Michał Włodarczyk
Damian Kacperski
Tomasz Płuciennik
Kamil Grabowski

IMAGE ACQUISITION SYSTEM BASED ON SYNCHRONIZED HIGH-RESOLUTION GIGABIT ETHERNET CAMERAS

Abstract *Over the past few years, a huge increase in the number of various computer vision applications can be observed. These are widely used in such areas as video surveillance, medical diagnostics, biometrics recognition, and the automotive and military industries. Most of these solutions take advantage of high-resolution cameras in order to obtain high-quality images. Surprisingly, little attention is paid in the literature to the practical implementation of off-the-shelf image acquisition systems. Most of the available solutions are composed of custom-developed electronic devices that use specialized multi-core DSPs and/or FPGA technology. Therefore, a novel realization of a scalable and comprehensive image acquisition system based on synchronized high-resolution Gigabit Ethernet cameras is presented in this paper. The proposed solution allows for the connection of multiple cameras along with any number of external illumination modules. The selected devices can be synchronized with each other in user-defined configurations; hence, a designed solution can be easily integrated in both simple and complex applications. The authors describe the design and implementation processes of the proposed platform in detail. The performance issues that can occur in such systems are presented and discussed. The obtained results are encouraging and useful for the development of similar solutions.*

Keywords image acquisition, cameras synchronized with illumination, biometrics, face recognition

Citation Computer Science 18(2) 2017: 179–194

1. Introduction

Over the last few years, a huge increase in the number of various computer vision applications can be observed. They are widely used in such areas as video surveillance [1], medical diagnostics [27], biometrics recognition [5], and the automotive and military industries [10, 35]. Most of these solutions take advantage of high-resolution cameras in order to obtain high-quality images; of which, the processing results are more exact and comprehensive. On the other hand, the data processing subsystems need to handle more data; therefore, the design and development of these modules has become a complex and significant challenge. This becomes even more complicated when the application requires the use of multiple cameras synchronized with each other as well as with external illumination sources.

Surprisingly, little attention has been paid in the literature towards the practical implementation of off-the-shelf image acquisition systems. Most available solutions, like [25, 39, 40] are composed of custom-developed electronic devices that use specialized multi-core DSPs and/or FPGA technology. Furthermore, they are often designed for specific purposes, which makes them difficult to integrate into other solutions. Therefore, a novel realization of a scalable and comprehensive off-the-shelf image acquisition system based on synchronized high-resolution Gigabit Ethernet (GigE) cameras is presented in this paper. The proposed solution allows for the connection of multiple cameras along with any number of external illumination modules. The selected devices can be synchronized with each other in user-defined configurations; hence, the designed solution can be easily integrated in both simple and complex structures. For instance, it allows for the combination and synchronization of two independent vision systems that operate in different light spectra (visible and near infra-red light) so that they do not interfere with each other. The paper is aimed at practical problems that occur in such scenarios. The authors describe both the design and implementation processes of the proposed platform in detail. Additionally, performance issues are presented and discussed. The presented solution is dedicated to the acquisition of high-resolution biometric data in a non-cooperative identification system.

The paper is organized as follows. Section 2 contains the overall description of the proposed system. Section 3 describes its software architecture. Section 4 presents implementation details. Section 5 shows our computing performance evaluation experiments. Section 6 describes the biometric data acquisition platform that demonstrates the validity of the proposed framework. Finally, Section 7 concludes the paper.

2. System overview

The system architecture is presented in Figure 1. It consists of the following components:

- GigE cameras,
- processing unit,

- triggering unit,
- triggered illumination sources.

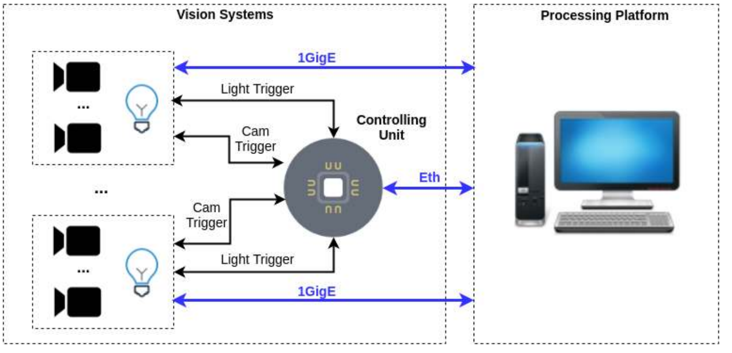

Figure 1. Proposed system architecture.

