FPGA-BASED IMAGE PROCESSING LASER SPOT DETECTION ALGORITHM IMPLEMENTATION FOR THE OPTICAL GUIDANCE SYSTEM

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Abstract: *The task of high precision instrumentation pointing is critical for robotic systems and mobile platforms. The pointing accuracy and stability can be significantly improved by introducing an optical spot detector for feedback in the tracking control loop. Several points affect the performance of such machine vision systems. The key factors are the time delay between sensors readings and the control signal generation. The standard approach is to use the centroid algorithm implementation on the processor system to perform computation and generate a control signal. This might block other commands from execution until all output image has been saved to the device's internal memory. While it is possible to use an external computational module for this task, this approach increases the system cost and complexity. In this work, an approach to image processing and the optical spot centroid search is implemented using parallel processing of pixel blocks after receiving them from the sensor is discussed together with its implementation on FPGA. This approach provides the acceleration in processing speed and thus increase the pointing accuracy of the system.*

Key words: *FPGA, machine vision, pointing system, optical communication*

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This Publication has to be referred as: Stepanova, D[aria] & Pryanichnikov, V[alentin] (2020). FPGA-Based Image Processing Laser Spot Detection Algorithm Implementation for the Optical Guidance System , Chapter 14 in DAAAM International Scientific Book 2020, pp.181-188, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-27-3, ISSN 1726-9687, Vienna, Austria DOI: 10.2507/daaam.scibook.2020.14

1. Introduction

For the stable operation of the pointing system with optical feedback, it is necessary to use an algorithm that can provide the smallest error of the beam center determination, taking into account the signal to noise ratio. Several factors significantly affect the performance of such systems. The key among them is the time lag between the sensor reading and the control signal. The standard approach is to use a processor or controller to implement the computation and generation of the drives control signal. In most systems, data processing blocks pause commands from execution until all image has been saved to the device's internal memory. This approach leads to suboptimal costs due to data buffering, which entails significant losses in the computing power of the system.

Several works have already considered the problem of the image center determination algorithms implementation on FPGAs (Guyon, 2005), (Boev et al., 2015), (Stepanova et al., 2018.), (Timothy et al., 1992), (Hamid Mahmoud et al., 2003), (Spann et al., 1988). However, observed algorithms have several disadvantages. Some depend on the type of receiver and are difficult to adapt to new conditions. Others have sub-optimal noise characteristics. Other algorithms do not provide the required image processing speed. Several works have evaluated the noise characteristics of centroid detection algorithms, but do not take into account the complexity of their implementation on FPGAs and do not allow splitting the image into blocks to speed up the process (Zhou et al., 2016), (Stepanova et al., 2019).

Some algorithms for an optical spot determination described in (Boev et al., 2015) take into account noise characteristics comparison. In the absence of noise, the optical beam forms a central symmetric spot on the detector of the guidance system. However, in a real system, this signal is also influenced by background noise and atmospheric turbulence, which distorts the received beam due to a change in its incidence angles and, in general, signal deformation. Besides that, the optical sensor can also capture radiation from other sources: Sun, reflection from the Earth. A charge-coupled device (CCD) receiver is best suited for filtering these interferences.

In this work, a combined approach to image processing is discussed together with its implementation on an FPGA using parallel processing of pixel blocks immediately after receiving them from the sensor. In this project, an FPGA of the Cyclone IV GX EP4CGX150N type is used. This system has 150 thousand logical elements, can operate at a master oscillator frequency of up to 180 MHz, and also has an internal memory capacity of more than 65 KB.

2. Centroid algorithm adaptation

The goal of the centroid algorithm is to determine the coordinates of the orientation beacon center (Crawford et al., 2013). The algorithm does not require to store a whole frame in memory; processing is carried out line by line. For each row, the row center coordinate is found as the weighted sum of the pixel numbers. Then the weighted sum of the resulting row centres (in x and y coordinates) is calculated:

$$x_i = \sum_j j \cdot V_{ij} ; V_i = \sum_j V_{ij} \quad (1)$$

$$x = \frac{\sum_i x_i V_i}{\sum_i V_i} ; y = \frac{\sum_i i V_i}{\sum_i V_i} \quad (2)$$

where i is the row number, j is the column number, x and y are the coordinates of the spot center, x_i is the coordinate of the row center, V_{ij} is the brightness of the pixel with coordinates (i, j) , V_i is the total brightness of the i -th row.

