Real-time Focus Detection and Adjustment Mechanism of Aerial Remote Sensing Camera Based on Liquid Crystal Light Valve

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Abstract

Whereas it is impossible for aerial remote sensing camera to detect and adjust the defocusing amount during photo taking, this paper presents a plan for real-time focus detection and adjustment of remote sensing camera through the combination of liquid crystal light valve and the auto-collimation in light of the linear array sweeping camera. By opening and closing the liquid crystal light valve, the plan achieves the fast switch between the imaging mode and auto-collimation focus detection mode of the camera. Based on the equipment in the lab, the author modifies the existing lens and focus detection and adjustment system and carries out a verification test. It is verified that the modified system satisfies the precision requirement of real-time focus detection and adjustment of remote sensing camera. The precision of auto-collimation focus detection stands at ±0.027mm, reaching the original focus detection and adjustment system. The real-time focus detection and adjustment method can be applied to the aerial remote sensing operation of sweeping camera to solve the problem of random defocus caused by changes to the parameters in the optical system. It also applies to the focus detection and adjustment system of remote sensor camera without the scanning mirror.

Keywords: aerial remote sensing, real-time focus detection and adjustment, liquid crystal light valve, photoelectric auto-collimation.

1. INTRODUCTION

Featuring high resolution, flexibility and instantaneity, aerial remote sensing imaging is widely used in resource survey, geo-mapping, flood relief, counter-terrorism response (Chen,2006;Zhou, Zhai et al.,2010; Zhuang and Fu,2016;Zhong,2016; De and Xiao, 2016). However, the image surface of the camera may shift away from the calibrated position due to changes to the camera's optical system under the changing temperature, pressure and other environmental factors(Chen and Di,2015; Chen,2016). Therefore, initial focus detection and adjustment should be carried out before the aerial remote sensing camera is put into operation so that the photo surface of the camera is adjusted to the position of the image plane(Guo and Wu,2016; Liu,2016). The photo taking should be performed on this basis. During photo taking, the external temperature of the camera varies with the flight height of the carrier, and the internal components of the camera continue to heat up(Yu and Xu,2012). These factors result in a temperature gradient in the camera's optical system, which causes the photo surface of the sensor to deviate from the image plane (Zhao and Xu,2012;Hao and Qiang,2016). If the temperature changes uniformly across the camera, some mature mathematical models are available to calculate and correct the defocusing amount. However, there is no ideal mathematical model for simulation of the defocus caused by uneven distribution of temperature in local areas of the optical system(Ma and Zhang,2004; Shi et al., 2008; Wang, et al.,2008). It is very difficult to measure and correct the defocus in real time. Once the camera is out of focus, the captured image would have lower resolution and poorer quality. In severe cases, it would be impossible to obtain necessary data information from remote sensing images, resulting in a huge waste of time and economic losses. In view of the working characteristics of sweeping aerial remote sensor camera, this paper puts forward a real-time focus detection and adjustment plan based on the principle of auto-collimation focus detection and adjustment. To achieve the real-time focus detection and adjustment of the optical system, the plan uses the liquid crystal light valve to realize fast switch between the imaging modes and focus detection mode of the camera, and switches the imaging optical path quickly to the focus detection optical path during the returning and waiting phases. The feasibility of the plan is confirmed by calculating the time and energy needed for focusing. After that, the author modifies the existing focus detection and adjustment system in light of the current conditions of the lab, and carries out a test to prove that the system meets the precision requirement of remote sensing camera on real-time focus detection and adjustment.

2. PREPARATION OF THE PLAN

It is very difficult to detect the temperature gradient in local areas of the optical system and analyze its influence on the defocus of the optical system in real time. The most effective method is to detect the defocusing amount by taking the optical system as a whole(Shi et al., 2008; Wang et al.,2008). Target at detecting the current state of the optical system, the auto-collimation focus detection lets the light from the objective grating to pass through the camera’s optical system twice and eventually form an image on the non-objective grating. The position detected is the actual focal plane of the optical system in the current environment. With the modulation signal fed back by the focusing mechanism, it is possible to inspect the state of the whole optical system in real time. Taking an aerial remote sensing camera as an example, this paper introduces the working principle of auto-collimation focus detection. As shown in Figure 1, the optical system consists of scanning mirror, lens, and focal plane components; the focal plane components are further composed of subsystems like detector, focus detection system, and focus adjustment system.