The system is based on GigE cameras because they are considered state-of-the-art for high-performance machine vision and industrial applications. Their advantages are:

- fast data transfer rates (up to 125 MB/s),
- single-line cabling (PoE [17]),
- long cable lengths (up to 100 m),
- large selection of available cameras and accessories,
- relatively low price of commercially available cameras,
- easy integration with existing infrastructure.

GigE cameras communicate with the use of the generic GigE Vision [13] standard that was introduced by the Automated Imaging Association (AIA) in 2006. This standard relies on the GenICam [11] to transform data and describe features supported by the cameras. Due to this fact, cameras from different manufacturers are compatible with each other in most cases, so they can be replaced or changed in a relatively easy manner. In most simplified scenarios, the image data collected from the cameras can be transmitted to a processing unit through a GigE switch. However, it may turn out that its network bandwidth is insufficient to provide high-quality images at a decent frame rate. Assuming that the number of cameras N that are multiplexed into one gigabit channel is 2, the frame rate F is set to 15 Hz, and a single image has a size S equal to 5 MB, the required network bandwidth B would be as in (1):

$$B = N \cdot S \cdot F = 2 \cdot 5 \cdot 15 = 150\,\mathrm{MB/s} \tag{1}$$

On the other hand, the maximum theoretical throughput of Gigabit Ethernet is 125 MB/s. Therefore, depending on the number of cameras, image resolution, and desired frame rate, an Ethernet extension card that provides additional sockets may be necessary to provide the required bandwidth connectivity.

The system provides the possibility to synchronize selected cameras with each other. There are many methods that can be applied to solve this problem, such as those presented in [4, 28, 31]. Initially, the IEEE 1588 Precision Time Protocol (PTP) [16] was tried for this purpose (which is one of the most-effective mechanisms for network device synchronization [36]). However, it is extremely time-consuming in its implementation and is not supported by all cameras.

The second method significantly reduces the number of available devices from which to select. Consequently, the authors have two approaches to choose from: a self-developed software mechanism or hardware synchronization from an external source. Because the hardware method is more reliable and time-secure, it was selected for our final implementation. Such an approach also allows for easy integration with external illumination modules that can be triggered from the same lines as the cameras. Additional light can then be turned on only for the duration of image acquisition. In a simple scenario, the external triggering unit can be realized with the use of an electronic device equipped with an Ethernet interface port. This allows for the use of a single Ethernet cable for communication with the camera and its controller. Moreover, this does not have an affect on a camera's maximum distance limit. As a triggering unit, an off-the-shelf device like *myRIO National Instruments card* [30] can be used. However, it is relatively expensive ($499 for universities). More-efficient in terms of cost and performance is the of use of any evaluation kit equipped with an embedded processor and Ethernet port socket.

Finally, the image data is received and processed by a high-performance CPU. The main tasks of the CPU are data acquisition, data analysis and processing, and controlling the triggering units. The PC also runs the control application for managing and monitoring the system operations. Moreover, it can provide a graphic interface for users and operators. Theoretically, the triggering unit can be removed so that the image acquisition and illumination is triggered directly from the CPU. Some PCs are still equipped with a parallel port (IEEE 1284 [18]) for communication; however, all of them feature older construction and are not readily available for purchase nowadays. There are IEEE 1284 converters available on the market, but most of them work only as virtual printer adapters. Due to this fact, they could not be used for digital output signal generation.

Summing up, the proposed construction is limited to only a PC computer, triggering unit board, and eventually a frame grabber card, if using multiple high-resolution devices. This means that the total cost of the system can be reduced to as low as $500 when using, for instance, a *Dell Optiplex 790 MiniTower Business High Performance Desktop Computer* for data processing and a *Tiva Connected LaunchPad* evaluation kit for camera and illumination synchronization [2]. This is much less then using custom-developed electronic devices with specialized multi-core DSPs or FPGA technology, like in [25, 39, 40]. Moreover, both DSPs and the FPGA technology are difficult to develop for, which implies high costs of software development and maintenance.

