High Performance FOV Switching Mechanism Design for an Infrared Zoom Lens

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Abstract: This paper presents the design and implementation of a prototype dual FOV (field-of-view) zoom lens mechanism. The infrared zoom lens uses a permanent magnet DC motor for the motion driver and a microcontroller as the controller. Through the cooperation of two major sensor signals, a shaft encoder and a position sensor, the FOV switching mechanism can achieve both high-speed and high-precision alignment. Experimental results showed an alignment accuracy average of 0.155 mrad and less than 0.5 second alignment settling time. Despite the influence of the non-zero backlash and the A/D uncertainty on the infrared zoom lens, the goal of alignment can be reached by the cooperation between the two major sensors and the controller. The control strategy for switching control was also proposed to help reaching the high-speed precision design specifications.

Keywords: switching control; infrared zoom lens; dual field-of-view; absolute alignment

1. Introduction

For the military, an infrared zoom lens must be capable of high-quality image and high-speed zooming rate so that each of the FOVs (field-of-view) is clear and able to change rapidly. The image quality greatly depends on the alignment accuracy of the lens. The higher the alignment accuracy is, the better the image quality is.

In order to meet the demand, a prototype of the infrared zoom lens having two FOVs and the ability of high-speed precision absolute alignment is designed and implemented. Also, because the infrared zoom lens may be carried by military machinery, such as a reconnaissance helicopter, a control system is developed and embedded as a part of the device of infrared zoom lens; this is, making the infrared zoom lens portable. Besides we propose a method to achieve the targets of the high-speed precision absolute alignment for each of the FOVs.

According to the difference of compensated methods, two methods have been proposed in an infrared zoom lens to solve the defocus of optical plane: **Optical Compensation** and **Mechanical Compensation** [1, 2].

Optical compensation

A clear optical image can be acquired by using a series of two or more lens which can be translated relatively in the infrared camera to move to a fixed position. It is easy to implement the method. In addition, the opto-mechanics [3] architecture is not uncomplicated and the controller is easy to be adjusted as well. However, the drawback of the optical compensation is requiring lot of space to install the lenses and not appropriate for the goal of little space [4]. The optical compensation is no longer popular because designers have found that better aberration correction and exact control of focus are possible using the mechanical compensation [5].

Figure 1. Schematic of a FOV switching mechanism [6].

Mechanical compensation

Mechanical compensation uses a mechanism of zoom lens which can rotate to provide different the field-of-view. There is a high-magnification narrow field of view when the FOV change group, also called as FOV switching mechanism, rotates on the alignment optical axis. On the contrary, when the group leaves from the alignment optical axes, we can obtain a wide FOV as shown in Figure 1 [6]. The rotating-group scheme achieves excellent optical performance in both the narrow- and the wide-field of view modes [7]. Due to the moving mode, the system has higher transmittance and image performance in narrow FOV [8]. In addition, by using the method of mechanical compensation, the volume and the weight of the infrared zoom lens would be smaller and lighter than that of the method of optical compensation.

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Figure 2. Assembly of the FOV switching mechanism for the infrared zoom lens.

2. Design of Infrared Zoom Lens System

2.1 Design of FOV switching mechanism

According to the concept from Figure 2, demonstrates the whole new infrared zoom lens after all components were manufactured and assembled successfully.

The dimension of the entire system is about 120 x 120 x 250 mm and the FOV switching mechanism is approximately 80 x 35 x 60 mm. It is stabilized by two bearing housings between the two horizontal metallic plates. In this paper, the goals of the FOV switching mechanism are to make the absolute alignment accuracy better than 1 mrad and the alignment time less than 0.5 seconds. The DC motor module is screw-fixed on the adjustable motor support structure and it contains a gearbox, a DC motor and a shaft encoder. The motor support structure is capable of shifting along slots, which are slotted on the bottom of the two vertical metallic plates, for an unexpected situation.

Two photomicro sensors (the limit sensors) are employed as limit sensors which are responsible for sensing a gap on the cam, which is screw-fixed on the higher rotary shaft. The angle between the measurement axes of the two limit sensors was approximated as one radian. In other words, the rotational motion of the FOV switching mechanism would be transmitted to the cam and cause its rotation. When one of the sensors detects the gap while the FOV switching mechanism rotates, it would generate the emergency signal and send it to the

controller. Then, the controller would stop the FOV switching mechanism immediately to avoid colliding with the high-resolution position sensor.

