Accelerometer Based Digital Video Stabilization for General Security Surveillance Systems

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Abstract

This paper is devoted to accelerometer based image stabilization for general video based security surveillance systems. At the beginning an introduction to the image stabilization is presented. Short description of the actual state of common algorithms for image stabilization follows, including our solution with some partial optimizations. At the end, we present a suitable hardware platform having a built-in accelerometer, which is responsible for advanced stabilization of a video-stream.

Keywords: *image, stabilization, video-stream, accelerometer, DSP, FPGA.*

1. Introduction

Classical security surveillance systems using video-cameras are well known. Resolution of such cameras often doesn't play an important role, but, in some cases (especially for military purposes), a high resolution is required. In this situation, not only a detection of some movements is expected, but some recognition or tracking is needed as well. The recognition can classify the object to one of predefined categories, i.e. a tank, soldier, ship, civil person, etc. If the object is recognized, the system should be able to track (follow the motion) this object, so that an automatic storage system has every time the tracked object in the middle of the video sequence or an operator can see this object in the middle of the screen.

Placing of the monitoring system plays an important role, especially to the output video stream. If we have a camera with a high resolution and the camera is placed in someone's hand or on a moving object (car, tank etc.), then the resulting video-stream is of very poor quality. An optimal solution is to place the camera on some stable holder, but if the height of such holder is too big, the camera will be exposed to the influences of the surroundings, e.g. wind, asperity of the road, waves on the sea etc. Therefore, the image stabilization in a video-stream is needed. The significant object is always in the same position in the screen.

We distinguish between two types of movements with the camera [2]:

- Weak shaking (app. ±10° variation in the horizontal and vertical directions and/or some small fractions of Hertz)
- Strong shaking (more than ±10° variation in the horizontal and vertical directions and/or tens of Hertz).

In the first case, the problem with shaking could be solved using pure software (digital) image stabilization. On the other hand, strong shaking is impossible to stabilize only with the software solution, i.e. some additional hardware is needed. This hardware can be based either on a servomotor unit or pneumatic/hydraulic unit, which are able to compensate the movements of the camera system in the opposite direction. Such hardware solution exceeds the scope of this article, however one solution is introduced here – an accelerometer based solution. Nevertheless, the hardware computing unit for digital image stabilization is described in the third chapter. This hardware unit is composed of two DSP processors with connected FPGAs and SDRAMs. The purpose of this unit is to ensure sufficient computational power for the digital image stabilization algorithm, which is introduced in the following chapter.

2. Image Stabilization Algorithms

Image stabilization algorithms mostly consist of three main parts [2]: motion estimation, motion smoothing and motion compensation. Main task of the first block is to estimate a several local motion vectors and on the basis of these local estimates calculate a global motion vector. The second block deals with filtering, integration (respectively), of the estimated global motion vector. The main purpose of this stage is to smooth the calculated value and prevent large and undesirable differences between motion vectors calculated in past. The last block shifts the acquired image in inverse direction according to the global motion vector. This block can take into account more sophisticated transformations like rotation or warping.

A lot of various approaches exist nowadays. The main difference lies in the resultant accuracy of global motion vector and algorithm used for estimation of local motion vector. We distinguish between pixel and sub-pixel resolution. Second approach is, however, complicated and more time consuming than the previous one because an interpolation method is needed. So it is rarely used in real-time applications. Some algorithms consider rotation or more complex warping in addition to translation. We will concentrate on algorithms that use translation with pixel accuracy only. In the following section is described a simply plain matching algorithm and some basic ideas of the stabilization. The next section will be devoted to one promising algorithm modification of which we used.

2.1. Plain Matching Algorithm

As stated above, the algorithms that deal with stabilization are based on estimation of a motion represented by a motion vector [4]. The straightforward solution leads to use of a discrete correlation, cross-correlation respectively [1]. The discrete correlation produces a matrix of elements. The elements with high correlation (value) correspond to the locations where a chosen pattern and image match well. It means that the value of element is a measure of similarity in relevant point and we can find locations in an image that are similar to the pattern.

