The Research About Adaptive Active Recognition and Tracking Technology of Fast Target Image Strength

Li Ning, Liu Chunxiang, Zhang Yunfeng, Cao Lihua, and Zhaobing Chen

***Abstract*—The distance change of the target distance tracking system will cause the image of the optical system to change in terms of size, radiation intensity, and target point jitter. When the laser is used for active detection, this change in distance will cause the echo strength to change in square relation. When the detection is strong or weak, the tracking will have gray Overflow, unclear imaging, difficult to lock the target point, and stable follow. In this paper, an adaptive laser divergence angle control method is proposed to match the distance between the target point and the passive imaging system. The algorithm model is established to solve the instability of echo intensity by adjusting the scattering angle of illumination laser and matching the image post-processing algorithm. Through the echo imaging test, it is found that the laser echo grayscale of fast targets in the range of 1 to 10 km can be stabilized between 4000 and 5000. Compared with the 600-17000 results, the method can greatly reduce the change of gray scale caused by the change of target distance and improve the system's ability of active identification and tracking.**

***Index Terms*—Image processing, image grayscale, fast target, image strength, adaptive technology.**

I. Introduction

No image active recognition is as this which being a new way to distinguish it from traditional passive imaging. The photoelectric imaging detection system, such as search, capture, and tracking, can be divided into passive imaging and active passive imaging according to the light source without lighting. Passive imaging detection technology relies on natural radiation light, reflected sunlight or moonlight for imaging. It does not need to apply light sources to irradiate the target. It has excellent concealment and is not easily detected or recognized by the other party. However, this type of passive imaging system has a short operating distance, and its imaging performance is easily limited by environmental conditions such as background illumination and meteorological conditions [1]–[5]. In bad weather conditions such as dark nights and air containing a large number of particles such as smoke and dust, fog, rain, snow, etc., due to low resolution and contrast, it is difficult to detect and identify targets. Other passive imaging systems for remote infrared radiation detection rely mainly on changes in scene temperature and radiation rates to provide images, such as the detection of extremely hot missiles and aircraft tail flames.

As an emerging technology in active imaging detection, laser active imaging technology has developed rapidly in recent years. It is a new photoelectric technology produced by the application of lasers to the field of photoelectric detection. It can not only overcome many shortcomings of traditional passive imaging systems. It is also possible to detect targets under all-weather operation, which has the advantages of clear imaging, high contrast, and resistance to external interference. There are many problems in the wide application of laser active imaging. Two of the most critical problems are laser backscattering and the image gray distortion caused by the rapid change of laser echo intensity. There are many researches on the first one, but the second one can not be avoided in engineering application. This paper proposes an adaptive target image processing algorithm that matches the distance between the target point and the passive imaging system. The algorithm model is established to solve the problem of unstable echo intensity by adjusting the integral time of the imaging device in real time and matching the image post-

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processing algorithm. Through the echo imaging test, it is found that the laser echo gray-scale of fast target can be stabilized between the appropriate gray-scale values within a certain range. The results show that the technique can greatly reduce the change of gray scale caused by the change of target distance and improve the system's ability of active identification and tracking.

