Design and achievement of hardware-in-the-loop simulation system for strapdown semi-active laser seeker

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Abstract. According to the work characteristics of semi-active laser-guided weapon system, at first, the optical characteristics of the laser received by seeker were analyzed; and mathematical model of the optical signal power received by seeker was established. Secondly, a hardware-in-the-loop simulation (HILS) system was designed for strapdown seeker. In order to simulate energy and laser spot’s continuous variations, a high-precision continuous dynamic laser energy attenuation system and a digital micromirror device (DMD) spot projection system were designed respectively. In the end, the HILS system was used to evaluate the performances of strapdown seeker and the seeker was tested for response coherence among the four quadrants, field of view (FOV), linear field of view, minimum received optical power, and angle measurement accuracy.

1. Introduction

Semi-active laser guided weapons are widely used because of high precision and strong anti-interference ability[1]. As the core device of precision guided weapons, it is an urgent problem for research and development department to evaluate the performance of laser seeker. Live-fire target shooting is one of the best methods for weapon performance measurement, but the measurement cost is expensive and it cannot obtain large amount of data resource. Hardware-in-the-loop simulation (HILS) introduces test components into the simulation loop, and corresponding performances are tested through simulating real working environment[2,3]. HILS has become an important performance evaluation method of new weapons. At present, HILS technology for guidance weapons is studied constantly by major military powers[4]. Therefore, it has important scientific and strategic significance to establish HILS platforms for the terminal guidance weapons.

Semi-active laser guidance is completed with the help of target designator and laser guided missile; the designator and the missile are mutually independent. The designator keeps laser spot irradiating target surface. The seeker can receive the laser echo signals diffusely reflected by target in real time, within an effective range and calculate the angle of sight which can generate guidance information to guide a missile to the target[5]. According to the similarity principle of simulation technology, the HILS system should implement the following functions[6]:

- simulate the real attitude of projectile.
- provide a laser irradiation environment, and simulate spot size.
- simulate laser energy received by seeker.
- receive instructions from missile-borne computer and complete 6-DOF trajectory simulation.
2. Optical characteristics of laser received by seeker

Figure 1. model of semi-active laser guidance system

Semi-active laser guidance process can be modeled as shown in figure 1. The relationship between the emitted laser power, $P_L$, of target designator and the received optical power, $P_s$, of seeker can be expressed by[7]:

$$P_s = \frac{1}{\pi} P_L \rho_T \Omega_D T_R T_F e^{-\sigma(R_L + R_M)} \cos \theta$$

(1)

where $\rho_T$ is the target average reflectance; $\gamma$ is the ratio of the target’s scattering area to the illuminated spot area; $\Omega_D$ is the target scattering solid angle; $T_R$ is the transmittance coefficient of the seeker optical system; $T_F$ is the transmittance coefficient of the seeker filter; $R_L$ is the distance between the designator and the target; $\sigma$ is the attenuation coefficient of the atmosphere; $R_M$ is the distance between the seeker and the target; $\theta$ is the angle between the target surface normal and the optical axis of the seeker; the target scattering solid angle $\Omega_D$ can be given by:

$$\Omega_D \approx \frac{\pi D^2}{4R_M^2}$$

(2)

where $D$ is the clear aperture of the seeker optical system.

Assuming that the laser spot emitted by the designator is illuminated on the target totally, the target scattering area and the illuminated spot area are the same approximately ($\gamma = 1$). In this case, equation (1) is simplified to:

$$P_s = \frac{D^2}{4R_M^2} P_L \rho_T T_R T_F e^{-\sigma(R_L + R_M)} \cos \theta$$

(3)

Fixed objects or slow-moving objects are usually attacked by semi-active laser-guided weapons. The distance, $R_L$, between designator and target keeps basically unchanged during the strike. It can be seen from equation (2) that the solid angle of the spot to the seeker is increasing as the distance between seeker and target decreases constantly, which is equivalent that the spot size captured by the seeker is increasing constantly in the process. It means that HILS system need to change the spot size constantly on the diffuse reflection screen. Assuming that the target reflectance, $\rho_T$, is known, other variables can be regarded as constants except $R_M$ in the right side of equation (3), and the received optical power, $P_s$, of the seeker is a continuous function of $R_M$. This requires that the laser energy can be updated in...
real time according to the distance between the seeker and the target during the simulation.