The input is formed by a pattern (in the form of an image) F and an input image I. It is not necessary to search the whole image, thus a smaller area (search window $N \times N$) is defined. At the same time, this area specifies the maximal shift in vertical and horizontal direction and is chosen in this manner. Eq. (1) represents a discrete 2D correlation function [4].

$$F \circ I(x, y) = \sum_{j=-N}^{N} \sum_{i=-N}^{N} F(i, j) I(x+i, y+j) \quad (1)$$

Note that matching according to the first definition is problematic. Correlation can also be high in locations where the image intensity is high, even if it doesn't match the pattern well. Better performance can be achieved by a normalized correlation [1]:

$$\frac{\sum_{j=-N}^{N}\sum_{i=-N}^{N} F(i,j) I(x+i,y+j)}{\sqrt{\sum_{j=-N}^{N}\sum_{i=-N}^{N}\left(I(x+i,y+j)\right)^2}\sqrt{\sum_{j=-N}^{N}\sum_{i=-N}^{N} F(i,j)^2}} \tag{2}$$

Figure 1 shows an input image, pattern (red small area) and correlation matrix obtained by the normalized correlation. We defined the search window (green big area) and the pattern is searched within this window. The result matrix has the same dimensions as the search window ($M \times M$). The pixel with the maximum value determines position of the pattern in the search window. Hence, it determines position of an area in the search window which is most similar to the pattern.

The correlation can be calculated in the original (time) domain according to equation 2 however this approach is rarely used due to enormous time consumption. Note that for every point of correlation matrix is necessary to perform $2N \times N$ multiplications and additions. We can obtain the same result with lesser effort in the frequency domain [1].

On the other hand, the Eq. (2) appears to be an ideal choice from the hardware processing point of view. The computation involves only the fixed-point arithmetic (adders and multipliers) which is suitable for an FPGA based implementation.

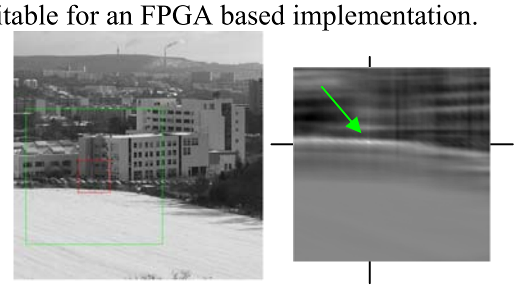

Figure 1. a) Input image with marked search window (left); b) Correlation matrix obtained by correlation (right) [5]

Stated principle is theoretically ideal solution when we consider only translation. But in practice we have to deal with two problems. The first problem arises from finite resolution of registers and sampling and it causes existence of several points with maximal values in the correlation matrix. The second problem is dependency of results on the background noise which is present in the input video signal.

It is necessary (in case of the image stabilization) to define several independent areas and to calculate correlation matrices for each of them. We obtain several local motion vectors and the global motion vector is calculated as their average or median. This method prevents errors coming from the correlation on problematic areas (e.g. with the same intensity).

2.2. Bit Plane Matching Algorithm

Some algorithms, in quest of improving the results, calculate the correlation from the images passed thru an edge detector [3]. This technique provides certain improvements, but the edge detectors tend to produce many useless pixels and are sensitive to the image intensity. Last but not least, the detector introduces additional time-consuming operation to the phase of processing. As most of edge detectors are nonlinear systems, it is not possible to make convolution in the frequency domain.

The noise can be suppressed by ignoring the least significant bits. Then we can consider only the higher bits or take only some bit-planes and calculate the correlation using that plane, which consists only from one and zero values.

