

# Technology Foresight on Biometrics for the Future of Travel

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## Abstract

In 2021, Frontex conducted a Technology Foresight on Biometrics for the Future of Travel, with the objective of studying the future of biometrics for its implementation in border check systems that may benefit the work of the European Border and Coast Guard community in the short-, medium- and long-term perspectives. Three experts' consultation events (two Technology Foresight Workshops and a Delphi survey) took place during the project. A broad group of relevant stakeholders was involved in these events to exploit collective intelligence and stimulate consensus-oriented discussions. A custom Technology Foresight methodology was developed, opening the door to the exploration of the vast field of biometric technologies, which were analysed from various perspectives in the context of border checks. Each of the phases of this complex research study produced its own set of insights. Due to the substantial amount of information provided and the adopted participatory foresight approach, this study will directly contribute to an enhanced understanding of the relevance and applicability of novel biometrics and technology foresight, as well as to identify areas of strategic interest and to make informed decisions about paths of future developments in biometrics. In this article we summarise the main results of the research study (see Frontex, 2022).

**Keywords:** Research and Innovation, Technology Foresight, Future Scenarios, Biometrics, Border Security, Border Control, Border Checks, Patentometrics, Bibliometrics, Technological Roadmaps, Capability Mapping

<sup>1</sup> About Frontex: Frontex, the European Border and Coast Guard Agency, promotes, coordinates and develops European border management in line with the EU fundamental rights charter and the concept of Integrated Border Management. The Agency also plays a key role in analysing and defining the capability needs in border control and in supporting the Member States in the development of these capacities. Furthermore, it provides qualified expertise to support the EU policy development process in the area of border control. Frontex Research and Innovation is responsible for leading and conducting transformational, need-driven research with academia, EU institutions and Agencies, international organisations and industries to stimulate and support innovation. The ultimate goal is to consistently enhance the capabilities of the European Border and Coast Guard in line with the Capabilities Development Plan, which includes those of the Member States and of the Agency itself.

## Introduction

Millions of travellers cross the EU's external borders every year and their numbers will likely increase even further. Thus, border checks will need to undergo significant transformations, both to safeguard the EU's external borders and to improve the border crossing experience for travellers, e.g. by enabling seamless or near-seamless travel. Innovative technological solutions will play an essential role in the transformation of border checks; biometrics is one of the fields expected to enhance the security of border checks while at the same time facilitating seamless travel. However, additional research is required to identify the most useful and relevant biometric technologies as well as to find a path of actions that leads to the attainment of these goals. Since Frontex proactively monitors and contributes to research and innovation initiatives relevant to European integrated border management, including those for the adoption of advanced border control technologies, this *Technology Foresight on Biometrics for the Future of Travel* was conducted to gain additional insights into the potential of biometric technologies that could serve as a foundation for future-oriented decision-making.

Biometric technologies were identified, and their possible future evolution paths studied, using *Technology Foresight*, a method that provides anticipatory intelligence which can successfully support evidence-based decision-making, strategy development and capacity building in both public and private organisations. In short, Technology Foresight is an approach that delivers strategic insights by analysing possible future technological development paths. However, there is no single recipe for conducting a foresight exercise: each study needs to be tailored to the specific context, requirements and fields of interest, as well as to the assets and data sources available. The benefits of foresight analyses are numerous and include identifying threats and opportunities, stress-testing long-term strategies, uncovering vulnerable assumptions regarding the future and detecting potentially disruptive technologies and events.

Therefore, a tailor-made foresight process was developed for the purposes of the *Technology Foresight on Biometrics for the Future of Travel* to provide Frontex with general insights into the development and implementation of foresight exercises.

## Motivation and goals

The primary goal of this research was to provide technology-related insights on the future of biometrics for its implementation in border check systems that could be utilised by the European Border and Coast Guard (EBCG) community in the short- (2022-2027), medium- (2028-2033) and long-term (2034-2040) perspectives. Secondly, Frontex wished to raise awareness about the relevance and applicability of foresight for forward-looking decision-making within its organisation and to acquire the related know-how. Finally, the study provided a comprehensive foresight methodology, tailor-made to Frontex's needs and outlined the implementation of this methodology using quantitative, qualitative and participatory approaches to identify biometric technologies of high relevance to future applications in border checks.

A good definition of the scope of the research was essential. The study was limited to biometric technologies and biometrics-enabled technological systems that could find applications in border checks, biometric recognition and access control. Additional constraints were imposed by disregarding the applications of biometrics in border surveillance as well as emotion and behaviour detection.

The outcomes of the exercise will provide Frontex with the practical knowledge required for further Technology Foresight (TF) studies in other technological fields and research areas. They will also supply in-depth information to underpin future strategic decisions on the application of biometric technologies in the context of border checks, e.g. with regard to future priorities, research directions and investment decisions.

More specifically, the following objectives were defined for the study in the context of border checks:

On a global scale:

- Identification of the current implementation status and future development pathways of biometric technologies by 2040;
- Identification of biometric technology accelerators, including the main actors and key Research and Development (R&D) initiatives.

On a European Union (EU) scale:

- Identification of future opportunities in terms of biometric technologies that could support EU external border management, e.g. facilitating seamless travel;
- Identification of biometrics-enabled technological solutions to future operational problems within the EBCG community;
- Analysis of legal, ethical and technological limitations intended to minimise the risks associated with applications of biometric technologies;
- Assessment of the impact of biometric technology trends on border checks and identification of future research needs.

