TARGET TRACKING AND ENGAGEMENT FOR INERTIAL FUSION ENERGY - A TABLETOP DEMONSTRATION -

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In the High Average Power Laser program, we have developed an integrated target tracking and engagement system designed to track an inertial fusion energy target traveling 50-100 m/s in three dimensions and to steer driver beams so as to engage it with ±20 μm accuracy. The system consists of separate axial and transverse detection techniques to pre-steer individual beamlet mirrors, and a final fine-correction technique using a short-pulse laser "glint" from the target itself.

Transverse tracking of the target uses the Poisson spot diffraction phenomenon, which lies exactly on axis to the centroid of the target. The spot is imaged on a digital video camera and its centroid is calculated in ~10 ms with 5 μm precision. In our tabletop demonstration, we have been able to continuously track a target falling at 5 m/s and provide a fast steering mirror with steering commands. We are on the verge of intercepting the target on-the-fly and of verifying the accuracy of engagement.

Future work entails combining transverse tracking, axial tracking, triggering and the final "glint" system. We also will implement a verification technique that confirms successful target engagement with a simulated driver beam. Results and integration progress are reported.

I. INTRODUCTION

In the HAPL direct-drive IFE power plant, an array of 60 driver beams, each composed of 50 beamlets, delivers an intense energy pulse directly onto the target. Targets must be injected into the chamber with a placement accuracy of ± 1 mm at a standoff distance of 20 m. The required engagement accuracy of the driver beams is ± 20 μm in 3-dimensions, also at a standoff of 20 m.

We have developed target tracking and engagement concepts to meet these requirements and have assembled a tabletop experiment that will engage an injected target on-the-fly.[1] The tabletop experiment will demonstrate proof-of-principle at reduced speeds and will establish the concepts' feasibility for a real power plant.

Prior work has been done at General Atomics on "ex-chamber" tracking of the target perpendicular to its flight path.[2,3] More recently, our work has been expanded so as to achieve three-dimensional tracking of a target's position along its trajectory, allowing real-time pointing of the driver beams. The design is composed of three main systems. First, the transverse tracking system looks along the target's flight path and uses the Poisson spot's centroid information to determine the x,y position of the target. Second, the axial tracking system counts interference fringes obtained by interfering light reflecting off the moving target with a reference beam. Third, a short-pulse laser overfills the target 1-2 ms before it reaches chamber center, thus using a "glint" from the target itself as the final reference point with which to align all the driver beams immediately before firing. Additional systems required for integration are also described.

Each system has been verified and characterized separately, the final goal being to integrate all systems and to present a hit-on-the-fly demonstration that meets the ± 20 μm accuracy requirement.

II. SYSTEM DESIGN

Figure 1 depicts the entire integration of the target tracking and engagement system for our hit-on-the-fly demonstration. This diagram will be explained and referenced in the following sections.

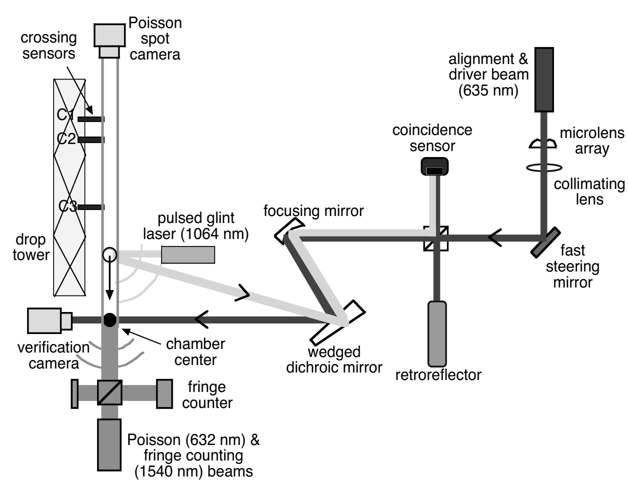

Fig. 1. Integrated target engagement demo diagram

It should be noted that, while some systems and devices are useful for diagnostic and characterization purposes, they are not necessarily needed in an operating power plant.

