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ORIGINAL RESEARCH

A real-time non-intrusive FPGA-based drowsiness detection system

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Abstract Automotive has gained several benefits from the Ambient Intelligent researches involving the deployment of sensors and hardware devices into an intelligent environment surrounding people, meeting users' requirements and anticipating their needs. One of the main topics in automotive is to anticipate driver needs and safety, in terms of preventing critical and dangerous events. Considering the high number of caused accidents, one of the most relevant dangerous events affecting driver and passengers safety is driver's drowsiness and hypovigilance. This paper presents a low-intrusive, real-time driver's drowsiness detection system for common vehicles. The proposed system exploits the "bright pupil" phenomenon generated by a 850 nm IR source light embedded on the car dashboard. This visual effect, due to the retina's property of reflecting the 90% of the incident light, makes easier the detection of driver's eyes. At the same time, the "bright pupil" effect is used to quantify the driver's drowsiness level as the percentage of time in which the driver's eyes are closed more than 80%. The efficiency of the image processing chain, together with an embedded hardware device exploiting the availability of mature reconfigurable hardware technology, such as Field Programmable Gate Array, allow to implement a real-time detection system able to process an entire 720 × 576 frame in 16.7 ms. The effectiveness of the proposed system has been successfully tested with a human subject operating in real conditions.

Keywords Driver assistance systems · Drowsiness detection systems · Real-time image and video processing · FPGA based prototyping

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1 Introduction

Embedded Systems have an important role in the realization of Ambient Intelligence because they are useful for the embedding of hardware devices into the environment and people's surroundings (Ducatel et al. 2001). Generally, less intrusive systems are preferred in real scenarios, so that embedded systems do not interact and affect the normal execution of human actions. Driver assistance systems (DASs) are included among the above systems, since embedded systems have to give their support to driver operations and safety without any interaction or influence with driver actions (Rakotonirainy and Tay 2004). At the same time, critical conditions detection and prevention is one of the challenges of the Ambient Intelligent Systems (Nehmer et al. 2006; Kleinberger et al. 2009; Ramos 2007).

In recent years, Automotive has gained several benefit from the Ambient Intelligent researches involving the development of sensors and hardware devices. So, future intelligent vehicles will be equipped with interacting systems and facilities. Vehicle automation has been used increasingly over the years to enhance driving performance: computers aid in controlling everything from the vehicle's engine and transmission to driver-assisted steering and braking, to the vehicle's climate control. Intelligent vehicles take automation to the next level: assisting the driver directly with making decisions related to the driving task or in actually taking action required to improve overall safety. So vehicles can be fitted with some combination of sensors, information systems and controllers designed to automate or enhance the drivers and/or the vehicles performance. However, the huge amount of data coming from the embedded vehicle devices require intelligent and fast algorithms to execute, check and complete an operation before a prearranged time. Clearly, if system processing exceeds the deadline, the whole operation becomes meaningless or, in the meantime, the vehicle can reach a critical condition.

On the other hand, the current availability of mature network technologies, such as Vehicular Ad hoc Network (VANET) (Lan and Chou 2008; Zhang et al. 2008) and Wireless Access for the Vehicular Environment (WAVE) (IEEE 2009), offers a good path for developing Intelligent Spaces (Varaiya 1993), in which the environment can continuously monitor what's happening in it and vehicles can communicate each other exchanging its relative positions and potentially dangerous conditions, such as the presence of an uncontrolled vehicle. In addition, different approaches for VANET video streaming and multimedia services, such as instant messaging, have been proposed. In (Qadri et al. 2010), authors demonstrate that the Flexible Macroblock Ordering codec is suitable for robust video stream transmission over VANETs. In (Manvi et al. 2009), authors propose an agent-based information dissemination model for VANETs. The model provide flexibility, adaptability, and maintainability for light information dissemination in VANETs as well as the needed tools for network management.

In this article the design and the development of a system able to monitor the drowsiness level of a driver in an ordinary vehicle is presented. Accordingly to the statistics, 10–20% of all European traffic accidents are due to the driver's diminished level of attention caused by fatigue. In the trucking industry about 60% of vehicular accidents are related to driver hypovigilance (Peters and Anund 2003).

One of the main constraints in the proposed system design and prototyping was the level of interaction with driver operations: the developed non-intrusive drowsiness monitoring system requires an IR CCD camera embedded on the car dashboard. Driver level of fatigue is based on the opening and closure frequency of driver eyes by mean of the Percentage of Eye Closure (PERCLOS) parameter, i.e. the portion of time eyes are closed more than 80% (Wierwille 1999). Due to the sensitive nature of processed data, real-time video stream processing is performed on the moving car, through the use of an embedded processor. Information dissemination models for VANETs (Manvi et al. 2009) can be adopted to transmit and share dangerous hypovigilance conditions. With more details, the whole monitoring system has been prototyped using the Celoxica RC203E FPGA board (Celoxica 2005a), achieving real-time performance [up to 60 fps (frames per second)]. The systems is able to process a video stream containing a person who is driving a vehicle in order to segment and recognize driver's eyes, to compute its level of fatigue, and to activate a car alarm. The drowsiness monitoring system exploits the *bright pupil effect*, since the retina reflects the 90% of a 850 nanometer (nm) wavelength incident light.