Within the EBCG community:

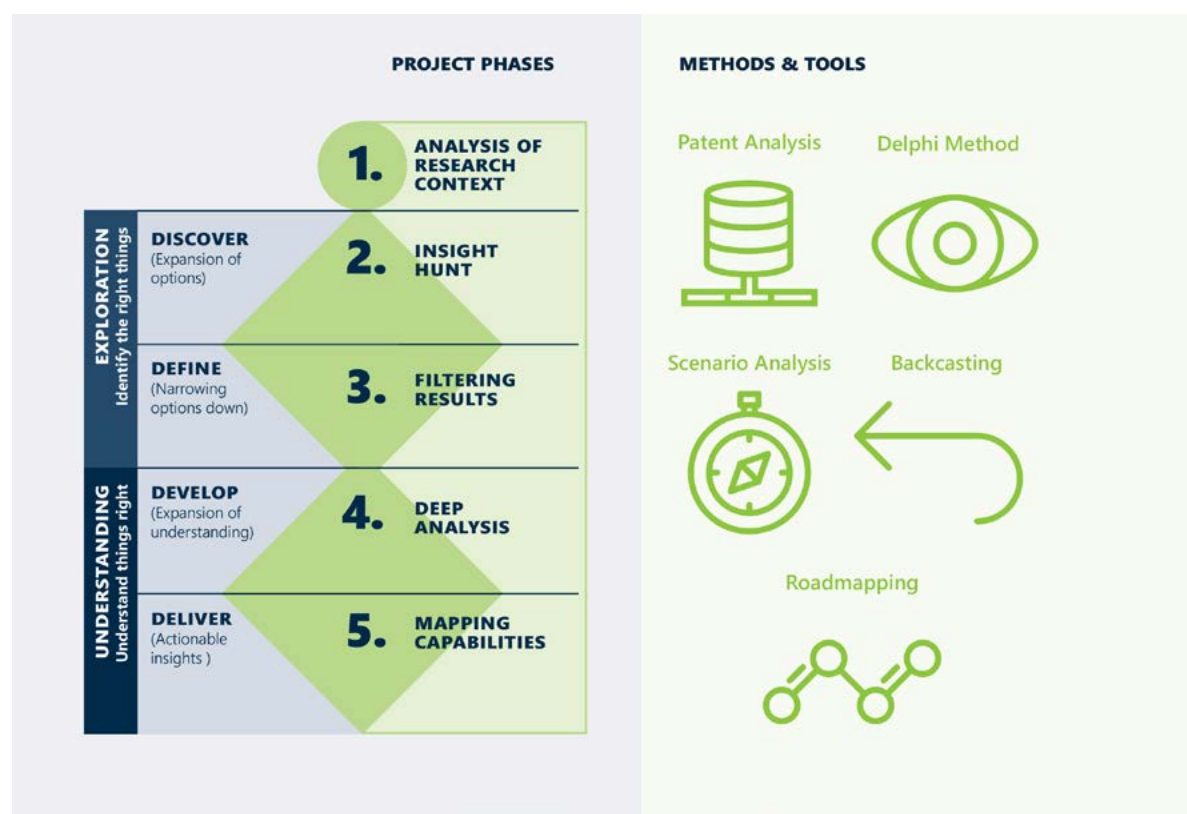
- Providing know-how on the implementation of TF projects;

- Raising awareness about the relevance and applicability of TF for forward-looking and evidence-based decision-making;
- Disseminating the results of this research study to encourage joint initiatives, the development of a shared vision and strengthened capability development.

## Structure of the study

This research study was structured in five phases, as shown in Figure 1. The first phase defined the overall methodology and framed the context according to Frontex's needs. The subsequent phases were dedicated to putting this methodological framework into practice. They can be depicted as two diamonds: each begins by opening up the horizon and broadening the knowledge, eventually narrowing down the obtained insights and thus, identifying the targeted outcomes. Figure 1 also provides a selection of the methods used throughout the project.

**Figure 1.** Overview of the project set-up, as well as of the main methods used within the project



## Phase 1 – Analysis of the Research Context

The identification of Frontex's needs regarding key functions and characteristics of biometric technologies and related systems was the first step of the Technology Foresight process (TFP). It aimed to specify the field and scope of the TFP and to set goals for the study, which in turn were used to tailor the TFP to Frontex-specific needs. The results of this step constituted the first filter for narrowing the area of further analysis to the technologies and technological systems of the greatest potential importance to Frontex.

As a result of the needs analysis, four “must-haves” were identified for reference in later phases of the project:

- low vulnerability to adversary attacks,
- seamlessness,
- applicability within pandemic-specific restrictions,
- compliance with fundamental EU values and regulations.

## Phase 2 – Insight Hunt

### Identification of main areas of research in biometrics and of key stakeholders

This study spans the operational fields of interest of the EBCG community in relation to border checks. To navigate the vast field of biometrics, 43 preliminary directions of analysis were defined. They included biometric technologies as well as biometrics-enabling technologies and applications.

Gaining further insights into stakeholders was another essential part of this phase, as the active involvement of stakeholders was a prerequisite for the study. This facilitated the dissemination and communication of project results within the EBCG community throughout the project, as well as ensuring that valuable insights from diverse fields of expertise were collected and could serve as the core input to the analyses. In total, over 200 stakeholders were initially identified, with more than 40 selected to participate in the study by way of three participatory activities: two *Technology Foresight Workshops* and a *Delphi Survey*.

### Taxonomy of biometric technologies and biometrics-enabled technological systems

The field of biometrics is highly heterogeneous and complex. Thus, a systematic categorisation was needed to identify the technologies and systems with potential for finding applications in the operational fields associated with border checks. This step aimed to enhance the comprehension of how the area of research in biometrics is structured and how the technologies relate to one another. For this purpose, two taxonomies were developed to map *biometric technologies* and *biometrics-enabled technological systems*.

Two distinct design approaches, differing in thoroughness and complexity, were followed to construct the taxonomies. The taxonomy of biometric technologies, which used the preliminarily identified main areas of research for initial guidance, was developed through an iterative process based on an analysis of patents and scientific literature with the employment of Natural Language Processing (NLP) automatic tools. This approach led to the creation of the three-level taxonomy shown in Figure 2.

A set of technological systems of potential interest to Frontex served as the initial input for creating the taxonomy of biometrics-enabled technological systems. The set was later expanded and consolidated to construct the two-level taxonomy shown in Figure 3.