III. INTEGRATION OF TRACKING COMPONENTS

There exist numerous tracking and engagement scenarios, each calling for different requirements on various subsystems (Table 1). One "ultra-fast steering mirror" (per beamlet) scenario assumes that the chamber is relatively free of gas and that the target can be positioned to within 1 mm in all dimensions at chamber center. Consistent with these assumptions, the glint system alone can provide the final steering information to the mirrors 1 ms before the target reaches chamber center. This, however, places stress on the steering mirrors by commanding them to accelerate, slew 0.05 mrad (1 mm at 20 m), decelerate and settle in one millisecond. The fastest piezo-electric steering mirrors available off-the-shelf have angular acceleration rates on the order of 1000 rad/s^2, however, bandwidths of 1 kHz and settling times of <0.5 ms currently are not achievable, especially with large steering mirrors (~15 cm diameter).

Another scenario uses the combined in-flight position-reporting capabilities of the Poisson spot and fringe counting systems. By tracking the target continuously along its trajectory, the mirrors can be "pre-steered" toward the target as it drifts off-axis. Then, when the glint fires, the magnitude of the final steering is substantially reduced.

We are pursuing both scenarios since the final requirements of a power plant are not yet defined. In either case, a combination of tracking systems will aid in trouble-shooting and in initialization of a power plant.

The specific subsystems identified in Table 1 are described in section III. It is important to understand that the method of tracking finally chosen will dictate specific requirements on each subsystem. The right-hand column of Table 1 lists the precision achieved to date by each subsystem.

TABLE I. Two Possible Tracking and Engagement Scenarios

Subsystem	*Example #1* *Ultra*-FSM	*Example #2* FSM	*Achieved* (1σ)
Target injector	± 1 mm	± 5 mm	4 mm
Poisson spot centroiding (x,y)	N/A	± 100 µm, kHz update	5 µm, 10 ms
Fringe counting (z)	N/A	± 100 µm	5 µm over 5 mm
Crossing sensors	± 0.7 µs, ± 70 µm	± 10 µs, ± 1 mm	45 µm
Glint/coincidence	± 10 µm	± 10 µm	5 µm at 0.5 m
FSM pointing precision	± 5 µm, ~2 ms	± 5 µm, ~2 ms	4 µm at 2 m
Target engagement	± 20 µm	± 20 µm	-

III.A. Transverse Tracking System

The continuous transverse (x,y) tracking system requires an open line-of-sight for the target's entire trajectory, since the target "rides" the tracking beam all the way to the chamber center. The transverse tracking method is accomplished by collimating a low-power (1 mW) HeNe laser such that it is collinear with the target trajectory. The diameter of this beam is on the order of 1 cm, which ensures the target remains entirely within the beam throughout its flight. When a circular obstruction is centered within a collimated Gaussian beam, an optical diffraction phenomenon occurs, known as the Poisson spot (Fig. 2). This intense diffraction spot (Fig. 3, 1st picture) lies on axis to the circular obstruction and exists for all points along the beam. By tracking the centroid of the Poisson spot with a high-speed digital camera, the position of the target can be calculated on-the-fly to a high degree of accuracy.

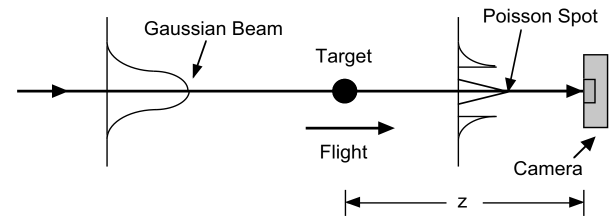

Fig. 2. Creation of Poisson spot

The goal is to obtain an update rate of 1 kHz with 5 µm accuracy, which corresponds to a position report every 10 cm at an injection velocity of 100 m/s. Due to the turbulent gaseous environment assumed for the chamber, there is a likelihood that the target will be buffeted (>20 µm) if allowed to continue more than 10 cm without a position update. Consequently, the last update before chamber center is especially crucial to alignment of driver beams with one another and with the target.

Initial Poisson spot centroiding was accomplished using a spoke technique within LabView Vision software and a 100 fps Basler camera. The algorithm looked for variations in pixel intensity along spokes radiating from the center of the spot to the first dark ring. By averaging the "edges" where the intensity changed, the target centroid could be determined with 5 µm accuracy, albeit at an update rate of 30 ms/frame.