3. Design of HILS system
The strapdown semi-active laser seeker consists of a quadrant PIN detector (QD), an optical system, and a shell. The QD and the optical system are fixed in the shell. In order to evaluate the strapdown seeker comprehensively, a HILS system designed in this paper is composed of a laser, an energy attenuation system, a digital micromirror device (DMD) spot projection system, a diffuse reflective screen, a three-axis turntable, simulation computer, etc. The diagram of the HILS system is shown in figure 2.

3.1 General equipment
A 50mW, 1064nm pulse laser is used in the HILS system, with a maximum repetition frequency of 4 kHz. Laser frequency and laser code can be controlled by external trigger. The maximum rotation speeds of the three-axis turntable in the three axes of pitch, yaw and roll are 80 °/s, 80 °/s, 3600 °/s; and the minimum step angle is 0.01°. The three-axis turntable is connected to a control computer adjusting the seeker attitudes according to the angle information calculated by the seeker, which can test the guidance and control system of the seeker.

3.2 Energy attenuation systems
In order to meet continuous dynamic laser energy attenuation, a half-wave plate-polarizer combination attenuation system is designed to control the laser energy. The system includes two linear polarizers, a half-wave plate, and a high-precision stepping motor. The optical components are place as show in figure 3.

![Figure 2. diagram of HILS system](image)

![Figure 3. components of laser energy continuous attenuation device](image)

The two linear polarizers are placed in parallel and the direction of the transmission axes is coincident. One is polarizer, and the other one is an analyzer. A half-wave plate fixed on a high-precision stepping motor is inserted between the two polarizers. The fast axis of the half-wave plate is consistent with the transmission axis of the two polarizers. The stepping motor drives the half-wave plate to rotate around the optical axis. The laser energy attenuation rate can be adjusted continuously between 0 and 1, by changing the angle between the fast axis of the half-wave plate and the transmission axis of the two polarizers. The transmittance, $T$, of the energy attenuation system satisfies the following express[8]:

$$T = \sin^2 \left( \frac{\alpha}{2} \right)$$
where $\theta$ is the angle between the fast axis of the half-wave plate and the transmission axis of the two polarizers.

\[ T = \cos^2(2\theta) \]  

(4)

Figure 4. (a) Fitting curve of transmittance (b) error curve of attenuation system

In order to attenuate laser energy precisely, the relationship between rotating angle of the half-wave plate and the transmittance should be calibrated. The calibration can eliminate the effects of inconsistent optical axes, the misalignment transmission axis of the linear polarizers, and the misalignment zero position. The half-wave plate’s fast axis is rotated from 0° to 45° with 3° as a step. The transmittance is measured at each point and the motor execution curve is obtained by fitting curve for measured data (figure 4). The maximum transmittance error is only $7 \times 10^{-3}$. The calibration result shows that the attenuation system can meet continuous and high-precision laser energy attenuation in HILS system.

3.3 DMD spot projection system

DMD spot projection system is designed to meet continuous laser spot size adjustment. The system consists of a beam expander, a DMD (German, ViALUX V-7001; refresh rate 22KHz, 7.6μm x 7.6μm/m/1microns, micromirror array 1064 pixel x 768 pixel) and a Nikon lens whose focal length is 80 mm. The laser beam is irradiated onto the DMD after being expanded by 5 times. The reflected beam of the DMD is imaged on a diffuse reflection screen by a Nikon lens.

Each aluminum mirror of the DMD is a light switch. When the mirror is “ON” state, the mirror reflects incident laser into the pupil of the projection lens. When the mirror is “OFF” state, the mirror reflects incident laser out of the pupil of the projection lens[9]. When the DMD projection system and the diffuse reflection screen are fixed, the spot size and the spot shape on the diffuse reflection screen are achieved by adjusting the switch of DMD micromirror array. DMD can realize arbitrary shape output by controlling each pixel switch. When the system works, the spot shape, size and position of the projection graphics should be preloaded into the DMD.

Figure 5. diagram of projection system

The experimental light path is show in figure 5. The spot on the reflective screen is measured by scientific CCD. To avoid CCD energy saturation, the attenuation system added between laser and
projection system adjusts the incident laser intensity.

![Figure 6. The results of projection test](image)

The figures in figure 6(a) are preloaded into DMD, the spot on the reflection screen is shown in figure 6(b) taken by CCD camera. By comparison, the experimental results show that the projection system can meet different spot shapes simulation.

