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A Method for Measuring the Angular Velocity of a Target by Laser Information Field and the Engineering Design

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Abstract. To address the problem that the data related to the relative motion angular velocity of the target encapsulated in the fire control system cannot be obtained in real time during training, this paper proposes to use a laser transmitter to emit multiple concentric laser pulses to form a laser information field, measure the position of the vehicle in the information field by detecting the movement of the vehicle in the information field and the laser frequency value, and then calculate the relative angular velocity of the target. This method simulates the effect of real operation training and is used to measure the relative angular velocity of the target movement in the laser information field to determine the tracking smoothness and aiming accuracy of the operator in the process of tracking the target, and can be applied to the design of a training system for operator training.

Keywords: laser, information field, training, measurement, angular velocity of the target, smoothness, accuracy

1 Introduction

The key to determine the tracking smoothness of the operator in the process of tracking the target is to obtain the relative angular velocity of the target's motion, which is one of the basic parameters for calculating whether the target can be hit [1]. In a stable image fire control system, the target angular velocity sensor in the stable image sight is used to measure the relative angular velocity of the target, which can be either the average angular velocity or the instantaneous angular velocity [2].

The method of measuring instantaneous angular velocity is usually used in stable image fire control systems because the firing elements can be calculated continuously in near real-time. The method of measuring the average angular velocity can either take the method of measuring the instantaneous angular velocity of multiple targets and then take its average, or take the method of measuring the angular velocity of the relative motion of the target over a period of time and then calculate the average [3-5]. The method of measuring the angular velocity mentioned in [3] is to measure the relative angular velocity of the target over a period of time by tracking the target with the target angular velocity sensor in the spherical coordinate system of the gun and calculate the average value, but the value is the average angular velocity. Literature [4] and [5] both proposed high-precision turret angular velocity measurement devices based on specific gyroscopes to meet the measurement accuracy requirements of different angular velocities of artillery. However, their methods were artificially operated to affect the accuracy, and were inconvenient to use and could not directly measure the angular velocity of the target, so they failed to be popularly applied.

The methods of measuring the instantaneous angular velocity are mainly using the actual installation with the velocimetric generator measurement, extracting the angular velocity signal from the targeting circuit or from the unloading torque motor of the scope servo mechanism. However, the acquired data on the relative angular velocity of the target movement is encapsulated in the fire control system, and it is not possible to obtain the relevant data in real time and plot the aiming tracking curve based on the data to evaluate the training effectiveness of the operator. To address this problem, this paper proposes a method to determine the tracking smoothness and aiming accuracy of the operator in the process of stable target tracking by using the information field to measure the relative motion angular velocity of the target. Current information field detection methods usually include: laser information field transient image detection method [6], short-time Fourier transform laser pulse detection method [7], two-dimensional translational and rotational angular motion measurement [8], etc. However, these detection methods are currently mainly used in laser driving beam guidance, where the laser information field is used only for guidance and not for measuring the angular velocity of the target.

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This paper proposes a method to measure the angular velocity of a target based on laser information field, and applies the method to design a training system with automation, high accuracy, easy installation, easy operation, and strong compatibility to realize the functions of collecting, uploading, and analyzing the shooting training results of operators, and completing the training analysis and evaluation of operators for the targeted guidance of operators. The structure of this paper consists of four parts. The first part is the principle analysis of the method, the second part is the design of the training system applying the method, and the third part describes how the training system is used. Finally, the fourth part is the conclusion about the method.

2 A Method for Measuring the Angular Velocity of a Target Based on a Laser Information Field

The laser information field-based method proposed in this paper to measure the relative motion angular velocity of the target is to measure the position of the vehicle in the information field by detecting its motion and the laser frequency value, and then calculate the real-time relative motion angular velocity value of the target [9]. The basic principle of the calculation method is: set the target plate and training vehicles at a maximum distance of 2.4km, five laser receivers placed in different locations (Fig. 1), each receiver contains a laser detector and amplifier, the laser signal pulses into TTL level pulses sent to the processor. Different detectors receive laser pulses with different frequencies, which indicates which ring the vehicle is in. The signal processor simultaneously processes the five detection signals and calculates the laser frequency value for each channel to find out which ring the vehicle is in, and solves the center coordinates of the concentric rings to compute the target angular velocity [10-11].