II. The Target Detection and Recognition Technology

In engineering, laser active imaging is divided into two types, namely, wide-band imaging of various passive targets, and the other is imaging optical systems in the same band as lasers. The former is more common and common, and the latter is relatively complex and can be called the cat's eye effect. This paper mainly discusses the latter kind. The focal plane of the optical lens used in the target optical system is equipped with a reflection or a semi-reflection element that can generate a straight reflector light returning from the original path when exposed to a laser beam. The reflected light is usually 102 to 104 times stronger than the echo of the diffuse reflection target. This feature is commonly known as the "cat eye" effect. Laser active detection technology is to use the principle of "cat's eye" effect to detect and identify these optical targets by transmitting laser beams. As early as the 1980s, the United States, Europe and other Western developed countries have applied laser active reconnaissance technology to portable, vehicle-borne, shipborne and airborne laser reconnaissance warning systems, and have achieved good results. Such as the United States' "Stingray Fish" laser weapon system, Russia's "Laser" vehicle laser blinding weapon, the French Laser Industry Corporation's SLD 400 and SLD500 laser anti-sniper detection system, and Canada's shipborne backward laser scanner [6]–[10]. Traditional infrared passive detection method, due to the change of temperature characteristic point of target skin, target reflection light angle and incoming missile tail flame will interfere with the image processing system, making it impossible to effectively extract the optical window of the target photoelectric device. There is also no guarantee that the tracking and laser irradiation points will always act on the optical window of the target optoelectronic device. This scheme adopts the laser active detection technology based on the cat's eye effect to directly identify, track and strike targets on the guide heads of enemy incoming missiles. Therefore, the tracking accuracy and laser illumination accuracy will be greatly improved, and the impact effect will be more direct. Compared with laser passive detection technology, laser active detection technology has higher positioning accuracy and faster detection speed. At present, the focus of domestic research mainly focuses on the research of the target characteristics of the "cat's eye" and other theoretical research aspects. The most core of the technology is the laser active detection technology based on the cat's eye effect. This technology has a series of advantages such as clear detection images, high contrast, and prominent feature points [11]–[18]. Laser active detection technology improves the precision of target extraction and tracking under complex background. It is difficult for the image processing system to identify the target accurately even if laser active detection technology is used when the target and the ground building appear simultaneously in the viewing field. Because there are many naturally luminescent high-brightness objects in the image, such as street lights, traffic lights, and buildings under sunlight, and the shape is similar to that of the target's optical window, this is not easy to distinguish in image discrimination. In this case, using the high grayscale difference between the target and the background, the target is accurately extracted from the complex background. Airborne optoelectronic countermeasures equipment needs to have high bandwidth, high mobility, strong anti-jamming capabilities, low power consumption, small volume, light weight and other characteristics to become a key part of airborne protection systems. Tracking precision is one of the main technical indicators to ensure the system's effectiveness. When the target enters the field of view of the optical system of the airborne confrontation and sighting transmission tower, the system corrects the tracking deviation in real time according to the off-target information output of the image processing part to ensure that the laser shines accurately on the target optical system and realizes the high precision tracking of the target. Laser active detection technology improves the miniaturization level of the system. The laser active detection technology based on the "cat's eye effect" can effectively improve the tracking accuracy from classification to second level. Corresponding to achieve the same blinding / jamming effect, the required laser divergence angle can also be reduced by an order of magnitude. Under the same power density conditions, the required laser energy is greatly reduced, and the goal of reducing the laser weight and volume is finally achieved. The reduction of laser energy can deal with the problems of heat, distortion, etc.. This is very beneficial for the guided light, combined beam, and expanded beam of the sighting launch system. It can effectively reduce the volume weight of the system and increase miniaturization. level. Figure 1 shows a schematic diagram of the laser emitter for active laser imaging.

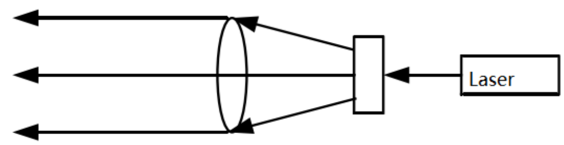


Fig. 1. Proactive laser imaging laser emission diagram.

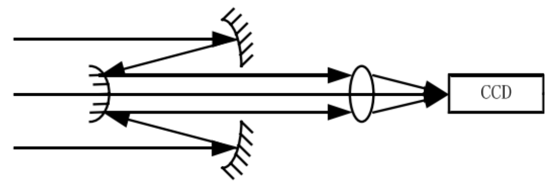


Fig. 2. Laser active imaging laser emission diagram.