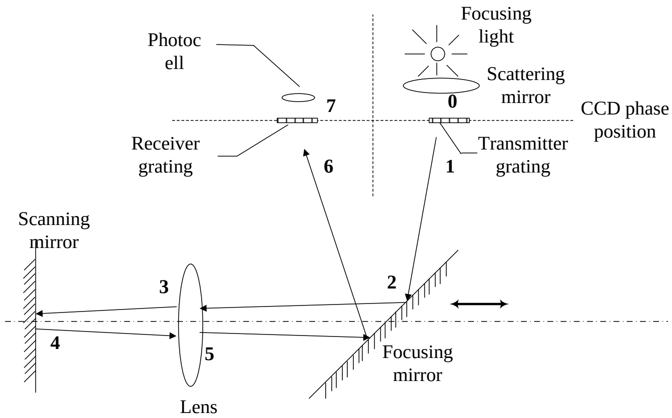

Figure 1 Schematic diagram of the working principle of auto-collimationfocus detection andadjustment

The prerequisite of auto-collimation focus detection is that there must be a scanning mirror in front of the lens of the camera. At the time of imaging, the scanning mirror makes a 45° angle with the optical axis. The light of ground scenery enters the lens through the mirror, and eventually forms an image on the photo surface of the detector. During auto focus detection, the scanning mirror is vertically erected, and is oscillated at a constant speed in the vicinity of the vertical position. Then, the focusing light emits a uniform, parallel light which illuminates the transmitter grating and generate a focus detection signal. Passing through the lens, the signal is reflected back by the scanning mirror. Passing through the lens again, the signal forms an image on the receiving grating and generates an optical modulation signal. Next, the focus adjustment system drives the focal plane to move step by step at a certain step length. For each step of movement of the focal plane, the plane mirror sweeps once and the focus detection system samples the focus detection modulation signal. After the entire focus adjustment range has been sampled, the samples are compared to generate a modulation signal, which is used to judge if the image plane of the optical system coincides with the photo surface of the detector on the focal plane(Shi et al., 2008). When the camera is in focus, the amplitude of the modulation signal is maximized; when the camera is out of focus, the amplitude of the modulation signal is smaller than that when the image plane coincides with the photo surface. As shown in Figure 2, the position corresponding to the tallest peak is the detected position of focal plane.

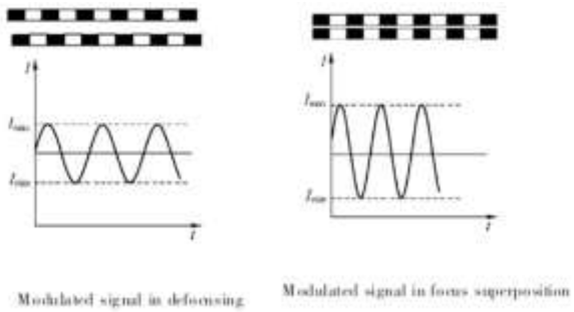

Figure 2 The amplitude of the focus detection modulation signal

According to the working principle of auto-collimation focus detection, the camera uses different optical paths in imaging and focus detection. In order to achieve real-time focus detection based on the principle of auto-collimation, the camera should be able to switch rapidly between imaging and focus detection. Due to the large rotational inertia, it is difficult for the scanning mirror to rotate from the imaging position at 45°to the focus detection position at 90°. Hence, the author considers adding an optical path controller between the optical lens and the scanning mirror to play the role of the scanning mirror in switching between the imaging mode and the focus detection mode. See Figure 3 for the principle of the replacement.