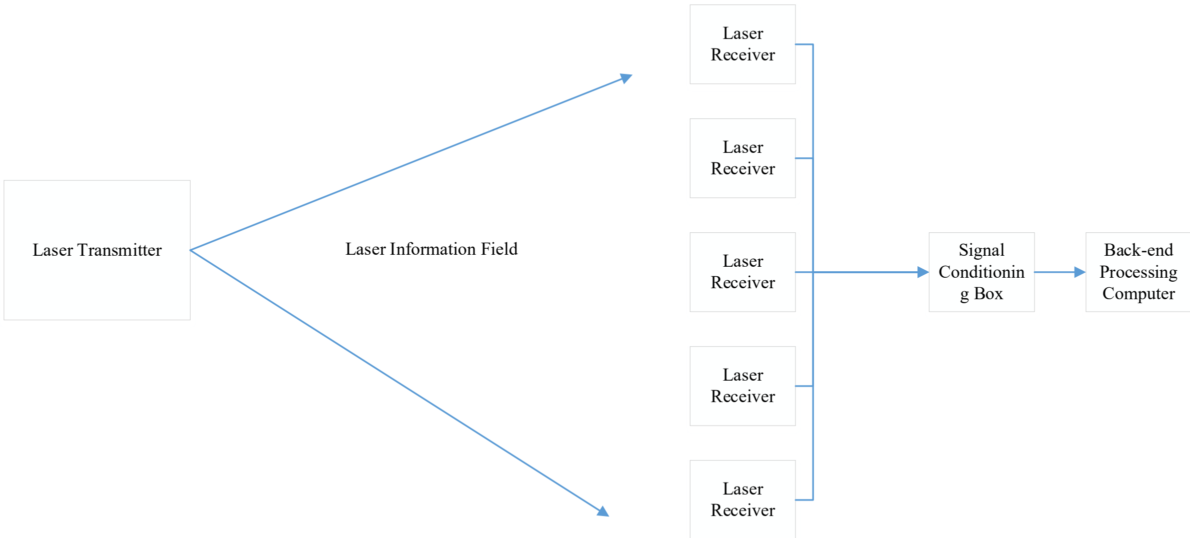

Fig. 1. The schematic diagram of the basic composition

2.1 Calculation of the Angle of the Vehicle Forward Route

The laser transmitter is mounted in the center of the target fabric and is capable of emitting 10 coaxial laser sources with different emission angles, each modulated using a different frequency, to form a laser information field. The laser receiver's sensor array is mounted perpendicular to the ground on the vehicle (Fig. 2). By aligning the optical axis of the laser transmitter to it, the vehicle moves forward along the optical axis, and the individual sensors move up and down in the laser information field, i.e., the change in vehicle height caused by the ground undulation. The terrain height can be derived by analyzing the laser modulation frequency received by each sensor through the laser receiver and dividing it by the distance to calculate the angle of the ground undulation relative to the target (Fig. 3) [12].