3. Software architecture

The crucial part of the presented system is software responsible for interaction with the hardware, data acquisition and processing, and system supervising. The control applications should provide communication between all modules of the system, interfaces for the system users, and mechanisms for data logging, archiving, and analysis. Moreover, they should be reliable and easy to maintain and upgrade; therefore, the system is based on a set of small independent services. It is somewhat similar to a microservice architecture [29, 37] that has grown in popularity in recent years. Such an approach provides a high level of generality, scalability, and fault isolation and reduces the impact of correlated failures. For instance, a connection to a GigE camera is blocking, which means that only one process can connect to a single device at the same time. Having this functionality as a separate service makes it possible to acquire images and then distribute them internally to other modules. As a result, many applications can receive and process images independently and at one time. The proposed architecture is summarized in Figure. 2.

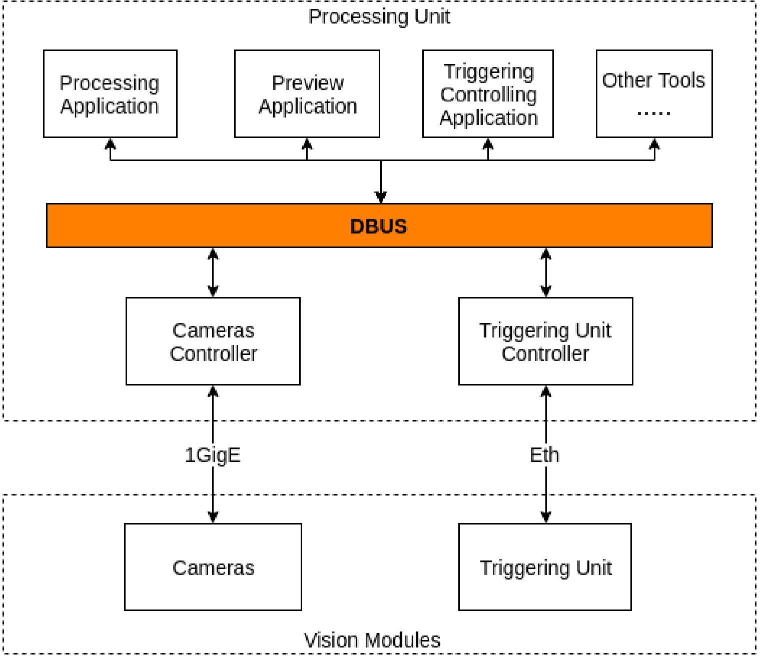

Figure 2. Software architecture.

The authors based the processing unit on a Linux operating system. The Ubuntu 15.04 distribution is used, as it provides a large selection of tools and is supported by a wide range of hardware. Each software component communicates with the others by using D-Bus [7]. D-Bus is a message bus system that contains interfaces for sharing data across multiple Linux processes. In addition to interprocess communication, it helps to coordinate the process lifecycle, makes it simple and reliable to develop a single instance application or daemon, and launches applications and daemons on demand when their services are needed [8]. The external modules are connected with the use of Ethernet, as was explained in Section 2.

4. Implementation

4.1. Triggering unit

The triggering unit is based on a *Tiva Connected LaunchPad* evaluation kit manufactured by *Texas Instruments*. It is equipped with a 120 MHz ARM Cortex-M4 TM4C1294 processor, 1 MB of flash memory, and 256 KB of SRAM. Moreover, it has a large number of digital outputs (66), which makes it possible to handle many independent triggering circuits.

The proposed implementation provides 16 channels that can be used to trigger a group of cameras or illumination modules. All outputs are synchronized with each other in such a way that only one triggering circuit can work at a time. Such a configuration means that each connected device works independently and do not interfere with each other. For instance, the illumination modules dedicated for selected cameras do not cause overexposure on images acquired from other devices. This approach also allows the application of more-sophisticated methods to manage scene brightness. The user can, for instance, turn on the illumination before data acquisition to prevent the red-eye effect on facial images.

Apart from triggering outputs, the triggering unit is also equipped with eight independent channels that allow for controlling the brightness level for each illumination module. They are based on Pulse-Width Modulation (PWM) and are realized by internal hardware blocks available in the ARM Cortext-M4 processor. The light power can be modified in real time and adjusted within a range of 0–100%. This means that each scene part can be illuminated with different intensity. Moreover, the processing algorithm can interactively match the current environment of a scene with the desired configuration. For instance, in a detection application, the appearance of a new object on the scene can result in extra light activation.