In the field of laser active imaging, the research of various countries is very in-depth. The United States OBZERV has developed the ARG-2400 long-range active reconnaissance system and the ATV-500 portable active reconnaissance system using semiconductor lasers and selective ICCD. Among them, the identification distances of ARGC-2400 for vehicles, people, and license plates are 10, 5, and 2 km, respectively, and the ATV-500 recognition distances for vehicles, people, and license plates are 2km, 500M, and 300M, respectively [19]. In the United States, INTEVAC began to develop the InGaAs distance selective EBCMOS camera in the early 1990s. At present, the company's distance selective camera has begun to be used in the laser active reconnaissance system of NATO allies. The development trend of laser active imaging technology is: ultra-long distance, which can be aimed and identified in real time, and the entire system can be easily carried. The INO laser active imaging equipment developed by Canada has been successfully applied in the homeland security, coastal alert and anti-terrorism operations of Canada, the United States and other countries. The results of the test of the ALBEDOS laser active imaging system in 1995 showed that the name of a large ship at 1.5 km can be recognized at night. The system uses a laser diode array with a wavelength of 810 nm, a frequency of 15.75 K Hz, and an average power of 13W. The image sensor consisting of a third-generation image selection Enhancer and a CCD camera is received. The gain of the enhancer is 3000-50000, the pixel is 750×480, the selected pulse width is 100ns-2μs, and the focal length of the lens is 16-800 nm. In order to optimize the detection capabilities of humans and small targets, Canada has also developed the ELVISS system, which is mainly composed of an improved ALBEDOS system, a thermal imager, and a laser rangefinder. It uses a new illuminator with a working wavelength of 855 nm and an average power of 20W. The beam divergence angle is adjustable in the 20-150 range [20]. The laser active imaging system developed by BAE Systems of the United Kingdom uses a 1.57μm laser and a 320×256 HgCdTe focal plane array camera. Among them, the laser pulse width is 20ns, the repeat frequency is 15Hz, the distance resolution of the distance selection camera is 9m, and the camera sensitivity can reach 10 photons. Using the system, BAE conducted long-range target imaging tests and penetrating imaging tests to hide targets in Yusenlin. The current field of laser active imaging mainly focuses on laser backscattering, laser distance selection, and laser three-dimensional target refinement. More mature solutions are now available in these key technical areas. However, the research on optical optical targets such as optical guidance head is not in-depth enough to support the current engineering needs. In this paper, we will study the problem of fast target movement, fast change of distance between the detection system and the target, and reduce the target.

III. Adaptive Recognition and Tracking Design

The fast movement of the target brings about rapid changes in the distance between the target and the tracking system. When laser active illumination is used, the power of laser Echo is proportional to the square of the distance. In this case, there will be a large gray level change in the optical imaging of the sighting detection system. When the gray level changes exceed the threshold of the imaging system or the ability to follow the target extraction, the system can not effectively detect and track the target. In order to solve this problem, a laser power image adaptive control method is proposed. The detection and identification process of the laser active detection system is as follows. The laser active detection diagram is shown in Figure 3. The beam divergence angle of the irradiated laser beam is θ, the emission laser power is Pt, the distance from the detection system to the target is L, the transmission rate of the emission optical system is T, the one-way atmospheric transmission rate of the laser is, and the optical aperture of the target optical system is Ds. The optical power received at the target lens is: $P = \frac{P_t \tau_t \tau D_s^2}{\theta^2 L^2}$.

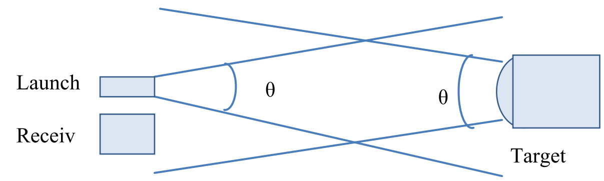


Fig. 3. Laser detection imaging.

The echo power received by the detection system after laser is reflected into the target optical system and transmitted through the atmosphere P_r:

$$P_r = P\tau\tau_r\tau_s^2\rho\frac{D_r^2}{\theta_s^2 L^2} = P_t\tau_t\tau_r\tau^2\tau_s^2\rho\frac{D_s^2 D_r^2}{\theta^2\theta_s^2 L^4} = P_t\tau_t\tau_r\tau^2 R\frac{D_s^2 D_r^2}{\theta^2\theta_s^2 L^4} \quad (1)$$

τr is access for receiving optical systems, Dr is receiving optical calibers, $R = \tau_s^2\rho$ is comprehensive reflectivity of the target seeker, τs is Target optical system penetration rate, ρ is Detector reflectivity, θs is echo divergence angle.

According to the integral time of 1ms, different laser emission angles correspond to different detection distances or different target images. It is necessary to stabilize the image in a certain gray scale to realize the stable extraction of the target image. In this paper, a continuous variable beam Extender is designed to realize the automatic adjustment of laser in real time in 1∼5mrad range. The beam Expander adopts a transmission scheme to achieve different beam magnification by controlling the distance between the two sets of lenses in the beam Expander, and then realizes that the lighting laser can illuminate the incoming target with approximately equal power density at different target distances.