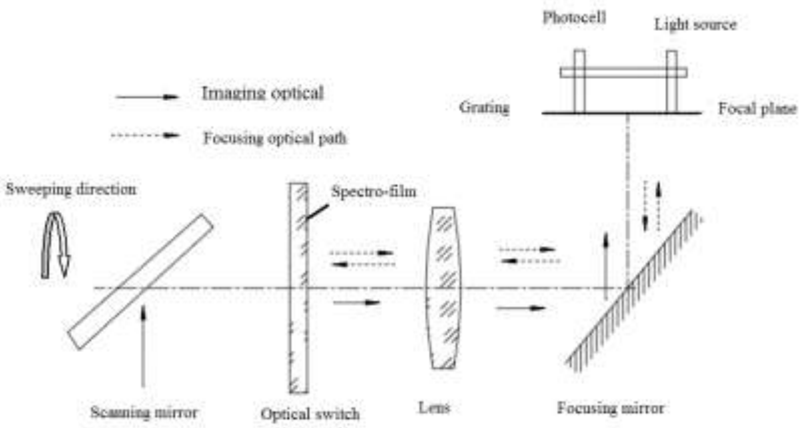

Figure 3 Real-time focus detection and adjustment system

During the imaging, the optical path controller is turned on so that the optical system can operate normally. During the focus detection, the controller is closed and oscillated within a narrow range at a constant speed in the vicinity of the vertical optical path; In the meantime, it reflects the focus detection signal emitted from the focus detection device to the optical system to produce the focus detection modulation signal. Based on existing technical means, two plans are developed for the controller. The first plan is to use the combination of mechanical shutter and optical plate. Specifically, the mechanical shutter is responsible for opening and closing the optical path; the optical plate, coated with a beam-splitting film of a certain light transmission ratio, ensures that enough light is received by the detector and the focus detection element in either the imaging mode or the focus detection mode. The second plan achieves the switching of optical paths via a liquid crystal light valve. To ensure the light reception in both modes, the inner surface of the liquid crystal light valve is coated with a beam-splitting film.

Mechanical shutter mainly falls into two categories: the curtain shutter, and the leaf shutter. The structure of the shutter is usually very complex. Since it is required to be placed in front of the optical system, the shutter should have a large aperture. Thus, the shutter blade has to travel a long distance, which slows down the shutter speed. The liquid crystal light valve Based on the birefringent effect of nematicon liquid crystal, the liquid crystal light valve controls the transmittance of the liquid crystal panel by changing the voltage applied to the liquid crystal, thereby realizing the fast switching of the incident light state switch. The switching speed can be controlled within 5ms. As shown in Figure 4, there is no moving part during the work of liquid crystal light valve, which avoids the impact of vibration. In comparison to the mechanical shutter, the valve has higher reliability and faster switching speed. Therefore, the plan of liquid crystal light valve is chosen for this research.

Figure 4 Schematic diagram of liquid crystal light valve

3. DETERMINATION OF THE TIMING FOR FOCUSING

After realizing the fast switch between working modes, the next issue to be tackled is the timing for real-time focus detection and adjustment. In this paper, the solution is to complete focus detection and adjustment during the waiting period of the linear array sweeping camera in the imaging cycle of each image. See Figure 5 for the working principle of the linear array sweeping aerial camera. The light of ground scenery passes through the scanning mirror, the lens, and the Focal plane mirror, and eventually forms an image on the photo surface of the detector of the focal plane components. The rotary axis of the camera is parallel to the flight direction of the aircraft. When the camera is working, the scanning motor drives the camera body and the components mounted thereon to rotate about the rotary axis at a speed that matches the line transfer frequency of the detector, enabling the photo taking of ground scenery.