The paper is organized as follows. Section 2 summarizes relevant works for preventing driver's drowsiness. In Sect. 3 a brief description of the adopted face model is reported. Section 4 presents a detailed description of the proposed system. In Sect. 5 hardware and software environment are described and the experiments conducted to validate the proposed system are reported. Finally, in Sect. 6 some concluding remarks are given.

2 Related works

Accordingly to the classification proposed in (Hartley et al. 2000), the techniques for preventing driver's drowsiness can be classified into the following categories:

- technologies to assess the vigilance capacity of an operator before the work is performed (Dinges and Mallis 1998);
- mathematical models of dynamics alertness (Åkerstedt and Folkard 1997; Dawson et al. 1998);
- vehicle-based performance technologies that detect the behavior of the driver by monitoring the transportation hardware systems, such as steering wheel movements, acceleration etc. (Artaud et al. 1994; Mabbott et al. 1999; Lavergne et al. 1996; Vitabile et al. 2007, 2008);
- real-time technologies for monitoring driver's status, including intrusive and non-intrusive monitoring systems.

An intrusive system can be defined as a system that provides physical contact with the driver (Yammamoto and Higuchi 1992; Saito 1992). The intrusiveness depends on the level of interaction between the monitoring system and the driver and, in particular, on the interference that the system can cause on the drivers performance and actions. Generally, this class of systems can achieve good results. On the contrary, a non-invasive approach provides no interference with the driver. However, these systems have usually lower performance when compared to the first ones.

In an intrusive systems, driver biometric features and physiological parameters by using body sensors are often detected. The principal technologies to measure physiological parameters can be found in (Rimini-Doering et al. 2001) and (Ogawa and Shimotani 1997) and are: the Electrocardiogram (ECG), Electroencephalogram (EEG), Electro-oculogram (EOG), skin temperature, head movements, pulse and oxygen saturation in the blood. Intrusive systems are characterized by their reliability and robustness, since most psychophysical parameters can be acquired in a straightforward way and therefore these systems achieve good results in terms of percentage of correct detection of the driver level of fatigue. However, due to the vast number of signals to acquire and process, these systems tend to be complex and extremely invasive. Moreover, the monitoring of physiological parameters, as the ones described above, requires voluminous and not practical devices that cannot be easily placed into a vehicle. A driver simulator that makes use of physical parameters of the driver was developed by Mitsubishi Electric in (Ogawa and Shimotani 1997).

The other class of drowsiness detection systems is represented by the non-intrusive systems. These are based on visual observation of the driver and therefore they do not affect him. In particular, computer vision represents the most promising non-intrusive approach to monitor driver's drowsiness. This class of systems can carry out the detection of the driver fatigue level, analyzing one or more parameters extracted from a video stream coming from a car installed CCD camera. Among the class of non-intrusive systems, it is possible to distinguish between mono-parameter and multi-parameter systems. However, both mono and multi-parameter systems make use of visual information coming from driver's eyes. One of the most used parameter is the PERCLOS. It measures eye closure rate and it is defined as the proportion of time the driver eyes are closed more than 80% within a specified time interval. Works using PERCLOS (Dinges et al. 1998; Grace 2001; Grace et al. 1999) as main visual parameter, are based on studies of Weirwille (1999), showing the effectiveness of this parameter to detect moments of driver hypovigilance. In (Kojima et al. 2001) the authors exploit the correlation between the driver attention level and the eye closure rate. The main part of the system is designed to determine the position of the eyes. In the first video frame an approximate eye area is manually pointed out. Successively, the algorithm detects the eyelids, measures the distance between upper and lower eyelids, and, finally, computes the duration of eye closure time. A preliminary evaluation of the association of driver's vigilance and eyelid movements can be found in (Boverie et al. 1998).

Special features of the human retina has been exploited in several works in order to facilitate driver's eyes detection. Retina reflects different amounts of infrared light at different frequencies. In (Morimoto et al. 2000), the retina behavior with light sources at different wavelength was analyzed. When the light direction is coincident with the optical axis, the retina reflects the 90% of an incident 850 nanometer (nm) wavelength light, while only the 40% of the incident light is reflected if a 950 nm wavelength light is used. This special behavior is known as the "bright pupil" effect. Many systems proposed in literature are equipped with video capturing systems, capable of exploiting this reflective behavior. In (Grace et al. 1998) the proposed system makes use of two separate cameras, both focused on the same point, one outfitted with an 850 nm filter and the other with a 950 nm filter. The external lens is surrounded by an IR led ring and the optical axis is coincident with the light direction. By subtracting the images coming from the two cameras, the authors obtain an image in which there are only two objects that correspond to the retinal reflections. This image is then processed to extract the regions corresponding to the driver eyes and to measure the degree of eye closure. Despite the simplicity of processing, a very complex acquisition system is required, in order to perform synchronization between the video streams coming from the two cameras. However, the implemented process requires image registration and synchronization, while retina detection is based on a simple image subtraction. In (Hamada et al. 2003) the eye closure rate is used to assess the driver's level of fatigue. The capturing system comprises a pulsed infrared light source with a wavelength of 850 nm and a CCD camera equipped with an 850 nm filter. However, this work does not exploit the "bright pupil" phenomenon, because light direction does not coincide with optical axis. This simplification leads to a complex algorithmic approach that includes the use neural network classifier for face detection, and eyelids identification for measuring the blinking time.