There are two common continuous variable drive methods: cylindrical cam drive mode and stepping motor combined with screw nut drive mode. The former kind of driving method has high requirements for the machining precision and assembly precision of cylindrical cam, and it has high precision in the aspect of variable multiplier, but the beam pointing accuracy of the moving lens can not meet the requirements of the system. The latter kind of driving method needs to couple two isolated movements. The coupling motion accuracy is difficult to ensure, that is, the variable multiple ratio is not very accurate, but the laser pointing accuracy is very high, and the laser divergence angle is small in the application of

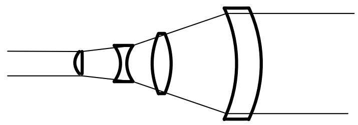


Fig. 4. Structure diagram of optical system of variable magnification diffuser.

this system. Very high laser pointing accuracy is required to meet the requirements of laser irradiation. Therefore, the beam Expander adopts stepping motor driving mode to realize continuous doubling.Variable magnification Expander generally adopts the combination of variable magnification and compensation. Its optical design is shown in Figure 4. The system consists of three parts: front fixed group, variable magnification group and compensation group. The variable doubling group and the compensation group carry on the related movement according to the specific position relationship, so as to achieve the requirement that the optical system not only becomes twice but the optical path is stable. When designing the lens, the coaxiality of the three sets of lenses is guaranteed by using a sliding rail combination structure.

A linear motor and a linear potentiometer are used as the actuator and feedback mechanism of the variable magnification mirror group and the compensation mirror group. The continuous doubling system needs to move the variational group and the compensation group at the same time to achieve continuous changes in the dilation rate. In order to maintain a good dilation effect during the continuous doubling process, From the theory of geometric optics, it can be concluded that the motion of the variational group and the compensation group must satisfy the function relationship of equation (2):

$$f_b'\left(\frac{1}{\beta_b}+\beta_b-\frac{1}{\beta_{bi}}-\beta_{bi}\right)+f_c'\left(\frac{1}{\beta_c}+\beta_c-\frac{1}{\beta_{ci}}-\beta_{ci}\right)=0 \tag{2}$$

f_b' and f_c' are the variational group and the compensation group, respectively. β_b and β_c are vertical axis magnification at the initial position of the variational group and the compensation group, respectively(the initial position can be any position, such as the telephoto position or the short focal position). β_{bi} and β_{ci} are the vertical axis magnification of the variational doubling group and the compensation group in the new position. In the process of doubling, the x_b amount of movement of the x_c variable doubling group is set to be the amount of movement of the compensation group, and it is stipulated that the movement along the optical axis is positive, the movement along the optical axis to the left is negative, and the x_b and x_c can satisfied the following function relationship:

$$\begin{cases} x_b = f_b'\left(\frac{1}{\beta_b}-\frac{1}{\beta_{bi}}\right) \\ x_b = f_c'\left(\beta_{ci}-\beta_c\right) \end{cases} \tag{3}$$

The vertical (2) and (3) equations can be calculated to calculate the displacement of both the variational group and the compensation group at each dilated beam factor. The displacement relationship between the variational group and the compensation group calculated from the above formula is shown in Figure 5.

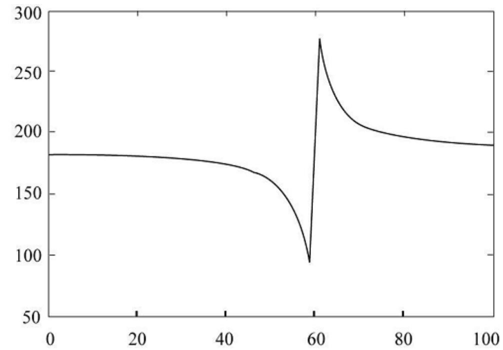


Fig. 5. Displacement variation of variable and compensated groups.

The guiding mechanism uses two sets of high-precision linear guide rail combination to achieve the guiding function, and the variable weight group and the compensation group move on the same guiding mechanism to ensure the stability of the laser pointing when the mechanism works. The guiding component is the direct force unit of the variable doubling group and compensation group. Its main role is to guide the linear motion of the variable doubling group and compensation group. The performance of the guiding mechanism has an important influence on the stability of the variable doubling process. Therefore, The guidance mechanism is required to achieve low friction and high stability. The laser power of the cat's eye target echo detected by the detector in the precision tracking medium-wave infrared camera is:

$$P_{rS} = P_{S2}\tau\tau_r A_r/S_r = P_t\tau_t\tau_r\tau^2\tau_S^2\rho_S A_s A_r/(S_s S_r) \tag{4}$$