Theoretically, backlash in the gearbox described previously should be zero, but in actual practice some backlash must be allowed to prevent interference between teeth due to thermal expansion and tooth errors. This gap means that when the FOV switching mechanism is reversed for alignment, the driving gear must be turned a short distance before all the driven gears start to rotate in the gearbox. Moreover, the encoder is attached on the bottom of the DC motor rather than on the output shaft in the gearbox. Therefore, while the FOV switching mechanism rotates for alignment, the gap would result in inaccurate calculation at each change of direction, even though the resolution of the shaft encoder is high enough. For this reason, we propose a method to minimize backlash. The anti-backlash device produces a clockwise and near-constant force on the tangent direction of the rotary shaft from the spring and transmits it to the entire FOV switching mechanism, including the coupling and the gears that connect with the output shaft in the gearbox. This way, the spring tension rotates the free gears in the gearbox until all backlashes have been minimized.

Figure 3. The Omron ZX-E series position sensor

As described above, the backlash is minimized by the anti-backlash device, but it still exists, and would certainly make an influence on the alignment accuracy. Therefore, a high-resolution position sensor, capable of measuring angular displacement more precisely than the encoder assisting the FOV switching mechanism, measures the rotation of the hypothetical alignment axis. The high-resolution position sensor is an inductive non-contact sensor which is able to measure the distance of nearby metallic objects without any physical contact. It is screw-fixed on the thin side of the relatively higher horizontal metallic plate. Therefore, by measuring the distance between the sensing head of the position sensor and the corner of the FOV switching mechanism as shown in Figure 3, the precision of the alignment can be guaranteed.

2.2 System identification

A dynamical mathematical model is a mathematical description of the dynamic behavior of a system or process in frequency domain. Real-time Workshop for the code generation in Simulink by Matlab is employed as the programmed development environment to design and implement the procedure of system identification. The tool will be briefly introduced in section 4. A sin-wave voltage command with fixed amplitude is chosen as the system input, furthermore, the range of the sine sweep extends from a low frequency to a cutoff frequency. The frequency is increased in 1Hz increments, and the sampling frequency of the input signal and output sensors is 1 kHz. After several times of measurement, the data is taken as the output of system identification.

Then, the linear parametric model toolbox in Matlab is employed to estimate the data-driven model and the structure will be in the transfer function. Also, there are two methods for estimating in this toolbox, one is PEM (Prediction-Error Method) [9] and another is N4SID [10]. For the Single Input Single Output (SISO) system and the reliability of the model, PEM method is accepted for estimating models of overall system identification. After estimating the model, a simulation is built in Simulink to compare the measured data and the output result of the estimated model from feeding the same sin-wave. Afterward the best fitted model will be selected as the final model of the infrared zoom lens, and will be employed for designing a controller.

Figure 4 shows the architecture of the infrared zoom lens. The DC motor drives the FOV switching mechanism to rotate. Through the measurement, the readable signals for the microcontroller are outputted from the two sensors. The shaft encoder generates a pulse signal for the corresponding angular displacement

Figure 4. Block diagram of the real system

Figure 5. Control architecture of the infrared Zoom Lens.

and the position sensor produces a voltage for the corresponding distance. From the previous section, we know that the relationship between the voltage input to the motor and the angular displacement output from the FOV switching mechanism is linear. Therefore, for the encoder, the voltage input to the motor and the pulse output from the encoder can also be modeled by a linear equation. However, the concept described above is not suitable for the modeling of the position sensor, because the rotational motion of the FOV switching mechanism is non-linear to the measurement of distance. Nevertheless, in this infrared zoom lens, the position sensor is only responsible for the final absolute alignment, meaning that the angular displacement of the mechanism would be very small and the distance change as well. So, we can suppose that the relationship between the voltage input to the motor and the voltage output from the position sensor is linear in the measurement of the small distance change.

The procedure of the system identification described previously is used to identify the system for the encoder and the position sensor respectively. Two

test results are acquired and the linear parametric model toolbox would estimate the two data-driven models with the two test results. One is the encoder model and the other is the position sensor model, meaning that two models are used to simulate our infrared zoom lens.