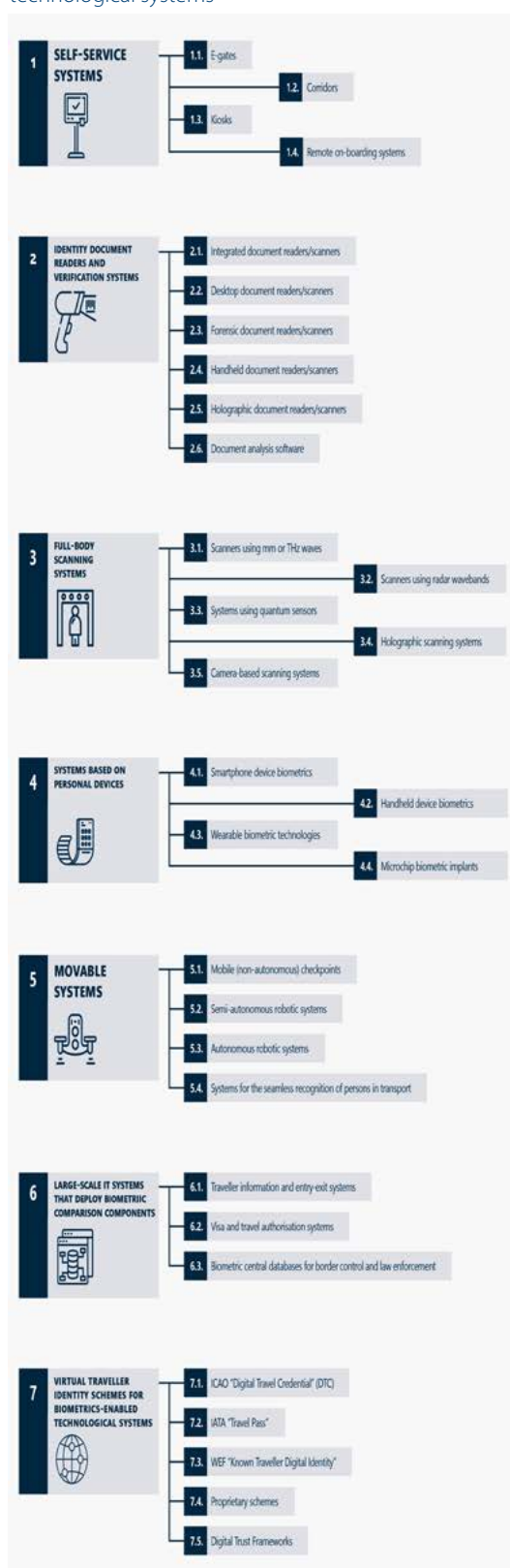
Together, the two taxonomies constituted an essential building block for the study:

- The taxonomy of biometric technologies was used to extract a set of *technological clusters* (TCs, shown in Table 1) required for the subsequent phases of the project.
- The taxonomy of biometrics-enabled technological systems played an essential role in guiding the development of technological roadmaps in Phase 4.

Figure 2. Taxonomy of biometric technologies





**Figure 3.** Taxonomy of biometrics-enabled technological systems

### Patentometric and bibliometric analyses of biometric technologies

Patentometric and bibliometric analyses were conducted to identify and analyse patents and scientific literature related to the 20 TCs outlined above, and to obtain insights into global R&D activities in the identified biometric TCs.

EU-funded research and innovation projects on topics revolving around the TCs were also analysed to outline the priorities of the European research, technology development and innovation (RTDI) community within the biometrics domain. This analysis supplemented the picture of the technological landscape of biometrics by providing an overview of the EU's investments in R&D projects and by indicating where the highest levels of knowledge and expertise may be found within Europe.

Through the patentometric and bibliometric analyses, the clusters' technological lifecycles were analysed following Altshuller's Theory of Inventive Problem Solving (see Altshuller & Williams, 1984; Slocum, 1998; Mann, 1999), according to which a technology's evolution over time follows distinctive patterns that can be assessed by observing the trend in the number of inventions. Such an assessment helped identify the current stage of a technology's lifecycle and provided a basis for projections of its future evolution. As a result of the analysis, the TCs were categorised as follows:

- Childhood stage: 2 TCs (Periocular recognition and Gait recognition);
- Growth stage: 5 TCs (Infrared friction ridge recognition, 3D friction ridge recognition, Iris recognition in the visible spectrum, Iris recognition at a distance and Heart signal recognition);
- Maturity stage: 10 TCs (Infrared face recognition, 2D face recognition in the visible spectrum, 3D face recognition, Contactless friction ridge recognition, Contact-based friction ridge recognition, Iris recognition in the NIR spectrum, Eye vein recognition, Hand vein recognition, Handwriting recognition and Speaker recognition);
- Maturity stage (but of minor relevance):<sup>2</sup> 3 TCs (DNA biometrics, Hand geometry recognition and Keystroke recognition).

2 The temporal distributions of patenting and publishing activities regarding these clusters showed poor similarity with the theoretical pattern proposed by the Theory of Inventive Problem-Solving. These clusters are likely to be characterised by low efficiency in biometric recognition processes. The long-time and low volumes of inventive activities suggest that no growth is foreseen.

The patenting activity related to the TCs appears to be located primarily in the United States. Europe and China alternate as the second most common location. This indicates that R&D, commercial and manufacturing activities are performed on a large scale in these three regions. Germany and the United Kingdom represent the dominant European regions for patenting activity.

The bibliometric analysis further revealed that the Institute of Electrical and Electronics Engineers (IEEE) dominates the editorial activity that concerns the biometric field. It is the most prolific publisher for 19 out of the 20 TCs, making it a key source for monitoring developments in biometrics.