P_t is laser emission power for lighting; τ_t is laser emission efficiency; τ_r is the transmission rate of infrared imaging optical system for turning tower; τ is the laser one-way horizontal atmospheric permeability; τ_S is the transmission rate of the target optical lens for the cat's eye; ρ_S is the reflectivity of the target surface of the cat's eye; AS is the effective area of the cat's eye target; A_r is the optical system area; SS is the light spot area where the lighting laser propagates to the target position of the cat's eye; Sr is the area of light spot where the cat's eye target lens echoes laser transmission to the position of the turret.

$$\begin{aligned} S_r &= \pi[\left\{R+\frac{D_s/2}{tg(\theta_s/2)}\right\}tg\frac{\theta_s}{2}]^2 \approx \pi[\left\{R+\frac{D_s}{\theta_s}\right\}\frac{\theta_s}{2}]^2 \\ &= \pi[\left\{R\frac{dD_s}{f_s^2}+\frac{D_s}{2}\right\}]^2 \end{aligned} \tag{5}$$

R is the distance from the turntable to the cat's eye target; θ_t is dispersed angles for laser emission; d is the focal amount of the optical system for the cat's eye target; D_s is optical aperture for the cat's eye target optical system; f_s is the focal length of the optical system for the cat's eye target; PrS∝1/R4θt2.

The combat mission distance of using laser lighting for cat eye detection is 500m to 10000m, and the change multiplier of R is 12 times. Therefore, the change multiplier of Pr_S is

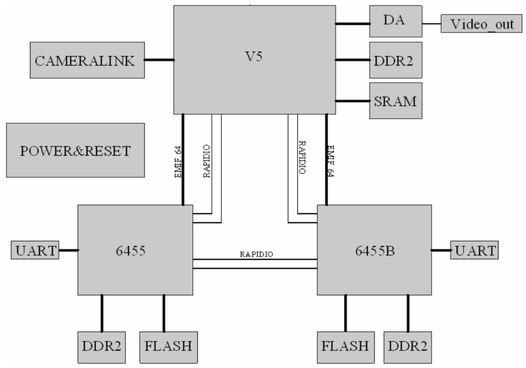


Fig. 6. The principle block diagram of image processing platform.

124 times. In order to be able to extract the cat's eye target in the image, real time compensation correction must be made for the change doubling rate of Pr_S.

In this paper, we use the technique of laser scattering angle of illumination and real time adjustment of detector integration time to compensate the distance change. The laser illumination emission path is to use 5 times transmission beam diffuser, and the change multiplier of θ T is 5 times. The detector integration time adjustment range is 0.1ms $\sim$ 5ms, and the adjustment doubling rate is 50 times. Therefore, after real-time adjustment compensation, the change rate of $Pr_S = 124/(52\times50)$. The results show that the conditions do not affect the normal extraction of laser target echo.

IV. The Experiment and Analysis of Target Image Self-Adaptive Recognition and Tracking

In order to verify the simulation calculation accuracy and model design effectiveness of the above fast target image strength adaptive recognition tracking system, the relevant experiments are carried out in this paper. The hardware platform consists of DSP, FPGA, and memory. DSP uses TI's TMS320C6455 chip. In order to improve the computing efficiency of the system, it adopts a dual DSP working mode. The main functions of target extraction and target location calculation are completed. When calculating the target position, the relevant information such as the shape and grayscale of the target is calculated to ensure the accuracy of the target extraction. Figure 6 shows the schematic diagram of the image processing platform.

After observing and analyzing the image, we found that the target in the image is not the highest in the entire image, but it is still different from the local background in the small area where it is located. The pixels in the higher grayscale background, although the grayscale value is large, are slowly transitioning with the surrounding background in its local area. Based on this grayscale feature of the target and background, the system adopts the local background prediction method. That is, using the 7 $\times$ 7 filter template convolution source image, the source image and convolution image are calculated differently, and the image target is processed on the difference image. The specific form of the template is as follows:

Fig. 7. Laser active lighting field test site.

$$Y(m,n) = \frac{1}{64}\begin{bmatrix} 2 & 2 & 2 & 2 & 2 & 2 & 2 \\ 2 & 1 & 1 & 1 & 1 & 1 & 2 \\ 2 & 1 & 0 & 0 & 0 & 1 & 2 \\ 2 & 1 & 0 & 0 & 0 & 1 & 2 \\ 2 & 1 & 0 & 0 & 0 & 1 & 2 \\ 2 & 1 & 1 & 1 & 1 & 1 & 2 \\ 2 & 2 & 2 & 2 & 2 & 2 & 2 \end{bmatrix} \quad (6)$$

