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Automated border control e-gates and facial recognition systems

Jose Sanchez del Rio [a,*], Daniela Moctezuma [b], Cristina Conde [a], Isaac Martin de Diego [a], Enrique Cabello [a]

[a] Department of Computer Science and Statistics, Rey Juan Carlos University, Mostoles 28933, Madrid, Spain
[b] Centro de Investigación en Geografía y Geomática Ing. Jorge L. Tamayo, Mexico DF 14240, Mexico

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ABSTRACT

A fast automated biometric solution has been proposed to satisfy the future border control needs of airports resulting from the rapid growth in the number of passengers worldwide. Automated border control (ABC) systems handle the problems caused by this growth, such as congestion at electronic gates (e-gates) or delays in the planned arrival schedules. Different modalities, such as face, fingerprint, or iris recognition, will be used in most of the ABC systems located at airports in the European/Schengen areas. Because facial recognition is the modality that travelers consider most acceptable, it was decided to include this modality in all second generation passports. Face recognition systems, installed in small kiosks inside the e-gates, require high quality facial images to allow high performance and efficiency. Accurate face recognition algorithms, which should be invariant to non-idealities, such as changes in pose and expression, occlusions, and changes in lighting, are also required for these systems. In this paper, a review of the most important face recognition algorithms described in the literature that are invariant to these non-idealities and that can be used in ABC e-gates is presented. A comparative analysis of the most common ABC e-gates located at the different airports is provided. In addition, the results of an experimental evaluation of a face recognition system when halogen, white LEDs, near infra-red, or fluorescence illumination was used, which was conducted in order to determine which type of illumination is optimal for use in ABC e-gates, are presented. To conclude, improvements that could be implemented in the near future in ABC face recognition systems are described.

1. Introduction

Eurocontrol (2013) has proposed different scenarios for predicting the number of flights in the coming years. According to the most likely scenario (named regulated growth), by 2035 the number of flights will have increased by 40%. Busier airports, a higher number of missed flights because of low capacity, an increase in the average distance per journey, delays in arrivals and departures, and a higher traffic flow are some of the predicted consequences of this continuous increase in flights. It is necessary to appropriately plan airport expansions and elaborate certain regulations that take third country nationals (TCNs) into account. Characteristics, such as economic, political, and social conditions, and the level of technological development must be carefully considered so that the effects

* Corresponding author.
E-mail address: jose.sanchezdelrio@urjc.es (J. Sanchez del Rio).
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mentioned above can be mitigated. In order to meet this growth in passenger flow and air traffic, automated border control (ABC) systems have been installed at different worldwide airport entries and exits with the aim of facilitating travel while maintaining the security of international border crossing points. In an effort to work toward this harmonization, several practice guidelines have been published by different organizations, such as Frontex (technical and operational) (Frontex, 2012a), International Civil Aviation Organization (ICAO, 2015), the International Air Transport Association (IATA, 2016), and the European Committee for Standardization (CEN, 2015). Their objective is to create a definitive guide to ABC specifications and design based on human–computer interaction and safety aspects. Biometric characteristics have been used in border controls for more than 100 years, from the time when a photo of the passenger was first included in the passport. However, the automation of the identification process could be realized only when the biometric technology became sufficiently mature to reach a satisfactory performance and accuracy level. The first attempt to introduce a biometric-based ABC was made in 1992 at the Amsterdam Schiphol airport, when a fingerprint biometric system, the Schiphol Travel Pass, was introduced. Since then, a growing number of countries have introduced ABC systems at their airports.

1.1. *The Schengen area and third country nationals (TCNs)*

The growing number of countries using these systems includes those in the Schengen area and third countries. The Schengen area countries include all EU member states except the United Kingdom and Ireland, which obtained an opt-out clause while being included in certain aspects of the intergovernmental co-operation based on the Schengen Agreement. The Schengen area also includes four countries that are not members of the EU: Norway, Iceland, Switzerland, and Liechtenstein, and three microstates, Monaco, San Marino, and the Vatican, which are de facto parts of the Schengen area, as they do not have border crossing controls with the surrounding Schengen countries. As of 2014, 28 countries, presented on the map in Fig. 1 in which the Member States are also listed, are included in the Schengen area. After the Treaty of Amsterdam was signed, the Schengen Agreement was incorporated in the EU framework; thereby, countries joining the EU will also become part of the Schengen area. One of the main aims of harmonization is to facilitate the travel of TCNs. A TCN is any person who is not an EU citizen within the meaning of Article 20(1) of the Treaty on the Functioning of the European Union (European Commission, 2008) and who is not a person enjoying the EU right to freedom of movement, as defined in Article 2(5) of the Schengen Borders Code. Several projects, such as the Automated Border Control for EU project (ABC4EU) project and the Smart Borders Package, have invested considerable effort in integrated border management (IBM), in particular for TCNs. For this integration, an entry/exit system (EES) was proposed using an electronic registry of the dates and places of entry and exit of each TCN admitted for a short stay. In addition, a registered traveler program (RTP) was suggested for prevetted, frequent TCN travelers in order to allow facilitated border crossings. On the one hand, an RTP is a registration program that allows traveling TCNs to enter the EU using simple or complex borders control systems, such as ABC systems. On the other hand, an EES registers the times and places of the TCN entries/exits to/from the EU, respectively. As a result, three legislative proposals were tabled by the European Commission, the Proposal for a Registered Traveller Programme, the Proposal for an Entry–Exit System, and the Proposal for an Amendment of the Schengen Borders Code, in order to meet the future challenges that the EU has been actively facing because of IBM. Registered travelers will enjoy the same right to free movement as EU citizens.

1.2. *Automated border control e-gates and different topologies*

This paper is focused on biometric face recognition systems that can be or currently are implemented in ABC electronic gates (e-gates). In order to offer to the reader a comprehensive review of this topic, the ABC (Frontex, 2012a) is defined and its different topologies are described in the following. An ABC (Frontex, 2012a) is a fully automated system that performs border checks. The basic functions of the system are to authenticate the travel document, establish that the traveler is the rightful holder of the document, query border control records, and on this basis, automatically verify the entry conditions for Schengen area citizens and TCNs. An ABC component is the e-gate consisting of the following main components: (a) an electronic passport reader, (b) biometric readers, (c) an electric door opened by electronic means, and (d) a device to display visual instructions, which guide the passenger through the border control. An e-gate may be also called an ABC-gate. The operation of an ABC system can involve one or two physical barriers (e-gates), which may have swinging or sliding doors. To read the traveler document and capture the facial image, a document reader and several biometric capture devices are used, respectively. Monitors, LEDs, signals, and audio devices are integrated in the user interface. Processing units and the network devices allow the system to be connected with the database central station. During the last few years, ABC e-gates have been located worldwide. Some of these were initially a part of pilot projects to test the capability of these systems and to improve the border crossing processes while maintaining high security levels. Currently, most are fully operational deployments, designed to facilitate the border crossing process. According to IATA, there are now numerous airports in the world with automated border controls. In Fig. 2, a map provided by IATA shows the location of these airports. Some are equipped to work with ABC machine-readable travel documents, in others, ABC preregistration is required, and still others have both characteristics. Most ABC systems use unimodal biometric systems for access control and operate in two phases: enrollment and authentication. During the enrollment phase, the user's biometric elements are acquired using a biometric reader and stored as a labeled template in a database. During the authentication phase the biometric patterns are captured for identification and verification of the user's identity. For identification (1:N), the pattern is compared with all the users' templates in the database and for verification (1:1) the comparison is performed only with the templates corresponding to the claimed identity. A more detail description of these processes is given in

Fig. 1 – Shengen area countries: Austria, Belgium, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, The Netherlands, Norway, Poland, Portugal, Sweden, Slovakia, Slovenia, Spain, and Switzerland. The three microstates, Monaco, San Marino, and the Vatican, are also included.

Section 1.4. The topologies and physical designs of current ABC e-gate systems vary. They may comprise different step processes, such as single-step, integrated, or segregated two-step processes, and be integrated in a mantrap, constituting a single or double e-gate. Each topology is affected by different external factors, such as lighting or humidity, and this should be taken into account during the design of facial recognition systems. In fact, biometric systems should be invariant to these factors. In the case of one-step processes, only one step is needed to verify traveler's identity and satisfy the document security checks. No registration or enrollment is required in this process and the verification is performed at the same time as the authentication. If a mantrap design is used, passport validation and facial recognition are performed simultaneously within the mantrap to reduce passage time through the gates. If the information does not match, the traveler is referred to an immigration officer who performs a traditional manual check. In the case of integrated two-step processes, the security document checks and the traveler's verification are performed in separate steps, usually in a mantrap e-gate. Here, the verification takes place after the document authentication only if the authentication is successful. Conversely, the segregated two-step process is the same as the integrated two-step process, but involves different physical structures. Usually in the first stage, the traveler's document is verified; the facial image is captured as biometric information and the fingerprint is used as a token for the registration or enrollment. In the second stage, the token is checked and

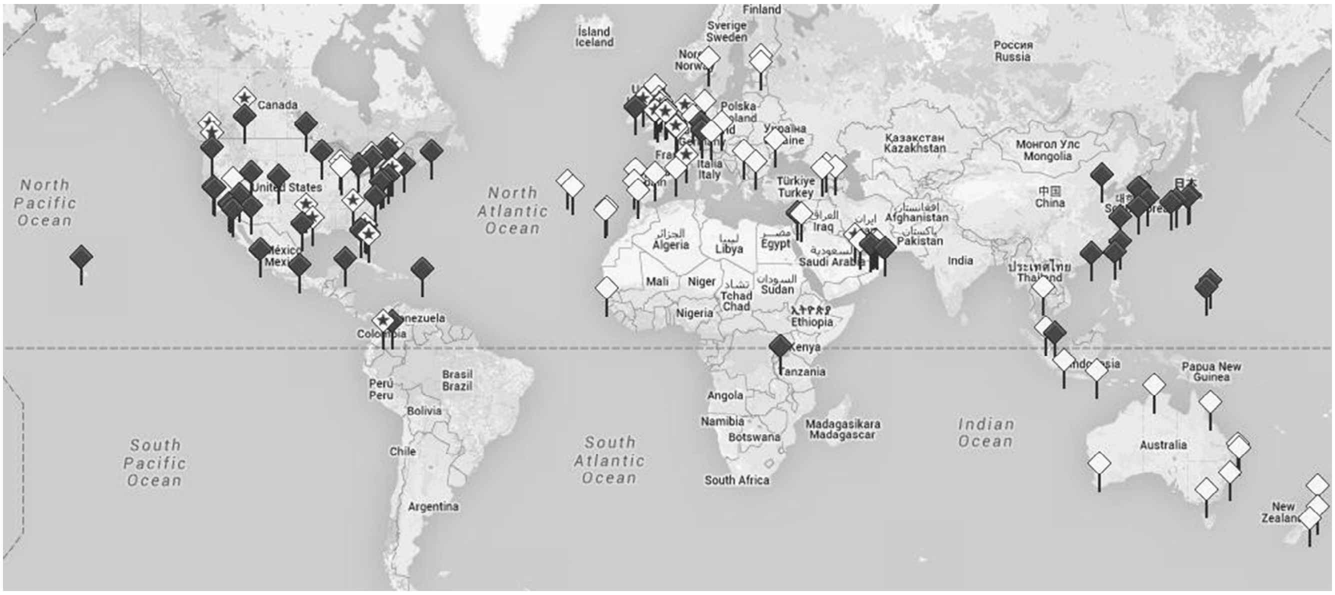

Fig. 2 – Airports with an ABC system (white symbol: ABC machine-readable travel document required; brown symbol: ABC pre-registration required; star symbol: ABC pre-registration and ABC machine-readable travel document required).

the traveler crosses the border. In some airports, such as Barajas and El Prat International Airports, a multimodal system is used. In the case where a face modality verification falls in an uncertainty score zone between the lower and upper thresholds, travelers are required to present their fingerprints for additional verification (Cantarero et al., 2013). If the identification remains unverified, then a border guard directs the traveler to a manual check.