A different class of works proposed in literature exploits the gaze direction, instead of the level of eyelid closure, in order to determine the level of drowsiness. These works are focused on driver distraction level rather than on the driver fatigue level. In (Wahlstrom et al. 2003), the authors propose a system for monitoring the driver activity on the basis of the gaze direction analysis. The analysis requires a complex computer vision analysis in order to detect the driver's face area, lips and eyes. Face area and lips are detected by means of color-based segmentation, while eyes are detected as the biggest and darkest components inside the region above the mouth. This processing phase requires "a priori" knowledge about skin and lips color. In addition, the system does not support on-line video processing, but only "a posteriori" analysis. Color-based analysis is also exploited to detect driver's eyes in (Smith et al. 2000, 2003), and to detect driver's mouth in (Rongben et al. 2004).

Multi-parameter systems use both several bio-behavioral sensors and information fusing techniques, generating highest complexity system with high processing time. In (Ji et al. 2004), the authors use eyebrow movements, gaze direction, head movements and facial expression as bio-behavioral parameters. These parameters are then combined through a probabilistic model for driver fatigue detection. The system consists of two infrared cameras, the first one focused on the eyes, and the second one focused on the face to monitor head movements and facial expressions. This system exploits the "bright pupil" effect for the eye-detection and tracking, as well.

In (Ueno et al. 1994; Onken. 1994; Gu et al. 2002; D'Orazio et al. 2004; Damousis and Tzovaras 2008; Liang et al. 2007) are presented interesting works concerning the detection of driver's drowsiness. Although these works show several interesting algorithmic solutions, they offer exclusively software implementation solutions and therefore they require the use of a workstation equipped with a video acquisition system.

In this paper a non-intrusive, real-time drowsiness detection system, exploiting the "bright pupil" effect to detect the driver's level of fatigue, is presented. The system can be classified as a mono-parameter system using the PERCLOS parameter to detect driver hypovigilance and, consequently, critical conditions and dangerous events. Despite to the previously developed approaches, the system has been designed and developed for an embedded FPGA based device, performing real-time frame processing (up to 60 fps) to be installed and used in a common car. General purpose computers are found to be inadequate to the high speed image processing and machine vision tasks, while custom designed hardware for real-time vision tasks are very expensive and they do not offer the necessary flexibility. The hardware solution proposed is driver friendly and not expensive thanks to the current availability of mature reconfigurable hardware, like Field Programmable Gate Array (FPGA) that, coupled with the usage of hardware programming languages, offers a good and rapid path for porting image and video applications on programmable devices.

Finally, the proposed approach represents a good trade-off between hardware deployment cost and algorithmic complexity. Our detection system is based on simple acquisition components and it does not require complex components synchronization, as outlined in (Grace et al. 1998). Adopting simplified hardware components increases the algorithmic complexity for eyes detection but leads to a simple and inexpensive deployment. At the same time, the "bright pupil" effect when the 850 nm light direction is coincident with the optical axis, simplifies the driver eyes detection phase, so that either neural network for face detection or eyelids identification for measuring the blinking time are not needed (Hamada et al. 2003).

3 The adopted geometrical face model

The proposed system exploits the "bright pupil" phenomenon in order to mark the video frames with the closed driver's eyes (less that 80%). The adopted image processing technique is based on a simple geometrical face model, that support the identification of image elements corresponding to driver's eyes.

In computer vision, several face models have been already proposed. Accordingly to the complexity of the task in which the model is used, i.e. face detection or face recognition, the model can be extremely complex or simple. A detailed survey of the main face detection techniques based on geometrical face models can be found in (Hjelmås and Low 2001).

In our work, the face model is used to detect driver's eyes. We select a light face model, so that its complexity degree is low in order to have low computational loads and real-time performance.

The adopted face model assumes that the driver's face is opposite to the IR CCD camera, embedded on the car dashboard. The driver–camera distance ranges through similar values, depending on the set of possible positions of the driver seat. The above general assumptions identify the image region in which driver's eyes are as the upper central image region (when the 720 × 576 image is ideally split in three columns and two rows). Despite to the simplicity of the adopted approach, the used face model leads to interesting results, as confirmed in (Rikert and Jones 1998; Su et al. 2002; Shin and Chun 2007).

Other useful information contained in the adopted face model concern the iris shape and size, and the geometrical–spatial relationships between the eyes. The assumptions on the iris shape and size are greatly generic and there is no relation with the driver's eye shape. We assume that the iris has a quasi-circular shape and it has similar size included in a given range in order to filter and drop image areas with high light intensity but different shape or size. The above feature allows us to select "bright pupil" related blobs and to drop light blobs coming from driver's glasses or little city light spots. At the same time, the assumptions on iris shape are confirmed by several works presented in literature (Moriyama et al. 2006; Moriyama and Kanade. 2007). Obviously, only a portion of the iris disk is visible when the iris is partially covered by the eyelids, and thus the circularity test will fail. Anyway, with our assumptions, we can assume that eyes are closed (more than 80%, as needed for PERCLOS) if the above overlapping happens and, consequently, the whole drowsiness detection chain is coherent.

To formalize the geometrical relationship among driver's eyes, we use the relationships between the centroids of the two irises. Once again, the assumed geometrical constraints are quite simple and they have only a filtering function. Given the distance d between the two centroids and the angle α between the connecting line of two centroids and the horizontal axis, we assume that d is included in a given range and α does not exceed 30°. Similar constraints can be found in (Tang and Zhang 2009).