The laser illumination adaptive recognition tracking test is carried out using the above image processing hardware and the laser divergence angle real-time adjustment hardware. Active illumination based on the cat's eye effect will have different effects when the target distance is different. In order to ensure stable tracking, it is necessary to maintain the consistency of the cat's eye echo image, and can be achieved by adjusting the laser divergence angle. It is found that under general atmospheric conditions, laser echo intensity is too large at a distance of 1km, which affects image extraction. Under the condition of 10km, if the output power is less than 2W under other conditions, the seeker can not be effectively extracted. Therefore, it is necessary to adjust the laser divergence angle in real time. Figure 7 shows the field test site.

Under complex background conditions, the acquisition probability of the target can be greatly improved by controlling the switch of active detection laser with the camera and using the difference strategy of active and passive images. By adjusting the laser scattering angle, the echo images of the same target can be stabilized in a very easy to extract range. Figure 8 is a background image when there is no target image.

Figure 9 shows the target image of 1mrad at 1km.

Figure 10 is target image of 5mrad at 1km.

Figure 11 is target image of 5mrad at 10km.

From the test results, if the divergence angle adjustment is not used, the target strength will be too large at 1km, the gray value will exceed 12000, and the target is too weak at 10km, and the gray value will be less than 1000. In this case, the system can not effectively extract and track the target. With the adjustment of 1 $\sim$ 5 Mrad laser divergence

Fig. 8. Background image when there is no target image.

Fig. 9. Target image of 1 Mrad at 1 km.

Fig. 10. Target image of 5mrad at 1km.

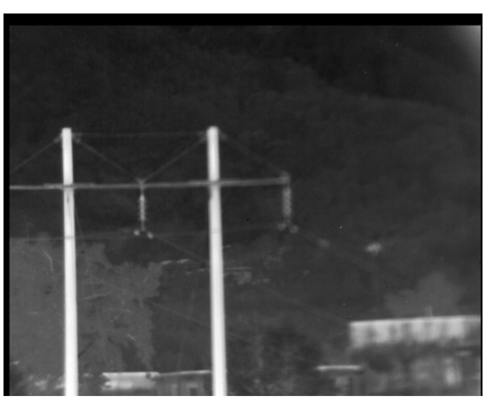


Fig. 11. Target image of 5mrad at 10km.

angle, the system can maintain the best value of the target grayscale in the whole range of 5000. It can be seen that this adaptive recognition and tracking technique based on image gray intensity can effectively extract and track the target when the target changes rapidly.

V. Conclusion

In this paper, the fast change of target image in the field of laser active detection is studied. An adaptive recognition tracking technique based on real time changes of image and laser divergence angle is proposed. The development of the technology is analysed and summarized, and the laser echo intensity involved in the technology is simulated and calculated, and a laser echo intensity change model is established. Finally, the model and simulation results are tested. From the experimental results, it is shown that using 1∼5 mrad laser divergence angle adjustment can achieve the system to maintain the optimal value of the target grayscale at about 5000 in the entire range. Through the echo imaging test, it is found that the laser echo gray-scale of fast target can be stabilized between the appropriate gray-scale values within a certain range. The results show that the technique can greatly reduce the change of gray scale caused by the change of target distance and improve the system's ability of active identification and tracking.

References

[1] Z. Chen, C. Lihua, W. Bing, Z. Xinyu, C. Ning, and G. Ruhai, "Outfield experiment research of mid-wave infrared detecting system by long distance mid-infrared laser," *Infr. Laser Eng.*, vol. 42, no. 7, pp. 1700–1705, 2013.

[2] S.-Y. Wang, "Evaluation of high energy laser effecting on remote distance photoelectron sensor system," *Opt. Techn.*, vol. 1, no. 28, pp. 28–30, 2002.

[3] H.-Y. Li, Y.-A. Hu, and X.-D. Liu, "Energy estimation method for laser disturbing photoelectrical detectors in remote distance," *Infr. Laser Eng.*, vol. 39, no. 6, pp. 1038–1043, 2010.

[4] X.-L. Chu, Z.-A. Qiu, Y.-S. Zhang, Y. Yang, Q.-F. Wu, and Z.-G. Shen, "Experimental research of infrared detecting system disturbed by mid-wave infrared laser," *Infr. Technol.*, vol. 33, no. 8, pp. 440–442 and 449, 2018.