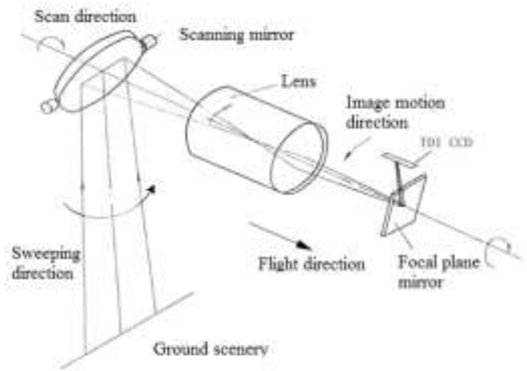

Figure 5 Schematic diagram of the camera's sweeping imaging

The photo taking consist of three stages: the scanning phase, the returning phase and the waiting phase. The imaging takes place during the scanning phase. Because the scanning direction is perpendicular to the flight direction of the aircraft, a strip region on the ground that is vertical to the flight direction is imaged. The returning phase aims at ensuring that the camera returns to the starting point of the scan after the sweep is complete. At this point, the aircraft has travelled a distance forward. The waiting phase guarantees that the image overlapping rate of the camera remains constant in the flight direction. In the scanning and imaging phase, the liquid crystal light valve is turned on so that the light from the ground scenery is reflected by the scanning mirror to form an image in the optical system. In the waiting phase, the liquid crystal light valve is turned off to block external light and to perform a focus detection operation that compares the amplitude of the modulation signal received by the photosensitive element. The comparison helps judge if the camera is out of focus. The focus adjustment should be completed before the beginning of the next photo taking cycle.

4. THEORETICAL CALCULATION

4.1 Calculation of the time cycle

To ensure the continuity of the aerial photos in the moving direction, the remote sensing camera has to meet certain requirements on overlapping rate. When the overlapping rate index is determined, the photo taking cycle can be calculated by Formula (1) according to the parameters of the characteristics of the optical system itself, the ratio between flight speed and altitude, etc.

$$T = \frac{n \times b\left(1-\rho\right)}{\left(V/H\right)\times f} \tag{1}$$

Where$n$ is the number of effective pixels in the moving direction of the detector; b is the pixel size in the moving direction of the detector;

ρ is the overlapping rate in the moving direction; is the ratio between flight speed and photo taking distance;

Each photo taking cycle consists of three parts: the scanning and imaging phase, the returning phase and the waiting phase. The scanning and imagining phase is divided into the period of the dynamic process of start/stop and the period of stable sweeping and imaging. For linear array sweeping camera, the time can be obtained by Formula (2):

$$T_S = \frac{2\beta}{\omega} = \frac{2\times\beta\times\pi\times f}{b\times f_c \times 180} \tag{2}$$

β is the sweeping angle of the camera; is the line transfer frequency of the linear array sensor;

Assuming the returning time of the camera is, the waiting time should be:

$$T_T = T - T_S - T_R - T_D \tag{3}$$

It can be inferred from the above analysis that, for a given remote sensing camera system, the scanning time and the returning time are fixed. Thus, the length of the waiting time mainly depends on the ratio between flight speed and altitude of the carrier. The higher the ratio, the shorter is the waiting time. Auto-collimation focus detection should be carried out rapidly to complete the focus detection and adjustment in the waiting phase. If the amplitude fluctuation of the focus detection signal falls within the allowable range of the reference value, the camera should be determined as in focus and can continue with the photo taking; if the deviation exceeds the allowable range, the camera should be determined as out of focus, and cannot continue with the photo taking unless the focal plane has been adjusted swiftly according to the strategy of fast focus detection and adjustment control. See Figure 6 for the process of the fast focus detection and adjustment control, where x_0 is the initial position and δ is the semi-focal depth of the camera.

4.2 Energy calculation

Assuming the brightness of the light source is B *lm/str·m*^{2}, the illuminance E' it forms on the image plane of the optical system can be derived by the illuminance formula:

$$E^{'} = \frac{t\,pB}{4}\left(\frac{D}{f}\right)^2 \cos^4 U_p^{'} \tag{4}$$

Where, D/f is the relative aperture of the optical system, U'$_p$ is the field angle, and τ is the total transmittance of the optical path.