Significant effort has been placed upon increasing the update rate while maintaining the centroiding accuracy. This has included the use of a faster (1000 fps) Mikrotron camera, a faster dedicated image-processing computer, and a new centroiding algorithm. The camera is capable of streaming frames to the processing computer every millisecond, and even faster with a reduced region of interest (ROI). The computer, running LabView software, is dedicated to processing each image on-the-fly. (For our purpose of R&D, a software-based system is more useful and versatile, albeit slower. A hardware-based, hard-coded version will be used in the final system.) The new algorithm (Fig. 3) uses brightness and contrast techniques to more sharply define the Poisson spot, followed by a thresholding step to group similarly-intense pixels. Next, those groups of pixels, as well as any extraneous ones, are removed so just the central Poisson spot is left. Finally, the algorithm calculates the centroid of the remaining spot. This new algorithm can capture an image and process it on-the-fly in 8-10 ms/frame while maintaining 5 μm accuracy (1σ).

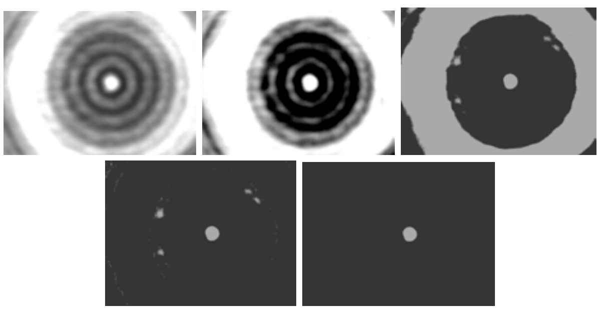

Fig. 3. Five-step centroiding algorithm sequence

Additional techniques, such as implementing a reduced ROI on the camera, are under development to further increase the update rate. The ROI effectively zooms in on the central spot and substantially reduces the number of pixels streamed to the image processing system. Due to a possible 1 mm target deviation, the ROI must be dynamic, which means that it must be able to move around the entire area of the camera's sensing chip. There also has been effort to employ a real-time operating system to make the algorithm deterministic.

Once the transverse location of the target is known, the signal is multiplied by a calibrated gain curve and is sent to the fast steering mirror (section III.F). The mirror then makes open-loop corrections while the target is in flight. Immediately before the target reaches chamber center, the glint system (section III.E) flashes the target and uses the glint return to "close the loop" and tie all the driver beams to a common reference, namely the target.

III.B. Target Injection

In an IFE power plant, a target injection velocity of 50-100 m/s is desirable both to minimize target heating and to attain a rep-rate of 5 Hz. For our demonstration, we intend to inject a target at a few m/s with the expectation of advancing to 50 m/s after the system has been operated successfully at lower velocities. The target (4 mm steel BB) was initially moved by hand on a horizontal translation stage, then by a model "beam train" to allow for a trackable range of 2 m. The wobbly motion of the train, however, was unprototypic and fairly slow (10 cm/s). The next upgrade was to turn the experiment vertical and to use a 1.5 m drop tower with gravity as the accelerator (Fig. 4). In this configuration, the target accelerates smoothly and reaches a velocity of 5.5 m/s.

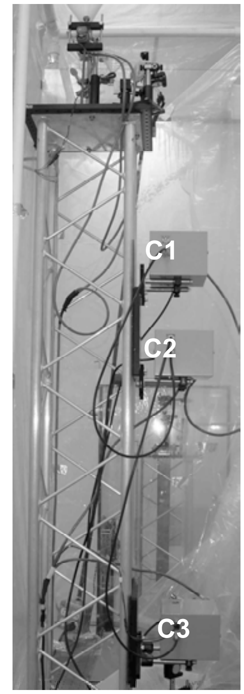

Fig. 4. Drop tower & crossing sensors

A mechanical hopper initially was used to provide a means of rep-rated target injection. This method provides a variable rate of 0.1 to 1 Hz, but the trajectory is curved due to the target rolling off a ramp and into the Poisson spot's field of view. This method yielded a placement accuracy of 3 mm. A later means of injection, which also allows an unobstructed view of the target, involves a vacuum chuck device that holds the target to a piece of glass until the vacuum is released. This later method has yielded a target placement accuracy (1mm) comparable to that expected for a power plant injector.