4 The proposed drowsiness monitoring system

As depicted in Fig. 1, the system proposed in this paper is able to perform real-time processing of an incoming video stream in order to infer the driver's level of fatigue by determining the number of frames in which driver's eyes are closed. Successively, processing system output is sent to an alarm system that will activate an alarm when an index, computed by mean of PERCLOS parameter, i.e. the portion of time eyes are closed more than 80%, is beyond a security threshold.

Figure 2 depicts the block diagram of the prototyped drowsiness monitoring system. The first step comprises a process of segmentation of the frames from the video stream in order to isolate the regions that could correspond to the driver's eyes. Subsequently, a connected component analysis allows to detect those blobs that could match the driver's eyes. Out of all the connected components a list of all the possible eye pairs is extracted, by means of shape and geometrical tests. Eyes region detection as well as shape and geometrical tests have been performed following the simplified face model described in Sect. 3. Then, by analyzing the past history of the system, only one pair is selected from the list as the likeliest eye pair taking into account past observations. Once established the presence or absence of the driver's eyes, the level of fatigue is estimated as the proportion of time the eyes have not been detected within a time window. Finally, if the level of fatigue is considered to be higher than a threshold value an alarm is activated.

System design and development strategies depend on the target the developed device is employed. The designed drowsiness monitoring system should have real-time performance, so that the system should be able to process at least 25 fps. Starting from the above requirements, the pipelined video input processing was used as main design strategy. Data flowing through the processing system are represented as a stream, in which the base element contains information about the pixel intensity and coordinates.

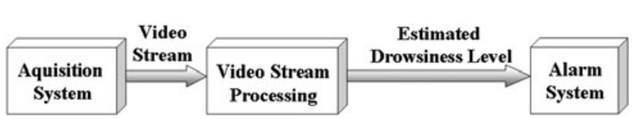

Fig. 1 The block diagram of the overall system

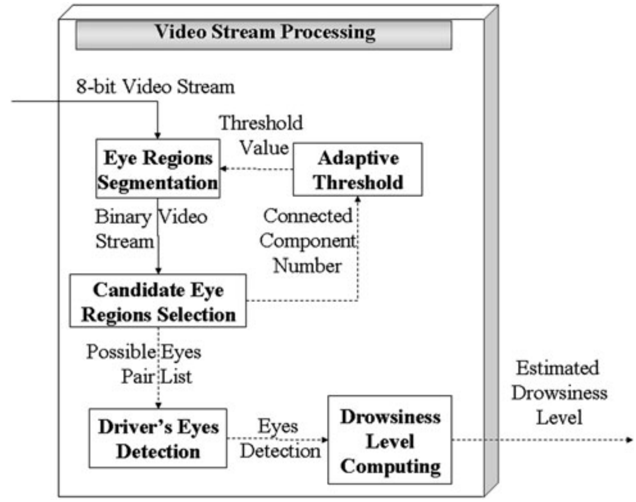

Fig. 2 The block diagram of the prototyped drowsiness monitoring system: each *rectangular box* is a processing stage, *continuous lines* indicate data streams, *dotted lines* indicate processing box parameters

Using streams, the system can be implemented as a network operating synchronously, with each stream passing one datum per clock cycle. The various system functionalities can be performed by blocks that can be thought of as filters, taking streams as inputs and returning streams as outputs. Thanks to this block implementation the system architecture can be organized as a pipeline, allowing the parallel execution of different functionalities in different processing stages. In this way, execution times are drastically reduced allowing real-time video processing.

Acquisition system output is split into two identical streams and sent to two processing chains that are executed as two parallel pipelines. The first pipeline deals with input video stream pixel processing in order to produce the output for display. The second pipeline deals with frame processing and it is used to extract information from the video stream such as the list of possible eyes, the list of possible eye pairs and the calculation of the driver's level of fatigue. The information concerning the position of the eyes are also shared with the first pipeline to display the eyes on screen. In the following, each block of the entire system will be detailed.

4.1 Eye regions segmentation

The system performs a segmentation operation on the eight bit video frame coming from the acquisition system in order to isolate the candidate eye regions within the current frame. The segmentation is carried out with a threshold operation that exploits the previously described "bright pupil" effect.

A segmentation is then carried out by means of a threshold operation so generate a binary image, where candidate eye pixels are set to white, while the background is set to black. However, a fixed threshold is not the optimal choice, since the video sequences may contain noise or can be acquired with different light conditions. So, the segmentation module uses a variable threshold that can adaptively change to compensate environment brightness variations. The designed adaptive threshold has a fixed upper value and a variable lower value that can grow or decrease accordingly to the computed connected components in the previous frame. With more details, if an high number of connected components is detected, then the lower threshold value is assumed to be too low and it is consequently incremented. On the contrary, if the number of connected components is too low, the lower threshold value is decremented. However, threshold increments and decrements are performed so that the lower threshold value is always within a fixed range.

As described in Sect. 3, a clipping operation is performed to select the central part of each acquired image. Successively, a chain of morphological operations (opening operations followed by a closing operation) is applied to reduce noise and delete little items and irrelevant details. Figure 3 shows the described steps.