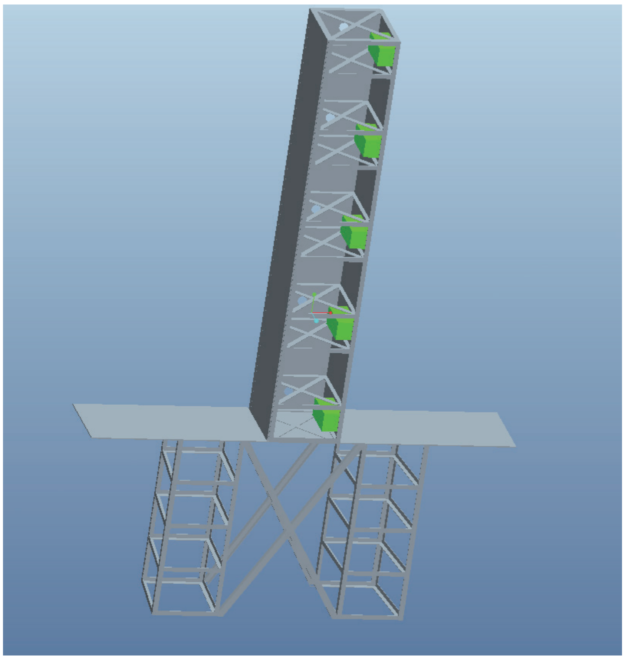

Fig. 2. Sensor array mounted perpendicular to the ground

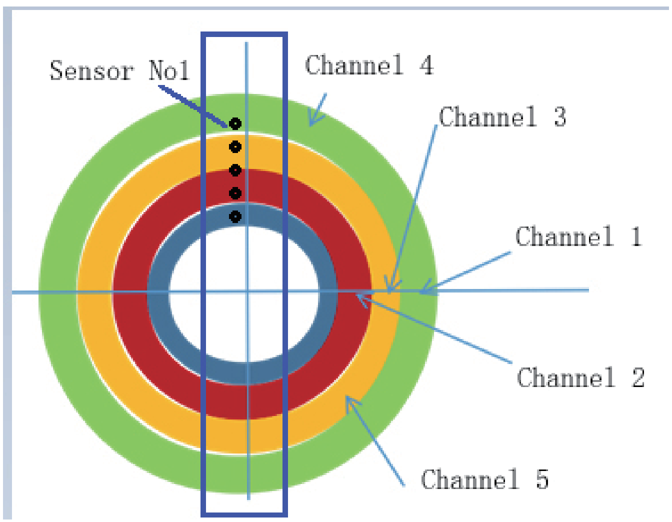

Fig. 3. Number of laser rings collected by the sensor array

The horizontal direction of the laser information field is defined as the *X*-axis, the vertical direction as the *Y*-axis, and the direction from the laser emitter pointing to the vehicle as the *Z*-axis. Using sensor N3 as the reference coordinate, the sensor will only move on the *Y*-axis of the information field because the optical axis at the transmitter is always aligned with sensor N3. The *Y*-axis has 2 intersections with each ring of the information field, and when the sensor obtains the ring number information, it is not possible to determine which of the 2 intersections it is. Therefore, the following equations are employed to deal with this issue:

if (sensor N1 + sensor N2 > sensor N4 + sensor N5)
{signum = 1;}
if (sensor N1+sensor N2<sensor N4+sensor N5)
{signum = −1;}
Coordinate_*Y* = signum × sensor N3;

If the sensor N3 indicates 2.5 rings, and sensor N1 and sensor N2 indicate that the number of rings is greater than that indicated by sensor N4 and sensor N5, it means that sensor N3 must be in the negative half-axis of the *Y*-axis, and vice versa, sensor N3 must be in the positive half-axis of the *Y*-axis (Fig. 4).

The truth table for sensor vertical run

Sensor	Number of rings	Polar coordinates
N1	1.5	
N2	2	
N3	2.5	2.5
N4	3	
N5	2	

Sensor	Number of rings	Polar coordinates
N1	0.5	
N2	1	
N3	1.5	1.5
N4	2	
N5	3	

Sensor	Number of rings	Polar coordinates
N1	-0.5	
N2	0	
N3	0.5	0.5
N4	1	
N5	2	

Fig. 4. Calculation of coordinates based on the number of rings

After solving the relative position (ring coordinates) of sensor N3 in the information field, every 0.7 seconds, the rangefinder in the system automatically measures the vehicle position and records the ring coordinates of sensor N3 calculated by the solution, forming the following truth table of the ground undulation, which depicts the undulation of the vehicle driving route at different locations (Fig. 5).

Truth table of the ground undulation

Distance (m)	2400	2390	2380	2370	2360	2350	2340	2330	2320	2310	2300	2290	2280	2270	2260	2250	2240
Undulation of the information field	0	0	0	0	0.5	0.5	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

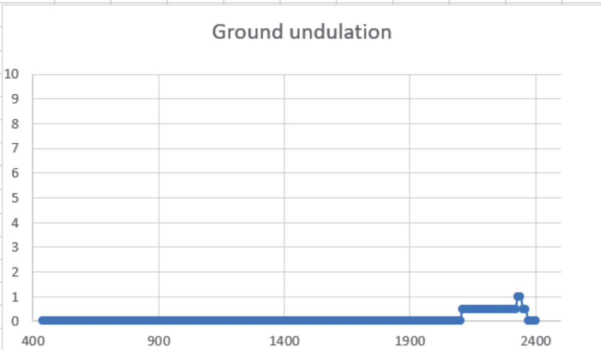

Fig. 5. Truth table of the ground undulation

Similarly, the laser receiver sensor array is mounted parallel to the ground on the vehicle (Fig. 6) and the laser emitter's optical axis is aligned with it. When the vehicle moves forward along the optical axis, the left-right movement of each sensor in the laser information field is the change of the vehicle caused by the curvature of the vehicle's forward path. The laser receiver analyzes the laser modulation frequency received by each sensor to derive the road bend, and then divides it by the distance to calculate the angle of the road bend relative to the target, thus obtaining the "truth table of road bend" [13].