3. Controller Design

3.1 Overview of infrared zoom lens

The infrared zoom lens consists of the microcontroller, the driver, the DC motor module, the FOV switching mechanism, two significant sensors, the encoder and the position sensor. Once we determine to rotate the FOV switching mechanism positions on the hypothetical alignment axis for the narrow view, the control loop will be started as shown in Figure 5. The encoder is responsible for the process of the coarse alignment and the position sensor plays the role of the final absolute alignment sensor. A control algorithm is applied to find the desired position. Then, the controller sends a control signal to the driver, and actuates the

motor to rotate the mechanism for alignment until achievement of the alignment. Hence, due to the feedback of position information from the two sensors, the overall system is a closed loop system.

3.2 Control strategies

Since the alignment achievement greatly depends on the controller performance and the feedback of the controller is acquired from the two different sensors in this system, just one controller might not reach the demand of the high alignment accuracy. The method, switching control, is employed to control this system which has two different sensors. As depicted in Figure 6, two controllers, Controller 1 and Controller 2, are placed in front of the entrance of the switching rule. The encoder presents the coarse alignment sensor and corresponds to Controller 1. The position sensor connects with Controller 2 and presents the final absolute alignment sensor. Both the two controllers would master the system, but in alternate time, in other words, only one of them can control the system at a time. Therefore, the switching rule is designed and employed to determine when and which one of the controllers would be actuated.

By applying the switching control, when the rotating FOV switching mechanism is very close to the hypothetical alignment axis for the narrow FOV, Controller 1 is substituted by Controller 2 to achieve the final alignment. On the other hand, Controller 1 would be actuated again when the mechanism makes ready to rotate off the axis for the wide FOV.

3.3 PID controller

Generally speaking, the three parameters (P, I, D) can be tuned in the control system by trial-and-error

method. However, the parameters tuning is a procedure which would take a lot of time. Besides time, the tuning result might not be satisfied. In order to improve the drawback, the Response Optimization [11] in Simulink was used to help us to tune and optimize the three parameters to meet the best performance requirement. This tool provides a graphical user interface so that it makes the procedure of the parameters tuning easy. Above all, it can save tuning time. Therefore, by the Response Optimization cooperating with the Code Generation in Simulink, the optimized parameters are easier to tune out and the C code program of the PID controller is automatically generated. The Code Generation tool will be briefly introduced in next section.

4. Experimental Results

4.1 Simulink implementation setup

Because of the embedded system, in general, the algorithms for the controller are programmed by computer language, such as C language. Also, significant time is required to program the dsPIC microcontroller by Microchip, as peripheral configurations and some real-time problems such as sampling rate and multitasking must be programmed. The handed code is compiled to an executable binary file and ready to be downloaded into the microcontroller for testing. Then, by comparing the system test data with the simulated model, the model or controller can be verified and validated. Although the process described above is a finite loop, it usually takes a lot of time on verification and validation. Furthermore, the efficiency of the handed code might decrease if the algorithms are larger.

Figure 6. Architecture of the switching control.

Figure 7. Part structure of the implementation in Simulink.

However, Real-time Workshop technology [12] in Simulink is used to develop the infrared zoom lens in another way. Through the graphical environment which is provided from the technology, the graphical blocks in Simulink can be developed to meet the algorithms for controllers or models. More importantly, the C code can be automatically generated by the Real-time Workshop technology rather than by hand. Besides, regarding the peripheral functions of the microcontroller, the Embedded Target for Microchip dsPIC by Lubin Kerhuel [13] is employed to program the microcontroller directly from a Simulink model. It provides a Microchip dsPIC blockset for most peripherals present in Simulink, so that we can also use the graphical interface to configure automatically the peripheral functions selected. Moreover, the tool is capable of compiling the C code to the executable binary file. Therefore, through the Real-time Workshop in Simulink cooperation with the Embedded Target for Microchip dsPIC, it is convenient to implement the simulation into the embedded system. The cooperation between the two technologies can be called as “rapid prototyping tool”. It makes the development easier and faster.

Figure 7 shows the part structure of this implementation. The objectives discussed in this paper are absolute alignment and high alignment accuracy; therefore, the two different sensors are used to provide the system’s information, which is the feedback source of the controllers. Also, the switching control described in section 3 is applied to the system as the control strategies. Controller 1 and Controller 2 are responsible for the encoder model and the position sensor model respectively. The switching rule as mentioned in section

3 is responsible for determining when and which PID controller must be actuated.

