Multi-modal Video Surveillance Aided by Pyroelectric Infrared Sensors

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Abstract. The interest in low-cost and small size video surveillance systems able to collaborate in a network has been increasing over the last years. Thanks to the progress in low-power design, research has greatly reduced the size and the power consumption of such distributed embedded systems providing flexibility, quick deployment and allowing the implementation of effective vision algorithms performing image processing directly on the embedded node.
In this paper we present a multi-modal video sensor node designed for low-power and low-cost video surveillance able to detect changes in the environment. The system is equipped with a CMOS video camera and a Pyroelectric InfraRed (PIR) sensor exploited to reduce remarkably the power consumption of the system in absence of events. The on-board microprocessor implements an NCC-based change detection algorithm. We analyze different configurations and characterize the system in terms of runtime execution and power consumption.

1 Introduction

Nowadays video surveillance systems and cameras aimed at monitoring private and public areas are gaining increasing popularity. This pushes forward the need for robust and reliable methods for video analytics, since they allow automatic processing of the data acquired by surveillance cameras with a much reduced need for human operators. In this paper we propose a system for video analytics which deploys synergically a PIR sensor and a smart camera. The aim of our method is to automatically detect structural changes occurring in a monitored scene which are due to events such as abandoned or removed objects in the scene. This class of events is often of critical importance for security reasons: as a matter of fact, a typical video analytics issue is the automatic detection of abandoned objects in venues such as airports or railway stations or the theft of objects in places such as museums and private properties [1–4].

A major issue for a reliable detection of such events is the presence of stationary cluttered parts of the scene caused, e.g., by subjects standing in front of the background of the scene or by objects slowly moving in front of the camera. This can easily cause an automatic video-surveillance system to produce false alarms. Our idea is to use the information coming from the PIR sensor to help increasing the robustness of a change detection algorithm used to detect this class of events. In particular, the PIR sensor can trigger the camera sensor only in absence of intrusion in the monitored scene: this greatly helps reducing the numbers of false alarms which could be produced by the change detection algorithm.

Moreover, power management is a critical issue when dealing with wireless and distributed embedded systems and it is well known that batteries does not scale as much as electronic device [5] thus posing a severe limitation in the achievable unobtrusiveness. We will show that adopting PIR sensors the average power consumption of the platform will be reduced remarkably.

The remainder of the paper is organized as follows. Related works are reviewed in the next section, with particular attention to the several implementations of the Change Detection algorithm. Section 3 describes the implementation of our wireless multimodal video platform, while Section 4 will discuss the proposed algorithm to detect abandoned or removed objects. Experimental results and the performance achieved are the focus of Section 5. Finally Section 6 concludes the paper.

2 Related Work

Energy-efficient sensor node architectures should be based on nodes with significant on-board object detection, classification and tracking capabilities. The key design challenge in this area is the development of energy-efficient algorithms and low-power architectures which can support these vision-related tasks. Research on wireless video system design has been very active in the last five years, and a number of node prototypes have been designed [6–14]. We can classify these approaches in three categories: (i) low-cost nodes with wired interface (e.g., the node designed by Corely et al. at CMU [9]), (ii) wireless nodes with significant power consumption (e.g., the Panoptes [12]), (iii) application specific single ultra-low power single chip solution [11]. Nodes in the first category obviously do not satisfy the basic requirement of being wireless and none of the presented works utilizes advanced low-power consumption techniques. However they witness a rapid growing of research and development of surveillance and multimodal applications using multiple sensors, including video and other kind of sensors. The aim of such systems is both to overcome some points of failure of a particular kind of sensor and to balance different parameters fixed by the application. In [15] a camera for remote surveillance is equipped with a PIR sensor. The PIR provides triggers for a light during nighttime that illuminates the scene in presence of moving animals. In this work the video node continuously processes images from the camera in order to detect movements in the scene. In [16] networks of infrared sensors (IR) and cameras are used to balance privacy, security and surveillance effectiveness. Cameras are exploited in public areas while networks of IR detectors are deployed in private areas. When a theft happens, information from IR sensors is correlated in order to find images of the thief. In this paper IR sensors and camera are used together to increase privacy in private area while still detecting the identity of thief, however the two systems are decoupled and information from the IR sensors are not used to enhance video recording and analysis. PIR sensor capabilities of detecting both presence and direction of movement have been exploited in [17] to enhance a video surveillance system. Finally in [18], a distribute network of motes equipped with acoustic and magnetic sensors have been deployed in order to achieve longevity, adjustable sensitivity, stealthiness and effectiveness in a military surveillance application. Since in this paper the authors aim at achieving longevity through sensor selection techniques, they use a high number of low power nodes with low resolution (magnetic field detector) and network life extension is obtained by reducing number of active sensors when any activity is detected and successively wake them up. In contrast we have a unique sensor, which provides much more information and we modulate its activity through the use of another low power sensor.