4.2 Candidate eye regions selection

This block takes as input the binary image returned by the previous block and determines a list of binary blobs, i.e. a list of possible eye pairs. With more details, the previously segmented blobs are heavily coupled generating connected component pairs. Accordingly to the face model described in Sect. 3, connected component pairs has been checked against the selected shape and geometric rules. The shape test detects binary blobs satisfying size and shape constraints (driver's eyes have a quasi-circular shape), while other bright components are discarded. To detect if a blob has a quasi-circular shape the following heuristic tests were performed:

- the blob's bounding box is almost similar to a square;
- the blob's area (computed as the number of pixels) is similar to the area of an ideal circle with radius equal to the half of the mean among bounding-box dimensions;
- the two dimensions of the bounding box have to be comprised in a fixed range.

Then, the geometrical test is performed to check and validate inclination and distance between all possible connected components. The last check guaranties that driver's head does not have a high inclination or an unnatural posture and that the distance between the eyes is kept within a useful range. The output of this block is represented by the list of all the possible eye pairs. Figure 4 shows the described steps. Block implementation has required a two stages pipeline for the connected-component analysis and the shape and geometrical test, respectively.

4.3 Driver's eyes detection

In Fig. 5 the overall functional scheme of the driver's eye detection block is shown. The process is aimed to detect the eye pair with the highest probability to represent the effective driver's eyes in the current processed frame.

Eye pair selection is based either on the analysis of the current frame, or on the results of the previous analyzed frames. In that sense, the process can be defined as a stateful process, since it validates the current results on the basis of the eye pair detected in the previous frames. In order to keep trace of the past history, this system uses a W sized temporal window to store position and inclination of eye pairs detected in the latest W frames. So, each eye pair detected in the temporal window is labeled with a class, to trace the different hypothesis (eye pairs) in the latest W frames, and a weight, showing the number of occurrences of eye pairs belonging to the same class within the temporal window.

The process selects eye pair in the current frame, accordingly to the number of detected candidate eye pairs, too. When no eye pair is detected, the system assumes no open driver's eyes are present in the current frame. When an unique candidate eye pair is detected, the systems assumes this is the eye pair for the current frame and assigns it a specific class. When two or more candidate eye pairs are detected, each eye pair is labeled with a specific class. Successively, the process selects the eye pair having the minimum spatial distance by its own class in the next frames. An example of how the class assignment is performed is shown in Fig. 6.

Given the temporal window, driver's eyes are marked as open when the number of occurrences of the predominant class exceeds half of the temporal window. The following equation defines the above statement:

Fig. 3 **a** the original image; binary images after: **b** segmentation process, **c** clipping and morphological operations (image **c** is zoomed with respect to the image **b**)

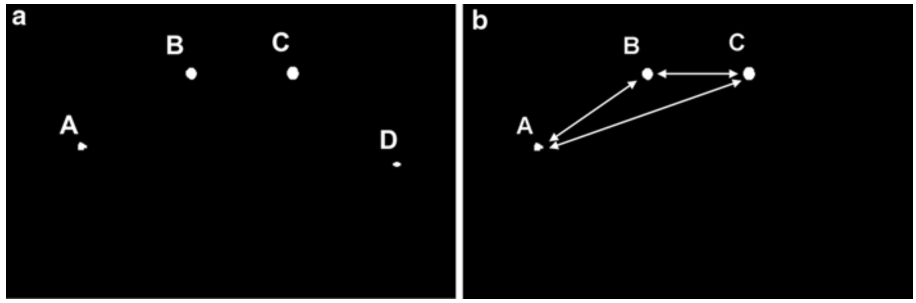

Fig. 4 **a** the performed shape test results: the quasi-circular blobs *A*, *B* and *C* fit shape constraints, while the *D* square marks the discarded blobs; **b** the performed geometrical test results: considering human eyes distance, *AB* is too steep, *AC* is too long, while *BC* fits the geometrical constraints

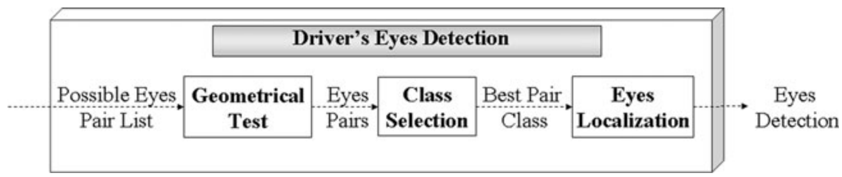

Fig. 5 Functional scheme of the driver's eyes detection block

$$detected\_eyes = \begin{cases} true & : \quad N(C_i) \geq \frac{Length(T_w)}{D_w} \\ false & : \quad otherwise \end{cases} \tag{1}$$

where $N(C_i)$ is the number of occurrences of the predominant class, $Length(T_w)$ is the temporal window lengthand D_w is the distance window, defined to trace the distance between eyes position in two consecutive frames.

4.4 Drowsiness level computation

Accordingly to the standard definition, PERCLOS measures the proportion of time that the pupils are at least 80% covered by the eyelids (Wierwille 1999). In the proposed system, driver's level of fatigue is computed as the proportion of frames within a given interval in which the driver's eyes are not detected. The above approximation is supported by the fact that the retina does not reflect the needed infrared light for blob generations when driver's eyes are at least 80% covered.