The triggering unit is based on a TI-RTOS operating system. It enables faster development by eliminating the need to develop and maintain system software such as schedulers, protocol stacks, and drivers. Communication with the processing unit is realized with the use of a TCP/IP connection. Specified messages allow it to configure and control the triggering process. Camera and illumination module triggering can be realized in a single or continuous mode. The following group of commands are implemented:

- *initialization* that configures connection parameters,
- *cameras controlling* that configures camera reserved outputs,
- *illumination controlling* that configures illumination reserved outputs.

4.2. Processing unit

The processing unit software components were fully developed in the C language with the use of the *GLib* library [14]. *GLib* implements advanced data structures, dynamic arrays, balanced binary trees, mutexes, asynchronous queues, secure memory pools, callback registering, and many others. It is released under the GNU license. A camera's remote control is realized with the Aravis library [3] developed by Emmanuel Pacaud. It is a *glib/gobject* framework for video acquisition from devices that implement the *GenICam* standard. When using *Aravis*, it is possible to simultaneously grab frames and change various camera parameters like exposure time or gain.

The obtained images are then saved in RAM memory. There are two main RAM-based file system types in Linux: *tmpfs* and *ramfs*. Thanks to these solutions, it is possible to allocate part of the physical memory to be used as a partition. From the user's point of view, it can be mounted and easily accessed by simple writing and reading files. The general difference between these two approaches is that *ramfs* will grow dynamically while *tmpfs* will not. Assume that one has 2 GB of RAM and created a 1 GB *ramfs* mounted as */tmp/ram*; when the total size of the */tmp/ram* crosses the 1 GB threshold, one can still write data to it (and the system will not stop this). However, when the data surpasses the total RAM size of 2 GB, the system may hang, as there is no room left in the RAM to keep data. On the other hand, when using *tmpfs*, it is not possible to write more than the size that has been specified during the mount procedure. This means that this situation does not need to be controlled manually, and it is more reliable and secure from the point of view of the entire system.

Once a new frame is acquired, processed, and saved, the software uses D-Bus to notify client applications about this event. In the proposed approach, the signals mechanism is used. This way, the receivers do not need to poll for the status continuously. Each signal has its own name and argument that provides paths to the acquired pictures. Accessing data only consists of opening the received RAM files. The number of client applications that can listen to this event is unlimited. Depending on its use, each of them performs the required image processing. It is up to the subscriber to determine whether the received data should be additionally queued or not. Such a situation may be essential when the processing time is relatively large as compared to the frequency in which new frames are available. D-Bus is also used to control the triggering unit.

5. Performance evaluation

The system's performance was evaluated with the use of an advanced high-resolution Dalsa TS-C2500 camera [12]. It is equipped with a 5 megapixel CMOS image sensor. The camera is able to acquire up to 30 frames per second in burst mode. The frame rate can be even greater when using the partial-scan mode. As a processing unit, the authors used a PC equipped with an Intel Core i7-4770 Quad-Core processor, 16 GB of DDR3-1600 memory, and a 128GB SSD hard drive. The obtained results are summarized in Table 1. The duration of the following operations were measured:

- preprocessing, which includes demosaicing (camera send images as RAW data),
- saving, which includes writing images to a file system,
- client access, which includes reading images from a file system.

Table 1

Software architecture computing performance verification results

	Preproc [ms]	Saving [ms]	Access [ms]	Total [ms]
RAW Data in RAM	7.0	5.4	4.5	16.9
RAW Data on SSD	7.1	11.5	9.0	27.6
JPEG Data in RAM	6.8	53.0	32.1	91.9
JPEG Data on SSD	6.8	54.5	34.5	95.8
PNG Data in RAM	6.5	171.8	162.5	340.8
PNG Data on SSD	6.5	174.9	167.2	348.6

The best performance was obtained when saving the RAW data in RAM memory and using sockets for event notifications. With this approach, it is possible to handle up to 58 frames per second for each camera. On the other hand, saving images without any compression requires a lot of free space in the RAM or disk. An alternative would be to use a different format such as JPEG or PNG; however, it turned out that system performance significantly decreased because of encoding and decoding operations (which are time-consuming). The time the image is compressed and decompressed can be lowered when using hardware encoding. This approach is currently not employed, but the authors are considering introducing it in the future. DBUS notification delay times are very low (microseconds) and do not substantially affect the overall performance. The obtained results depend directly on image size; therefore, they may differ when using different cameras. However, the developed strategy for saving the RAW data in RAM memory is universal and scalable.