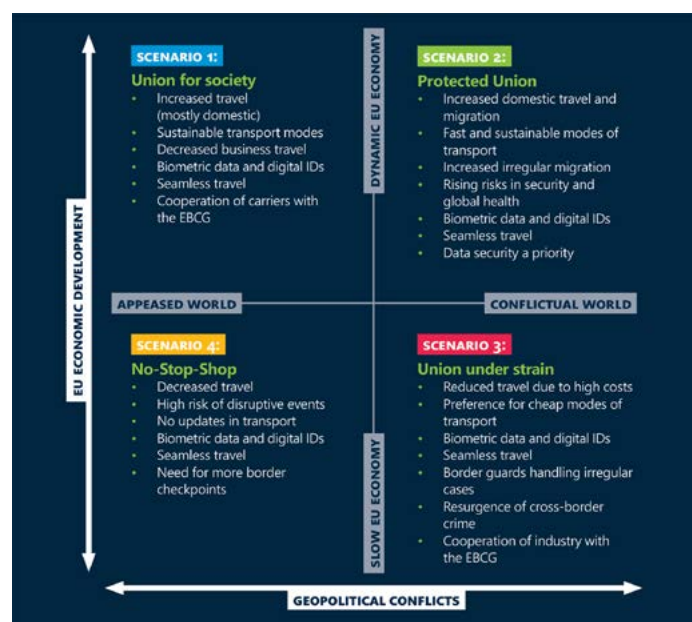
The analysis of EU-funded projects showed that five technological fields (*Face recognition*, *Friction ridge recognition*, *Vascular pattern recognition*, *Periocular recognition* and *Speaker recognition*) are of particular interest for co-funded industrial and academic research in the EU; *Face recognition* and *Friction ridge recognition* seem to be dominating. Contrastingly, *Heart signal recognition* and *Handwriting recognition* are presumably of minor relevance to the EU.

The results also indicated that British, German, Spanish and French organisations are likely to possess the highest levels of knowledge and capability required to implement these technologies, as they participated in the largest number of EU-funded projects related to the considered TCs.

### Scenarios for the future of travel, border checks and biometric technologies in 2040






Parallel to the patentometric and bibliometric analyses, we conducted scenario development. *Scenario Analysis* is one of the most widely used methods in strategic foresight. Its primary focus is on assessing how various futures might influence the subject of the analysis. The method involves stress-testing strategies, insights and solutions to verify the extent to which they can be considered “future-proof”. The scenarios developed in the framework of this project were based on those presented in *The Future of Customs in the EU 2040: A foresight project for EU policy* (Ghiran et al., 2020).<sup>3</sup> During the first experts’ consultation workshop, they were challenged and adapted to incorporate aspects relevant to the travel and border check context. An overview of the adapted scenarios in a 2x2 matrix is presented in Figure 4.

**Figure 4.** An overview of scenarios on the future of travel, border checks and biometric technologies used in this study – 2x2 scenario matrix










<sup>3</sup> This study was published in 2020 by the European Commission's Joint Research Centre (JRC) and conducted in collaboration with the Directorate-General for Taxation and Customs Union (DG TAXUD). The scenarios were constructed using a 2x2 Matrix technique, wherein 2 important factors were selected and placed on 2 axes, thus forming 4 quadrants. The chosen factors were geopolitical conflicts (with a peaceful world at one end of the spectrum and a world in conflict on the other) and EU economic development (slow vs dynamic EU economy).

**Table 1.** Description of the examined biometric technological clusters

| Technological clusters  | Description  |
|---|--|
| <b>DNA biometrics</b><br>                              | Biometric technologies that rely on the recognition of human DNA. These technologies find easier applications in forensic science, however, applications in biometric recognition have also been proposed. Although these systems are still unsuitable for applications in border checks, advances are being made to expedite the analysis process. This technological cluster includes DNA phenotyping, DNA profiling and DNA sequencing.   |
| <b>Infrared face recognition</b><br>                   | Technologies for the recognition of human faces using infrared (IR) imaging, commonly subdivided into: near-infrared (NIR, 0.78–1.0 µm in wavelength) imaging; short-wavelength infrared (SWIR, 1–3 µm) imaging; mid-wavelength infrared (MWIR, 3–8 µm) imaging; long-wavelength infrared (LWIR, 8–15 µm) imaging. NIR and SWIR are sometimes called “reflected infrared”, while passive MWIR and LWIR techniques are sometimes referred to as “thermal infrared”. This cluster is formed by two biometric technologies: thermal infrared face recognition and near-infrared face recognition. |
| <b>2D face recognition in the visible spectrum</b><br> | This technological cluster deals with the automated recognition of individuals through the matching of a face — from a digital image or a video frame acquired in the visible spectrum of light — against a database of face images or a specified biometric reference image. It encompasses video-based face recognition and image-based face recognition.  |
| <b>3D face recognition</b><br>                         | Solutions aimed at recognising an individual by the three-dimensional (3D) features of their facial components. Once the 3D geometry of the human face is acquired, it is used to extract distinctive features on its surfaces. 3D face recognition is claimed to have the potential to achieve better accuracy than its 2D counterpart.   |
| <b>Infrared friction ridge recognition</b><br>       | The skin on the palms of hands, fingers, soles and toes is known as <i>friction ridge skin</i> in the biometric and forensic communities. This technological cluster includes biometric recognition modalities (such as <i>Fingerprint recognition</i> , <i>Palmprint recognition</i> , <i>Footprint recognition</i> and <i>Finger-knuckle-print recognition</i> ) implemented through thermal imaging or near-infrared imaging of friction ridge skin.  |
| <b>3D friction ridge recognition</b><br>             | Biometric modalities capable of acquiring the frictional ridges of one or multiple body parts (e.g. fingers, palms, feet or finger-knuckles) and producing three-dimensional representations in order to recognise an individual. For example, extracted features from 3D palmprint data usually include depth and curvature of the palm lines and wrinkles on the palm surface.   |
| <b>Contactless friction ridge recognition</b><br>    | Biometric technologies in which the friction ridge mark signature of a finger, palm, foot or finger-knuckle is acquired without direct contact of the relevant body part with a sensing surface, mostly employing video or image acquisition.  |
| <b>Contact-based friction ridge recognition</b><br>  | Biometric technologies in which the friction ridge mark signature of a finger, palm, foot or finger-knuckle is acquired through the contact of the relevant body part with an acquiring surface. For example, contact-based palmprint capture may be performed by asking users to put their hands on a planar surface where their fingers are typically restricted by pegs.  |
| <b>Iris recognition in the NIR spectrum</b><br>      | The iris is a thin, circular structure in the eye that controls the diameter and size of the pupils. Its back surface is covered by a layer of pigmented epithelial tissue, which gives an eye its distinctive colour. <i>Iris recognition in the NIR spectrum</i> is the field of biometrics that deals with the recognition of individuals through images of the textural features of the iris captured using near-infrared illumination.  |
| <b>Iris recognition in the visible spectrum</b><br>  | This cluster includes iris recognition technologies based on images of the iris captured in the visible spectrum of light. This presents many challenging aspects, especially in the case of individuals with dark irises (caused by higher melanin pigmentation and collagen fibrils) because the unique pattern of the iris is not clearly observable under visible light.   |