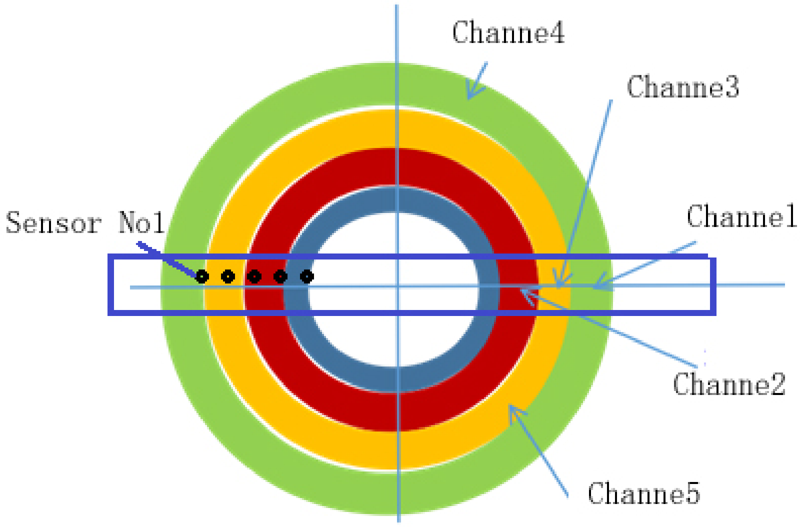

Fig. 6. Horizontal mounting of the sensor array of the laser receiver

2.2 The Calculation of the Operator Tracking Smoothness

The sensor array of the laser receiver is mounted horizontally (Fig. 6). During the forward motion of the vehicle, the laser rangefinder always keeps measuring the vehicle distance, and after obtaining the vehicle distance, the laser transmitter controller retrieves data from the above-mentioned "Truth Table of Ground Undulation" and "Truth Table of Road Bending" to obtain the data of terrain undulation and road bending in the information field at the corresponding distance.

Taking the horizontal direction as an example, the 2 intersections of the undulation value with each ring are the possible positions of the current 5 sensors. Based on the number of N rings for each sensor, 2 possible coordinate positions of that sensor in the information field can be inferred, which are symmetrical with the *Y*-axis.

According to the following equation:

if (sensor N1 + sensor N2 > sensor N4 + sensor N5)

{signum = 1;}

if (sensor N1+sensor N2<sensor N4+sensor N5)

{signum = −1;}

Coordinate_*Y*=signum × sensor N3;

The exact position of sensor N3 in the information field can be determined from the 2 possible coordinate points.

The position of sensor No. 3 represents the coordinates of the vehicle in the information field as the system coordinates *X*. The rangefinder obtains the distance H between the vehicle and the rangefinder at a certain moment.

Then, according to $Z = 2400\text{-}H$, *Z* is calculated to get the system horizontal coordinate *X* where the vehicle is at a certain moment, and the coordinate it consists of with the vehicle undulation coordinate *Y* at that place is the current information of the vehicle's position in the training field. Based on the two coordinates, the corresponding angular deviation can be calculated when the vehicle is pointed at the target. Take the horizontal direction as an example: $sin\alpha_1 = X/Z$.

Where α_1 is the angle calculated from the above equation by measuring the coordinates of the point during preparation, and α_2 is the actual aiming angle measured and converted during operator training.

$$\alpha_3 = \alpha_2 - \alpha_1$$

α_3 is the amount of aiming deviation, expressed as an angle, hereafter referred to as the aiming deviation angle.

At the same time, the laser aiming and firing controller collects the vehicle console height and orientation drive voltage in real time, and draws the magnitude of this voltage, which indicates the operator's operation of the console angle size and the degree of fast and slow, into a curve to describe the operator's operation, defined as the operation curve. The firing level of the operator is evaluated by comparing the consistency between the amount of aiming deviation collected within 2 seconds before firing and the operator's operation curve.