6. Biometric data acquisition for a non-cooperative identification system

The system is dedicated for the acquisition and processing of high-resolution biometric data in a non-cooperative identification system that the authors are building. In the proposed concept, two wide-field-of-view (WFOV) and one narrow-field-of-view (NFOV) cameras are used. The WFOV cameras operate in the visible light spectrum, observe the entire scene, and locate potential objects that are to be identified. They form a stereo pair, so they need to be precisely synchronized with each other. Once the system decides that the distance and the pose of a tracked subject is sufficient to perform a recognition, the NFOV camera is directed to a specific point of the scene to capture high-quality images with the required features. In order to provide stable lighting conditions, the NFOV images are acquired in near-infrared light. Figure 3 presents the described use case and proposed construction.

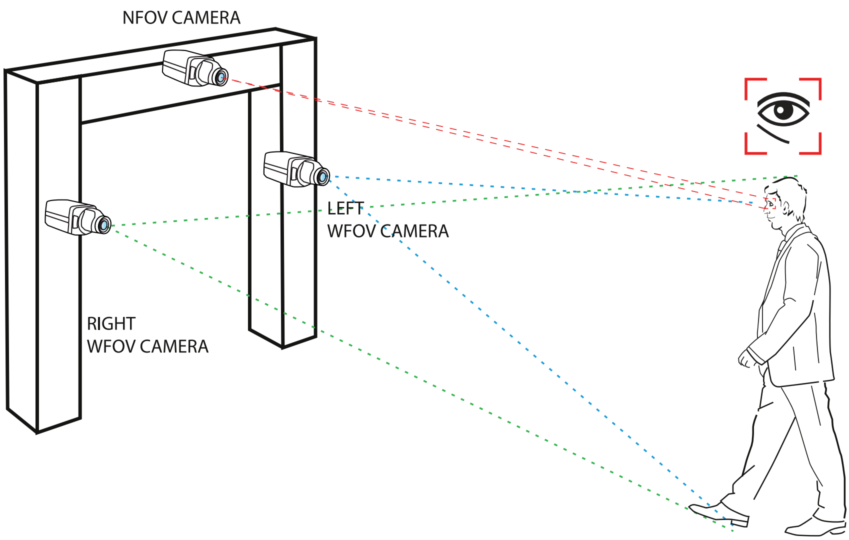

Figure 3. Example application for the presented system.

In the authors' realization, the WFOV vision system consists of two monochromatic Imaging Source DKM33GR0134 cameras. Each camera is equipped with a 1/3" optical sensor with a resolution of 1280 x 960 pixels and a pixel size of $3\mu m$. They use a global shutter so the acquired images are free of visual artifacts like motion blur or distorted shapes. The cameras are equipped with H614-MQ lenses manufactured by Pentax. They are mounted on a c-profile handle with movable camera holders. The NFOV vision system is realized with the use of a custom-designed solution proposed by the authors. Its construction is protected by two patent applications: P30994PL00/MB and PCT/B2016/052779. The designed device is based on a specialized lens with advanced pupil and galvanometric motors equipped with mirrors. This allows the system to change the camera view position like with Pan-Tilt-Zoom (PTZ) cameras. However, in this case, the motion is much faster and free of undesirable vibrations. This is somewhat similar to the solution in Okumura et al. [33]. The NFOV camera operating range is equal to $\pm 26°$ and $\pm 30°$ for pan and tilt directions, respectively. It is equipped with a specialized focusing mechanism that allows for the capture of sharp images within a distance range of 0.8 to 3.0 meters. Data acquisition is realized with the use of a Genie TS-C3500 camera manufactured by Teledyne DALSA. It includes a CMOS color sensor with a resolution of 3520 x 2200 pixels and a pixel size of $6\mu m$. The utilized devices are shown in Figure 4.

a) b)

Figure 4. Utilized WFOV (a) and NFOV (b) vision systems.

The data acquisition process in the proposed identification system consists of the following steps:

- human silhouette detection and face localization,
- tracking and movement prediction,
- WFOV and NFOV vision system calibration,
- NFOV camera scheduling and targeting.