PERCLOS value is directly related to the number of frames with no driver's eye detection. However, experimental trials have suggested that a robust measure of the level of fatigue has to follow sudden changes by incorporating information about the past history of those levels. So, PERCLOS value is carried out by a weighted function including the present value as well as the weighted past values:

$$overall\_PERCLOS(t) = \alpha * PERCLOS(t) + (1 - \alpha) * PERCLOS(t - 1), \tag{2}$$

where α is a scale constant. In our trial, the alarm system is activated either when the $overall\_PERCLOS \leq 0.5$ or driver's eyes are undetected in 18 consecutive frames (300 ms). Lower thresholds leads to a very sensible system with a considerable number of false positive.

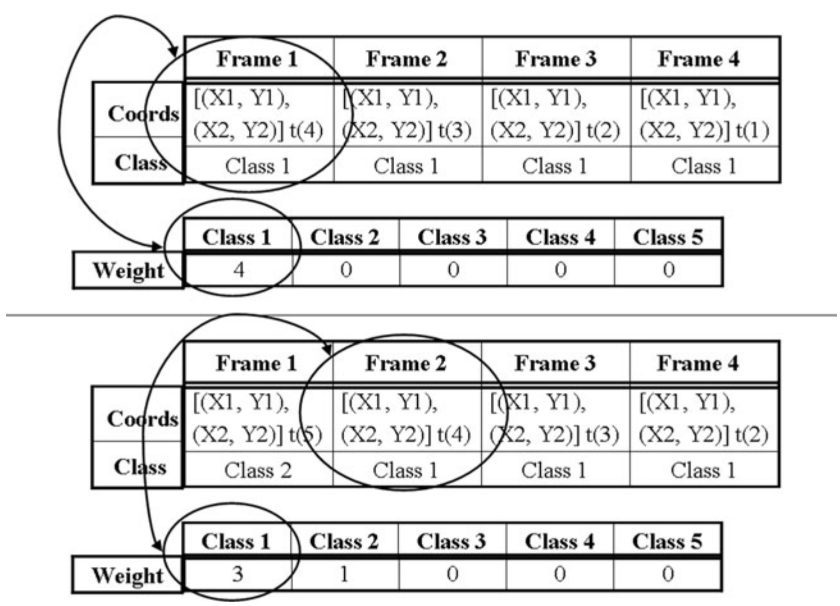

Fig. 6 Temporal window in two consecutive time steps. The final item, associated with the highest weighted class, will be selected. Time sliding is implicit in the occupied columns, i.e Frame 1 contains the item detected in the (t − 1) frame, Frame 2 contains the item detected in (t − 2) frame, and so on

5 Experimental results

System behavior and performance are concerned with eyes position tracking by exploiting the bright pupil phenomenon. The acquisition system, used for monitoring the driver's face, is based on the JSP DF-402 infrared-sensitive camera with a spectral range of 400–1,000 nm and a peak at approximately 800 nm. Specifically, the camera works as a color camera in daylight and as an infrared camera under low light conditions. Moreover, the camera is provided with a led ring, placed around the lens, which emits infrared light. In Table 1 the technical specifications of the JSP DF-402 IR camera are listed.

The camera was placed over the car dashboard, assuring that the light emitted from the infrared leds is coincident with the optical axis (see Fig. 7).

5.1 Hardware and software environments description

The previous described drowsiness monitoring system has been prototyped with the Celoxica RC203E board employing the Xilinx Virtex II XC2V3000 FPGA (Celoxica 2005a). The flexibility and high speed capability of FPGAs make them a suitable platform for real-time video processing.

The entire system was described using the Handel-C language (Celoxica 2005b). Handel-C is an algorithmic-like hardware programming language for rapid prototyping of synchronous hardware designs that uses a similar syntax to ANSI C, with the addition of inherent parallelism and communications between threads. The output from Handel-C compilation is a file that is used to create the configuration data for the FPGA. The Celoxica DK 4.0 software design suite (Celoxica 2005c) was used to create system design starting from Handel-C description. The tool used to design the processing system was the PixelStreams library (Celoxica 2005d), an architecture and platform independent library where image-processing blocks, known as filters, are assembled into filter networks and connected by streams. This library is designed primarily for dealing with high-speed video input processing and analysis, and high-speed back-end video generation and display. The PixelStreams architecture makes it easy to create custom filters for performing specialized image processing operations.

Table 1 Camera technical specifications

Specification	Value
Style	35 mm camera
Optical zoom	Fixed focus
Lens F	3.6 mm
IR series distance	10 m (8 Unit infrared led)
IR status	Under 10 lux

Fig. 7 The IR CCD camera on the car dashboard

5.2 Experimental trials

System development and tuning were performed with a human subject on a light controlled environment, including natural driver head movements as well as driver hypovigilance and drowsy events. The subject simulates regular eye blinks, slow and accelerated heads movements. In same cases, eye blink duration was extended to simulate a drowsiness event. Figure 8 shows some snapshots of the system output in this artificial deployment: frames 8a, b, and c show that system performance is not affected by driver–camera relative distance; frames 8d, e, g, and h show the tracked driver's eyes when driver's head horizontal and vertical position is perturbed. Finally, frames 8f and i shows two detected alarms, in which driver's eyes are closed or out from the camera visual field.