| Technological clusters   | Description  |
|--|--|
| <b>Iris recognition at a distance</b><br> | <i>Iris recognition at a distance</i> (metres away from the subject) might be implemented even for a person walking, thus enhancing travellers' experience at border checks by reducing the need for user cooperation and achieving low intrusiveness, high acceptance and transparency.   |
| <b>Eye vein recognition</b><br>           | In general, vein (or vascular) pattern recognition uses a light source (usually near-infrared light) to acquire images of blood vessels. In the case of <i>Eye vein recognition</i> , scanners typically use low-energy lasers and users are typically asked to put their eyes in front of the scanner, as eyes must be very close to the sensors for the vein patterns to be acquired. This cluster encompasses retina recognition and sclera/episclera recognition technologies.                                     |
| <b>Hand vein recognition</b><br>          | Recognition of individuals through images of the complex structure of larger blood vessels near the skin surface in human hands. These may be captured from hand surfaces as well as from fingers and wrist, using non-invasive and safe imaging techniques. This technological cluster includes finger, palm, back-of-hand and wrist vein recognition.  |
| <b>Heart signal recognition</b><br>       | Heart signals belong to the wider group of physiological characteristics of an individual, i.e. signals that can be acquired and monitored to assess a person's clinical state. This technological cluster includes biometric recognition technologies based on the detection and acquisition of heart-rate variability (HRV), electrocardiographic (ECG) signals, phonocardiographic (PCG) signals and photoplethysmographic (PPG) signals.   |
| <b>Hand geometry recognition</b><br>     | Hand geometry readers take measurements of an individual's hand — including height, width, deviation and angle — and compare those measurements to a reference sample. This cluster is formed by two biometric technologies: contact-based hand geometry recognition and contactless hand geometry recognition.  |
| <b>Periocular recognition</b><br>       | The region around the eye, including the <i>sclera, eyelids, lashes, brows and skin</i> , is known as the <i>periocular region</i> and can be acquired non-intrusively and used as a biometric characteristic. <i>Periocular recognition</i> offers advantages over face recognition as it is least affected by expression variations, ageing effects and facial hair.   |
| <b>Keystroke recognition</b><br>        | Keystroke dynamics is a behavioural biometric characteristic that describes the unique timing pattern used by a person to type on the keyboard of a digital device, derived mainly from the two events that make up a keystroke: Key-Down and Key-Up. <i>Keystroke recognition</i> utilises off-the-shelf computer keyboards or virtual keyboards. This technological cluster includes static keystroke recognition and dynamic keystroke recognition.   |
| <b>Gait recognition</b><br>             | Gait is a behavioural biometric characteristic used to recognise individuals by their walking style and pace. Gait has several advantages compared to other biometric characteristics: in most modalities, <i>Gait recognition</i> is non-intrusive, does not require cooperation from the individual and can function at moderate distances from the subject. This technological cluster is formed by <i>Gait recognition</i> technologies based on video sensors, radar sensors, floor sensors and wearable sensors. |
| <b>Handwriting recognition</b><br>      | <i>Handwriting recognition</i> is the process of recognising the author of a text from their handwriting style; it can be applied to a generic text or to a specific predefined text (usually a signature) and implemented according to two main modalities: dynamic and static.   |
| <b>Speaker recognition</b><br>          | Group of biometric technologies that use information extracted from a person's speech to perform biometric operations such as speaker identification and verification. It is based on the extraction of acoustic features of speech that differentiate individuals. This technological cluster includes text-dependent and text-independent recognition.   |

Clusters found especially vulnerable to future scenarios include *Handwriting recognition*, *Keystroke recognition*, *Eye vein recognition*, *Heart signal recognition*, *DNA biometrics* and *Hand geometry recognition*, primarily because of the challenges associated with the seamless acquisition of biometric data using these technologies. The analysis of technological clusters' compatibility with scenarios serves as a warning, especially in the case of clusters that received low compatibility ratings in some or all the analysed future realities. Futureproofing some of these clusters may be impossible due to fundamental incompatibilities with specific scenarios. This does not mean that they cannot be pursued, but such cases require a more detailed risk assessment and, preferably, also the introduction of a Strategic Early Warning System (SEWS) to indicate the emergence of unfavourable scenarios.

### Phase 3 – Filtering the Results

#### Security aspects of biometric technologies

The security analysis helped filter the 20 biometric TCs, focusing on their comparative inherent vulnerability to adversary attacks. Only attacks at user-level (presentation attacks) and morphing attacks (in the case of face recognition) were considered. The lowest level of vulnerability was assigned to *DNA biometrics*, which is, at least at the current level of technological development, far from seamless and highly intrusive. On the other hand, it is highly secure. *DNA biometrics* is closely followed by *Infrared face recognition* and *Eye vein recognition*, which display relatively low vulnerability to adversary attacks. At the other end of the scale is *2D face recognition in the visible spectrum*, which is intrinsically highly vulnerable to presentation attacks (such as artefacts and make-up) and morphing attacks, but has a remarkably high level of social acceptance and – contrary to DNA biometrics – a simple acquisition process. The outcomes of the security analysis were used as an additional filter in the subsequent prioritisation of biometric technologies.