Taking the horizontal direction as an example, the curve of the console output signal V_1 collected during firing is shown in Fig. 7(a).

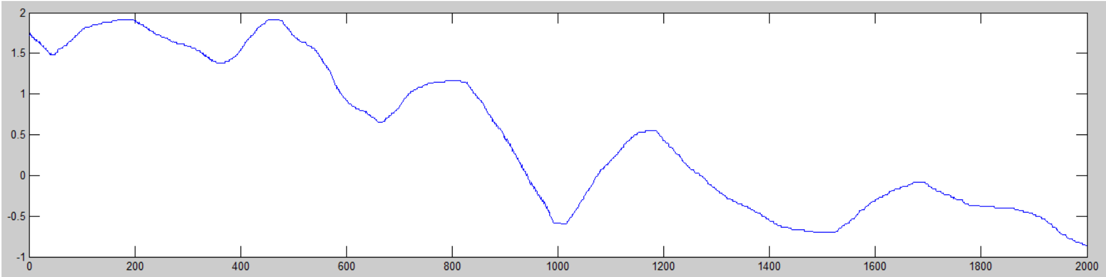

Fig. 7. (a) Console output voltage (V)

The horizontal aiming deviation angle signal θ_2 curve obtained by laser array calculation is shown in Fig. 7(b).

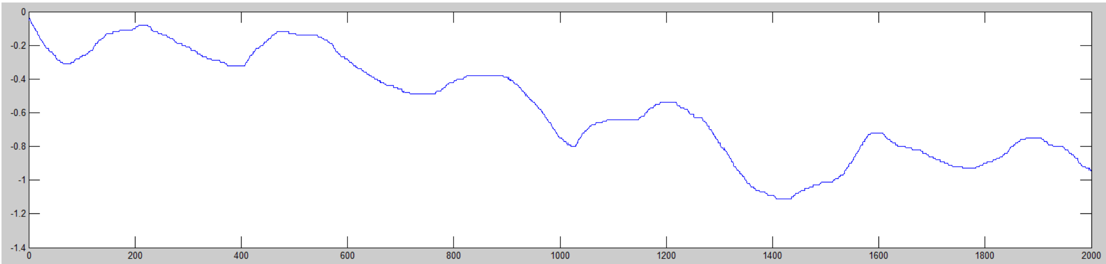

Fig. 7. (b) Aiming deviation angle (mil)

If the collected data were compared directly, the calculation would not be possible due to the inconsistency between the two sets of data units (Fig. 7(c)).

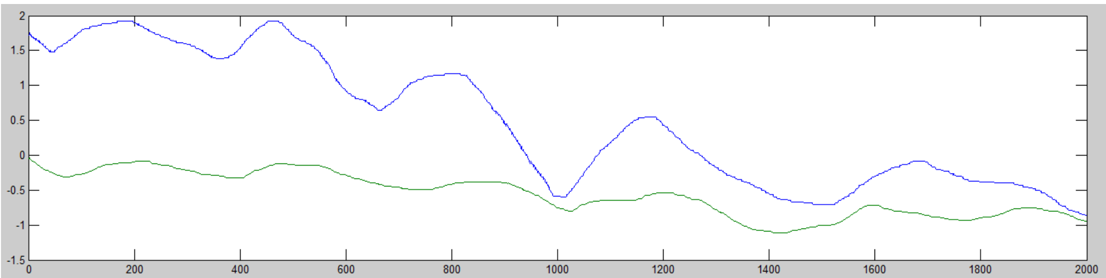

Fig. 7. (c) Operator operation evaluation curve - direct comparison

To be able to quantify the smoothness of tracking for each operator when the posture of the equipment changes (declination changes), the LIP (multi-line position distance method) is used to evaluate, specifically by calculating the area of the two curve envelopes. The larger the area between the two curves, the worse the operator's operational smoothness is proven. When the area between the two lines is zero, the operator is proven to be able to track the target in a timely and stable manner. To facilitate the calculation, it is first necessary to normalize the two sets of waveforms and find out the maximum and minimum values of the two sets of curves respectively, which are $\max V_1 = 1.92$, $\min V_1 = -0.86$; $\max\theta_2 = -0.04$, $\min\theta_2 = -1.11$. The declination curve is normalized according to the following equation (Fig. 7(d)).