2.1 Change Detection

Change detection aims at detecting changes occurring in a scene by analyzing video sequences. It is typically employed for video-surveillance applications since it enables automatic surveillance of camera-controlled areas. In addition, the information output by change detection algorithms is often deployed as input for higher-level vision tasks such as object tracking, event detection, behavior analysis.

One common approach to perform change detection is referred to as *background subtraction*, and consists in comparing each frame of the analyzed video sequence, F, with a model of the background of the scene, B, under the assumption that the background is stationary. In particular, each pixel at coordinates (x, y) in the current frame is compared with its homologous in the background model by means of a function f aimed at measuring the similarity between the two image points. In the common case of a static camera, homologous pixels have identical image coordinates:

$$S(x, y) = f\left(F(x, y), B(x, y)\right) \tag{1}$$

S represents the scores reported by applying function f on each pixel $\in F$, B. These scores are thresholded in order to obtain a binary image, referred to as *change mask*, C, which highlights those parts of the current frame which have been subject to a change:

$$C(x, y) = \begin{cases} changed, & S(x, y) < \tau \\ unchanged, & otherwise \end{cases} \tag{2}$$

In the simplest approach f is the absolute difference between two intensities: though simple, this approach hardly handles photometric distortions between F and B which can severely affect the intensity values of corresponding pixels. Indeed, sudden illumination changes occurring in the scene represent a major issue for most practical motion detection applications, since the resulting photometric variations can be easily misinterpreted as structural changes, leading to false positives in the change mask. Hence, more advanced approaches rely on comparing not only the two corresponding pixels but also a neighborhood of spatially correlated points, and f is a measure invariant to a specific class of photometric transformations. In particular, such algorithms take the decision of voting a pixel as changed or unchanged by applying f on a given spatial support (e.g. a window of radius r centered at the pixel under evaluation).

Two commonly used matching functions are the Normalized Cross-Correlation (NCC) and the Zero-mean Normalized Cross-Correlation (ZNCC) [19], which are invariant, respectively, to linear and affine photometric transformations. Instead, other measures refer to a more general class of transformation, known as *order preserving*, that assumes that the order between neighboring intensities does not change in presence of such distortions: some examples are the Rank and Census Transforms [20], and more recently [19, 21, 22]. Finally, other methods exist still based on the order preservation assumption, but proposing a probabilistic model to solve the binary classification problem represented by (2) [23–25].

3 System Architecture

The block-level architecture of our video sensor is displayed in Fig. 1 and consists of several modules: the vision board which hosts both the CMOS imager and the PIR sensor with a common area under monitoring, the wireless module, the microprocessor and other peripherals.

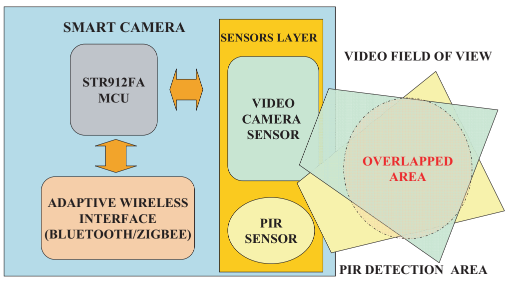

Fig. 1. Video sensor node architecture.

The node architecture is centered around a STR912F microcontroller from STMicroelectronics with an ARM966E 16/32-bit RISC architecture, 96 MHz operating frequency, 96 KB SRAM and several interfaces including Ethernet, USB, I2C, UART. It is employed mainly for digital image processing and control using single-cycle DSP instructions, and provides configurable and flexible power management control. Power consumption can be dynamically managed by firmware and hardware to match the system requirements adjusting the operating frequency. For example a typical current consumption for this microcontroller is about $1,7\,mA/MHz$ in RUN mode and only a few mA in sleep mode which is an attracting feature for wireless sensor networks design where the power consumption is a main constraint. STR912F provides a high-speed logic interface necessary to capture images from the camera and processing data for people detection or object classification.