#### Prioritisation of biometric technologies – Findings of the Delphi Survey

Before proceeding with an in-depth analysis of future technological developments, the initial list of 20 technological clusters needed to be narrowed to a shortlist of the most promising ones. The tool selected for this filtering phase of the project was the so-called *4CF Matrix*. To prepare a 4CF Matrix, hypothetical future technological solutions for border checks that would use

each of the 20 TCs needed to be quantitatively evaluated in terms of two criteria:

- *Relative Advantage (RA)*: is the advantage that the envisaged technological solution would have over the best available contemporary solutions. RA is rated on a scale of 0-10, where:
  - 0 means that the envisaged solution would not provide any significant advantage over currently available best-in-class solutions or would be impossible to achieve;
  - 10 indicates a game-changer, i.e., a solution that would drastically improve travellers' border check experience.
- *Earliest Time to Mainstream (ETM)*: is the shortest time (from the present moment) required for the solution to become available on the market and widely adopted in border checks at external EU borders. In other words, ETM represents the shortest time necessary for the development, commercialisation and adoption of such a solution, taking into account not only the possible technological barriers, but also other relevant factors, including social, political and economic ones. ETM is assessed on a scale of 0-20 years, with:
  - 0 signifying that the envisaged technological solution is already available on the market and is widely adopted;
  - 20 indicating periods of 20 years and longer, including technological solutions which can never be realised.

To assess the 20 TCs according to these criteria with the support of a group of experts, a *Delphi Survey* was set up using an online real-time platform. Pre-selected stakeholders were invited to assess the 20 TCs.

Based on the assessments from the *Delphi Survey*, the 4CF Matrix was constructed, allowing the identification of technological clusters belonging to the 4 quadrants of the matrix (see Figure 5): from areas containing solutions that show little promise in terms of relative advantage but could be implemented quickly (*Coral reef*) to those that are very distant in time but contain ground-breaking solutions (*Pirate treasure*).





trum and Contactless friction ridge recognition. These 5 clusters are marked green in Figure 6, which presents their placement on the 4CF Matrix.

The five key technological clusters are all located in the “Squalls” quadrant of the 4CF Matrix, a clear indication that their importance should be emphasised in strategic plans. However, the placement of the other 15 technological clusters on the 4CF Matrix is equally important.


#### Phase 4 – Deep Analysis: Roadmaps for the key biometric technological clusters by 2040

Within the Deep Analysis phase of the project, technology roadmapping was the planning method of choice. In general, it is applied to envision the short-, medium- and long-term paths in the development and evolution of technologies and products. The roadmapping approach aligns with technology-push and market-pull perspectives, thus supporting innovation and strategic planning at the level of an organisation, a sector or even a nation. Its role in the Technology Foresight on Biometrics for the Future of Travel was threefold: (a) to identify the development paths of the key biometric technological clusters in the 2021-2040 timeframe,

(b) to determine key turning points in technological developments (factors delaying or accelerating the envisioned developments) and (c) to confront technology roadmaps with alternative scenarios regarding border-check processes and the future of travel. Each of the roadmaps for the five KTCs which were created during a two-day participatory expert workshop consists of three layers: application areas, functions and products or systems (see an example in Figure 7).






The roadmapping analysis, conducted under business-as-usual conditions, included an assessment of the opportunities (drivers) and challenges (bottlenecks) that could potentially affect the technological projections. It should be noted that the roadmaps should not be treated as a forecast but rather as an invitation to analyse the development paths of the technological clusters further, monitoring associated opportunities and threats and questioning the assumptions underlying strategic plans. Among the crucial takeaways are the identified key opportunities and challenges to the development of the KTCs in the 2021-2040 timeframe (Table 2) and the qualitative assessment of the impact of the four scenarios on the clusters' development (Table 3).

**Figure 7.** Example of technology roadmap (for the *Contactless friction ridge recognition* technological cluster)































| Contactless friction ridge recognition  | 2021 (ETM: 7.7 years)   | 2022-2027   |           |           | 2028-2033   |           |           | 2034-2040  |           |           |
|--|---|---|-----------|-----------|---|-----------|-----------|--|-----------|-----------|
|  |   | 2022-2023   | 2024-2025 | 2026-2027 | 2028-2029   | 2030-2031 | 2032-2033 | 2034-2035  | 2036-2037 | 2038-2040 |
| <b>APPLICATION AREAS OF TECH CLUSTER</b><br>Where is it used?  | It is not used in border checks. Pilot tests took place within the "Biometrics on the move" Frontex project at Lisbon Airport in 2019<br><br>Self-driving cars<br><br>Entertainment sector (e.g. digitising paintings and sculptures via 3D scanning) | Growing number of pilot applications in seamless border check processes   |           |           | Mainstream applications in the area of seamless border checks |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
|  |   | Military and security applications  |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           | Public (i.e. e-government) and private sector services (i.e. physical access control and information security) |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
| Financial services (authentication process in banking and digital transactions)  |   |   |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
| <b>FUNCTIONS OF TECH CLUSTER</b><br>What can it do?  | Person recognition at a very short distance   | Recognition of persons from a very short distance   |           |           |   |           |           |  |           |           |
|  |   | Recognition of persons from a short distance  |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
| Stand-off person recognition (a few meters' distance)  |   |   |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
| <b>PRODUCTS / SYSTEMS USING TECH CLUSTER</b><br>What is it?  | Stationary scanners (and sub-systems)   | Stationary scanners   |           |           |   |           |           |  |           |           |
|  |   | Mobile scanners (e.g. portable/handheld devices; portable/handheld mobile phone-based scanners; portable/hand-held tablet-based scanners) |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
| Self-service systems   |   |   |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |
| Stand-off scanners (a few meters' distance)  |   |   |           |           |   |           |           |  |           |           |
|  |   |   |           |           |   |           |           |  |           |           |