1.3. *Travel documents*

Travel documents are one of the main factors in the border crossing process. Travelers need them for identification and verification purposes in the ABC e-gates. However, there is no unified or standardized travel document that can be used at all borders worldwide or even in only the EU. They can be classified as electronic passports (e-passports) (ICAO, 2006a), Schengen visas (ICAO, 2015; Visa, 2007–2016), national ID cards (BSI, 2011; ICAO, 2011), and residence permits (BSI, 2011). ICAO (2014a) has already defined the characteristics of the e-reader. In addition to the Schengen acquis, the Council Regulation 2252/2004 of December 13 2004 calls for the use of the document bearers facial image and two fingerprints in interoperable formats (Article 1). Member states were instructed to apply the regulations stipulations for facial images within 18 months and fingerprints within 36 months (Article 6). This regulation states that biometrics information is to be used only to verify document authenticity and the identity of the holder (Article 4), and for no other purpose. Because the most common travel documents used in ABC systems are e-passports, a classification and description of the types used in the different Schengen countries and TCN borders is given in the following. An e-passport can be defined as an identification document with an embedded radio frequency identification (RFID) chip, which contains significant biographic and biometric information of the e-passport holder. Depending on the travelers category, which in the near future will be checked in either the RTP or EES (PWC, 2014), and the security authentication protocols, different e-passports are used by travelers of different nationalities. EU member states have been responsible for issuing biometrically enabled passports to their citizens since August 2006, as per the EU Councils December 2004 regulation No. 2252/2004 (Council of the European Union, 2004). The first generation e-passport, which features only one biometric modality, i.e., the facial marker, is now broadly available. The second generation e-passport featuring two biometric modalities has been in circulation since June 2009. Standard ICAO compliant second generation passports of ID-3 size are defined in ICAO Document 9303, part one (ICAO, 2006a, 2006b). This specification also holds for TCNs. For e-passports of Schengen member states, the Federal Office for Information Security (BSI) specification TR-03110, parts 1 and 3 (BSI, 2012, 2013) are also applicable for the definition of Extended Access Control (EAC). Future third generation passports will have a new security mechanism, Supplemental Access Control (SAC), as specified in ICAO (2010). This comprises an evolution of the Basic Access Control (BAC) and protects the contactless chip in the same manner as the data exchange between the chip and the reading device, which is encrypted. The new SAC is planned to gradually replace the BAC because of the higher degree of security it provides. The use of a six-digit password with the name of the Card Access Number (CAN) is also allowed by SAC, with the aim of accessing the data stored on the cards RFID chip. The CAN, which is typically printed on the document, may therefore replace the machine-readable zone (MRZ) as a prerequisite for reading data from the chip. The migration from second to third generation passports has recently begun in some airports. BAC will still be supported for global interoperability and backward compatibility reasons and the two security mechanisms, BAC and SAC, will coexist for some time (Gemalto, 2011).

1.4. Enrollment and verification processes

Because the enrollment and identification processes constitute critical parameters at ABC e-gates, this section is focused on describing both processes. Their efficiency and performance must both be high level; however, it is difficult improve both simultaneously, because the minimization of the enrollment and verification times usually demands an increase in the system performance. Enrollment is the process that comprises all the required actions to grant access or obtain documents, which are mandatory for specific categories of travelers, in order to cross a border. It applies to an RTP and the Visa Information System (VIS) (European Commission, 2016). Enrollment of registered travelers in an RTP is similar to that in the VIS. Therefore, future enrollment processes will be inherited from the existing VIS enrollment process. Enrollment consists of four sub-processes: receipt of an application, collecting biometric data, examining the application, and issuing the travel document. Traveler identification is the process that comprises a set of activities that result in the validation of the traveler identity. It consists of three sub-processes: biometric capture, biometric data consultation, and biometric verification. In the biometric capture sub-process, the required biometric features of the traveler are captured live at the location. Currently, these features depend on each Border Authoritys requirements. Biometric data consultation is the sub-process in which the encrypted biometric data queried from the enrollment biometric database are decrypted into usable information for biometric verification. This sub-process is executed only when the border authorities require additional biometric data in addition to the data stored in the traveler's passport. If the border authority requires additional biometric data, the system can decrypt the biometric information from the enrollment to match with the biometric information in the travelers document. In the biometric verification sub-process, it is verified that a traveler who is at the border control point (BCP) is the same as the person whose biometric data are stored in the document (e-passport or corresponding document) or queried in the central biometric database. The system matches the biometric data captured previously with the biometric data in the document to verify that they belong to the same citizen. If some irregularity occurs, the border authorities can reject the traveler and prohibit him/her to cross the border. The logs resulting from the biometric verification sub-process are saved in a searchable repository. Individual checking can be performed and in some cases this determines whether this sub-process is one of the different checks required to verify that the traveler can cross the border.

1.5. International Civil Aviation Organization requirements for automated boarder control e-gates that operate with second generation passports

As reported at the beginning of this introductory section, several organizations, such as ICAO, IATA, and CEN, are responsible for the passenger flow control and its automatization using different systems, such as ABC e-gates, at BCPs. More specifically, the ICAO suggests several recommendations for ABC systems regarding face image characteristics, performance, and efficiency. These recommendations, in particular for second generation passports, which are the most common and secure travel documents available in the Schengen area, are described in this section.

1.5.1. Facial image characteristics

Regarding facial images, the ABC e-gates biometric image ICAO requirements for second generation passports are very specific and determined by the requirements concerning the travel documents' security and size. They should follow the ISO/IEC 19794-5 constraints for facial images (ISO/IEC, 2004). The operational and technical recommendations required to meet these constraints should be followed by travelers during the photo capture (ICAO, 2010) process; for example, regarding operational issues they should look straight into the camera keeping a neutral pose with both eyes visible; regarding technical issues, the parameters of the camera should ensure the provision of face images within a broad range of contrasts; there should be at least 90 pixels between the centers of the eyes in facial images provided by the face image capture unit (Frontex, 2010); the face image capture unit should give the traveler feedback on his/her expected action; the angle covered by the cameras should be less than 45 degrees with respect to the traveler walk flow; the cameras resolution should be of at least 2 megapixels, and they should have short fields of view and frame rates of at least of 10 frames per second; image formats used, such as BMP, JPEG, JPEG 2000, and PNG, should have a storage compression of 24 bits/pixel, and, based on resolution, in face images there should be at least 90 pixels between the centers of the eyes. Another recommendation is to set a standard for template usage of biometric features instead of images. As the ICAO prescribed in Document 9303, the JPEG or JPEG2000 image within e-documents should have a size of 12 K (in practice, in the range 15–20 kb). The current ICAO-standard for machine-readable documents includes a facial image of 300 dpi resolution compressed with JPEG or JPEG2000 to a typical size of 12–20 kb. Again, the standard is based on physical and practical constraints (e.g., available storage and the baud rate of the contactless chip) and on experiments conducted using face recognition software. Furthermore, it is recommended that a quality assessment of the captured images be performed so that the good quality of the images provided for the verification process is ensured. The quality assessment should cover at least the face and eye region. ISO/IEC 19794-5 (ISO/IEC, 2004) gives guidelines for image quality analysis. Additionally, quality assessment may be useful for test and evaluation purposes.

1.5.2. Performance and efficiency

Following best practical technical guidelines for ABC systems, the false accept rate (FAR) for facial capture and verification should be less than 0.1% and using this configuration the false rejection rate (FRR) should be less than 5% (CEN, 2015; Frontex, 2012a; ICAO, 2014b). As stated above, these recommendations suggest several constraints regarding the face image quality required at ABC e-gates when second generation passports are used (Sánchez del Rio et al., 2015). These constraints are in the scenery and in the photographic and digital requirements (Frontex, 2010; ISO/IEC, 2004). To ensure the efficiency of the process, a standard time for normal cases or a longer time for travelers with disabilities to pass through the e-gates should be established. In normal situations, the time for crossing the mantrap, from the time the traveler places the passport on the reader until he/she exits the ABC system, should not exceed 30 s. This time is the sum of the times required for the electronic and optical checks, the image capture process (the period of time between the frames being recorded by the cameras and their storage in the templates), and the match of the captured image with the electronic images. An interesting study on performance and efficiency in possible hypothetical smart border scenarios may be read in PWC (2014). The best practices toward interoperable biometrics standards can be read in two important sources, the ICAO (ICAO, 2014b) and the Frontex Research and Development Unit (Frontex, 2012a). Besides the aforementioned organizations, the National Institute of Standards and Technology (NIST) is also contributing to interoperable standards in the use of biometric information (Romine, 2013).

1.6. Examples of automated border control systems at third country national airports

Before reviewing the potential ABC facial recognition systems described in the literature, some examples of ABC e-gate check procedures performed at some of the TCN airports (Seoul, Vancouver, USA, Hong-Kong, Brazil, and the United Arab Emirates (UAE)) are described below. In this paper, we define a TCN airport as one located in a third country, meaning a country the citizens (nationals) of which are not EU citizens: they do not enjoy the EU right to freedom of movement, as defined in Article 2(5) of the Schengen Borders Code. As a result, TCN ABC systems are the ABC systems used in the TCN countries. The authors consider this section important for the reader, because a general idea about the working process of some of the most important TCN ABC systems is needed to gain a general understanding of current ABC system state of the art. For this purpose, the guidelines followed by Schengen area travelers and TCNs with their corresponding RTP when crossing a BCP are first explained and then a general view of the TCN ABC systems working process is described. If implemented, the RTP would allow full automation of the border checks for registered travelers (RTs). It would operate at the border as follows. A registered (i.e., pre-screened and pre-vetted) traveler will be issued a token in the form of a machine-readable card containing only a unique identifier (i.e., an application number), which is swiped on arrival and departure at the border using an automated gate. The gate will read the token and the travel document (and visa sticker number, if applicable) and the fingerprints of the traveler, which will be compared to those stored in the central repository and other databases, including the VIS for visa holders. If all checks are successful, the traveler will be able to pass through the automated gate. If any issue arises, the traveler will be assisted by a border guard. When the ABC system is used by a TCN, the system should display the allowed duration of stay to the traveler and to the border guard officer. If the traveler has exceeded the allowed stay, the system should also display a warning to the border guard officer. In addition, the ICAO-compliant standard for second generation passports of ID-3 size defined in ICAO Document 9303 part one (ICAO, 2006a, 2006b) also holds for TCNs. Examples of TCN airports with ABC systems are now presented. At Incheon International Airport serving Seoul, South Korea, passengers using their e-passports can take advantage of a fully automated system; when departing, they can proceed from airport check-in to self-boarding and when arriving, complete an ABC procedure, with no contact with border officers. In Vancouver, a form of ABC, where eligible passport holders can clear customs faster, has already been implemented. A visual inspection of the passport by a border officer is still required, since the process is not fully automated. At US airports, there are several different types and models of automated border check gate, which are usually operated under different RTPs. However, the ABC kiosks at Miami International Airport, called Passport Express Kiosks, are not part of any set RTP, but may be used by any US or Canadian citizen carrying an e-passport. In order to use the ABC gates in the US, a person must be registered, pre-vetted, and screened in order to prove to the government that he/she is a trustworthy citizen. At Hong-Kong's airport, the ABC gates are known as e-Channels. An e-Channel is an integrated two-step system, using fingerprints as the biometric identifier means; pre-enrollment is required. The biometric verification process is presented in pictures and writing and a video is available, guiding the viewer through the process. The manner in which the immigration officers will assist the traveler in the case of a malfunction is also presented at the e-Channel. Brazil is one of the most significant countries in terms of increased traveler flow to the Schengen area. Therefore, it is of interest and importance to launch new technology in this area. In this case, the gates are available for people over the age of 18 years with Brazilian e-passports. In the UAE, the border control system is comprehensively managed in accordance with strict pre-qualification and visa issuing processes. Border control forms a key aspect of controlling the various ports of entry and exit throughout the UAE. The Information Technology Department at Abu Dhabi Police GHQ found that biometric feature verification would be an effective method to prevent illegal immigrants or any unwanted passengers entering the country.