A key function of derived algorithm is to detect point motion to measure absolute pointing deviation and to estimate residual error in a closed loop system. To obtain numerical values of the deviation, the position of the centroid is calculated for the spots in each aperture. The amended algorithm takes into account a significant change in intensity in the vicinity of the center of the spot and provides noise reduction, which is reflected in the correlation coefficient:

$$R_{ij}^{int} = \sqrt{\frac{\sum_{i=1}^7 K_m^2}{\sum_{i=1}^7 K_m^2 - \sum_{i=1}^7 (K_m - P_m)^2}} \quad (3)$$

where K_m is the gray level value for the real image, P_m is the gray level value for the tuning curve. Taking into account the obtained coefficients, a new calculation of the center of the spot image will be performed using the following formulas:

$$x = \frac{\sum_i \sum_j i \cdot R_{ij}}{\sum_i \sum_j R_{ij}} \quad y = \frac{\sum_i \sum_j j \cdot R_{ij}}{\sum_i \sum_j R_{ij}} \quad (4)$$

This algorithm takes into account a significant change in intensity in the vicinity of the center of the spot, which is reflected in the derived correlation coefficient. Due to this, noise is reduced and filtered. Algorithm steps are shown on Fig. 1

Fig. 1 Diagram of the image centroid search algorithm

3. Algorithm analysis on noise cancelation

To evaluate the efficiency of the algorithm, the characteristics comparison between simple centroid and the proposed algorithm for suppressing Gaussian noise

was made. Both algorithms were implemented in Matlab. The error of the algorithms was estimated as the value of the deviation, calculated and the true centers of the signal beams. The parameters for the simulation are the beam width and the value of the noise density.

Fig. 4 shows the results of the error modeling for the center of a spot determining with the laser beam opening width of 0.1 degrees and a noise variance of 0 and 0.2.

Fig. 2 Comparison between algorithms determining the centers of the spot with and without noise

It can be observed, that the centroid search method with correlation coefficients provides more accurate center of the spot determination. Changing the input parameters of the spot width and noise density, the centroid search method is significantly inferior to the correlation method. For example, when noise with a variance of 0.1 is added to the image, the accuracy of the centroid algorithm deteriorates by 5.7% of the pixel size, while the accuracy of the centroid algorithm using correlation coefficients deteriorates only by 0.9%.

4. Algorithm implementation on FPGA

Fig. 5 visualizes the architecture of the elements inside the FPGA, where all the necessary steps for reading, processing the image stream and displaying the value of the center of the optical spot are implemented. The main criteria for system development are the use of free data flow through the FPGA and minimization of processing latency, which affects the final system throughput and limits the buffering capabilities. The data from the "matrix" optical sensor through the interface arrives pixel by pixel to the internal FPGA interface and to the processing module. A time synchronization block is required for the algorithm. In the pixel characterization block, each pixel block is assigned an address corresponding to the position in the image of the upper left pixel, the frame number and the time required to synchronize the processing blocks and evaluate the algorithm performance.

Fig. 3 Block diagram of FPGA architecture

5. Algorithm validation results

To conduct an experimental confirmation of the algorithm's performance and compare the quality indicators of the implementation on FPGAs, the following technique is proposed:

The algorithm is implemented in the Matlab environment and tested using an experimental stand, indicators of the efficiency and productivity are obtained

The algorithm is implemented on FPGA and tested using an experimental stand, the performance indicators of the algorithm are recorded.

The test-bed includes the following subsystems: an electronics unit, FPGA and drive control drivers, a PC for generating, receiving and checking data, a D-Link DMC-805G master oscillator-converter for signal transmission between a twisted pair (Gigabit Ethernet) an optical transceiver SFP standard, and two-axis drive.