**Table 2:** Key factors (opportunities and challenges) in the timeframe up to 2040 – a cross-cluster comparison

| Technology roadmap analysis |                       | Key biometric technological clusters   |   |   |   |  |
|-----------------------------|-----------------------|--|---|---|---|--|
| Key turning points          | Layers of the roadmap | Contactless ridge recognition                   | 3D face recognition    | Infrared face recognition   | Iris recognition in the NIR spectrum   | Iris recognition in the visible spectrum                      |
| Opportunities               | APPLICATION AREAS     | Research aimed at the development and analysis of the quality of contactless fingerprint samples                                 | Consumer market uptake (e.g. entertainment) would drive further development and reduce costs  | Pilot programmes to compare wave-lengths and implement sensor fusion  | Low vulnerability to presentation attacks   | Healthcare market uptake could increase understanding that iris acquisition is eye-safe  |
|                             | FUNCTIONS             | Contactless biometrics is advantageous during pandemics  | Adopting multi-modal biometric solutions which combine 3D face recognition with other biometric modalities to achieve better accuracy                       | Use of thermal infrared cameras for temperature measurement, which can be an important feature in case of pandemics                                 | NIR light sources (850, 905, 940 nm) are readily available  | Research on the use of multi-spectral or hyperspectral iris imaging for the increased accuracy (spatial resolution)                              |
|                             | PRODUCTS AND SYSTEMS  | Possibility of using existing sensors (e.g. cameras in smartphones)  | Introduction of digital identity management schemes and novel algorithms for processing non-ideal images  | Enabling acquisition (and processing) of IR images at different wave-length bands and effectively working at sensor fusion level via pilot projects | Integration of <i>Iris recognition in the NIR spectrum</i> into stand-off seamless systems for border checks would improve societal acceptance of this modality   | Low technical barriers to implement digital identity wallets including Iris biometric reference data   |
| Challenges                  | APPLICATION AREAS     | Accuracy and security might be a challenge in mainstream use for border checks   | Legal and ethical aspects (an agreement on what the biometric data might comprise)  | Technology issues linked to IR illumination might require additional witness-based methods of recognition, which lowers seamlessness                | Capturing biometric samples of such a small body part in motion and from a distance makes the technology difficult to develop and integrate into seamless systems | Functional limitations (stated below) might be a challenge for mainstream use in border checks   |
|                             | FUNCTIONS             | Extension of the distance and increase of the accuracy of the technology   | Acquisition methods for obtaining high-quality, reliable and interoperable data formats for 3D face images (especially for image acquisition at a distance) | Availability in the EU of foundries of affordable, accessible NIR-SWIR-LWIR image sensors   | Eye safety issues when using IR illumination at wavelengths shorter than 1500 nm  | Inclusivity (dark iris limitations)<br>Suitable illuminators in visible light<br>Iris image acquisition at a distance                            |
|                             | PRODUCTS AND SYSTEMS  | Motion stability<br>Interoperability<br>Lack of harmonised regulations and standards for biometric data acquisition and exchange | The use of e-passports would require reading the passport and processing a large volume of data, which would rule out seamlessness                          | Development of EU regulations and standards for IR image acquisition  | Introduction of enrolment via smartphone dependent on adoption of suitable solution by the mobile phone industry  | Lack of harmonised guidelines and standards for the assessment of the operational performance of technological systems based on iris recognition |

**Table 3.** The impact of external realities described in the four scenarios on the technological developments envisaged in the roadmaps — a cross-cluster comparison

| Scenario impact analysis   | Key biometric technological clusters   |   |   |  |  |
|--|--|---|---|--|--|
|  | Contactless friction ridge recognition  | 3D face recognition  | Infrared face recognition  | Iris recognition in the NIR spectrum  | Iris recognition in the visible spectrum  |
| <b>SCENARIO 1</b><br>Union for society   |   |                      |                            |                                        |   |
| <b>SCENARIO 2</b><br>Protected Union   |   |                      |                            |                                        |   |
| <b>SCENARIO 3</b><br>Union under strain  |   |                      |                            |                                        |   |
| <b>SCENARIO 4</b><br>No-stop shop  |   |                      |                            |                                        |   |
| <b>Legend</b><br>Compared to the roadmap projections, developments are:  Much faster  Faster  Same  Somewhat slower  Much Slower |  |   |   |  |  |

During the road-mapping analysis, the stakeholders' experts underlined that biometrics is a highly regulated environment. Therefore, advances are introduced gradually and external conditions (e.g. unfavourable economic standing or geopolitical situation) do not have a crucial impact on technological evolution. Nevertheless, examining developments of the key clusters in light of possible scenarios of EU development through 2040 revealed that the solutions are not entirely resistant to changes in the external environment.

### Phase 5 – Mapping the Capabilities for the key biometric technological clusters

The road-mapping described above was accompanied and supplemented with a capability mapping exercise, the fifth and final phase of the research study. The exercise aimed to identify the existing capabilities for the five KTCs in the EU, as well as the expected development of capability readiness through 2040. The capability landscape shown by this exercise highlights opportunities and gaps associated with each of the technological clusters, providing a good foundation for strategic decision-making.

The outcomes of the capability mapping are presented in the form of heatmaps of capability readiness (defined as the degree to which cluster-specific capabilities

ty-related needs are or will be met) for the five KTCs, distinguishing three timeframes (present, 2022-2027 and 2028-2033)<sup>4</sup> as well as the four customised scenarios (see an example in Figure 8). This analysis revealed that at present the majority of research, industrial and institutional overall capability readiness of any KTC is relatively low (with the exception of research capabilities for *Contactless friction ridge recognition*). Fortunately, most of those needs are expected to be met by 2027 or 2033 at the latest. *3D face recognition* and *Iris recognition in the NIR spectrum*, followed by *Iris recognition in the visible spectrum*, are expected to perform better than the other KTCs as they display good capability readiness from 2028 onwards.

One recommendation emerging from the study is that any assumptions on future capability readiness levels should be closely monitored, both to track which scenario best matches the emerging trends and to track whether the assumptions themselves are still realistic. Adapting capability-based planning to the actual unfolding trends minimises the risk of missing the defined capability target for each KTC.