1.7. European Union projects focused on harmonization of the automated border control e-gates

To conclude this introduction to ABC and face recognition systems, several European projects (Berglund and Karbauskaite, 2008) related to ABC e-gates, funded by the EU and with the aim of achieving harmonization of the current and near future growing traveler flow, are now described. Most of these involve EU passport model biometric data with the objectives of preventing the illegal entry of travelers into a specific country, limiting the use of fraudulent documents, and making the border control more efficient (Kosmerlj et al., 2006). FastPass is one of the Seventh Framework Programme (FP7) projects. This project is designed to establish and demonstrate a harmonized, modular approach for ABC gates (FastPass, 2016). Another FP7 project is the ABC4EU project (ABC4EU, 2014), the primary aim of which is to make border control more flexible by enhancing the workflow and harmonizing the functionalities of ABC e-gates. It involves the utilization of the ABC systems operational features, paying special attention to second generation passports. One goal of this project is to adapt the e-gates and mechanical reader traveler documents (e-MRTDs) to the TCN. An RTP and EES will be tested to assess their feasibility and an EU level border management command, control, communication, and computing intelligence (C4I) concept will be developed for the end-user. A project that is still active today is Automatic Recognition of Passengers with Credentials (RAPID) (Frontex, 2010), which was launched by the Portuguese authorities to facilitate the increasing flow of passengers at airports, enhance their service levels (speed and convenience), save personnel resources, and reduce costs. The RAPID system is based on facial recognition and allows the automated border crossing of passengers holding EU/European Economic Area (EEA) e-passports. The European Agency for the Operational Management of Large-scale Information Technology Systems in the Area of Freedom, Security, and Justice (EU-LISA) (Eu-LISA, 2016) was founded in 2011 through Regulation (EU) No. 1077/2011. One of its objectives is to provide a long-term solution for the large-scale management of operational information technology (IT) systems that are necessary for the implementation of EU border migration policies. These systems, such as the Schengen Information System (SIS), the Visa Information System (VIS), and EURODAC (Council of the European Union, 2000), assure travelers' protection and the exchange of information between national authorities. Different biometric tests at air, sea, and land borders are performed by this agency under the Smart Borders package. This package comprises a European record of TCN entries and departures, containing biometric data and an RTP, also for TCNs, which enables them to use automatic borders, in the Portuguese case at RAPID electronic borders. The goals of Smart Borders are to speed up border crossing, enhance travelers experience at the border, and eliminate manual passport stamping, thus providing border guards more time to focus on passengers rights and duties, facilitating the acquisition of information on over-stayers, and fighting irregular immigration.

1.8. *Objectives of this work*

A review of the face recognition systems described in the literature with the aim of determining which can be used in ABC e-gates is presented. Many of the face recognition systems were designed such that they should be unaffected by external factors, such as changes in lighting, pose, occlusions, or different face expressions. These factors are often called system non-idealities. A review of several face recognition systems presented in the literature that are invariant to non-idealities, a quality that is strongly required by ABC e-gate systems, is provided. Because ABC systems with high performance and efficiency are needed to maintain the level of security recommended by different authorities and organizations, such as the ICAO, Frontex, or IATA, in these types of scenarios, this review examines the methods presented in the literature for achieving face recognition systems having high efficiency and performance levels that can be integrated in ABC e-gates at BCPs. An experimental evaluation was performed of a face recognition system very similar to real ABC systems, including halogen and fluorescence lamps and white LEDs and near infrared (NIR) for homogeneous illumination. The main objective of this experiment was to determine the best illumination system, so that a novel system can be designed for use in ABC systems that is able to control non-idealities, such as changes in illumination. Then, a comparative analysis of ABC systems in terms of maturity, applicability, acceptance, performance, cost, constraints, and deployment was performed. This evaluation was conducted according to the real requirements of current ABC systems and covers the studies in the literature related to this topic. To conclude, some improvements in ABC face recognition systems that can be integrated in the near future ABC e-gates are presented. One of main contributions of this paper is that the state-of-the-art face recognition methods applied in ABC e-gates are described, providing a general insight into face recognition systems that satisfy the most relevant characteristics that should be applied in ABC e-gates. Algorithms that mitigate non-idealities are presented and the provided evaluation of several face recognition systems chosen according to the characteristics that need to be integrated in ABC systems will allow the reader to gain an idea about the current situation of ABC systems worldwide. The analysis presented here determines whether sufficient studies that are applicable to ABC systems exist or whether, on the contrary, more research focused on ABC systems should be conducted. The paper is organized as follows. A study of face recognition techniques focused on ABC e-gates is presented in Section 2. The studies related to invariance to 2D face recognition system non-idealities are summarized in Section 3. A comparative analysis comparing several ABC systems is described in Section 4. An experimental evaluation of an ABC e-gate face recognition system very similar to that used at Barajas Airport is presented in Section 5. Improvements that could be implemented in near future ABC face recognition systems are presented in Section 6, and finally, conclusions are given in Section 7.

2. Face recognition studies focused on automated border control e-gates

Several studies reported in literature, which are considered to be relevant to the design of a high efficiency and performance recognition system, are described below. Some are related to the travelers' documents check, others to the evaluation of the extent to which the non-idealities in either uncontrolled or controlled environments affect facial recognition in ABC systems, and others are based on the manner in which low image quality affects the traveler face matching performance. Kosmerlj et al. (2006) conducted an experiment to evaluate the operation of face recognition systems in large scale applications. For this purpose, the author compared face recognition system errors with those incurred when a human supervisor attempted to detect false acceptances of the computerized system. The sample used comprised Norwegian citizens exhibiting different appearances, in particular different hairstyles. It was concluded that automated identity verification of a passport holder by using a face recognition system may not give significant additional security in large scale applications and another more secure modality, such as fingerprints, should be used instead of or in addition to the face recognition system. Spreeuwers et al. (2012) evaluated the automated facial recognition reliability for automatic border passage in two gates at Schiphol Airport. Image quality face recognition accuracy was evaluated. Live images of every traveler were compared to the digital photographs stored on their passports. Different sets of images were used: a clean set, a realistic set, a challenging set, and a last in series set. The clean set was created using standard quality, and the images were without blur, lighting, pose, or scan line problems. The realistic set contained images with lighting and scan line problems. The challenging set comprised blurred images and images with faces with large pose variations, and the last in series set contained three of a series of the same subject. A very good performance was obtained, achieving a high verification rate (VR) in each test set (clean, realistic, challenging, and last in series sets) with the best algorithm: 97.1%, 98.1%, 97.5% and 99.2% and 99.7%, 99.6%, 98.6% and 98.5% for the first and second gates, respectively. These results are very acceptable for automatic border passage gate operations (a VR above 99% for a FAR of 0.1%, or even lower). Although not an ABC system, Conde et al. (2011) evaluated a general recognition system applied in public access areas at Madrid-Barajas International Airport, Spain. Three video surveillance cameras were selected: two in corridor areas and one at a control point. Images with lighting changes, with several quality levels, of collaborative and non-collaborative users, and compressed using four data compression methods, 1DPCA, 2DPCA, 2DLDA, and coupled subspace analysis (CSA), were considered. An SVM was used for classification purposes. It was concluded that CSA achieved the best performance for the face images used and that the SVM obtained excellent results given the difficult conditions of this type of scenario. In Beom-seok and Kar-ann (2013), a technique for face feature extraction using sinusoidal projection was used. Essentially, the technique uses a projection matrix, which is formed by stacking vectors with sinusoidal values at different frequencies, to directly multiply with a raw image matrix for weighted feature extraction. Orthogonality among vectors within the sinusoidal projection matrix is observed when the frequencies are chosen as multiples of the fundamental frequency. The proposed technique is of interest for application in ABC e-gates, because the study showed a promising verification performance for three different face databases. Non-idealities, such as illumination, poses, expressions, and occlusions, are avoided by using this type of system. In Hwang et al. (2011), a face recognition system using the extended curvature Gabor classifier bunch with the Face Recognition Grand Challenge (FRGC) version 2.0, XM2VTS, BANCA, and PIE databases was described. This method has a high application potential in ABC e-gates because it extracts different features with high accuracy. First, Gabor kernels are converted to extended curvature Gabor (ECG) kernels, which leads to numerous feature candidates. Then, single EGC classifiers are separated and implemented applying linear discriminant analysis (LDA) to the corresponding feature vector. Although a single classifier is used like the ECG classifier bunch that combines multiple ECG classifiers using the fusion scheme, high accuracy is obtained. The system presented here is invariant to several non-idealities, such as illumination changes and occlusions.

3. Non-idealities in automated border control systems

As reported previously, several problems should be considered when designing and constructing an ABC system. These problems are called the *non-idealities of the system* in this paper. Some of these non-idealities are low quality images, non ICAO compliant photography, inhomogeneous illumination, lack of neutral expressions and poses, skin conditions, aging, inhomogeneous background and object occlusion, extreme temperature and humidity, scalability problems, and non ICAO-compliant performance and efficiency. The objective of decreasing the number of non-idealities through the design of the ABC systems hardware or software elements presents a great challenge. In the case of hardware, components must be located such that the appropriate ergonomics and correct signalization for the traveler are achieved. The different components that constitute the interaction with the traveler, namely, the document reader, display, and biometric modules, must be strategically located in the most ergonomic position, while still assuring stable environmental lighting conditions. This is essential for both maximizing the individual performance of each component and speeding up the ABC process by making the crucial steps more intuitive for travelers. Furthermore, the correct location protects the module from vandalism and improves fire protection in the case of hazardous environments. The components should be grouped together, creating a streamline for the travelers interaction. Concerning software, several studies exist in the literature, in most of which attempts were made to improve performance and efficiency with fast and powerful recognition algorithms. Databases with face images that were captured in either an uncontrolled or controlled environment, different poses and expressions, or low quality images, such as damaged travelers passport photos, are often used for training and testing in order to create a real scenario similar to that present in an ABC system. A summary of face recognition studies reported in the literature based on the solutions to these non-idealities is presented in the next section.

3.1. Solutions to automated border control system non-idealities: invariant 2D face recognition system models

As previously mentioned, ABC systems have to operate with face recognition algorithms invariant to non-idealities, such as changes in lighting, rotation, and pose (Zhang and Gao, 2009). Most of these methods are described in the literature and a review of some of them that are applicable for solving ABC systems non-idealities is presented below.

3.1.1. *Non-ideality of the difference in pose. Degradation caused by image quality factors*

Difference in pose is defined as the different possible positions of the face in front of the camera. In Duta et al. (2012), the effects of a difference in pose between the test and reference images together with performance degradation caused by image quality factors, such as illumination, resolution, noise, blur, and Gaussian noise, were studied. In order to find a solution to this problem, a high performance and robust face recognition system (FaceVACS C++ SDK Version 8.4.0. developed by Cognitec Systems GmbH) was tested with face images of the MultiPIE database to determine the effect of different poses and lighting. An open set recognition scenario was created so that some variations in several test and reference image quality factors, such as illumination, resolution, noise, blur, and Gaussian noise, were introduced with the aim of determining the extent to which they affect the system performance. Furthermore, it was proved that differences in general poses between the test and reference images increased the performance degradation caused by these image quality factors. In order to calculate the system performance for the different poses, a scheme involving the overall difference in the area under the relative operating characteristic (ROC), called AUC, for each of the quality parameters was used. It was concluded that the system can reach a near optimal recognition performance provided that the pose mismatch is small. This study is interesting for those studying ABC systems because of the similarity of this scenario with the real one in ABC systems.

3.1.2. *Non-ideality of different expressions*

The non-ideality of different expressions, which is responsible for lowering face recognition systems performance and defined as different features obtained because of emotional states, such as happiness, sadness, or concern, can be solved by improving the feature extraction technique. In Er et al. (2005), the discrete cosine transform (DCT) was used to reduce the dimensionality of the original facial image. First, low frequency DCT coefficients were discarded so that large area lighting variations were alleviated. These truncated coefficients were clustered. Then, Fishers linear discriminant (FLD) was implemented with the aim of obtaining the most invariant feature of human faces; thus, the original vectors were linearly projected in a low-dimensional sub-space. The training samples were then clustered and classification using a radial base function (RBF) neural network was performed. For this purpose, system structure was determined and the RBF neural networks parameters were estimated. In the study, this technique was applied to the ORL, FERET, and Yale databases, and it was concluded that an enhanced system performance with a low susceptibility to changes in lighting was achieved. Another study that focused on the non-ideality of expression was presented in Zhang et al. (2008). In this study, a new method with a high performance under different expression conditions was developed. Scale invariant feature transform (SIFT) for features extraction and an SVM for classification was used with the ORL and Yale face databases.

3.1.3. *Non-ideality of different illumination*

A large number of studies were focused on the optimization of functions that are invariant to the non-ideality of illumination change. Changes in illumination produce variations in the face texture, color, feature extraction, etc., similar to the differently illuminated face regions, degrade the performance of the face recognition system. For example, in Chen et al. (2000) a probability approach was proposed for analytically determining a probability distribution for the image gradient, which is dependent on the surface geometry and reflectance. This distribution showed that the direction of the image gradient was not affected by changes in lighting and this was tested for face recognition. It was constructed from more than 20 million samples of gradients in a database of 1280 images of 20 inanimate objects under different lighting conditions. In addition, images of 10 faces, each under 45 different lighting conditions, were used. Each face under frontal lighting was considered as the training image and the recognition test was performed for the remaining 440 images. Four subsets were obtained based on the lighting angle with respect to the frontal or camera axis. Higher recognition accuracy than when using other methods, such as correlation, eigenfaces, linear sub-spaces, cones-attached, and cones-cast, for the subsets and measures immune to light change for image comparison was achieved. Furthermore, it was shown that for objects with Lambertian reflectance, there are no discriminative functions of images that are invariant to lighting. Other examples of this non-ideality were studied using the Harvard face database in Belhumeur and Kriegman (1996). In this study, the set of images of a convex object with a Lambertian reflectance function, under all possible lighting conditions, is a convex, polyhedral cone. It was proved that for convex objects with Lambertian reflectance functions, the dimension of the cone equals the number of distinct surface norms. The results should be taken into account for any recognition system under variable lighting.