$$\theta = \theta_2 \times \left(\frac{\max V_1 - \min V_1}{\max \theta_2 - \max \theta_2} \right) + \left(\min V_1 - \max \theta_2 \right) . \quad \textbf{(1)}$$

The two curves will intersect in multiple places after the normalization process, and the curve similarity can be calculated by calculating the area of the intersecting part of the two curves for a quantitative assessment of the training situation [14].

$$S = \sum_{n=1}^{2000} \left(V_n - \theta_n \right) \; . \tag{2}$$

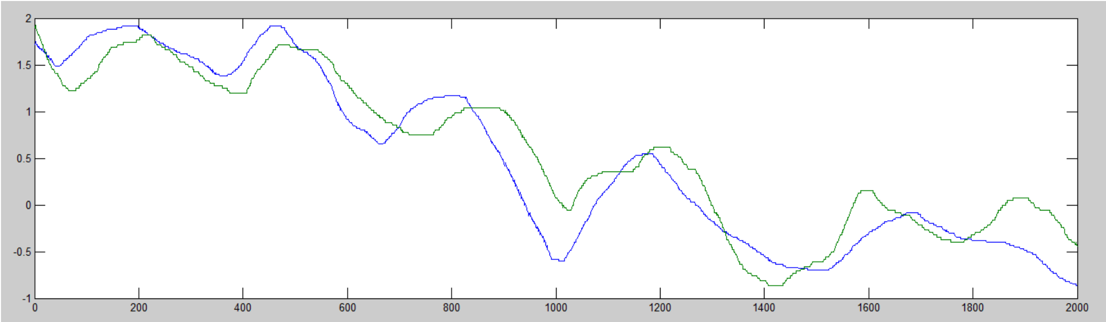

Fig. 7. (d) The normalization of operator operation evaluation curve

The data analysis showed that the tracking stability coefficient for this operator's firing process was 513.2, with a theoretical best stability coefficient of 0 and a worst stability coefficient of 2000. The quantitative assessment allowed for the recording of each operator's training (Fig. 7(e)).

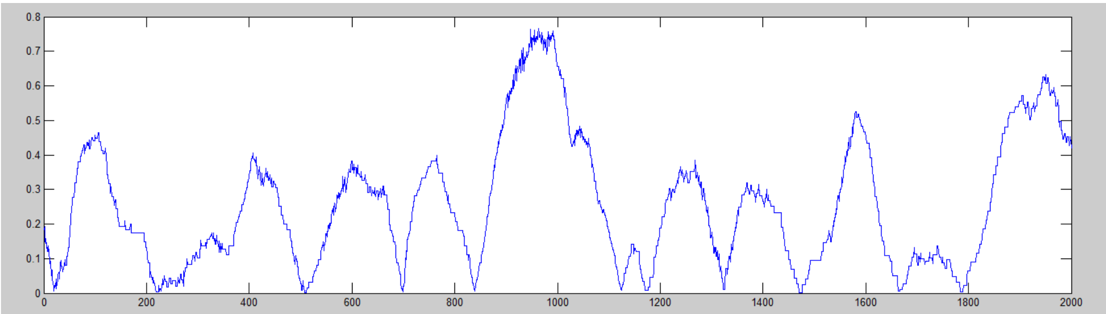

Fig. 7. (e) Operator operation fluctuation

2.3 Judgment of Aiming Situation

The laser emission controller acquires the video signal from the autotracker through the image acquisition module, which acquires the outer edge of the target cloth as the target during the training process. The minimum target size for image recognition is 8 pixels. The video resolution of the auto tracker is δ = 0.1mil, the size of the target cloth is 3m×5m, and the image size of the target cloth at 2000m is:

θ_h = 1.5mil δ_h = 15 pixels

θ_h = 2.5mil δ_h = 25 pixels

The image size meets the image recognition requirements, and the center of the target cloth image is used as the center position of the shooting target during training. The aiming error at the shooting moment can be calculated by calculating the offset of the target cloth in the field of view of the autotracker. The smallest unit of image recognition is 1 pixel, and the resolution of video image is 0.1mil, the error of aiming angle deviation is therefore 0.1mil judged by the auto-tracker.

3 Design of Training System Applying this Principle

3.1 System Composition

The system mainly consists of the following components: laser aiming and transmitting controller, laser transmitter, laser receiver, laser range finder and target controller. The system composition diagram is shown in Fig. 8 [15].