[5] V. Larochelle, P. Mathieu, and J.-R. Simard, "Two generations of Canadian active imaging systems: ALBEDOS and ELVISS," *Proc. SPIE*, vol. 3698, pp. 229–243, Jul. 1999.

[6] W. Zhi, "Research on multi-frame postprocessing algorithm based on images of laser active imaging," Ph.D. dissertation, Changchun Inst. Opt., Fine Mech. Phys., Chin. Acad. Sci., Beijing, China, 2005.

[7] M. Hewish and L. J. Janssen, "Pinpoint and pick up: Combat search and rescue," *Jane's Int. Defense Rev.*, vol. 31, no. 1, pp. 35–39, 1998.

[8] Y.-W. Liu and H.-X. Wang, "Experimental research on FOV laser disturbing CCD detectors," *Transducer Micro Syst. Technol.*, vol. 29, no. 10, pp. 34–36, 2010.

[9] P. H. Merritt and M. A. Kramer, "Field test of active tracking of a ballistic missile in the boost phase," *Proc. SPIE*, vol. 3086, pp. 2–9, Jun. 1997.

[10] X. Song, J. Chen, C. He, and X. Zhou, "A robust moving objects detection based on improved Gaussian mixture model," in *Proc. Int. Conf. Artif. Intell. Comput. Comput. Intell.*, Oct. 2010, vol. 2, no. 6, pp. 54–58.

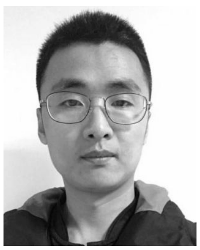
[11] C. Pollak, T. Stubbings, and H. Hutter, "Differential image distortion correction," *Microsc. Microanal.*, vol. 7, no. 1, pp. 335–340, 2002.

[12] S. Harput, J. McLaughlan, D. M. J. Cowell, and S. Freear, "New performance metrics for ultrasound pulse compression systems," in *Proc. IEEE Int. Ultrason. Symp.*, Sep. 2014, pp. 440–443.

[13] P. Gorur and B. Amrutur, "Speeded up Gaussian mixture model algorithm for background subtraction," in *Proc. 8th IEEE Int. Conf. Adv. Video Signal Based Surveill. (AVSS)*, Aug./Sep. 2011, pp. 386–391.

[14] V. T. Wang and M. P. Hayes, "Synthetic aperture sonar track registration using SIFT image correspondences," *IEEE J. Ocean. Eng.*, vol. 42, no. 4, pp. 901–913, Oct. 2017.

[15] H. E. Psillakis, "Consensus in networks of agents with unknown high-frequency gain signs and switching topology," *IEEE Trans. Autom. Control*, vol. 62, no. 8, pp. 3993–3998, Aug. 2017.
[16] G.-L. Chen, S.-H. Tsai, and K.-J. Yang, "On performance of sparse fast Fourier transform and enhancement algorithm," *IEEE Trans. Signal Process.*, vol. 65, no. 21, pp. 5716–5729, Nov. 2017.
[17] Z. Zhang, H.-J. Wang, D.-R. Wang, W.-M. Qu, and Z.-L. Huang, "Red light at intensities above 10 lx alters sleep–wake behavior in mice," *Sci. Appl.*, vol. 6, Sep. 2016, Art. no. e16231.
[18] E. Maguid, I. Yulevich, M. Yannai, V. Kleiner, M. L. Brongersma, and E. Hasman, "Multifunctional interleaved geometric-phase dielectric metasurfaces," *Sci. Appl.*, vol. 6, Feb. 2017, Art. no. e17027.
[19] S. Psilodimitrakopoulos, L. Mouchliadis, I. Paradisanos, A. Lemonis, G. Kioseoglou, and E. Stratakis, "Ultrahigh-resolution nonlinear optical imaging of the armchair orientation in 2D transition metal dichalcogenides," *Sci. Appl.*, vol. 2, 2018, Art. no. 18005.
[20] W. T. Chen *et al.*, "Generation of wavelength-independent subwavelength Bessel beams using metasurfaces," *Sci. Appl.*, vol. 6, Dec. 2016, Art. no. e16259.



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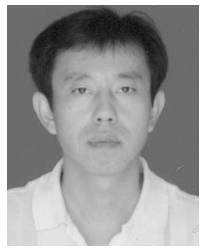

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