Assume that designator is 1 km away from target, the laser beam divergence angle is 0.4 mrad, and the laser is vertically irradiated on the target, the diameter of the spot is 0.4 m on the target. When the seeker is 5 m away from the diffuse reflection screen, and the distance between the missile and the target are 200m, 400m, 800m, 1000m respectively, the spot corresponds to 10 mm, 5 mm, 2.5 mm, 2 mm on the reflection screen. Figure 6(c) shows the simulated spot size by the projection system. The results show that the DMD spot projection system can simulate the spot changes well during the flight of the seeker.

4. Test results of the seeker

4.1 Response coherence among the four quadrants test

A large-area, uniform-intensity spot is needed to illuminate the whole detector for calibrating the response coherence among the four quadrants. The four-quadrant detector (QD) is fixed on a three-axis turntable and rotated around its optical axis. The position of the QD is adjusted until the output voltage values are not changed due to rotation. Record the output voltage of the four channels and calculate the response coherence among the four quadrants. The uncalibrated result is 0.946; after calibration, the response coherence of the QD is 0.984, with an increase of 3.8 %. The response coherence meets the requirement for use after calibration.

4.2 Field of view and linear field of view test

When measuring the angle of field of view (FOV), the seeker is fixed on the three-axis turntable first. Then, adjust the position of seeker so that the spot is on the center of the QD. Last, make angular movement to the seeker in both directions around the centrally aligned position and record its response. The experimental results show that the FOV is 30.28 ° and the linear FOV is 5.96 °.

4.3 Minimum received optical power of the seeker test

The laser beam is divided into two beams by a beam splitter prism, one is used to irradiate the seeker, and the other is used to irradiate the optical power meter. The minimum received optical power of the seeker is measured by gradually reducing the received optical power until the SNR is 1 with the help of energy attenuation system. The minimum received optical power of the seeker is 1.769nW.

4.4 Angle measurement accuracy test

The seeker is about 8 m away from the diffuse reflection screen. The spot is 10 mm on the diffuse reflection screen, and the field angle of the spot to the seeker is 1.25mrad, which means that the missile
is 0.2 km away from the target. The angle measurement accuracy of the seeker can be measured by the absolute error, which refers to the difference between the deflection angle controlled by turntable and the angle processed by the seeker. When the seeker works in the linear FOV, the pitch angle, $\varepsilon$, and the yaw angle, $\theta$, of the spot to the seeker can be calculated by the following equations:

$$
\begin{align*}
    x &= \frac{R}{2} \left( \frac{V_1 + V_4}{V_2 + V_3 + V_4} \right) \\
    y &= \frac{R}{2} \left( \frac{V_1 + V_3}{V_2 + V_4} \right) \\
    \varepsilon &= \arctan \left( \frac{y}{f} \right) \\
    \theta &= \arctan \left( \frac{x}{f} \right)
\end{align*}
$$

where $V_1, V_2, V_3, V_4$ are the output voltage of the photosensitive sectors; $R$ is the radius of the photosensitive surface; $(x, y)$ is the coordinates of the spot center on the photosensitive surface; $f$ is the focal length of the seeker’s optical system.

| deflection angle (°) | processed angle(°) | error (°) |
|----------------------|--------------------|----------|
| 0                    | 0                  | 0        |
| 0.22                 | 0.24               | 0.02     |
| 0.44                 | 0.45               | 0.01     |
| 0.66                 | 0.70               | 0.04     |
| 0.89                 | 0.88               | 0.01     |
| 1.13                 | 1.09               | 0.04     |
| 1.38                 | 1.44               | 0.06     |
| 1.64                 | 1.72               | 0.08     |
| 1.93                 | 2.02               | 0.09     |
| 2.26                 | 2.28               | 0.02     |
| 2.81                 | 2.73               | 0.08     |

Here, we only list part results of the yaw because the yaw presents a symmetric distribution. The angle measurement accuracy in the linear FOV is an important index of the seeker. The result in table 1 shows that the angle measurement accuracy of the strapdown seeker is smaller than 0.1° within the linear FOV, which meets the work requirements of the system.

5. Conclusion

In this paper, to meet the demand of actual simulation tasks and functional requirements, we designed a HILS platform for strapdown semi-active laser seeker. In order to simulate the real flight environment better, the irradiation characteristics were studied from received energy of seeker and spot size on the diffuse reflection screen. Concrete schemes for laser energy continuous attenuation system and spot size continuous control system were put forward. It made the simulation environment closer to the real flight environment of the seeker. Some performances of the strapdown seeker were tested repeatedly. The results indicates that the angle measurement error of the seeker is smaller than 0.1° within the linear FOV, which means the seeker has the ability to hit the target precisely.
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