4 It is assumed that once a biometric KTC has entered the mainstream, it will be available for implementation in border check systems and will not require any further capability development. Therefore, the long-term timeframe (2034-2040) was eliminated from the capability mapping exercise, as all five KTCs demonstrate an average ETM before 2033.

**Figure 8.** Example of heatmap of capability readiness (for the *Contactless friction ridge recognition* technological cluster)

| Contactless Friction Ridge Recognition |                         |         | SCENARIO 1 | SCENARIO 2 | SCENARIO 3 | SCENARIO 4 | SCENARIO 1 | SCENARIO 2 | SCENARIO 3 | SCENARIO 4 |
|--|-------------------------|---------|------------|------------|------------|------------|------------|------------|------------|------------|
| Capability domain                      | Capability-related need | Present | 2022-2027  |            |            |            | 2028-2033  |            |            |            |
| Research                               | Res1                    |         |            |            |            |            |            |            |            |            |
| Industrial                             | Ind1                    |         |            |            |            |            |            |            |            |            |
|  | Ind2                    |         |            |            |            |            |            |            |            |            |
| Institutional                          | Inst1                   |         |            |            |            |            |            |            |            |            |
|  | Inst2                   |         |            |            |            |            |            |            |            |            |
|  | Inst3                   |         |            |            |            |            |            |            |            |            |

## Conclusions

This research study provided an overview of the foreseen evolution and future applications of biometric technologies in border check systems that may prove useful for the EBCG community in the short- (2022-2027), medium- (2028-2033) and long-term (2034-2040) perspectives. Each of the phases of this complex study comes with its own set of insights meant to support the EBCG community in deciding about the adoption of novel biometric technological solutions and exploiting new opportunities while avoiding or mitigating associated threats. When transferring these insights into actionable recommendations, the context, as well as the process during which they were identified, should be considered. The outcomes of the prioritisation and roadmapping of emerging biometric technologies with the strongest potential to influence the future strategic development of Integrated Border Management deserve particular attention. The following were identified as the five KTCs:

- Contactless friction ridge recognition,
- 3D face recognition,
- Infrared face recognition,
- Iris recognition in the NIR spectrum,
- Iris recognition in the visible spectrum.

Due to the substantial amount of information provided and the participatory foresight approach adopted, the research study will directly contribute to an enhanced understanding of the relevance and applicability of foresight for forward-looking decision-making within

the EBCG community. We believe that a thorough analysis of the output will reveal that its benefits extend far beyond the immediate value of the information. To leverage this value, however, further effort is needed to merge the results with additional sources of knowledge-based evidence and fuse them into the relevant streams of innovation management and strategy development, thus arriving at a well-grounded vision of the future with clear implementation pathways. The expected result of such an approach is the increased application of innovative biometric technologies in border checks, which will benefit both travellers and the EBCG community in the coming years.

This project resulted in a number of outcomes and deliverables which are expected to provide essential insights for Frontex and the larger EBCG community regarding future research directions, strategic planning and decision-making:

- A **Technology Foresight Manual** was created to provide a thorough explanation of the TF process, customised to the needs of the project with successive future implementations in mind, as well as the adopted methods and tools.
- The **taxonomy of biometric technologies and biometrics-enabled technological systems** can be of great benefit to future research and innovation activities revolving around these subjects.
- The **analysis of patents, scientific literature and EU-funded projects** provides an overview of the global technological landscape and shows the evo-



lution of EU interest in biometrics over time. The results can help focus future research initiatives.

- The **customised set of scenarios** can be used to future-proof any potential new technology as well as systems or products intended for use in the areas of travel and border checks (not limited to biometric technologies).
- The **4CF Matrix** of biometric technological clusters can serve as the groundwork for future strategic planning, decision-making, research and investments, allowing for the systematic comparison of new biometric technologies (not limited to the five KTCs identified in the research study) as well as tracking the impact of technological advancements and other factors on the placement of those technologies on the Matrix.
- The **set of roadmaps** developed for the key biometric technological clusters can be used as a starting point for further analysis of these technological clusters' development paths, monitoring associated opportunities and threats and questioning the assumptions of underlying strategic plans.
- The **capability readiness heatmaps** show a comprehensive overview of the extent to which cluster-specific needs are met or will be fulfilled in the future. They can be used by the EBCG community to identify the actions needed for strategic capability development.

In conclusion, the information obtained during this Technology Foresight study provides multiple opportunities for the further use of the findings in other contexts. Beyond Frontex, it is hoped that the entire EBCG

community can take stock of the results and employ them for strategic planning to take more immediate actions regarding the development and implementation of biometric technologies for border checks. Furthermore, we believe that the findings can be used by public organisations, research and technology organisations, academia and industrial entities in Europe to identify areas of strategic interest and to make informed decisions about paths of future developments in biometrics, acting towards strengthening European strategic autonomy in the field of biometrics.

## Acknowledgements

This research study was conducted by Frontex under contract OP/515/2020/AH with Steinbeis 2i GmbH, supported by its subcontractors 4CF Sp. z o.o., Erre Quadro S.r.l. and the Instytut Optoelektroniki – Wojskowa Akademia Techniczna. The following Research Team members dedicated considerable time and effort to successfully completing this study: Sabine Hafner-Zimmermann, Melanie Gralow, Norbert Kołos, Anna Sancio-Szymańska, Maciej Jagaciak, Kacper Nosarzewski, Giovanni Pianigiani, Giovanni de Santis, Tommaso Pavanello, Dario Brugnoli, Donata Gabelloni, Riccardo Aprea, Marcin Kowalski, Norbert Pałka, Raffaele Bruno and Martin George.

Furthermore, the study took stock of the numerous and highly valuable contributions of all stakeholders' experts who actively participated in the two *Technology Foresight Workshops* and the *Delphi Survey*. Frontex expresses its special gratitude to all participants of the aforementioned activities, who generously shared their time and expertise.

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