3.1.4. *Non-idealities of different expressions and illumination*

To address the non-idealities of expression and lighting, a new face verification system based on integral normalized gradient images (INGIs) was proposed by Hwang et al. (2011). In this work, invariance in illumination and expression was obtained with face images captured in uncontrolled environments with lighting variations. The FRGC database, containing neutral and smiling facial expressions, was used. The subject image sets consisted of controlled still images (with two different lighting conditions and facial expressions), uncontrolled still images (in which lighting conditions varied because of being taken outdoors and in hallways), and 3D images. To solve this non-ideality, multiple face models in three groups with different between-eye distances within a regular face image region were constructed, and thereby, three different classifiers were obtained. A similarity score for each was calculated by a normalized correlation. It was concluded that the use of this lighting and expression invariant method improves the system performance for this database. Figs. 3 and 4 summarize the steps followed in this work and described above. They respectively show the facial images preprocess and hybrid Fourier based on principal component analysis (PCA) followed by linear discriminant analysis (LDA) (PCLDA) schemes. In Fig. 3, the face image is transformed into a light-insensitive image (INGI) by normalizing and integrating the smoothed gradients of the facial image. Then, the lighting invariant image is reconstructed and fused with the original image in order to recover the information that might have been lost because of the previous processes. In Fig. 4, the three different Fourier feature domains, that is, the real and imaginary component domain, Fourier spectrum domain, and phase angle domain, are presented. All the Fourier features were independently projected into discriminative sub-spaces by applying PCLDA theory.

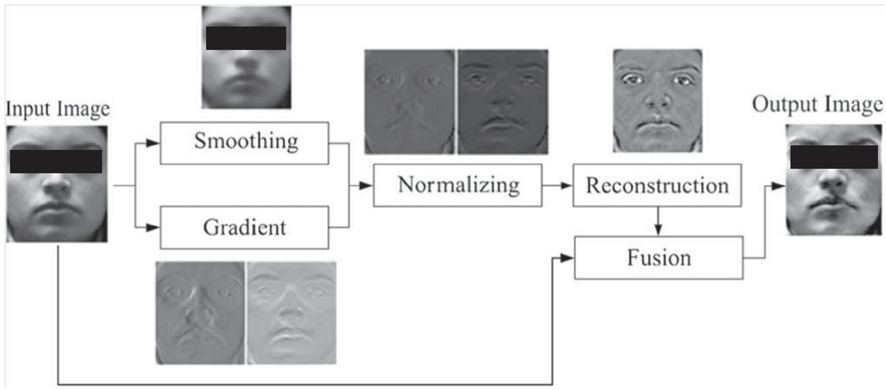

Fig. 3 – Structure of an integral normalized gradient image (Hwang et al., 2011).

3.1.5. *Non-ideality of age*

An attempt to design a face recognition system invariant to the non-ideality of age was presented in Li et al. (2011). In this study, every face was represented with a patch-based local feature representation scheme with the aim of solving the age variation problem. Multi-feature discriminant analysis (MFDA), with SIFT and multiscale local binary patterns (MLBP), was used to reduce the large feature vector dimensionality problem. The face aging MORPH and FG-NET databases were used for this purpose.

3.1.6. *Non-ideality of a single sample per person*

In the study presented in Hu et al. (2015), the non-ideality of a single sample per person was solved using a face recognition method based on the lower upper (LU) decomposition algorithm. For this purpose, first the single sample and its transpose are decomposed into two sets of base images by using an LU decomposition algorithm. Then, from these two basic images, two approximation images are constructed by applying the reverse thinking approach. In order to evaluate the optimal projection space (with a training set), the Fisher LDA is then used. Finally, a nearest neighbor classifier based on Euclidean distance is considered as the final classification. For experiments and method evaluation, four public face databases were employed: FERET, AR, ORL, and Yale B. The results showed the best recognition rate, 81.50%, with the AR database.

3.1.7. *Combined non-idealities*

The effects of a mix of different non-idealities, such as orientation, scale, facial expression, and occlusions, were described by Lai et al. (2001). To reduce these non-ideality effects, a holistic face representation, called spectroface, was used. In this representation, the wavelet transform and the Fourier transform are combined in order to obtain an invariant to translation,

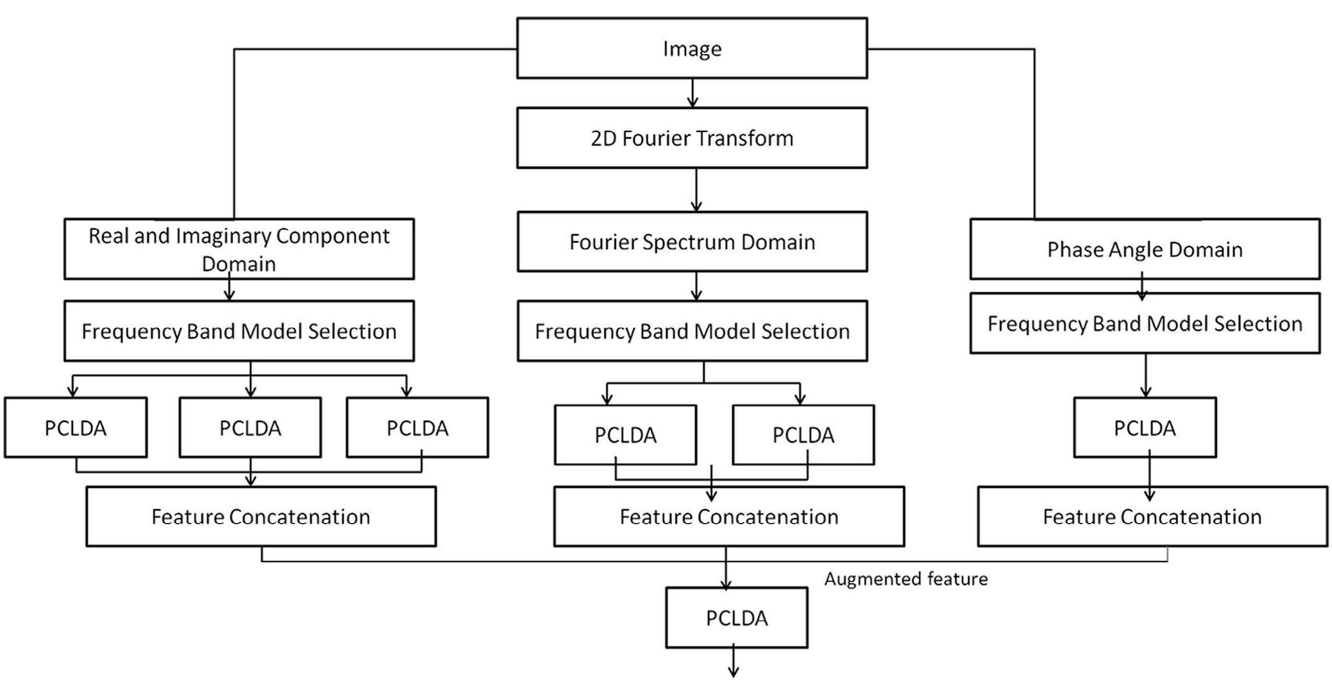

Fig. 4 – Structure of hybrid Fourier transform based on PCLDA (Hwang et al., 2011).

scale, and on-the-plane rotation and a highly accurate and efficient face recognition system. The Yale and Olivetti databases, which contain different orientations, scale, facial expressions, small glasses/eyes, and different lightings, were used to evaluate the proposed system. For improving recognition in scenarios where a combination of several non-idealities, such as lighting, expressions, pose, scale, and occlusions, are present, a method based on PCA, kernel principal component analysis (KPCA), and LDA approaches was described in Wang and Liu (2015). The aim of this study was to improve on the covariance-based methods, such as PCA and KPCA. For this purpose, an entropy matrix was proposed to load the uncertainty information of random variables. Then, an entropy-difference matrix was used as a weighting (EW) matrix for transforming the original images. In this method, the information provided by LDA and PCA is integrated as a new form for extracting features. For experimental analysis, a nearest neighbor classifier was employed, and two public databases were considered: ORL and Yale. The images of some subjects in the ORL database were captured at different times, with varying lighting, facial expressions (open/closed eyes, smiling/not smiling), and facial details (glasses/no glasses). Facial poses changed to some extent. The Yale database, which includes center-light, with glasses, happy, left-light, without glasses, normal, right-light, sad, sleepy, surprised, and winking face images, was used. A high recognition rate, 96%, was obtained, outperforming individual methods such as KPCA. Non-idealities, such as changes in uniform illumination and local appearances changes, e.g., facial expression, pose, and occlusion, were addressed in Chen et al. (2015). To resolve the problem related to the single-structural feature extraction methods, a new feature fusion strategy was proposed. A novel discriminant criterion function was established combining the Euclidean and manifold structures of the facial images. A performance superior to that of some single-structural feature extraction approaches was obtained with publicly available face datasets, such as ORL, FERET, and CMU PIE. Non-idealities, such as large variations in pose, illumination condition, or expression, are considered to limit the performance of variance-based or distance-based methods. To examine this, an experiment involving the recognition of participants in a conference was conducted in Zhao et al. (2015) and its results are applicable to conference socialization scenarios. It is an interesting study, because its results can be easily extrapolated to ABC systems. The steps in the method proposed in this study for performing face recognition are as follows. First, the local feature points are automatically detected by the proposed framework. Second, template matching is used to determine the important feature regions of faces using different angles. This means that large pose variations between training and test images are allowed. Third, no specific distribution of the training data is required, and thus, the system is flexible to various kinds of input data. In this proposed framework, frontal images are used as training images, and verification is performed using any arbitrary view of subject. The identity of a person can be recognized from a picture taken from a standard mobile phone. Experiments were conducted with the standard FERET database and two self-collected datasets composed of images from real conference socializing environments. The recognition accuracy rate achieved was 86%, which is higher than that of other existing methods. In Kaur and Himanshi (2015), a method for facial recognition based on PCA was proposed. The main aim of this study was to investigate the effect of possible non-idealities, such as excess of accuracy, strict time limitations, high processing speed, and availability. Experiments were conducted using the ORL and AR databases, and the best result was a 96.35% recognition rate. It was concluded that PCA is one of the simplest and fastest recognition approaches.

3.1.8. *Non-ideality of using only some of the face image color cues*

This non-ideality, in which only some colors are used for face recognition, sometimes as a result of the hardware employed, was addressed in Xiang et al. (2015). The method in this study was designed to improve the accuracy of color face recognition based on PCA. For this purpose, the color images matrix-representation model, based on the framework of PCA for color face recognition, is used with the GATech color face database. In this study, the problem of color information omission when images are transformed into gray scale was resolved. The recognition rate increased as compared to that obtained with conventional PCA methods, and an average accuracy rate of 80% was obtained.