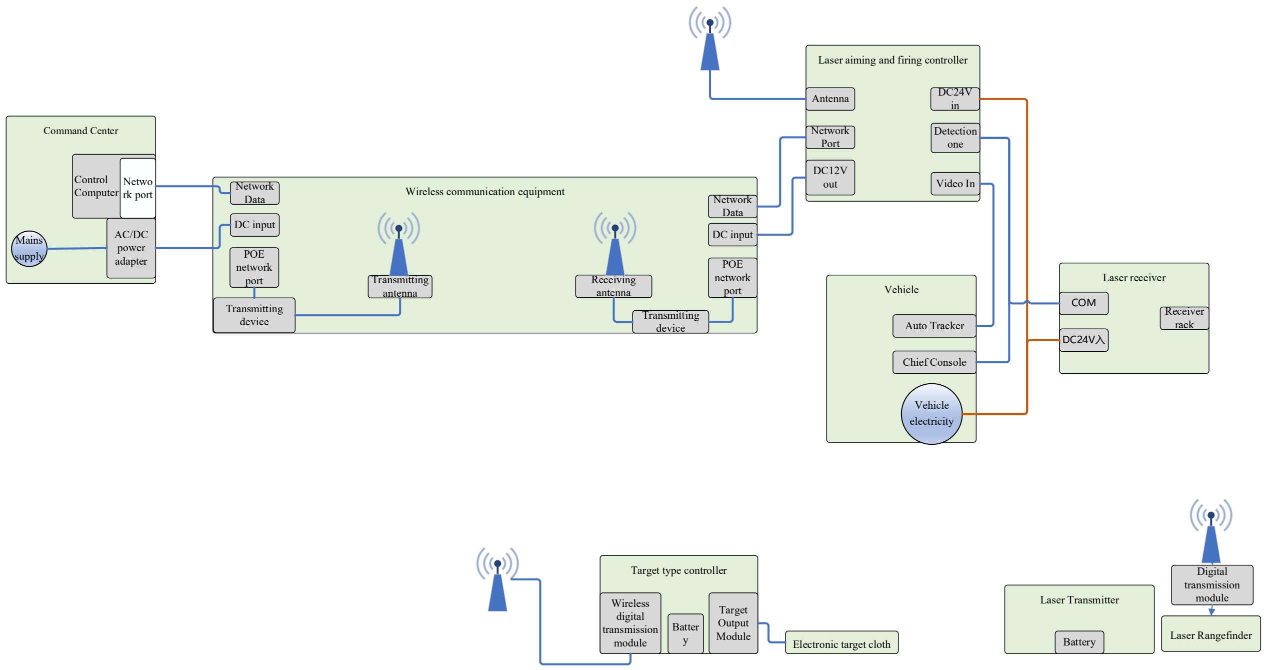

Fig. 8. The composition of the system

3.1.1 Laser Aiming and Firing Controller

The laser targeting and transmitting controller consists of power input module, signal detection module, video acquisition module, wireless communication module, Ethernet communication module and output power supply module. The power input module converts the vehicle's DC24V input power into the power required by each module inside the controller; the signal detection module is used to collect the orientation and high-low drive signals output from the console and receive the position coordinates output from the laser receiver; the video acquisition module is capable of collecting the video signal output from the vehicle's automatic tracker in real time; the wireless communication module is used to remotely control the target-type controller; the Ethernet communication module connects the wireless communication device to receive commands from the control center; the output power supply module is capable of supplying power to the wireless communication device.

3.1.2 Laser Emitter

The laser emitter is composed of a laser light source and a light source control unit. The light source control component controls the laser light source on and off and the laser frequency and other parameters, and is designed as a modular integrated structure, using direct pulse drive LD method to achieve laser output. The laser light source is capable of outputting 10 coaxial laser spots with different divergence angles, all with a laser wavelength of 905nm and different modulation frequencies for each laser.

3.1.3 Laser Receiver

The laser receiver consists of 5 sensors and 1 signal processing box. The signal processing box calculates the receiver coordinate position by collecting the modulation frequency of the laser received by each sensor and sends the coordinate information to the laser targeting and transmitting controller via RS422 interface.