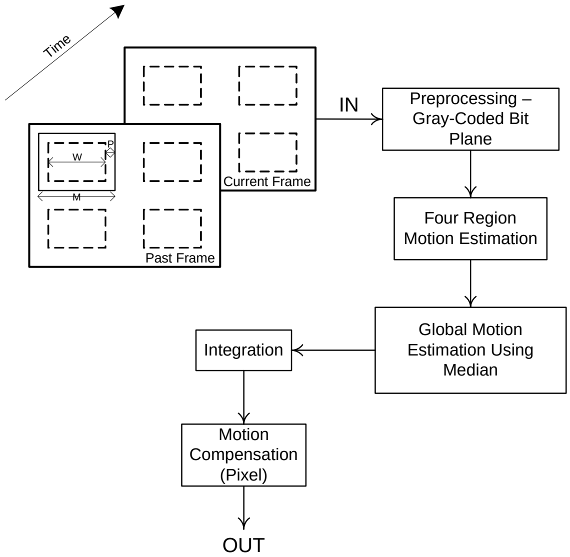

Figure 2. Diagram of digital image stabilization

Better results can be achieved by gray coded bit planes. The gray coding allows the motion estimation vector using a single bit-plane by encoding most of the useful information into a few planes. A small change in the gray level leads to a small change in the binary digits representing the intensity.

Bit plane matching algorithm does not use correlation, as defined above, and defines a new, but very similar, operator (see Eq. (3)) that has to be minimized. Note that, in the previous task, we deal with maximization. In fact, it is the definition of correlation where the multiplication operator is replaced by the binary operator – exclusive or.

$$E(x,y) = \sum_{j=-N}^{N} \sum_{i=-N}^{N} F(i,j) \oplus I(x+i, y+j) \quad (3)$$

This error operator is calculated by minimizing the resulting local motion vector. Several (typically four) local motion vectors from each area along with the previous global motion vector are passed through a median operator to produce the current global motion vector estimate.

Then, the global motion estimate can be optionally passed through a filter that is tuned in order to preserve intentional camera motion while removing the undesirable high frequency motion.

The final filtered motion estimate is used then for shifting the current frame by an integer number of pixels in the opposite direction of the motion. The whole system is depicted at Figure 2.

2.3. Enhancement – Our Solution for Image Stabilization

The method described in the previous section uses only one bit plane to estimate the local motion vector. In order to improve the estimation of the local motion vector, we experimentally determined that at least two bit planes are suitable to increase the reliability of estimation.

The next improvement lies in the usage of more than one maximum. This solution will be stable in the situations, where the edges have very low contrast. Now we are trying to use 5 highest maximum peaks in the searching area. This could be taken into the account by the computation of global motion vector.

The last optimization is to split the image to some predefined number of regions, in which the maximums are searched. Robustness of such algorithm increases using this optimization.

Our intention is to reduce the computational demands on processor (DSP) that the standalone unit without cooling could operate, and our algorithm should be stable also in regions, where nearly no clear edges exist, e.g. desert or sea.

3. Hardware Design

Algorithms mentioned in the previous chapter can be easily implemented in a common PC. Our goal, however, is to design a standalone solution to the image stabilization, which has to fulfill defined specifications. Result of our aims should be a device able to stabilize an input video stream and to send the stabilized stream to an output.

The specifications that must be fulfilled are defined as follows:

- Size of the final board must not exceed 100×120 mm.
- Height of the final product must be lower or equal to 12 mm.
- The board should contain four layers not exceeding total width of 1.5 mm.
- The final product must be able to operate under military conditions, e.g. temperature of operation ranges from -40° to 85° C.

3.1. Description of our Hardware Layout

The board consists of input/output connectors, persistent storage units, processing units, microcontroller, and video processing unit.

The connectors serve simply for the video input and output purposes. The persistent storage is in a form of a FLASH memory containing software, which is booted after reset of the board. There is a slot for an SD card too, which enables user to upgrade the software. A new version of the software is uploaded to the FLASH memory automatically when an SD card is present in the slot. The microcontroller provides means of communications between the individual components (FLASH memory – SD Card, FLASH memory – FPGA etc.). The video processing unit consists of an encoder and decoder determined to encode/decode the video stream.

The main part of the board is the processing unit. For this task we decided to use a combination of an FPGA and digital signal processor (FPGA-DSP combination) as the engine of the board.

Since the board must count on future upgrades, it contains an independent pair of the FPGA-DSP combination (see Figure 3) working in parallel. Each FPGA-DSP combination has its own memory bank to avoid memory stalls and shared memory issues. This way there is one FPGA-DSP pair for the image stabilization and the other FGPA-DSP pair for the future upgrades (e.g. for an object tracking). Each module can operate separately, is independent (even though they can use each other's results), and can be omitted from the final design, which makes the board very variable.