3.2. *Face databases*

In this section, a review of the most common databases used in different facial recognition studies to test their algorithms performance and efficiency are presented. Multiple facial recognition algorithms have been developed to obtain high recognition rates, high performance, and high accuracy, so that they can be used in high security applications such as ABC e-gates. A general facial recognition system evaluation benchmark framework does not exist and every public or private agency system is evaluated using the private datasets of the respective agency. This lack of standardization has motivated many researchers to generate several face databases, which provide as many variations as possible in their images (different lightings, poses, expressions, etc.) so that system performance and efficiency analyses can cover situations involving different environmental conditions. The most common databases used for face recognition systems evaluation that were reported in the literature are the following (Grgic and Delac, 2005): AR, FERET, SCface, Multi-PIE, Yale face database, Yale face database B, PIE, FIA, AT&T, Cohn-Kanade AU-Coded Facial Expression Database, MIT-CBCL, Image Database of Facial Actions and Expressions (Expression and Image database), Essex University, NIST Mugshot, NLPR, M2VTS, XM2VTS, the University of Oulu Physicsbased Face Dataset, CAS-PEAL, JAFFE, BioID HumanScan AG, PICS, UMIST, Max Plank, Caltech, EQUINOX HID, VALID, UCD Colour, Georgia Tech Face, Indian Face, VidTIMIT, LFW-a, 3D RMA, GavabDB, FRAV2D, FRAV3D, BJUT-3D, Bosphorus, PUT Face Database, BFM, Plastic Surgery, IFDB, Hong Kong Polytechnic University NIR Face Database, PolyU-HDFD, MOBIO, Texas 3DFRD, USTC-NVIE, FEI, ChokePoint, UMB database of 3D occluded faces, VADANA, MORPH, LDHF-DB, PhotoFace, EURECOM KFD, YouTube, YMU Dataset, VMU, MIW, 3dMAD, Senthilkumar, McGill Real-world Face Video, SiblingDB, the Adience image set and benchmark of unfiltered faces for age,

Fig. 5 – Example of 15 camera views from the PIE database with frontal flash illumination.

gender, and subject classification, FaceScrub, LFW3D and Adience 3D set, FG-NET, FRVT, FRGV, FRGC, BANCA, PubFig, and the LFW dataset. Fig. 5 shows an example of a face database in which 15 face images of the same PIE database user are presented. In this case, 15 camera views with frontal flash lighting are presented. The most important facial databases that can be downloaded via the Internet from public and private institutions are presented in Table 1. They were chosen based on the information they can provide toward achieving ABC e-gate recognition systems with the highest performance and efficiency. A classification is shown in terms of the different conditions under which the images in the facial databases, comprising either photo images or videos, were captured.

One of the most useful facial databases that can be used to create highly accurate face recognition systems for use in ABC applications is the CMU AMP Project Face In Action (FIA) Face Video Database. Real-world applications can be simulated using this database in which, for example, a person going through the airport check-in point is recorded. Six different cameras at three different angles were used to capture images in different time periods and in indoor and outdoor scenarios. Facial images with different poses and expressions were obtained and can be downloaded via the Internet. Greater security against presentation attacks is obtained using facial databases with images taken at different wavelengths. The most common wavelengths used and reported in studies in the literature are inside the NIR–VIS spectrum. New features, textures, and different ROC and efficiency values can be obtained with the same facial database for each of the wavelengths employed. By introducing make-up and plastic surgery in facial databases, a more realistic scenario can be obtained. In addition, when using 3D facial databases, by rotating the 3D facial surface around the symmetry lines, additional information of texture, depth, and pose correction is obtained (Blanz and Vetter, 1999, 2003; Godil et al., 2004). The 3D facial surface information is invariant under both different lighting and pose conditions. Databases that store facial images with changes in the subjects appearance that occur over a period of time are very important for ABC e-gate recognition. In these cases, age progression should be considered by the comparison algorithm. This algorithm can sometimes compare the passport photo and/or the facial image with the image taken at the ABC e-gate, moments before the passenger crosses the border. This may occasionally affect the verification of certain travelers, although only a very short period of time passed since the last time they were enrolled.

4. Comparative analysis of different automated border control systems

In this section, the different ABC systems identified as state of the art are compared (Table 2). This analysis was performed with respect to the real needs of the ABC systems, remarking on the relevance of the systems according to their different elements as used in ABC scenarios. Although not all the studies presented in the tables refer to ABC systems, they were chosen as addressing the most suitable systems for use in an ABC scenario. In order to maintain the same criteria, an evaluation of "high" is considered the best qualification in all cases. As an example, the applicability of the system in Kosmerlj et al. (2006) is high, meaning that the system proposed has a high applicability for an ABC system. The aspects included in the comparison are maturity, applicability, acceptance, performance, cost, constraints, deployment, and over-all score. Maturity refers to the level of plenitude presented by the technologies, both those being developed in research studies and emerging technologies. Applicability is the measure of the suitability of a certain technology for the ABC environment. Acceptance refers to the users' attitude to dealing with a specific technology. This factor depends on whether individuals consider it an intrusive technique, in particular in the case of

Table 1 – Classification of facial databases by conditions varied.

Different conditions of:	Face image data base	Face image videos
Illumination	SCface, MultiPIE, the Yale Face, the Yale database B, AT&T (formerly named the ORL database of faces), the NLPR Face, The University of Oulu Physics-based Face Database, AT&T "The Database of Faces," NLPR Face Database; The AR Face Database, the Ohio State University, USA; The University of Oulu Physics-based Face Database; CAS-PEAL Face Database; The UCD Colour Face Image Database for Face Detection; FRAV2D Database; Natural Visible and Infrared facial Expression Database (USTC-NVIE); The EURECOM Kinect Face Dataset (EURECOM KFD); YMU (YouTube Makeup) Dataset	McGill Real-world Face Video Database; Indian Movie Face Database (IMFDB); BU-4DFE Database (Dynamic Data)
Changes in a subject's appearance that occur over a period of time (age progression)	The Color FERET Database, USA; Georgia Tech Face Database; VADANA: Vims Appearance Dataset for facial ANAlysis; MORPH Database (Craniofacial Longitudinal Morphological Face Database)	
Different wavelengths (hyperspectral databases)	SCface – Surveillance Cameras Face Database; The University of Oulu Physics-based Face Database; The Hong Kong Polytechnic University NIR Face Database; The Hong Kong Polytechnic University Hyperspectral Face Database (PolyU-HSFD); Natural Visible and Infrared facial Expression Database (USTC-NVIE); Long Distance Heterogeneous Face Database (LDHF-DB)	
With landmarks	SCfaceDB Landmarks; PUT Face Database; SiblingsDB Database	BP4D-Spontanous Database
Different viewpoints	MultiPIE, AT&T "The Database of Faces"; The MIT-CBCL face recognition, NIST Mugshot; Identification Database; Georgia Tech Face Database; 3D-RMA database;	VidTIMIT Database; McGill Real-world Face Video Database; Indian Movie Face Database (IMFDB)
Occlusions: use of glasses, scarf, beard, etc.	The Yale Face Database, AT&T "The Database of Faces," Face Recognition Data, University of Essex, UK, NLPR Face Database; The Bosphorus Database; UMB database of 3D occluded faces; The EURECOM Kinect Face Dataset (EURECOM KFD);	McGill Real-world Face Video Database; Indian Movie Face Database (IMFDB); BP4D-Spontanous Database
Pose	The Yale Face Database B, PIE Database of CMU, The MIT-CBCL face recognition, CAS-PEAL Face Database; The UCD Colour Face Image Database for Face Detection; FRAV2D Database; The Bosphorus Database; UMB database of 3D occluded faces; The EURECOM Kinect Face Dataset (EURECOM KFD); VMU (Virtual Makeup) Dataset	Project – Face In Action (FIA) Face Video Database, AMP, CMU; McGill Real-world Face Video Database; Indian Movie Face Database (IMFDB); BP4D-Spontanous Database
Real world applications	Labeled Faces in the Wild; The LFWcrop Database; Labeled Faces in the Wild-a (LFW-a); ChokePoint; PhotoFace: Face recognition using photometric stereo	Project – Face In Action (FIA) Face Video Database, AMP, CMU; YouTube Faces Database; McGill Real-world Face Video Database; LFW3D and Adience3D sets; BP4D-Spontanous Database
High resolution images	The MIT-CBCL face recognition; PUT Face Database	The Extended M2VTS Database, University of Surrey, UK
3D model	The MIT-CBCL face recognition; 3D-RMA Database; FRAV3D Database; BJUT-3D Chinese Face Database; The Basel Face Model (BFM); Texas 3D Face Recognition Database (Texas 3DFRD); UMB database of 3D occluded faces; UMB database of 3D occluded faces; PhotoFace: Face recognition using photometric stereo; BU-3DFE Database (Static Data)	The Extended M2VTS Database, University of Surrey, UK; Denver Intensity of Spontaneous Facial Action (DISFA) Database; BU-4DFE Database (Dynamic Data); BP4D-Spontanous Database
Use of neural networks for matching gray scale	Image Database of Facial Actions and Expressions – Expression Image Database	
People of various racial origins	Face Recognition Data, University of Essex, UK; BU-3DFE Database (Static Data)	Texas 3D Face Recognition Database (Texas 3DFRD)
Camera calibration	The University of Oulu Physics-Based Face Database	
Large scale	CAS-PEAL Face Database; FaceScrub – A Dataset with Over 100,000 Face Images of 530 People; Labeled Wikipedia Faces (LWF)	YouTube Faces Database
Manually set eye and fiducial points or classification in sets	BioID Face DB – HumanScan AG, Switzerland; Psychological Image Collection at Stirling (PICS)	Texas 3D Face Recognition Database (Texas 3DFRD)
Different quality	The UCD Colour Face Image Database for Face Detection; 3D-RMA database	
Different scales and rotations	Georgia Tech Face Database; The LFWcrop Database; FEI Face Database; FaceScrub – A Dataset With Over 100,000 Face Images of 530 People	
Plastic surgery	Plastic Surgery Face Database	
Different ages	The Iranian Face Database (IFDB); MORPH Database (Craniofacial Longitudinal Morphological Face Database); The Adience image set and benchmark of unfiltered faces for age, gender, and subject classification	McGill Real-world Face Video Database
Adding make-up	VMU (Virtual Makeup) Dataset; YMU (YouTube Makeup) Dataset; MIW (Makeup in the "Wild") Dataset	Indian Movie Face Database (IMFDB)
Spoofing	3D Mask Attack Database (3DMAD)	3D Mask Attack Database (3DMAD)
Facial expressions	The Yale Face Database PIE Database of CMU; AT&T "The Database of Faces" (formerly "The ORL Database of Faces"); NLPR Face Database; The AR Face Database, The Ohio State University, USA; CAS-PEAL Face Database; Japanese Female Facial Expression (JAFFE) Database; the UCD Color Face Image Database for Face Detection; Georgia Tech Face Database; The Bosphorus Database; UMB database of 3D occluded faces; The EURECOM Kinect Face Dataset (EURECOM KFD); VMU (Virtual Makeup) Dataset; Senthilkumar Face Database (Version 1.0); 10k US Adult Faces Database; BU-4DFE Database (Dynamic Data)	Project – Face In Action (FIA) Face Video Database, AMP, CMU; Texas 3D Face Recognition Database (Texas 3DFRD); McGill Real-world Face Video Database; Indian Movie Face Database (IMFDB); BP4D-Spontanous Database

Table 2 – Overview of several aspects of analyzed papers.

Bibliography analyzed	Maturity	Applicability	Acceptance	Performance	Cost	Constraints	Deployment	Overall score
Kosmerlj et al. (2006)	High	High	Medium	Medium	Medium	Medium	Medium	★★★★★★
Kwon and Moon (2008)	Low	Medium	Medium	Low	Medium	Low	Medium	★★★★
Cantarero et al. (2013)	High	High	Medium	High	High	Medium	Medium	★★★★★★★
Spreeuwers et al. (2012)	Medium	High	High	High	Medium	Medium	Medium	★★★★★★★★
Conde et al. (2011)	Medium	High	Medium	Medium	Medium	Low	Medium	★★★★★
Frontex (2010)	High	High	High	Medium	Medium	Medium	High	★★★★★★★★
Bourlai et al., 2009	Low	High	Medium	Low	Medium	Low	Medium	★★★★★
Kim (2005)	Medium	High	Medium	High	Medium	Low	Medium	★★★★★★
Kim and Kim (2008)	Medium	High	Medium	Low	Medium	Low	Medium	★★★★★
Kumar et al. (2009)	Low	Medium	Medium	Low	Medium	Low	Medium	★★★★
Karthikeyan et al. (2013)	Low	Low	Medium	Low	Medium	Low	Medium	★★★★
Manjupriya et al. (2013)	Low	Medium	Medium	Medium	Medium	Low	Medium	★★★★
Beom-seok and Kar-ann (2013)	Low	Medium	Medium	Medium	Medium	Low	Medium	★★★★
Li et al. (2013)	Low	Medium	Medium	Medium	Medium	Low	Medium	★★★★
Hwang et al. (2011)	High	Medium	Medium	High	Medium	Medium	Medium	★★★★★★
Zafeiriou et al. (2013)	Medium	High	Medium	Medium	Medium	Low	Medium	★★★★★
CurrentABCs	Medium	High	Medium	Medium	Medium	Medium	Medium	★★★★★★