Initially, Controller 1 begins to control the encoder model for the coarse alignment while starting simulation. The reference of the encoder model based on the measurement experiment initiated above is set as 1.065 rads. When the error between the reference and the feedback is below a certain number, the switching rule triggers the subsystem of the position sensor model for the final absolute alignment and stops Controller 1. The process of the final alignment will be stopped until the simulation time, which is set as 0.6 second, is over. The optimization block is used to tune the parameters of PID controllers.

The following expresses targets which must be reached in this simulation:

- The absolute alignment reference is 5.5 mm with the position sensor measurement.
- The total alignment time must be below 0.5 second.
- The alignment accuracy must be below ± 1 mrad.

4.2 Experimental results

In the experimental results, the alignment results for the narrow FOV mode are shown due to the requirement of high image quality. Further, the results are classified into two different types. One contains the braking procedure in the switching control and the other does not.

Figure 8 shows the five experimental results of the switching control without the braking procedure respectively including the encoder signal, position sensor signal, and the switching time. It can be seen that the FOV switching mechanism contains a tiny swing at the final alignment. Nevertheless, the targets of alignment accuracy are still reached.

The reasons for the tiny swing may be:

- Due to the A/D uncertainty mentioned previously, the alignment vibration of the FOV switching

mechanism would be enlarged by the feedback control.

- For this position sensor, ZX-E series by Omron, both the measurable area and depth at the corner of the mechanism are too small to reduce the measurement resolution. Besides the measurable dimension, the material of the mechanism, aluminum alloy, may also increase the measurement error due to the relatively worse linearity for aluminum.

Figure 8. Alignment accuracy, (rad) and (mm), for the position sensor.

Figure 9 shows the results of five experiments with the braking procedure. It can be seen that the A/D uncertainty remains on the position sensor signal after the motor brakes. In addition, because of the non-linearity of the A/D uncertainty, the exact position of

the FOV switching mechanism could not be calculated from the position sensor signals. It can be acquired from the displayer on the amplifier of the position sensor. So, the final alignment accuracies are calculated by humans and the results are expressed in Table 1.

Table 1. Final alignment accuracy of the FOV switching mechanism.

	Brake 1	Brake 2	Brake 3	Brake 4	Brake 5	Average
(mm)	0.000	0.011	0.005	0.006	0.009	0.0062
(rad)	0.000	2.75×10^{-4}	1.25×10^{-4}	1.5×10^{-4}	2.25×10^{-4}	1.55×10^{-4}

Figure 9. Results of alignment accuracy, (rad) and (mm), with braking procedure for the position sensor.

Figure 8 and Figure 9 show the alignment accuracy of the two type results. The units on the left side of the Y axis are radian (rad) and the units on the right side are micrometer (μm). Because the value of the accuracy in mm is small enough corresponding to the rotational radius of the mechanism, the length can be taken as an arc. Therefore, the arc divided by the rotational radius, about 40 mm, equals the radian and it can be known if the target for alignment accuracy is reached.

Unlike the switching time, the braking time of the five experiments is quite different. However, all of the alignment accuracies are higher than that of the five experiments without the braking procedure after the braking time. Comparing Figure 8 with Figure 9 the performances on the alignment accuracies can be known.

A problem to the implementation is that the values of all position sensor signals at the switching point are truly different even though the reference and the switching rule for the encoder are same. Nevertheless, the controller can achieve the targets of the precision absolute alignment.

5. Conclusion

This thesis established a high precision absolute alignment and a high-speed FOV switching rate system for an infrared zoom lens, which includes a FOV switching mechanism handling the two different FOVs and the microcontroller controlling the DC motor to produce the desired motion.

Two major sensors, a shaft encoder and a position sensor, are applied to the infrared zoom lens as the alignment sensors. Through the cooperation between the two sensors, the FOV switching mechanism achieved the goal of the high-speed precision absolute alignment in spite of the non-zero backlash and the A/D uncertainty.

A software development environment in Simulink for simulating and implementing the infrared zoom lens was integrated. The control strategy, switching control, was designed and developed for the high precision absolute alignment in this environment and easily implemented to the microcontroller. Results showed successful alignment on the infrared zoom lens with the switching control.

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