The goals guiding the electrical design of this node architecture were the integration of a video camera and a Pyroelectric sensor. Moreover the main motivation in keeping the STR9 is to have a good power-efficient 32-bit RISC architecture that can be clocked up to 96MHz and has a simple power management, reduced power consumption and mote cost. In fact the whole system is designed with low power consumption as the primary goal. The vision module includes a SXGA CMOS color digital camera targeted for mobile applications featuring low-size and low-power consumption and a Pyroelectric Infrared Detector, whose detection area is overlapped with the field of view of the video sensor. Wireless communication capabilities have been supported through a suitable interface for both ZigBee and Bluetooth compliant transceiver. Figure 2 shows the first version of the developed prototype.

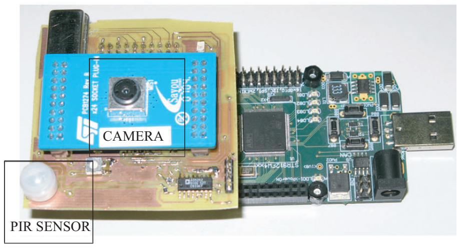

Fig. 2. Developed prototype of the video sensor node.

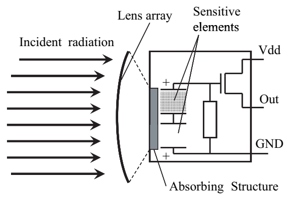

Fig. 3. Typical commercial PIR sensor.

3.1 Multisensor Layer

Figure 2 shows the multisensor layer that hosts both the CMOS camera and the Pyroelectric sensor. The video sensing device is a VS6624 CMOS imager from STMicroelectronics. It supports up to 15 fps SXGA with progressive scan and up to 30 fps with VGA format. It operates at 2.8 V and 12 MHz frequency and the power consumption is $120\,mW$ when active, while it decreases down to $23\,mW$ when switched to standby. Although it supports SXGA resolution, we have used only 160×160, mainly with the aim of saving time and energy for storing and processing of data. CMOS camera can be programmed and controlled via internal registers using I^2C serial interface. It supports several output formats, in particular we adopt 8-bit grayscale images with YCbCr 4:0:0 format.

Pyroelectricity is the electrical response of a polar, dielectric material (crystal, ceramic or polymer) to a change in its temperature. The pyroelectric element behaves like a planar capacitor whose charge Q changes according to $\Delta Q = Ap\Delta T$, where A is the area of the element, p is the pyroelectric coefficient of the material and T is the temperature [26]. Commercial PIR detectors typically include 2 sensitive elements placed in series with opposite polarization (Fig. 3). Such a configuration makes the sensor immune to slow changes in background temperature. PIR sensors are used in conjunction with an array of

Fresnel Lenses. The aim of the lenses is both to shape the field of view of the detector and modulate incident radiation by optically dividing the area to be protected into a number of separate cones.

Typically PIR sensors are used in surveillance and automated lighting system to detect presence of people and provide a simple, but reliable, digital presence/absence signal. However their output depends on several features of the object moving in front of them such as direction of movement, distance, and number of people. Such information can be used for video analysis in multi-modal sensing applications [27].

4 Video Processing Algorithm

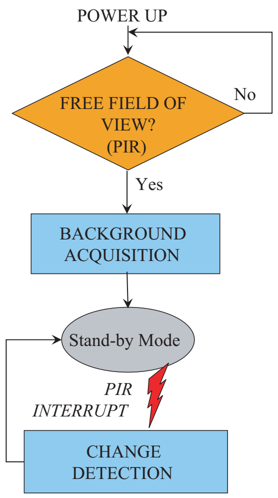

Fig. 4. Flow chart of the application.

The following application example demonstrates the use of a smart camera with PIR. The application example presented here is primarily intended to introduce the potential of multiple sensors on the same node. Note that in this application the PIR sensor plays a two-fold role: it is adopted both to wake up the camera and to provide information for a more accurate processing of the image. Since the field of view of the PIR overlaps the field of view of the image sensor, the main advantage of using the PIR sensor is the awareness of objects presence/absence in the surveilled area.

For this example we have used only the SRAM on core die, so the camera is set to send 160x160 gray scale image in YCbCr 4:0:0 format. With this format we have one byte per pixel, and the total amount of data per frame is 25KB. Under these conditions the whole application needs 75KB (3x25KB). In fact one third are needed for the background frame, one third for the current frame, and the last 25KB are needed by the background subtraction algorithm.