biometric technologies. In turn, it is necessary to take into consideration social and cultural factors, according to which it may be assumed that certain techniques are more or less accepted, according to the environment in which they are introduced. The performance was measured in different terms according to the nature of the technology. For example, for biometric technologies, the performance also included efficiency. This was defined in terms not only of the false positive rate, but also of the process speed or rate in cases where this parameter is referred to. The costs refer to the technology implementation and maintenance. Constraints refer to the limitations that affect the performance of the technologies, such as difficulty in meeting the work load demands and problems of interoperability between systems. This aspect allows measuring the technology used in the ABC systems. The evaluation of deployment refers to the degree of difficulty of implementing the technologies, depending on the type of technology used. Furthermore, an overall evaluation based on the number of stars assigned to the technology presented in each study is determined. It should be noted that the number of stars is related to the score of the previous aspects (maturity, applicability, etc.). The more stars assigned, the more relevant is the technology in each study, from our point of view. The maximum score is 10 stars and the minimum 0 stars. This scale was decided based on the comparison of the works presented in the tables. However, because the current use of biometrics is not yet well accepted by end-users, the maximum score of 10 stars was not given to any study. In Table 2, the systems in the studies (Cantarero et al., 2013; Conde et al., 2011; Kosmerlj et al., 2006; Kwon and Moon, 2008; Spreeuwers et al., 2012; Frontex, 2010) are evaluated. It can be seen in this table that the systems having the highest evaluation of all the them are those described in Frontex (2010) and in Spreeuwers et al. (2012), with eight stars. Frontex (2010) gives information about RAPID and SmartGate ABC systems, which have already been implemented in Portugal and Australia, respectively. Neither system requires the prior registration of the traveler and they are both interoperable. Face recognition in combination with e-passports are used for travel document checking and biometric verification is used for traveler identification. In these cases, there is no control over the original registration of biometric data. The systems are very well accepted and could be integrated in other international airports. They were applied in real situations and their applicability and performance are high, although their maturity may not be sufficiently high to allow their adaptation for use in other countries. In Spreeuwers et al. (2012), an evaluation study was conducted in which automated facial recognition reliability for automatic border passage in two ABC e-gates at Schiphol Airport was investigated. The study consisted of a comparison of the live images of every passenger and the digital photographs stored on their passports. Again, the system is very well accepted and its high performance, maturity, and applicability are key factors for the good evaluation given by the authors. In Kosmerlj et al. (2006), the use of the California State University (CSU) face identification system 5.0 for identifying different face images of subjects and for passport holders photo verification was described. The study used different databases in order to estimate the percentage of Norwegian people who have look-alikes in the Norwegian population. For the verification performance,

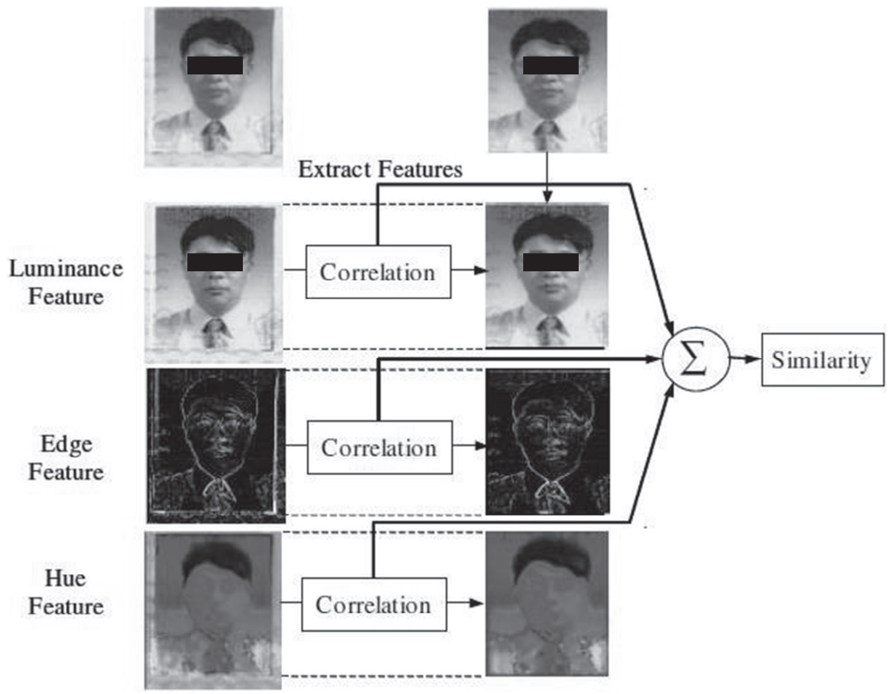

Fig. 6 – Feature extraction and similarity measurements of a passport photo (left) and the face image retrieved from the immigration database (right) (Kim, 2005).

illumination and occlusions were controlled in order to simulate the best border controlled scenario. Although the applicability and maturity of the technology are high, it has several constraints, such as the appearance of the subjects hair, that play an important role in its performance. From this study, it is concluded that the face image verification is not sufficiently secure to allow its implementation in ABC systems. For this reason and despite the real scenario used, the system presented in Kosmerlj et al. (2006) scored six stars. The system requires improvements in terms of security to allow its integration in ABC systems. In Kwon and Moon (2008), a face identification system with cryptographic mechanisms based on the current Public Key Infrastructure (PKI) that is compatible with ICAO's Public Key Directory (PKD) was used for border control applications. Although the system is enhanced in terms of security as a result of the cryptographic mechanisms, its applicability at borders is low because the performance values are not sufficiently high to be ICAO-compliant. Furthermore, in the study, its physical design is not explained. Only the software algorithms presented in the study could be implemented in ABCs because of their similarity to other algorithms for ABCs presented in literature. The efficiency of the system satisfies ICAO recommendations; however, the study gives no information of either FAR or FRR values and the database used was not a database created for an ABC system scenario. The system scored four stars because of this lack of information. The face and fingerprint biometric recognition system used at Barajas Airport in Spain was described in Cantarero et al. (2013). Biometric data available in the electronic travel document and more specifically in the second generation passport are needed for correct verification. High applicability, maturity, and performance levels characterize this ABC system. The system was assigned seven stars. As mentioned in section 2, in Conde et al. (2011) an evaluation of the results obtained for a face recognition system in a real uncontrolled localization, such as Barajas Airport, was presented. In the study, three video surveillance cameras at different locations in the airport were selected for capturing travelers' images. Varying illumination changes and quality levels, collaborative and non-collaborative subjects, and different data compressions were considered. CSA gave the best performance. For classification purposes, SVM was used. Although the system is not sufficiently mature, its applicability is high. A medium score is given to the other classifiers, mainly because the cameras are not currently used for this purpose. The system presented in this study was assigned five stars. In this Table 2 the works (Bourlai et al., 2009; Kim, 2005; Kim and Kim, 2008; Kumar et al., 2009; Karthikeyan et al., 2013) are evaluated as well. That presented in Kim (2005) received the best score. This study focused on using the passport codes to search the traveler in an immigration database. Forged passports are detected by using automatic recognition of passport codes and picture and face verification. When the traveler has been located, his/her facial image is retrieved from the database and verified with the photo in the passport. The main problem of this study is the system's low efficiency due to the immigration database search engine that is not designed for scalability. This database can be sizable and contain millions of registered travelers (see Fig. 6). The system has a high performance and applicability, the latter due to its relevance in terms of spoofing; however, the other parameters are evaluated as medium or low, mostly because the system has not been operated in a real environment and external conditions are not considered in the study. In Bourlai et al., 2009, international passports exhibiting a variety of facial image qualities and security marks were used and the problem of matching high resolution digital face images with low-resolution passport photos scanned from the original document was addressed. The study's applicability to ABC systems is high because of the relevance of international passports to these systems. The systems performance does not satisfy ICAO requirements, except when the system is trained with high resolution face images. The other qualifications are medium and low because the system was not operated in a real environment and high resolution face images are not used in ABC systems. In Kim and Kim (2008), passport recognition and face verification methods were applied together with passport code recognition in order to discriminate forged passports in ABC systems. In this system, the face is authenticated by measuring the similarity between the feature vector of the passport facial image and that in the database, which was constructed using PCA. The applicability of the system in this study is high but its performance is not ICAO-compliant. Acceptance of the system was evaluated as medium, because the passengers passport must be in very good condition. The deployment of the system was considered medium, because the e-MRTD and the kiosk should be prepared for this specific algorithm and should be well protected from external conditions. The system is not sufficiently mature to be safe against spoofing attacks. The authors assigned five stars to the proposed system. In Kumar et al. (2009), two novel methods for face verification with real-world images, such as those in the "Labeled Faces in the Wild" (LFW) dataset and those from the PubFig dataset comprising images of public figures acquired from the Internet, were presented. In the first method, attribute classifiers and binary classifiers trained to recognize different visual appearance aspects, such as gender, race, and age, are used. In the second method, smile classifiers are used, in which the similarity of faces or regions of faces to specific reference people is learned. The system performance is not ICAO-compliant, but was very high for the complex sample population studied. Although the database used is very similar to those employed in ABC systems because several factors, such as illumination, pose, occlusions, and expressions, are considered, only the software part, and neither its physical appearance nor hardware components, are described in the paper. Because of this lack of information, the aspects of applicability, acceptance, and deployment were evaluated as medium and the overall score assigned is four stars. In Karthikeyan et al. (2013), a face verification system operating with the FRGC dataset, which comprises 3D scans and high resolution still images taken under controlled and uncontrolled conditions, was presented. Although the authors assured that the performance is high, no value was provided. The characteristics of the system described in this study are that 3D scanned images and integral normalized gradient images are used in the pre-processing stage for avoiding image noise and the halo effect, which could be useful in ABC systems. However, as in Kumar et al. (2009), only the software algorithms are applicable to ABCs because the hardware used was not described. Furthermore, the evaluation of the applicability of the system is lower than that of the system in Kumar et al. (2009), because 3D scanners are not used in current ABC systems. The works (Beom-seok and Kar-ann, 2013; Hwang et al., 2011; Li et al., 2013; Manjupriya et al., 2013; Zafeiriou et al., 2013) and the general situation of current ABC systems are evaluated in this table as well. The system presented in the study in Hwang et al. (2011), briefly described previously, in which a face recognition framework based on the ECG classifier bunch was proposed, is evaluated as the best of them. The bunch is made of plural ECG classifiers combined by means of a log-likelihood ratio-based score fusion scheme. The evaluation was performed using the FRGC database with two experimental protocols, called EXP1 and EXP4. The first protocol was designed to measure the performance of traditional frontal face recognition systems under controlled illumination conditions and the second contains unexpected illumination changes, blurred images, and some occlusions in images. The ROC curves were calculated and the performance values obtained with EXP1 classifiers were such that the system satisfies the ICAO performance recommendations. The system is considered by the authors sufficiently mature to be installed in ABC systems. Its performance and applicability are also high, because of its robustness against illumination, occlusions, and low quality images. The hardware components required in order to integrate the algorithms in ABC systems are not described in the study. The final score assigned to the system by the authors is six stars. In Manjupriya et al. (2013), a face verification system that is very robust to changes in illumination was proposed. In the study, the Yale-B database was used. For image normalization, integral normalized gradient image including the Retinex method was employed, KPCA was used for feature extraction, and the Score Fusion-based Weighted Sum Method was used for achieving the scores. This paper is relevant to ABCs only because of the systems invariance to illumination variation. A final evaluation score of four stars is assigned by the authors to the system presented in this study. In Beom-seok and Kar-ann (2013), a face verification system, previously mentioned in Section 2, which uses sinusoidal projection for feature extraction with the AR, ORL, and BERC databases, was proposed. The applicability of this system to ABC systems is provided by its invariance to external and intrinsic factors, because the databases used in the study contain images captured with varying illumination, time, expressions, poses, and occlusions. The verification results were compared with those of other methods, such as H2DPCA, V2DPCA, and structured projections. A higher performance was obtained with sinusoidal projection, although the values recommended by ICAO for use in ABCs were not obtained. The system presented in this study was assigned four stars, because neither the hardware components nor their distribution and system physical appearance were described in the paper. The authors of Li et al. (2013) addressed the problem of pose variant face verification in uncontrolled settings using a probabilistic elastic matching method with the LFW and the YouTube video face databases. In their system, in order to improve feature localization, a Gaussian mixture model (GMM) is trained to capture the spatial appearance distribution of all face images. Each Gaussian component builds the correspondence of a pair of features to be matched with two faces/face tracks. For face verification, an SVM is used to decide whether a pair of faces/face tracks matches or not. Furthermore, a joint Bayesian adaptation algorithm was proposed to adapt the universally trained GMM to better model the pose variations in each pair of faces. Although the performance of the system does not meet ICAO requirements, it was considerably improved by using this procedure. The main contribution of this study to an ABC system is the systems robustness against different poses as a result of the algorithms used. However, although a considerable amount of information is given about the state of the art of face recognition, information about neither the physical design and hardware processing nor the setup components distribution of the system is provided. Furthermore, this study was not conducted in a real ABC scenario. The authors assigned a score of four stars to the system presented in this study. In Zafeiriou et al. (2013), a verification system device in which the presence of a subject is automatically detected using an ultrasound technique was located at the entrance to a busy workplace, capturing 1839 face images with natural poses and expressions. The Photoface database was used, being suitable for both 2D and 3D face recognition based on photometric stereo (PS). The highly realistic data obtained and the different reconstruction and recognition methods, using the albedo, surface normals, and recovered depth maps, make this systems implementation in ABC systems very valuable. Although the system deployment is not evaluated as high because of the complexity of the stereo system, there is less interaction of the system with the passenger, and therefore, the acceptance of the system will not be poor and it will suffer very few physical constraints. As soon as this system is implemented in ABC systems, more devices will be fabricated with great success and therefore the costs will be reduced. Furthermore, by using these stereo photos, security in ABC systems will be increased. In addition, the scenario used in the study was far from that of ABC systems. The overall evaluation score is five stars. To conclude, a general evaluation of the current ABC systems was presented. Although in our opinion the end-user perception of these systems is very good, people are becoming more familiar with biometric information collection, and the systems are now more user friendly, problems related to general acceptance remain. In addition, the costs of the ABC systems were average and some effort should be invested in decreasing them. Furthermore, facial identification algorithms have improved significantly during the last few years, in particular for use in ABC systems, mainly because of the controlled conditions under which they operate. This explains why experts in biometrics technology have begun to believe in facial biometrics as the only modality to be used in future ABC systems, instead of fingerprints or other modalities. An important characteristic that an ABC system should have is interoperability, so that it can be interoperable in any location, that is, interoperable with those of other national airports and also with the ABC systems of other countries.