The WFOV images are used for detecting and tracking multiple subjects. Face detection is realized by a HOG detector [22], while tracking is based on the Kalman filter. Having a stereo pair of cameras, the authors can obtain the 3D position (x, y, z) of each person. Subsequently, the tracking record is analyzed for inferring their 3D position some seconds ahead. This stage is particularly important to compensate for the time shift introduced by the mechanical delay of the lens focus mechanism. The final step is to transform the subject's 3D position to the galvanometer's coordinate system.

WFOV cameras return position data in a Cartesian coordinate system, while NFOV cameras use a polar coordinate system. Therefore, at this point, the authors rely on a novel calibration and verification procedure [20] that allows for the determination of proper transformation matrices. The accuracy estimation experiments yield the maximum mapping error for the horizontal and vertical axes as not exceeding 0.6°. As for the depth, the obtained error can be approximated with the use of a linear function as presented in Figure 5.

The images obtained by the proposed system are captured in a fully non-cooperative manner. This allows data to be acquired at-a-distance and on-the-move and assures an effective representativeness of the covariates of biometric recognition in the wild. The obtained data includes multiple biometric traits: iris, periocular, face, ear, or gain. An illustrative example of the biometric data acquired by the proposed system is shown in Figure 6.

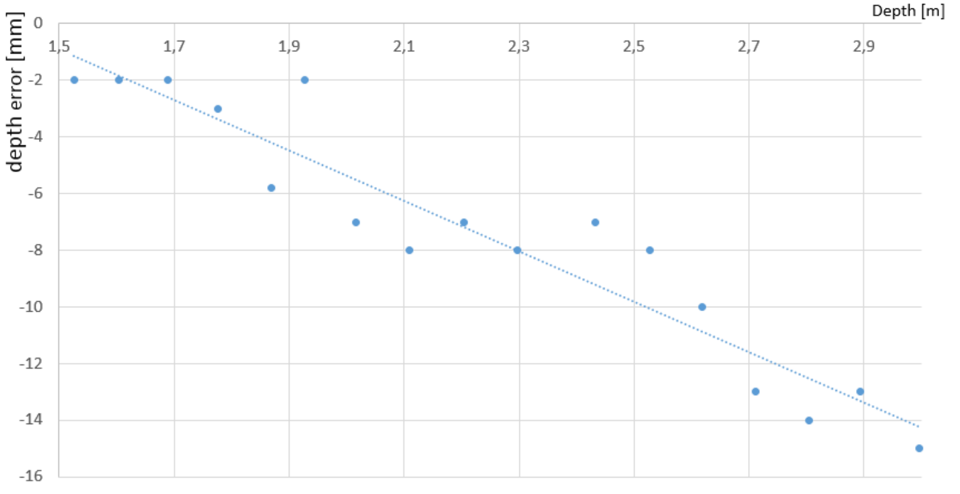

Figure 5. The calibration error of the *depth* parameter in the proposed acquisition system [20].

Figure 6. Illustrative example of biometric data acquired with use of proposed system: WFOV Right camera (left), WFOV Left camera (middle), NFOV camera (right).

In order to verify whether the obtained images are useful for biometric purposes, the authors acquired a preliminary dataset of 12 people. Each person was asked to slowly pass through the recognition gate looking straight ahead. The recognition performance under identification modality was evaluated with the use of the ocular region [34]. The proper area was cropped based on localization of the eye corners obtained from face landmarks [21]. Three types of features were used to assess the feasibility of the periocular trait: LBP [32], HOG [9], and SIFT [24]. For HOG and LBP, the selected region was further divided into a grid of 10×10 blocks, while SIFT was applied on the whole periocular region. These features were then fused using the linear fusion at the match score level. The obtained rank-1 result is equal to 96%. The corresponding CMC curve is presented in Figure 7.