III.C. Axial Tracking System

The target's axial (z) position must be known for timing and triggering of the glint laser and simulated driver beam. Axial tracking is accomplished by propagating a laser beam collinear to the target trajectory using a 1540 nm JDSU telecom diode laser. The basic principle employed is the Michelson interferometric technique in which laser light reflecting off the moving target is interfered with a stationary reference leg (Fig. 1). The resulting fringes, occurring every λ/2 of travel, are then detected by a photodiode and counted after the target passes a reference location. The reference used is a "zero-crossing" sensor in which the target interrupts a beam/photodiode configuration to begin the fringe counting. The frequency of the incoming fringes is used to determine the target's velocity and to predict its arrival at chamber center.

We have successfully counted interference fringes from a moving target over a short distance horizontally on the tabletop and are currently working to track a target in free flight. Further work includes improving the signal-to-noise ratio and extending the usable range and transverse robustness of the system. The axial tracking system is further described in reference 4.

III.D. Crossing Sensors & Timing/Triggering System

At least one crossing sensor is needed as the reference for commencing the fringe counting. Two additional crossing sensors have been used to determine the target's anticipated time of arrival at chamber center. Each crossing sensor incorporates an LED and a 6x1 mm photodiode (Fig. 5). As the target falls through the LED's beam, it casts a shadow on the photodiode, causing a drop in voltage and thus providing the time of crossing.

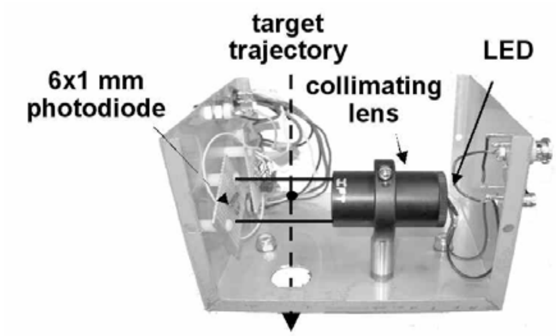

Fig. 5. Crossing sensor exploded view

Using existing hardware originally designed for the ex-chamber target prediction system, we have modified it to calculate and verify the anticipated target position at chamber center while the target is in flight. The timing and triggering system determines when to fire the glint laser and driver beam, as well as to trigger the verification camera (section III.H). A real-time operating system uses a combination of time-to-digital converters and digital delay generators to calculate the velocity of the vertically-dropped/injected target between the first and second crossing sensors (Fig. 1). The system then computes an on-the-fly timing prediction as to when the target will arrive at "chamber center" (bottom of the tower). The third sensor is used to verify the timing prediction and is able to report on-the-fly target placement repeatability of 45 μm (1σ). This is sufficiently precise to trigger the glint laser. Therefore, using the crossing sensors to determine the target's final position alleviates the need for an ultra-sensitive fringe counting system. However, we are continuing to advance both tracking scenarios in parallel.

III.E. Glint System

While the target is in flight, the transverse and axial tracking systems provide steering information to the steering mirrors. This enables the steering mirror to direct a driver beam toward the anticipated target location at chamber center. The mirror movements, nevertheless, rely upon an open-loop calibration curve that, no matter how fully characterized, is still subject to uncertainty due to structural vibration, thermonuclear explosions in the chamber, etc. In light of this, we have devised a method for closing the feedback loop immediately before chamber center with a "glint" system, which uses the target itself as the final reference point. Hence, the transverse and axial tracking systems are used to steer the mirrors close to the final location, while the glint system provides final fine-steering correction. In the ultra-fast scenario, there is no pre-steering so the glint alone provides the final steering correction.

For our demonstration, we are using a New Wave Orion 1064 nm, 35 mJ pulsed laser as the glint source (Fig. 1). Since the beam overfills the target, light is reflected uniformly over 4π steradians. The glint return propagates back through the driver beam line and reflects off the back surface of the wedged dichroic mirror (long-pass filter backed by a broadband mirror). The dichroic mirror is wedged such that the glint return signal represents the target's location *as if* it were at chamber center. The glint return is collimated after reflecting off the focusing mirror and then is focused onto the coincidence sensor, a position sensitive detector (PSD). The driver beam is given a final steering input that is based on where the glint return hits the PSD. We have verified the operation of the glint system with a low-power laser, and are on the verge of integrating it in the full demonstration. The glint system is further described in reference 1.