5. Experimental evaluation

In order to reproduce an automatic border control (ABC) e-gate scenario and implement an ABC e-gate face recognition system with high performance and efficiency, an experimental setup with a design very similar to that of the system used at Barajas Airport using halogen lights, white light-emitting diodes (LEDs), near-infrared (NIR) illumination, and fluorescent illumination was designed. The main aim of this experiment was to evaluate the influence of different illuminations on the ABC systems performance. An evaluation of the system was performed, as well as a comparison with other ABC systems presented in the literature, using the classical standards for evaluating biometrics: efficiency and accuracy. Efficiency was considered to be a measurement of resources used in relation to the systems accuracy and completeness; it can be measured by evaluating the time spent during the whole process or during different steps of it. Accuracy was determined by evaluating error indexes, usually in the case of biometric systems the false rejection rate (FRR) and the false acceptance rate (FAR), and their graphical representation in a receiving characteristic operating (ROC) curve. Furthermore, the system presented is a highly reliable ABC system. In the context of biometrics, reliability tends to be associated with the systems performance in terms of accuracy. It is used to determine how the biometric system performs its matching function (measuring and evaluating system performance through e.g., FAR and FRR). More importantly, it indicates how different performance rates and their alteration affect the overall security of the border check process.

5.1. *System description*

ABC systems used in airports have very similar characteristics. Typical elements that constitute an ABC system are cameras to capture images, a fingerprint reader, a reader for machine-readable travel documents (e-MRTD), an illumination system to avoid external light variations, usually a video screen with images or videos to give instructions for system use, and fast and highly efficient recognition software for traveler verification and identification. In this study, the experimental setup was very similar to the system used at Barajas Airport (see Fig. 7).

5.1.1. *Hardware*

Following Frontex best practice guidelines, and with the purpose of capturing high quality facial images, halogen, white LED, NIR, and homogeneous fluorescent illumination were used in the setup. Three Logitech QuickCam Sphere AF cameras were placed in a static configuration covering a complete range of human heights (175 cm, 160 cm, and 145 cm, respectively). The cameras have two megapixel sensors and can capture images with an improved resolution of 8 megapixels using the correct illumination. When there are no moving objects, as in this setup, hardware is less prone to failure. Illumination is a key aspect in facial verification, and therefore, was carefully considered. Two illumination sections were placed to the right and left of the cameras. Two diffusers blocked direct light and generated ambient illumination. Diffusers minimize reflections and distribute illumination almost homogeneously. This configuration allowed several changes in the illumination to be studied. In our experiments, several light conditions were taken into account: LED illumination, and fluorescent and halogen bulbs. In an additional experiment, near-infrared (NIR) illuminators were used. The LED illumination configuration consisted of 6 LED bulbs in each illumination section, for a total of 12 LED bulbs. Each LED bulb featured 48 LED diodes with a white light emission of 280 lumens. The bulbs were protected by white diffusers that made illumination more homogenous for both sides of the user's face. The illumination section was directed toward the user at an angle of 45 degrees. The main difference between

Fig. 7 – Experimental evaluation setup. The circles in front of the subject are the cameras that capture the face images, and those to the side (left and right) are the light emitters. Explanatory video screens, the fingerprint reader, and the e-MRTD are below the cameras.

the studied prototype and a real application is that the tested system included neither a travel document reader nor a validation subsystem. These subsystems were not required for these tests, as the facial samples for comparison were obtained from an external image database.

5.1.2. *Software*

The recognition and verification software used in this study was a commercial product. An application interface (API) was developed based on libraries provided by the owner of the product, although the recognition algorithms used were not shown. The recognition process was split into two main steps. First, an image was acquired and preprocessed. It was discarded if it was considered of low quality (no face was detected, the face was too small, etc.); otherwise, it was compared with the identity photo. The recognition algorithm used was a commercial one suitable for use in ABC systems. This initial process was repeated with several live images for each subject. The result of the comparison was a score that was stored. Finally, the highest score from the set of stored scores was set as the final score. If the final score was sufficiently high, the subject was allowed to continue.

5.1.3. *Database*

One hundred and thirty-four volunteers participated in constructing the datasets. The reference dataset contained the images used as a reference or template to verify the subjects identities (see Fig. 8). The images were newly acquired live reference images, of high quality, captured with a reflex camera,

Fig. 8 – Reference (left) and test image (right) using LED illumination of the same subject from the database.

printed using a photographic printer and paper, scanned using a flatbed scanner, and finally post-processed according to ICAO standards. The test dataset contained four classes of illumination: LED, halogen, fluorescent, and NIR (see Fig. 9). These four illuminations were tested in order to know which of them could provide better face recognition results in ABC systems. Images were acquired over the course of several days to allow for variations in make up, beard growth, clothes, and natural illumination. The mean time span between image acquisitions was seven days. The setup was an indoor environment. In the acquisition of the database, no disturbing light from other sources was allowed in the setup of the ABC e-gate. The experiment (Fig. 7) introduced a more realistic variability, since each day one type of illumination was used. Subjects were requested to remain in front of the system for at least 6.5 s. During

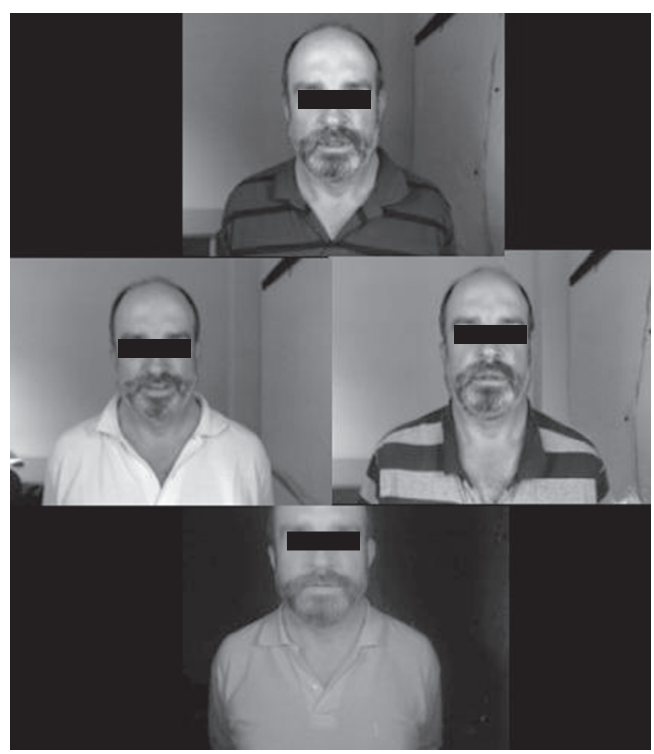

Fig. 9 – Test images of a subject in the database. Illuminations considered, from left to right, and top to bottom: LED, halogen, fluorescent, and near-infrared.

this time, one image was acquired every 180 ms. The minimum number of images captured per subject was 30 and the maximum was 34. The mean number of images per subject was 32.61 (with a standard deviation of 1.49). The image size was 960 × 720 pixels for a color image with 24 bits per pixel. Each image was compressed in JPEG, and the mean final size was 64 kB.

5.2. *Results and discussion*

The first measurement used to evaluate the ABC system is based on the system accuracy, as it was previously defined. In this paper, the biometric system evaluation approach considered was the FAR and the FRR. The point at which both errors are equal is called the equal error rate (EER). In the work presented the EER is used as the accuracy measurement of the ABC system. Every test image was compared with all the acquired reference images in a cross-validation manner. In this experiment, the reference or template image was the high quality image acquired following the protocol of passport image acquisition. Reference images were recently captured, and the same acquisition protocol, acquisition device, and scenario were applied for all subjects. An example of the test and reference images is presented in Fig. 8. As in real ABC systems, subjects wearing glasses were asked to remove them during the verification step. In the first experiment, one hundred and forty-four subjects were used with all the illuminations under consideration. In order to analyze only the influence of illumination, a time variation between the test and reference images greater than three weeks was not allowed. Results are presented in an ROC curve, which is frequently used in the biometrics community (FAR vs FRR). In Fig. 10, the system performance for each illumination is presented. It can be seen that the best results (i.e., the lowest EER) are obtained from halogen illumination, with an EER of 0.42%. The EER for LED and fluorescent illumination were 0.79% and 1.03%, respectively. In the case of NIR illumination, the error increases to 5.70%. The FRR rates at FAR 0.1% were 3.4%, 0.8%, 0.8%, and 26.3%, for fluorescent, halogen, LED, and NIR illumination, respectively, satisfying the best practical technical guidelines for ABC systems (FAR = 0.1%, FRR ≤ 5%) (Frontex, 2012a), except from the NIR illumination. Thus, the influence of illumination is relevant, since the EER of the best illumination condition (halogen) is nearly twice that of the second best (LED) and nearly three times that of the third best (fluorescent). NIR presents an EER approximately 13 times higher than does halogen. Notice that even the best results imply a poor performance as compared to the results of state-of-the-art studies. The main differences between the results presented in state-of-the-art studies and the results presented in this paper are due to the fact that the proposed setup was intended to be realistic. That is, it is not reasonable to compare our results with those of studies in the literature, since in general no results for a real system are presented in those studies. It can be concluded that the illumination applied in the ABC prototype was very relevant and greatly affected the final results. Efficiency was also considered as a second measurement to evaluate the system. The approach that was followed for measuring the execution time between different points of the ABC process was similar to the work developed in the FastPass project (FastPass, 2016). The verification time was less than 1 s for each subject when the face image was considered to be of good quality for subsequent processing. This calculation was performed based on the time information given by the software developer. The efficiency value, which comprised the time between the image being captured by the cameras and correct user verification, was about 2 s. This value was measured using an API that we developed that measures the photo capture time, as well as the identity verification efficiency given by the program that was a characteristic of the algorithm used and that was not given by the vendor. The evaluation was done using a PC Intel Core i5-2400, 3.10 GHz with 8 GB RAM. These results satisfy the best practical technical guidelines for the efficiency of ABC systems (Frontex, 2012a). In addition, the total efficiency of the system located at Barajas Airport, which uses a one-step mantrap, was calculated, although in that case document checks and a fingerprint reader were also used. The total efficiency consisted of the time measured between the point when the traveler placed his or her passport on the e-MRTD and the point when the traveler crossed the ABC e-gate, which was 10 s on average. This value was calculated as the average time for 100 people and is in agreement with Frontex recommended efficiency (Frontex, 2012a). The direct quantitative comparison between these results and other in-field results of different ABC gates is not simple. Because of security reasons, there are very few published results and the databases used to obtain these results or the measurements used in evaluation are generally not thoroughly explained. It should be noted that currently, the formal evaluation framework for ABC systems is not yet completely defined. Considering these strong restrictions, we present a comparison of these results with the work described in Oostveen et al. (2014), which is one of several studies carried out as part of the FastPass project and is based on ABC systems. In this paper, one hundred and twenty-five face-to-face surveys with passengers describing their experiences with ABC biometric systems are shown. Two different approaches, such as the two-step mantrap design and the one-step mantrap design, were considered. Problems like passport scanning and facial recognition were the cause of delays in the entrances. Regarding the former, 58% of passengers had problems with the passport scanner and 20% were not able to solve their problems by themselves, so that a manual check by a border officer was required. Regarding the latter, 13% of passengers experienced problems. In the two-step mantrap design, many live images showed people looking down at the passport scanner, causing a high delay in access time. In fact, on several occasions, a manual check was required and time-out was reached. This problem could only be solved if the length of time to reach a time-out were increased. In this paper, efficiency results are the following: when the e-gates work and the passengers know exactly what to do, the system is fast, taking about 15–20 s to let a passenger through. This is slightly higher than our measurements, in which only 10 s was needed. However, when people have problems understanding the system, this paper reports that access time can be as long as 5 minutes. In our case, this situation was not observed. Regarding facial recognition, it takes a border guard 10 s to process a person, the same as in our measurements. Considering ABC system accuracy, some public results of dif-