Fig. 4 depicts the main steps of the implemented algorithm. After switching on the system, the microcontroller reads the digital output of the PIR sensor and does not start acquiring the background until the PIR signal is low for at least five seconds. Once the acquisition starts, the first frame is stored in ARM9 SRAM and the following ten frames are used to compute the average background values for each pixel, so that the final stored background is less noisy than the background obtained by means of a single frame acquisition. Moreover we deploy an interrupt on the digital output of the PIR sensor, so that if something comes in the field of view while the Background Process (BP) run, the PIR raises its output signal, thus the current frame is not used to calculate the final background and the BP process ends immediately.

When the Background Process is over, the system switches to a stand-by mode. In this mode the ARM9 microcontroller runs in SLEEP mode and its power consumption becomes notably lower, as it will be shown later. In addition, also the camera is switched in stand-by mode to reduce the power consumption. Instead the PIR sensor stays in run mode since it is used to wake up the microcontroller.

4.1 The Proposed Algorithm

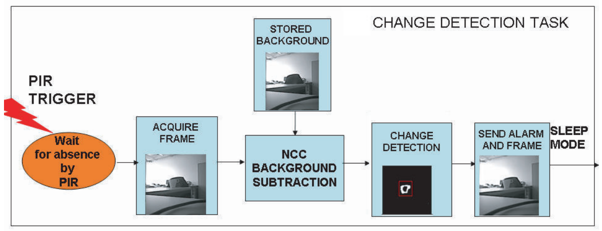

Fig. 5. Flow chart of the background change detection task.

This section describes the proposed approach aimed at detecting stationary background changes occurring in the monitored scene, e.g. such as the detection of abandoned/removed objects. The flow chart of the algorithm is sketched in Fig. 5. When an intrusion event which occurred within the field of view of the smart camera is over, the PIR sensor alerts the microcontroller by turning high its output signal. At this point, the ARM waits a certain amount of time (e.g. 5 seconds) for the output of the PIR to remain low, so to make sure no intrusion is currently occurring in the scene and thus to enhance robustness towards false alarms. If the scene is stationary for the required amount of time, then the microcontroller switches on the camera sensor and starts acquiring image frames. Each new frame is first stored in SRAM, then a change detection algorithm based on background subtraction is applied. In particular, each pixel of the current frame is compared with its homologous on the background model, which was previously initialized at start-up, by means of the NCC function:

$$S(x,y) = \frac{\sum_{i=-r}^{r}\sum_{j=-r}^{r} F(x+i,y+j)\cdot B(x+i,y+j)}{\sqrt{\sum_{i=-r}^{r}\sum_{j=-r}^{r} F(x+i,y+j)}\cdot\sqrt{\sum_{i=-r}^{r}\sum_{j=-r}^{r} B(x+i,y+j)}} \quad (3)$$

where r is the radius of the window centered on (x, y). The use of the NCC is motivated by the fact that it improves the robustness of the background subtraction stage against photometric distortions and sudden illumination changes occurring between the current frame and the background model since, as previously mentioned, it is invariant to linear transformation between F and B. In fact, the system ought to be robust toward these kinds of distortions which can typically be found since the background model is computed at initialization. On the other side, the implementation of the NCC function is particularly simple compared to other more advanced approaches, and this aspect is particularly relevant since the algorithm has to be implemented on an ARM-based embedded architecture. Since STR912F is not equipped with a floating point unit, the algorithm is implemented using fixed point arithmetic to maximize the processing time and save power consumption on the microprocessor. Nevertheless the quality of the detection is not degraded as depicted in Fig. 6 where starting from the same background and current frames, we compare the change masks obtained from a NCC implementation with floating point Pentium4 architecture and our fixed point ARM-based solution.

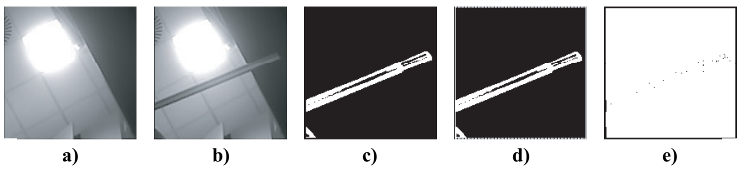

Fig. 6. Frames used for quality evaluation: a) stored background b) current frame c) changed mask on ARM with fixed point NCC d) changed mask on Pentium4 with floating point NCC e) difference between masks (only 43pixels in this example).