III.F. Beam Steering

Since targets will vary in their placement accuracy at chamber center due to chamber gas and thermal effects, the driver beams must be steered so as to guarantee target engagement. For this demonstration, we are using an Optics In Motion voice-coil-driven fast steering mirror (Fig. 6) to actively point the simulated driver beam to engage the target regardless of its position within the 1 mm cube injection accuracy box. While the target is in flight and possibly being buffeted, position information from the Poisson spot tracking system is used to "pre-steer" the mirror toward the anticipated target location at chamber center. As previously noted, this eases the requirement of the mirror having to slew the entire 1 mm (standoff distance 20 m) in 1 ms.

Fig. 6. Optics In Motion fast steering mirror, 1" diam.

In the ultra-fast scenario, there is no pre-steering of the driver beam. Consequently, the glint will be used to make one large steering correction in the final 1 ms before the driver beam fires. If the chamber gas pressure is less than 1 mTorr, the target is not expected to deviate more than the allowable engagement accuracy in the last millisecond. Since it is not known if mirror steering technology is able to meet the bandwidth and settling time requirements, or if there are fundamental physical limitations of moving a reflective mirror, we are considering both scenarios. Further research will consider other possible beam steering techniques.

Another method to alleviate the requirements on the steering mirror is to steer the target while in flight. Work conducted on the electrostatic steering of targets at General Atomics has yielded a target placement standard deviation of 104 μm with 0.8 m standoff in air. The electrostatic target steering system is further described in reference 5.

III.G. Driver Beam Simulation

The simulated IFE driver beam for this demonstration consists of a low-power modulated diode laser that propagates through the same beam path in two modes. The first mode is a CW alignment mode in which the beam is steered so as keep it from drifting away from chamber center. The second mode is the driver/verification mode, which is pulsed for 2 μs to engage the target at chamber center. The alignment/driver/verification beam (all emitted by the same laser and common path) passes through a micro lens array and then a collimating lens, which creates an array of four “verification beamlets” (Fig. 1). The beamlets are spaced 4 mm on the diagonal and are equally eclipsed by the target if it is precisely engaged (Fig. 7).

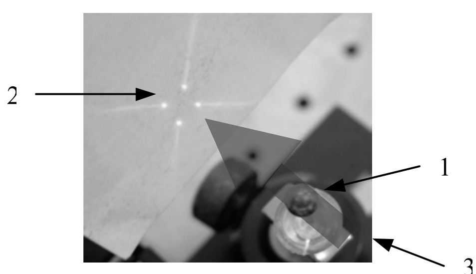

Fig. 7. A perfectly engaged target (1) will equally eclipse the four verification beamlets (2) of the simulated driver beam (3)

III.H. Target Engagement Verification System

For our hit-on-the-fly demonstration, we cannot use a thermo-nuclear explosion to rate engagement success, so it becomes imperative to have a means for verifying accurate target engagement. We have devised a verification system (incorporating the aforementioned driver/verification beamlets), which uses a triggerable camera that views chamber center (Fig. 1). The camera and driver beam are triggered simultaneously using the crossing-sensor’s prediction of when the target will arrive at chamber center. In this way, the camera takes a snapshot as the driver beam is pulsed for 2 μs. The short duration of the pulse minimizes the blur of pixels on the camera as the target passes. By comparing the light centroid of the four beamlets, we can verify engagement to the micron level.

IV. SUMMARY

The target tracking and engagement demonstration is well under way and on the verge of exhibiting a full hit-on-the-fly demo that meets the anticipated accuracy requirement of a laser fusion facility, albeit at reduced distances and target velocity. Two tracking and engagement scenarios have evolved and their operational feasibility will be tested and compared. Each subsystem of the integrated demo has been developed and tested separately. The goal now is to integrate these systems so as to present a hit-on-the-fly demonstration that meets the ± 20 μm accuracy requirement.

ACKNOWLEDGMENTS

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