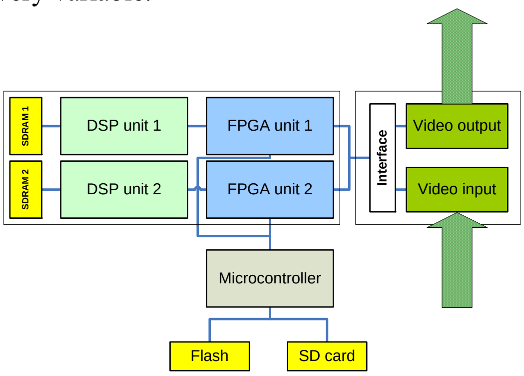

Figure 3. Proposed design of the board for the image stabilization [5]

The first processing unit serves for the purposes of the image stabilization. It can read frames from the input video stream, store them in its memory and process them. The resulting frames can be sent to the output video stream. The second processing unit doesn't need to be included on the board. When it is present on the board however, it can communicate directly with the first module. It can read frames of the input video stream and send them to the output video stream too. When both units are functional and working, the output stream is produced by the second unit. Each module can be turned off so that each stage of the video stream processing can be easily bypassed (it can be useful in some cases to see the unprocessed input video stream).

This solution is a compromise between the hardware specifications, given constraints and algorithm requirements. The combination of an FPGA and DSP allows us to distribute tasks given by the algorithm between both – the processor and gate array. Hence, FPGA can perform some general operations (preliminary steps of the algorithm), whereas the DSP can focus itself on the calculations (e.g. Fast Fourier Transform).

3.2. Solution with an Accelerometer

When a camera is placed on some stable holder and the height of this holder is too big, the camera will be a subject o motion, caused by e.g. wind, asperity of the road, and waves on the sea. Motion of the camera is both rotational and linear. Rotational motion can be measured using a gyroscope, linear motion using an accelerometer. When a camera holder is not so big, rotational motion of the camera is the dominant form of camera movement. However, as the height of camera holder increases, linear motion becomes the dominant form of camera motion. Because we suppose high camera holders, we decided to use MEMS accelerometers for motion detection. Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate. MEMS accelerometers and gyroscopes are emerging at a very fast pace in consumer electronics products. Since 1998, MEMS gyroscopes were widely integrated into camcorders to provide optical stabilization features. In 2003, MEMS accelerometers entered consumer applications, in large volume, as a protection feature for Hard Disk Drives.

We have done some experiments with this accelerometer, placed on mast (7 m long) – see Figure 4.

Figure 4. Experiments with accelerometer (acquired during fine shaking of camera)

We have a built-in MEMS accelerometer on our hardware board. We use the accelerometer from STMicroelectronics with the following characteristics [6]:

- Accelerations: ± 6g
- Bandwidth: 640 Hz
- Temperature ranges: -40°C till +85°C
- Interface: I2C or SPI
- Supply voltage: 2.5 V

Using this accelerometer we are able to measure movements of the whole camera system in all three directions and therefore we know the actual deviation from the balanced status. The stabilization algorithm receives the respective acceleration data from each of the accelerometer axis, and also knows a mechanical model of the camera holder. The algorithm then uses the data from mechanical model of the holder and the acceleration data to produce motion vector to correct the image captured by a camera that is in motion.

For the computation we use the approximation of measured values in a time interval of 1 sec. The curve is smoothed and we take only the deviation of this average value from the balanced status, what gives us additional information to our algorithm for image stabilization. This information is used together with the values from software to combine them and to get the resulting needed value for image movement.

4. Conclusion

We have a standalone unit with two DSP processors ready to realize digital image stabilization. One backup DSP-FPGA pair is ready for future use, e.g. for the task of an object tracking.

At the moment, three parallel ways for the algorithm of image stabilization are used. We try to use common algorithms for this task, but with our optimizations and improvements to ensure strong robustness.

The future work is to load the optimized parallelized program to the hardware unit. Testing and further optimizations, especially in parallelism, will be performed soon. Of course, further improvements will be needed, e.g. for different regions of usage (e.g. arctic ice region, windy areas etc.). In the future, we want to try to implement the image stabilization on another DSP platform which does not use a fixed point as our contemporary solution.

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