3.1.4 Laser Rangefinder

The laser rangefinder is capable of performing point-to-point automatic periodic ranging, which measures the distance between the vehicle and the target at regular intervals and sends the results to the laser targeting transmitter controller via a wireless data transmission module.

3.1.5 Target-shaped Controller

The target controller is composed of wireless digital transmission module, battery and target output module. The target controller receives the target transformation command from the laser transmitting controller through the wireless digital transmission module, and drives the electronic target cloth to change the target through the target output module in real time, and the equipment is powered by lithium battery for the convenience of moving the target cloth.

4 Steps of the Method

4.1 System Installation

The wireless network bridge is set up in the command center to connect the command and control terminal and debug the software. The laser aiming and transmitting controller installation bracket, laser receiver and wireless network bridge are installed on the vehicle, and the target cloth, laser transmitter, target-shaped controller and laser rangefinder are set up in the target area. The laser emitter is installed in the center of the target cloth and the vehicle is ensured to be in line of sight with the target during the training process. In this way, after the laser is placed in the center of the target cloth, the laser divergence angle can be adjusted to ensure that the vehicle travels in the laser irradiation range at all times and that the coaxial laser source with 10 different emission angles using different frequency modulation can be received by the laser receiver.

4.2 Pre-training Preparation

Firstly, the sensor array is installed vertically, and the vehicle advances along the training road without the operator's operation, and the laser emission controller records the longitudinal deviation of the road relative to the target at different distance points, and then generates the ground undulation truth table and saves it. After that, the sensor array is mounted horizontally and the vehicle moves along the training road again without the operator's operation. The laser emission controller records the bending changes of the road at different distance points relative to the target, and generates the road bending truth table and saves it.

4.3 Training Steps and Operation of the Operator

When training starts, the terminal in the command center (instruction center) sends the training start command to the vehicle through the wireless bridge. The laser aiming and firing controller first sends the target transformation command to the target controller according to the command, and the target controller displays the target (that is, the target used for training) on the target cloth as specified in the training course.

The vehicle receives the command and starts to move forward, and the operator receives the command and starts to track the target on the target cloth. At the same time, laser aiming and firing controller sends laser on command to laser emitter, which emits coaxial modulated laser spot to the vehicle.

The laser receiver receives the modulated laser signal and calculates the coordinates of the gun at the laser spot according to the modulation frequency. The laser aiming and firing control calculates the height and orientation deviation of the gun relative to the target based on the coordinate information from the laser receiver and the distance information from the laser rangefinder, and plots the curve by time axis. The laser targeting and firing controller takes the height and orientation signals collected from the operator operating the console, plots the curve according to the time axis, and compares it with the height and orientation deviation of the gun relative to the target to calculate the smoothness of the operator's tracking.

When the operator finishes tracking, he presses the firing button to send the firing signal. When the laser aiming and firing controller collects the firing signal, it triggers the video acquisition module to obtain the video information of the automatic tracker, and derives the coordinate deviation between the target and the aiming center through image processing to judge the aiming situation of the operator.

The laser aiming and firing controller transmits various results to the terminal in the command center (instruction center) in real time, and the terminal displays and stores them in real time.

5. Conclusions

The method proposed in this paper measures the position of the vehicle in the information field by detecting the movement of the vehicle in the information field and the laser frequency value, and then calculates the real-time target relative motion angular velocity value. This approach has two main advantages. One is the use of a one-dimensional line array sensor to realize the training process of vehicle positioning in the two-dimensional laser spot plane, which solves the problem of not being able to obtain the data related to the relative motion angular velocity of the target encapsulated in the fire control system in real time during training. The other advantage is that the designed system can also achieve the functions of recording the operator's aiming and tracking process, judging the results of target position hits, evaluating the operator's operating actions and automatically uploading them to the terminal system. The training system based on this basic principle can be used for operator training in steady image mode.

There are two limitations of the method proposed in this paper. One is that the laser emitter cannot be too close to the vehicle in training and the energy density cannot be too high in order to ensure the safety of the operator's eyes. The second is that the distance between the laser emitter and the vehicle setting in training will affect the accuracy of the calculated height and orientation deviation of the gun relative to the target, i.e., the farther the distance, the lower the accuracy and the lower the energy density, thus making it more susceptible to fog, rain, snow and other weather conditions, and even making it impossible to use properly. These two limitations can adversely affect the practical application of the system designed by applying this method.

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