Successively, the tuned drowsiness monitoring system has been installed on the car dashboard and tested in real operating condition, while the driver and the car moves along the city streets. In that case, the environment is very noisy due to the several external light sources (cars, unidentified city lights). Figure 9 shows three snapshots of the system output in this real deployment. As it can be noticed, external illumination does not compromise the correct eyes detection. Three PAL compliant videos were recorded and used to test system performance. The first video (ID = 1) was recorded in the controlled environment and it can be considered as the starting test, since driver's movements were slow and limited. However, the four simulated driver drowsiness events were correctly detected by the system. The second video (ID = 2) was recorded in the controlled environment, as well. However, in that case, driver head movements were very fast, simulating short driver consciousness losing. The drowsiness monitoring system have correctly detected three consciousness losing events. Finally, the last video (ID = 3) was recorded with a subject in a real driving situation. External illumination was not controlled and there was much noise in the scene

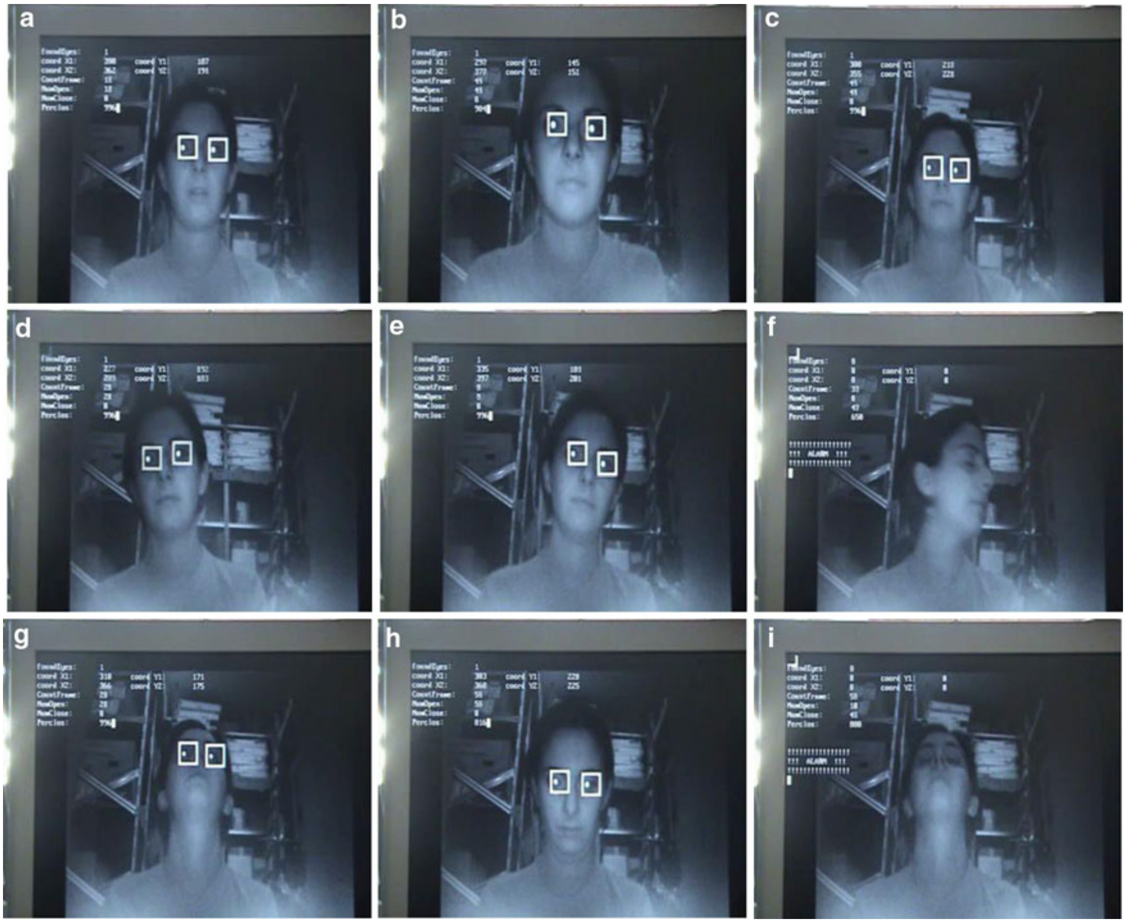

Fig. 8 System evaluation—Snapshots from video 1 (frames **a**, **b**, and **c**), and video 2 (frames **d**, **e**, **f**, **g**, **h**, and **i**). Tracked driver's eyes are marked with *white squares*. System performance is not affected by driver–camera relative distance (frames **a**, **b**, and **c**), by driver's head horizontal (frames **d** and **e**), and vertical (frames **g** and **h**) position. Frames **f** and **i** show two detected alarms, in which driver's eyes are closed or out from the camera visual field

Fig. 9 System evaluation—Snapshots from video 3 (frames **a**, **b**, and **c**). The environment is very noisy due to the several external light sources (cars, unidentified city lights). Tracked driver's eyes are marked with *white squares*

due to the several light sources in the environment. The system recognized nine eye blinks, none of them was prolonged. There were not false positives, but there were four wrong eyes detections caused by the presence of external blobs. The previously described results are summarized and presented in Table 2.

