stacks, and their repeatable motion and positioning resolution of 25 nm and 1 μrad met our requirements. Figure 5 shows how closely the lens of the OCMM approaches the Manipulation System when positioned for a side–view of the assembly arena. Because the control systems for the Manipulation System and the commercial OCMM are independent of each other, significant operator vigilance is required to avoid a collision between the two systems. Errors in this regard are initially accommodated by a pressure-activated emergency–stop switch in the OCMM, setting low over-current limits on the linear motor-driven stages so that they have low break-away forces, and the addition of an operator's dead-man enable switch for driving the OCMM optics assembly below the top of the Manipulation system. We plan to transfer the Manipulation System to a similar OCMM having a higher bridge and longer working–distance lens, eliminating the possible interference between the two systems.

FUTURE WORK

Ideally, all of the degrees of freedom needed for manipulating the target components during the assembly process would be motorized. For instance, when an operator reaches into the assembly arena to align the orientation of one component with respect to another, the tooling deflects due to the pressure of the operator's hand, and target components, tooling, and fixtures in the area are at risk of being bumped. One trade-off during the design phase was to retain the TMP-half tooling and manual pitch/roll/yaw stage

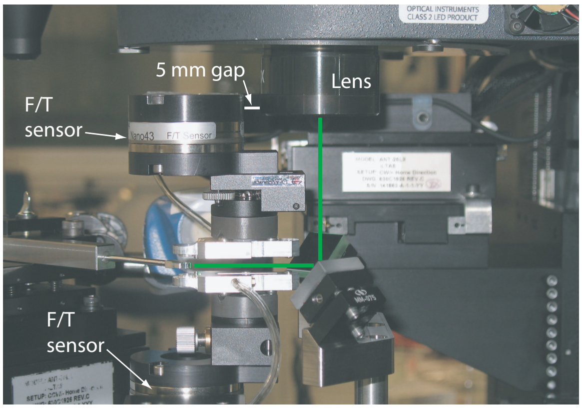

FIGURE 5. Side-view of the assembly arena, with the lens of the OCMM positioned over a mirror that provides a horizontal-direction view of the components being assembled. The force/torque sensors are centered on the TMP-halves.

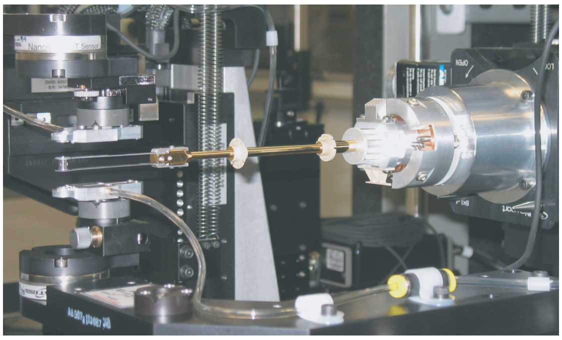

FIGURE 6. A prototype NIF ignition target that was assembled and mounted to its base using the Final Assembly Machine.

used in previous target assembly stations, instead of developing a compact motorized pitch/roll/yaw stage and new tooling that would fit into the space available. This choice allowed a shorter development path to fielding a system that provides an early proof-of-principle demonstration of other, more critical aspects of the Final Assembly Machine. A significant drawback of that choice is that the rotation axes of the manual pitch/roll/yaw stages do not pass through the desired pivot points on the TMP-halves. This results in unwanted translations of a TMP-half when adjusting its orientation, which precludes adjusting the orientation of a TMP-half after it engages the diagnostic band. Moreover, those manual stages require that an operator reach into the assembly arena to adjust them. If these issues unacceptably limit the target assembly process or quality of the targets, we have a contingency plan to replace those stages with custom motorized stages and new tooling. In this case, all six degrees of freedom of each TMP-half would be motorized. A possible follow-on is to add a haptic interface consisting of two force/torque reflecting joy sticks; providing the operator with a more intuitive feedback of the forces and torques developed between the TMP-halves and diagnostic band. Currently, all of the feedback to an operator is visual: displacements of the components being assembled and the forces and torques between the major components are displayed in graphical user interfaces. Controlling sub-micron machine motion of multiple objects with only visual feedback requires a high level of operator skill and sustained vigilance. By allowing the operator to feel amplified representations of the critical forces and torques, the aggregate feedback information (displacements, forces, and torques) can be split between two functionally parallel processing paths in the operator's mind. Compared to a visual-only feedback system, being able to see the relative position of the components in a vision system while feeling an amplified representation of their contact via a haptic interface will enhance an operator's skill level while reducing fatigue, leading to quality and productivity gains in the assembled NIF ignition targets.

CONCLUSION

The Manipulation System has been used to assemble prototype NIF ignition targets, both off of the OCMM (with the use of a microscope) and after it was integrated with the OCMM to form the Final Assembly Machine. Figure 6 shows one of these targets, assembled in one day by one person on the Final Assembly Machine, fourteen months after starting this project. The combination of the deterministic motor-driven motion, force and torque feedback, in-situ metrology, accurate remove–and–replace tooling and fixtures, and relatively open assembly arena present in Final Assembly Machine successfully demonstrated that it provides the needed transformation in how inertial confinement fusion targets are assembled.

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[1] National Ignition Facility Programs. http://www.llnl.gov/nif/.

[2] National Ignition Campaign. https://lasers.llnl.gov/programs/nic/icf/.