It is important to note that to alleviate the problem of photometric distortions between F and B a proper background updating stage could also be deployed, which aims at updating B to the current appearance of the scene background by means, e.g., of an alpha-blending procedure [28].

Once S is computed as in (3), it is thresholded as in (2) and the change mask is obtained highlighting those parts of the background which have reported meaningful changes compared to the original background model. In this preliminary version of our algorithm, a very simple approach is used: that is, the number of changed pixels in each change mask is determined, and when this number becomes higher than a threshold an alarm is communicated to a host station via Bluetooth. Instead, the information contained in the change mask could be used as low level input data to higher level algorithms such as a blob detector or an abandoned/removed object detector: this will be investigated as a part of our future work.

5 Experimental Results

The above-mentioned application was fully implemented in ARM9 firmware. In the following we will focus on mote sensor power and performance.

5.1 Sensor Node Characterization

The ARM microprocessor STR912F offers configurable and flexible power management control which allows dynamic power consumption reduction. We can switch the microcontroller in three global power control modes: RUN, IDLE and SLEEP. SLEEP mode is used by the video sensor node when no events are registered in the field of view. When triggered by an event from the PIR sensor, the system switches into RUN mode the ARM core that keeps the camera turned off until the digital output of the PIR sensor is low for a programmable and fixed time. Then the microcontroller switches on the camera and starts the detection application, then the system switches back into SLEEP mode where the power consumption decreases up to 90% since only the PIR module operates. Power consumptions are reported in Table 1a).

(a) Power consumption of the video sensor node.

Component	Power $[mW]$
ARM9 (RUN mode)	450
ARM9 (IDLE mode)	49,5
ARM9 (SLEEP mode)	15
Video sensor (ON mode)	165
Video sensor (IDLE mode)	23
TX/RX (ACTIVE mode)	98
TX/RX (IDLE mode)	10
PIR sensor	1,5
Video Node	
Active with video sensor	626,5
Active, without video sensor	484,5
Alarms Transmission	572,5
Sleep, only PIR is Active	51

(b) Energy requirement of the tasks.

Task	Energy $[mJ]$	Time $[ms]$
Frame Acquisition	72	115
NCC Background Subtraction	417,5	860
Image Transmission	801,5	1400

Table 1. Energy requirements of the Hardware/Software system.

5.2 Detection of Abandoned/Removed Objects

Fig. 7 gives screenshots of the proposed change detection example which emphasizes that NCC starts only when the PIR sensor detects that the scene is empty after someone entered the field of view, as depicted in Figure 7a). The first image of each example displays a the frame after the PIR wakes up the system.

Fig. 7. Screenshots of change detection example.

Clearly, it is only for test purpose, since this first image is not necessary for the application. The second image in each row depicts the frame actually acquired and processed, after PIR sensor detects that everybody has left the field of view. Finally the last image displays the change mask provided by the adopted algorithm. Since the number of changed pixel is higher than the threshold used for our experiments (i.e. 500 pixels, about 2% of total pixels), the current frame is sent to host station. The screenshots depicted in Fig. 7b) and 7c) respectively display the return to the initial state and a removed object event. In this last case, the number of changed pixel again turns out to be higher than the threshold and thus the system sends an alarm and the current frame to the host.

5.3 Change Detection Energy Requirements

As we have explained in the previous section, our application is composed by different modes Fig. 4. Table 1b) summarizes the components typical energy and runtime values. We considered a hypothetical surveillance scenario where events occurrence ratio is 4% of the time. Since the PIR sensor wakes up the video acquisition only after people has moved out the scene, the number of not-interesting events to process decreases guaranteeing longer lifetime to the system. We estimated that a system supplied with a $100Ah$ gel battery can extend its lifetime from 25 days to 506 days when the proposed wake-up method is implemented. For unobtrusive video sensor node powered with small size Lithium battery of $2500mAh$ the autonomy is prolonged up to 12 days, while a PIR-less solution can guarantee only 11 hours of uninterrupted service.

6 Conclusions

An integrated video sensor node for energy efficient surveillance able to detect changes in the scene has been proposed. The adoption of a multimodal platform equipped with different family of vision sensor with heterogeneous features of power consumption and resolution allow to achieve longer autonomy reducing considerably the overall power consumption of the system.

Moreover the adoption of PIR sensor helps to increasing the robustness of our video processing algorithm, activating the camera sensor only in absence or intrusion in the monitored area, reducing the numbers of false alarms.

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