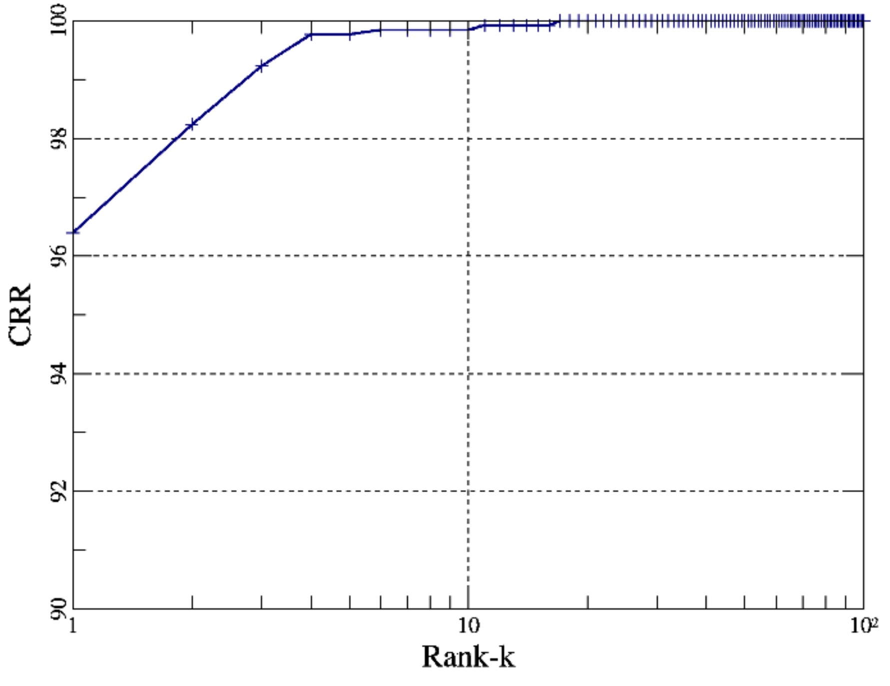

Figure 7. Identification performance for periocular recognition on data acquired by proposed acquisition system.

The number of genuine comparisons is 2560, while the number of impostor comparisons equals 28,160. The registration data was acquired independently as a set of face images of different poses [19]. The authors are aware that the low number of people in the evaluated dataset is not enough to draw any conclusions. However, these preliminary results show that the proposed system architecture can be successfully used to collect images for a complete high-quality biometric database.

7. Conclusions

In this paper, the authors present the novel realization of a comprehensive image acquisition system based on synchronized high-resolution Gigabit Ethernet cameras. The proposed system allows for the connection of multiple cameras and integrates them with any number of external illumination sources. The selected devices can be synchronized with each other in user-defined configurations. The paper is aimed at practical problems that occur in such constructions. The designed solution can be easily integrated in both simple and complex structures.

The obtained results are encouraging and useful for the development of similar solutions. The proposed system is based on a set of small independent services that are responsible for very specific tasks. Thereby, it provides a high level of generality, scalability, and fault isolation. This layered structure enables us to build multi-domain image analysis tools on the basis of the presented foundation. The designed platform allows for the combination and synchronization of two independent vision systems that operate in different light spectra (visible and near infra-red light) so that they do not interfere with each other. Finally, the total cost of the system is limited only to a PC, a triggering unit board, and eventually a frame grabber card (if using multiple high-resolution devices). This is notably less than the commonly realized and available solutions, such as [25, 39], and [40], which use specialized multi-core DSPs and/or FPGA technology.

The proposed design was used as the acquisition and processing platform of high-resolution biometric data in a non-cooperative identification system. It allows data to be captured in a fully non-cooperative manner (at-a-distance and on-the-move). The preliminary results show that the proposed system architecture can be successfully used to acquire images for a complete high-quality biometric database, which is the authors' further directions for this work.

Acknowledgment

The presented research was funded by Polish National Center for Research and Development in the frame of the project LIDER/027/591/L-4/12/NCBR/2013, entitled: "Non-Cooperative bioMetric system for Positive AuthentiCaTion" (COMPACT).

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Affiliations

Michał Włodarczyk
Lodz University of Technology, Department of Microelectronics and Computer Science, Lodz, Poland, `mwlodarczyk@dmcs.pl`

Damian Kacperski
Lodz University of Technology, Department of Microelectronics and Computer Science, Lodz, Poland, `dkacperski@dmcs.pl`

Tomasz Płuciennik
Lodz University of Technology, Department of Microelectronics and Computer Science, Lodz, Poland, `tpluciennik@dmcs.pl`

Kamil Grabowski
Lodz University of Technology, Department of Microelectronics and Computer Science, Lodz, Poland, `kgrabowski@dmcs.pl`

Received: 06.06.2016
Revised: 15.11.2016
Accepted: 15.11.2016