The master generator of the system is the DMC-805G converter receives the test signal from the PC and transmits them via an optical waveguide. The beacon simulator is a board with an LED attached to the outside of the lens mirror. At this stage, the drive is controlled from a PC using an electronics unit. The turntable platform with the drives is used for their relative orientation.

The developed algorithm for the centroid search is able to detect an optical spot against the background of other objects, including emitting ones, determine the distance based on the spot size, and calculate the guidance vector for the control system.

In Matlab implementation, the image processing time reached 0.013 seconds per frame, while a control cycle refresh rate achieves 60 Hz. The average accuracy of the algorithm calculated as the deviation of a certain spot center from a given one, is 14% of the pixel size.

In FPGA implementation, a clock frequency of 180 MHz was used. Discussed above configuration allows to divide each image into 100 to 400 blocks depending on the number of frames per second. Fig. 7 shows an example of a guidance vector search for two adjacent measurements.

Fig. 4 An example of the deviation vector search algorithm

The algorithm works with signed integers and allows you to determine an image centroid with an accuracy of 9.12% of a pixel. The image processing time when implemented on FPGA is 0.00143 seconds per frame. The algorithm processing time allows up to 1650 frames per second analysis, which significantly increases the control loop update frequency. Thus, taking into account the requirements for the guidance system control loop, this implementation of the algorithm will make it possible to achieve a control cycle update rate of 572 Hz. The average accuracy of the algorithm, also calculated as the deviation of a certain spot center from a given one, was 9.12% of the pixel size.

The advantage of using the developed algorithm on FPGA are proven experimentally. Comparison of variations of algorithms and their implementations is shown in Table 1.

	PC centroid	PC correlation	FPGA centroid	FPGA correlation
Processing time for 1 frame	0,013	0,021	0,00143	0,00158
Accuracy,% of pixel size without noise	14.8%	9.12%	14.8%	9.12%
Accuracy,% of pixel size with noise variance 0.1	20.5%	10.03%	20.5%	10.03%
Control loop frequency, Hz	69	42	631	572

Tab. 1 Algorithms comparison

6. Conclusion

This work has addressed an optical spot tracking algorithm upgrade and implementation for further signal utilization in a closed control loop. During the work, an analysis of existing algorithms, their characteristics in terms of noise suppression, and performance was carried out. Also, the implementation options were analyzed from an algorithm acceleration and memory efficiency perspective. It was revealed that existing algorithms for the center spot detection implementation on FPGAs is not optimal, since the algorithm format does not allow splitting the image into several parts and parallelizing the computation. As a result, the advantage of using FPGAs for this task was proved by increasing the performance and bandwidth of the channel. The disadvantage of this approach should also be noted: the implementation of algorithms on FPGAs is a more laborious process and requires significant resources both for development, testing, and reprogramming of the system.

Further, the algorithm for the optical spot centroid search was supplemented with correlation coefficients. A comparative analysis of proposed algorithm and the standard centroid search was carried out using the simulation experiment methods. This functionality provided noise reduction and increase the accuracy of the center determination. Finally, the architecture for the algorithm on FPGA implementation was proposed. The algorithm allows the split the image into several blocks and process them in parallel. The characteristics of the algorithm were obtained in terms of processing time, deviation determining accuracy at various noise levels. It has also been proven that the developed algorithm can provide greater accuracy for the guidance system of a laser communication terminal in conditions of optical interference. The advantage of using the developed algorithm on FPGA has been shown experimentally.

As for future work, in short term, developed algorithm shall be tested together with the control system and center determination error influence on the control system performance shall be evaluated. After that, the final system test including mobile platforms and integrated pointing systems shall be set up and performance of the algorithm shall be proved.

In long term, an algorithm might be advanced in terms of processing time for further increase in control loop update rate. On the other side, an algorithm noise resistance shall be studied for different noise models and improvements shall be performed.

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