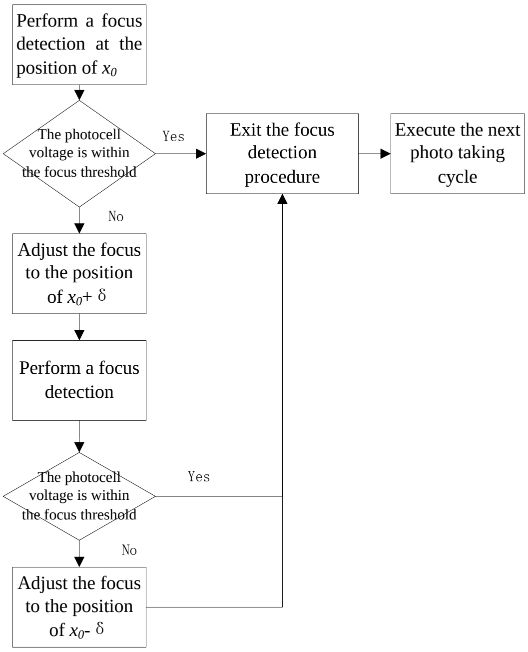

Figure 6 The flow chart of fast focus detection control

It can be inferred from the above formula that, for a given optical system, the total transmittance of the optical path is the main factor influencing the Target illuminance of the image plane. The transmittance of the optical path in the working modes is discussed below.

In the imaging mode, the light from the ground scenery, reflected by the scanning mirror, passes through the liquid crystal light valve and the optical system before it is finally received by the detector. Its total transmittance τ_C is:

$$\tau_C = \tau_F \times \tau_K \times \tau_B \times \tau_G \tag{5}$$

In the focus detection mode, the light from the focus detection light source, reflected by the beam splitting film on the liquid crystal light valve, passes through the optical system twice before forming an image on the focal plane. Its total transmittance τ_J is:

$$\tau_J = \left(1 - \tau_B\right) \times \tau_G^2 \tag{6}$$

The transmittance of the beam splitting film and the brightness of the light source must be reasonably selected so that the CCD sensor in the optical system receives enough energy for imaging, and that the focus detection photovoltaic cell can also receive sufficient energy during the auto-collimation focus detection.

5. THE SPECIFIC IMPLEMENTATION PLAN

Based on the above analysis and calculation and in light of the existing equipment in the lab, the author decides to modify the current lens and focus adjustment mechanism. A liquid crystal light valve capable of one-dimensional rotation is added in front of the optical lens to achieve auto-collimation focus adjustment, and a rotary table is used to simulate the sweeping camera's movement in the angle of depression, thereby achieving sweeping imaging. The system is provided with a liquid crystal light valve (τ_K=67%) coated with a beam splitting film on the inner surface (transmittance τ_B=70%). The feedback element is a potentiometer. The actuation part is a voice coil motor with high precision and response frequency. See Figure 7 for the structure of the system. The liquid crystal light valve, the focus detection potentiometer and the voice coil motor are installed in the framework capable of one-dimensional rotation. The liquid crystal light valve receives instructions from the focus detection and adjustment controller and achieves the fast switch between the optical paths. In the imaging mode, the liquid crystal light valve is turned on; in the focus detection and adjustment mode, the valve is turned off, and oscillated in a narrow range under the control of the voice coil motor to generate the focus detection modulation signal. The focus detection potentiometer is used to feed back the position of the liquid crystal light valve.

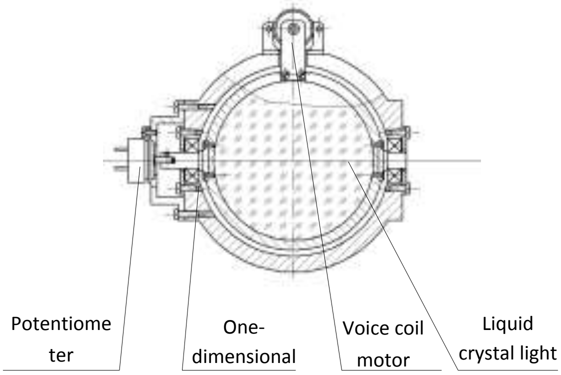

Figure 7 The schematic diagram of the liquid crystal light valve

The test platform uses the line array of TDICCD. The pixel size b=0.013mm; the effective number of pixels n=4000, line transfer frequency fc=22KHz; lens focal length f=600mm. Assuming that the camera's sweeping field angle is ± 30°, overlapping rate is 12%, and the maximum ratio between flight speed and altitude is 0.02, it can be obtained by Formula 1 that the photo taking cycle of each sweep is T=3.8s and the period of stable sweeping and imaging T_s=2.2s. According to the control parameters of the camera control system, the dynamic process and the return phase are estimated to be about 550ms, and the minimum waiting time is 1.05s. Therefore, the time it takes to perform a round of fast focus detection and adjustment never exceed 1s, indicating that the system can meet the time requirements of real-time focus detection and adjustment.