5.3 FPGA resources

As stated before, the drowsiness monitoring system has been prototyped with the Celoxica RC203E board employing the Xilinx Virtex II XC2V3000 FPGA (Celoxica 2005a). In addition, the board is equipped with the following devices:

- Xilinx XC95144XL CPLD;
- 2 × 4 MB SRAM;
- Cypress CY22393 programmable clock generator;
- Philips SAA7113H video input processor (with A/D converter);
- VGA video output processor;
- n. 2 led;
- n. 2 7-segment display;
- LCD touch screen display.

The prototyped drowsiness monitoring system performs real-time processing of a video stream coming from the JSP DF-402 infrared-sensitive camera. System output is visualized through the board LCD display. Table 3 summarizes the used FPGA resources for the prototyped system. The IOB row reports information about board input-output blocks, the MULT18X18 reports information about board combinational signed 18-bit × 18-bit multipliers, BLOCKRAM row reports information about board SRAM memory, the BUFGMUX row reports information about board multiplexed global clock buffers, and finally, the SLICE row reports information about board logical cells contained in the Configurable Logic Block (CLB).

5.4 Processing times

As stated before, the drowsiness monitoring system is based on two parallel pipelines. The first pipeline deals with input video stream pixel processing in order to produce the output for display. The second pipeline deals with frame processing and it is used to extract information from the video stream such as the list of possible eyes, the list of possible eye pairs and the calculation of the driver's level of fatigue. The information concerning the position of the eyes are also shared with the first pipeline to display the eyes on screen. In addition, the basic elements of the pipeline were designed so that they could complete a single processing in one clock cycle.

The prototyped system is able to process the video stream coming from the IR CCD camera. With more details, the board video input processor (Philips SAA7113H) gives a real-time PAL compliant video (720 × 576 pixels, 25 fps). The processing core, having a working frequency of 65 MHz, performs the entire frame processing in only 16.7 ms, so that real-time PAL video stream processing is achieved. In addition, the processing core has the potentiality to implement real-time processing also with an advanced video input device, generating 60 720 × 576 fps.

In the current version, the board video output processor, using an ad-hoc designed FrameBuffer, is able to drive the board LCD display showing a 1,024 × 768 video at 60 Hz with a throughput of 47.2 Mpixel/s.

Table 2 Result summary

Video ID	Duration (s)	Natural eye blinks	Drowsiness events	Alarms
1	57	4	4	4
2	95	0	3	3
3	57	6	0	0

Table 3 The used FPGA resources for the prototyped system

Resource type	Used resources (%)	Available resources
IOB	178 (36)	484
MULT18x18	8 (8)	96
BLOCKRAM	42 (43)	96
BUFGMUX	3 (18)	16
SLICE	10,324 (72)	14,336

6 Conclusion

Microcontroller incorporation into vehicles is very common. Automotive manufacturers continue to improve in-vehicle comfort, safety, productivity, and entertainment through their use. However, a microcontroller is an application specific product, thus for each application a new device with a different set of functions and features is needed. Alternatively, FPGA re-programmability and reusability shorten time to market, improve performance and productivity, and reduce system costs compared to traditional DSP (Digital Signal Processing) and ASIC (Application-Specific Integrated Circuit). FPGAs scalability and code reuse eliminate product obsolescence and can reduce costs because developers can quickly and easily upgrade their designs to target the latest low-cost device. In addition, the re-programmable nature of FPGAs offer yet another level of advantage. In-vehicle devices programming enables algorithm and functions to be upgraded after each product version development. Programmable and re-configurable hardware offers high potential for real-time video processing and its adaptability to various driving conditions and future algorithms.

In this paper an embedded monitoring system to detect symptoms of driver's drowsiness has been presented and described. By exploiting bright pupils phenomenon, an algorithm to detect and track the driver's eyes has been developed. When a drowsiness condition is detected, the system warns the driver with an alarm message. In order to prove the effectiveness of the proposed approach, the drowsiness monitoring system was tested first in closed and controlled environments with different illumination conditions, and then in a real operation mode, installing an IR CCD camera on car dashboard.

The system has correctly detected driver drowsiness symptoms. As shown by the experimental trials summarized in Figs. 8 and 9, the presented monitoring system shows good performance also in presence of rapid driver's head movements, i.e. when driver's head horizontal and vertical position is perturbed. Even if the system has been tested with a fixed focus IR camera, system performance is not affected by driver–camera relative distance. Overall, the proposed system belongs to the non-intrusive monitoring system class, causing reduced annoyance or unnatural interactions for the driver. During our test trials, natural driver's head horizontal and vertical movements were absorbed by the system. However, some false positive alarms had been detected when driver looked the other way or driver was distracted. In that case, driver monitoring system alarms curbed driver distraction.

Due the use of infrared camera, the drowsiness monitoring system can be used with low light conditions. However, statistics confirm that the most of the drowsiness related car accidents happen during the evening/night hours, i.e. with low external light conditions. In the real operation mode, when the IR CCD camera is installed on car dashboard, the system encountered some problems with light poles, since they were classified as eyes for their shape and size. In addition, other faulty operations have been detected when the driver is wearing glasses or earring IR-reflecting objects. Future versions will be aimed to overcome these limitations.

On the other hand, the current availability of mature network technologies, such as VANET and WAVE, offers a good path for developing intelligent roads in which the environment can continuously monitor what's happening in it and vehicles can communicate each other exchanging its relative positions and potentially dangerous conditions, such as the presence of an uncontrolled vehicle.

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