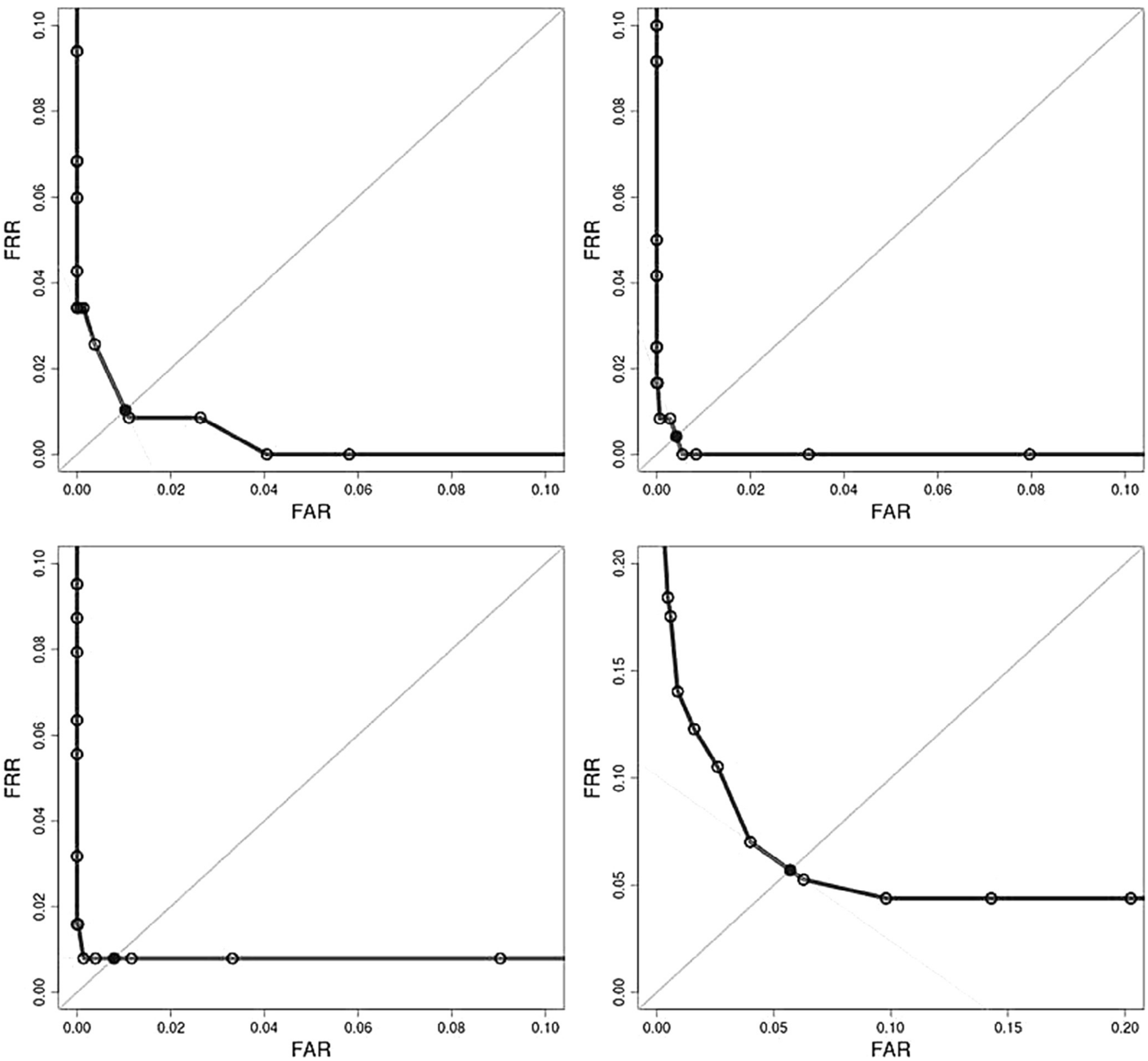

Fig. 10 – ROC curve results for the different illumination test datasets and acquired reference image dataset. From left to right, and top to bottom: fluorescent, halogen, LED, and near-infrared illumination.

ferent ABC approaches are reported in the literature, such as in the Frontex workshop, "1st Global Conference and Exhibition on Future developments on Automated Border Control," held in Warsaw in 2012 (Frontex, 2012b). Following the line of other meetings, in this workshop the Spanish National Police presented several ABC accuracy results, although the exact location of the ABC system evaluated was not named. In addition, they referred only to FRR values because only bonafide users were considered; consequently it was not possible to measure the FAR. The FRR of the facial recognition algorithm was 11.99%, and when a multi-biometric algorithm was used (facial + fingerprint recognition), the FRR value decreased to 1.40%. It should be noted that the multi-biometric approach can only be applied to Spanish users. In other cases, fingerprint information is not accessible. No details about the database used were given and only an average of 50,000 passengers per month was mentioned. Other ABC performance data available were presented in 2013 at the Frontex "2nd Global Conference and Exhibition on Future developments on Automated Border Control," held in Warsaw and organized by the Immigration and Border Service of Portugal (Frontex, 2013). In this case, the evaluation details were more specific, presenting a database of 125,933 pairs of photos at Lisbon Airport, only considering facial information. An FRR of 6.32% at a measured FAR of 0.046% was shown. Finally, other ABC performance values can be found in the different documents written for the FastPass project, such as in Opitz and Kriechbaum-Zabini. In this work, two commercial facial verification systems were applied to a database of 3224 sessions acquired at Schipol airport (Amsterdam), considering only facial information. System A presented an FRR of 0.9% at an FAR fixed at 0.1% and system B presented an FRR of 2% at an FAR fixed at 0.1%.

6. Improvements in face recognition systems in automated border control e-gates

In this section, some of the possible future improvements in ABC e-gates face recognition systems are described. Most of these are based on acquiring high quality images so that high-level efficiency and performance can be achieved. Researchers working on advanced recognition models are continuously searching a universal invariance to non-idealities so that systems are not affected by subjects wearing glasses or changes in rotation, translation, pose, expression, lighting (Martinez, 2002; Zhang and Gao, 2009; Zou et al., 2007), etc. The identification of individuals appearing in more than one camera, simultaneous verification and identification of various people in an e-gate, and the elaboration of novel algorithms able to recognize young children and impaired travelers are important goals. Individuals in a group of faces can be detected, using, for example, the Viola Jones algorithm and Fisherface and eigenface algorithms. These algorithms are frequently employed for this purpose, in particular when a high level of invariant external parameters, such as lighting, is desired (Belhumeur et al., 1997). Interfaces using video-based approaches that can track travelers when they are entering a gate could be used for many applications, such as monitoring the traveler's behavior, capturing several face gestures and expressions, detecting or interpreting liveness motion, determining the patterns of an individual's movement, estimating crowd densities, measuring line lengths, and/or issuing alerts about abandoned baggage. The use of mobile cameras at ABC e-gates for intelligent video surveillance purposes in order to obtain relevant information about the scene in an e-gate will be introduced in the near future. This can be also used for remotely informing the guards about the situation occurring in a scene. The mathematical algorithms for detecting moving objects in an image and filtering non-relevant movements will be improved. The attributes of all the objects detected and their movement properties will be recorded in databases. Events of interest will be searched in these databases and decisions will be reached by the system according to the relevance of these events. Security at the borders will be reinforced by video analytic techniques. These techniques can result in real-time or non-real-time alerts, leading to video searches to investigate the event at the pixel and object level. The different tasks to be performed by these techniques, such as change detection, segmentation, monitoring, and classification of humans according to knowledge about their activities and behaviors, will be developed. ABC system performance will be improved with the integration of specialized software in the ABC e-gates to infer the attributes of travelers, such as gender and age. Multispectral image capture (Chen et al., 2003; Pan et al., 2003) will be used to capture 3D face images and detect features.

7. Conclusion

In this paper, an introduction to the ABC e-gates that are currently operational in most of the airports worldwide, e-passports, face databases, and the various EU projects focused on ABC systems was presented. Non-idealities, such as changes in illumination, temperature, humidity, pose, position, translation, and rotation, should be considered in the design of ABC e-gates. A review was presented of some of the algorithms reported in the literature that are used in face recognition systems and are invariant to these non-idealities and can therefore be implemented in ABC systems. A comparison of the different ABC systems that can be found in many ABC Schengen area airports and that were reported in the literature and face recognition systems with characteristics that are highly compatible with an ABC scenario, in terms of maturity, applicability, acceptance, performance, costs, constraints, and deployment, was presented. To conclude, an experimental evaluation of a face recognition system having a design very similar to that used in the Barajas Airport ABC system, under halogen, white LEDs, NIR, and fluorescence illumination, was presented. A test using a 144-subject database showed that halogen illumination is superior to all the other different illumination configurations analyzed, closely followed by LED illumination, which can be more suitable in real operation conditions because of power consumption, dissipated heat, and user convenience. Given that there are no relevant differences between the real system and the proposed prototype, the presented results could be generalized to the real case. Further work will include the acquisition of a larger database of real passport images to allow more relevant tests. Future improvements in face recognition systems for ABC e-gates were discussed.

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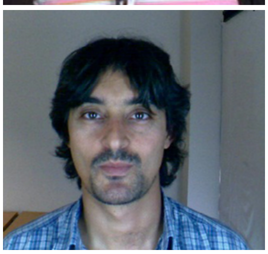
José Sánchez del Río Sáez has been working in biometrics for more than 5 years, firstly, in a private company as a patent researcher in biometrics and after as a postdoc in the Face Recognition and Artificial Vision (FRAV) group of the Computer and Statistics department at Rey Juan Carlos University (URJC). He has written 4 patents in biometrics and written documentation related to computer vision and biometrics for the project ABC4EU. He has also worked in IEM-CSIC for 5 years analyzing big data collected from nuclear physics experiments at big facilities. He did his Ph.D. in photonic bio-sensing and experimental analysis in IMM-CNM-CSIC. He was working as a SW/HW testing engineer in the aerospace field for a private company and nowadays he is member of the IMDEA Materials staff working as an electronic technician specialized in instrumentation and software.

Dra. Cristina Conde Vilda is a permanent lecturer in the Face Recognition and Artificial Vision (FRAV) group of the Statistical and Informatics department at Rey Juan Carlos University (URJC). Her main research areas are 3D facial recognition, normalization techniques, recognition registers algorithms, image processing and artificial vision techniques for security.



Dr. Isaac Martin de Diego is a permanent lecturer in the Face Recognition and Artificial Vision (FRAV) group of the Statistical and Informatics department at Rey Juan Carlos University (URJC). His main research areas are pattern recognition, support vector machines, kernel methods, biostatistics, facial recognition based on local algorithms and artificial vision.

Dr. Enrique Cabello Pardos is the director of the Statistical and Informatics department at Rey Juan Carlos University (URJC) and director of the Face Recognition and Artificial Vision (FRAV). He is a permanent lecturer in Computer Science and his main research areas are biometrics (2D facial verification), normalization techniques, neural networks, image processing and artificial vision.

Dra. Daniela Moctezuma is a research professor at National Council of Science and Technology in Mexico (assigned at CentroGEO). She received the Ph.D. degree from Rey Juan Carlos University in 2013. She received the B.S. in Computer Sciences from Technology Institute of Los Mochis, Sinaloa, Mexico, in 2006 and the M.S. degree from National Center of Research and Technologic Development, Cuernavaca, Mexico, in 2009. Her primary research interests include computer vision, video surveillance systems, soft-biometrics, pattern recognition and image processing.