Whereas the transmittance of the camera lens τ_G=0.89 and the transmittance of the scanning mirror τ_F=0.98, it is calculated that the transmittance of the imaging optical path τ_C=0.41. The decrease in transmittance results in a reduction in the energy received by the detector. The problem is solved by adding the series or gains of TDICCD. The transmittance of the focus detection optical path τ_J=0.24. Compared with the original focus detection system, the energy received by the focus detection element is reduced by 2/3. The energy reduction weakens the contrast between the black and white stripes of the focus detection grating, resulting in a decrease in the precision of the focus detection. The problem is solved by replacing the light emitting element with one of higher brightness.

6. EXPERIMENTAL VERIFICATION

After completing the modifications, the author carries out an experiment to verify the precision of the focus detection and adjustment system and the imaging of the optical system. As shown in Table 1, the precision test of auto-collimation focus detection is conducted at 25°C in the lab. Analyzing 10 groups of focus detection data, the author convert them into the data on the position of the focal plane. It is discovered that the repeated precision of the focus detection and adjustment system is ±0.027mm, which is basically in line with the precision of the original focus detection and adjustment system (±0.025mm). The experiment verifies that the precision meets the requirements when the focus detection and adjustment are performed with the liquid crystal light valve in the off state. Then, the author sums up the statistics of the focus detection test on the optical system. The statistics show that the photovoltaic cell voltage is higher than 6.4V when the camera is in focus, and is lower than 6.4V when the defocusing amount exceeds the semi-focal depth. Hence, 6.4V can be used as the threshold voltage to judge whether the camera in focus.

Table 1 Precision test data of focus detection and adjustment

Encoder value (°)	Photovoltaic cell voltage (V)
89.846	6.406
90.171	6.426
89.846	6.431
89.748	6.431
89.253	6.445
90.099	6.406
89.467	6.421
89.544	6.401
89.748	6.421
89.621	6.411

As shown in Figure 8, the system is placed on a one-dimensional rotary table used to simulate the sweeping camera's movement for the exterior imaging test. The TDICCD series and gains are automatically adjusted by the camera dimming algorithm. See Figure 9 for the exterior photo. The photo taken by the optical system is clear and exposed evenly, which proves that the optical system can take a clear image when the liquid crystal light valve is turned on.

Figure 8 The photo taken in the imaging test

Figure 9 Exterior imaging

7.CONCLUSION

This paper presents a plan for real-time focus detection and adjustment based on the principle of auto-collimation. Adding a liquid crystal light valve to control the open/close of the optical path in front of the lens, the plan achieves the fast switch between the imaging mode and auto-collimation focus detection mode of the camera. Besides, the real-time focus detection and adjustment is completed by driving a liquid crystal light valve to oscillate in a narrow range in the returning and waiting phases of a linear array sweeping camera. This solves the problem that it is impossible for aerial remote sensing camera to detect and adjust the defocusing amount during photo taking.

The author makes modifications to the existing optical lens and focus adjustment component in the lab and enables them to detect and adjust the focus in real-time. The verification test indicates that the modified system boasts good imaging performance. The precision of auto-collimation focus detection stands at ±0.027mm, reaching the original focus detection and adjustment system. Characterized by simple structure, sensitive response and small size, the liquid crystal light valve can be applied to the modification of the real-time focus detection and adjustment system of most aerial remote sensing cameras in the principle of auto-collimation focus detection. It can also be used to make real-time focus detection and adjustment of remote sensing cameras with no scanning mirror.

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