Biometrics Beyond the Visible Spectrum: Imaging Technologies and Applications

Miriam Moreno-Moreno, Julian Fierrez and Javier Ortega-Garcia

Escuela Politécnica Superior. Universidad Autónoma de Madrid.
C/ Francisco Tomás y Valiente, 11 – Cantoblanco – 28049 Madrid, Spain.
{miriam.moreno, julian.fierrez, javier.ortega}@uam.es

Abstract. Human body images acquired at visible spectrum have inherent restrictions that hinder the performance of person recognition systems built using that kind of information (e.g. scene artefacts under varying illumination conditions). One promising approach for dealing with those limitations is using images acquired beyond the visible spectrum. This paper reviews some of the existing human body imaging technologies working beyond the visible spectrum (X-ray, Infrared, Millimeter and Submillimeter Wave imaging technologies). The benefits and drawbacks of each technology and their biometric applications are presented.

Keywords: Imaging Technologies, X-ray, Infrared, Millimeter Waves, Submillimeter Waves, Thermograph, Passive Imaging, Active Imaging, Terahertz Imaging, Biometrics, Face Recognition, Hand Vein Recognition.

1 Introduction

The ability to capture an image of the whole human body or a part of it has attracted much interest in many areas such as Medicine, Biology, Surveillance and Biometrics. Biometric Recognition, or simply Biometrics, is a technological field in which users are identified through one or more physiological and/or behavioural characteristics [1]. Many biometric characteristics are used to identify individuals: fingerprint, signature, iris, voice, face, hand, etc. Biometric traits such as the ear, face, hand and gait are usually acquired with cameras working at visible frequencies of the electromagnetic spectrum. Such images are affected by, among other factors, lighting conditions and occlusions (e.g., clothing, make up, hair, etc.)

In order to circumvent the limitations imposed by the use of images acquired at the visible spectrum (VIS), researchers in biometrics and surveillance [2] have proposed acquiring images at other spectral ranges: X-ray (XR), Infrared (IR), Millimeter (MMW) and Submillimeter (SMW) waves (see Fig. 1). In addition to overcoming to some extent some of the limitations of visible imaging, the images captured beyond the visible spectrum present another benefit: they are more robust to spoofing than other biometric images/traits [3].

In this work, we present an overview of the state of the art in body imaging beyond the visible spectrum, with a focus on biometric recognition applications. In particular,

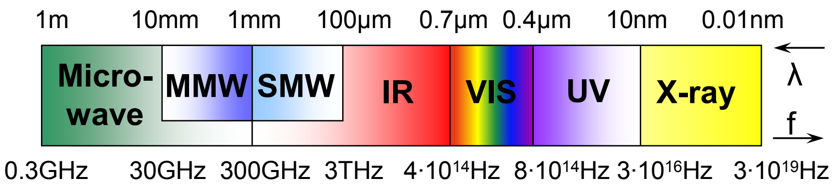

Fig. 1. Electromagnetic spectrum showing the different spectral bands between the microwaves and the X-rays. The IR band is sometimes considered to extend to 1 mm including the SMW region.

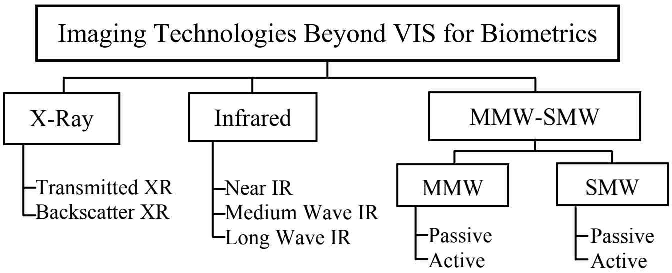

Fig. 2. A taxonomy of imaging technologies beyond visible spectrum. The figure only shows the technologies adequate for biometrics.

a taxonomy followed by the properties and the biometric applications of each imaging technology beyond the visible spectrum is presented.

2 Fundamentals and Taxonomy of Imaging Technologies beyond the Visible Spectrum

Many imaging technologies beyond the visible spectrum have been used to capture a body part: IR, magnetic resonance, radioisotope, XR, acoustical, MMW- and SMW-imaging, etc. Not all of them can be used for biometric purposes because of their high level of intrusiveness. The imaging technologies more adequate for biometric applications are: XR, IR, MMW and SMW imaging. A taxonomy of them is shown in Fig. 2.

Imagery can be classified in two architectures: *passive* or *active*. In the former group the image is generated by receiving natural radiation which has been emitted and reflected from the scene, obtaining a map of brightness temperature. On the other hand, in active imaging the radiation is transmitted to the scene and then collected after reflection to form the image, which is a map of reflectivity.

The contrast in the scene in any part of the spectrum is a function of the optical properties of the object being imaged and its background. In particular, the apparent temperature of an object T_0 is defined by:

$$T_0 = T\varepsilon + T_s r + T_b t \quad (1)$$

where T is the physical temperature of the object, ε its emissivity, T_s is the temperature of the background which is reflected by the object with reflectivity r, T_b is the temperature of the background behind the object and t the object's transmissivity [4].

3 X-ray Imaging

X-radiation have a wavelength in the range of 10-0.01 nm ($3{\cdot}10^{16}$-$3{\cdot}10^{19}$ Hz) and enough energy to pass through cloth and human tissues. In addition to cloth penetration, XR imaging provides high image resolution. On the other hand, this technology presents some disadvantages: low speed, limitation to very short distances and the health safety concerns it raises because of using ionizing radiation.

The natural background X-radiation is too weak to form an image, therefore active imaging is required in both XR imaging modalities: *transmission* and *backscatter* X-ray imaging. X-rays are commonly produced by accelerating charged particles.

Transmission X-ray Imaging. Conventional X-ray radiographic systems used for medical purposes produce images relying on this kind of imaging: a uniform X-ray beam incident on the patient interacts with the tissues of the body, producing a variable transmitted X-ray flux dependent on the attenuation along the beam paths. An X-ray-sensitive detector captures the transmitted fraction and converts the X-rays into a visible projection image.

Only a few works on biometric identification making use of the conventional X-rays can be found: Shamir *et al.* [5] perform biometric identification using knee X-rays while Chen *et al.* [6] present an automatic method for matching dental radiographs (see Fig. 3a-c). These knee or dental X-rays are difficult to forge and present additional advantages: they can be used in forensic identification where the soft tissues are degraded.

Backscatter X-ray Imaging. In this technique the XR scattered photons, instead of transmitted photons, are used to construct the image [7]. This technology utilizes high energy X-rays that are more likely to scatter than penetrate materials as compared to lower-energy X-ray used in medical applications. However, this kind of radiation is able to penetrate some materials, such as cloth.

A person is scanned by moving a single XR beam over her body. The backscattered beam from a known position allows a realistic image to be reconstructed. As only scattered X-rays are used, the registered image is mainly a view of the surface of the scanned person, i.e. her nude form. As the image resolution is high, these images present privacy issues. Some companies (e.g. AS&E) ensure privacy by applying an algorithm to the raw images so that processed images reveal only an outline of the scanned individual. Raw and processed backscatter XR images are shown in Fig. 3d and e.

According to our knowledge, there are no works on biometrics using backscatter X-ray images. The application of this technique includes medical imaging [8] and passenger screening at airports and homeland security [9]. There are currently

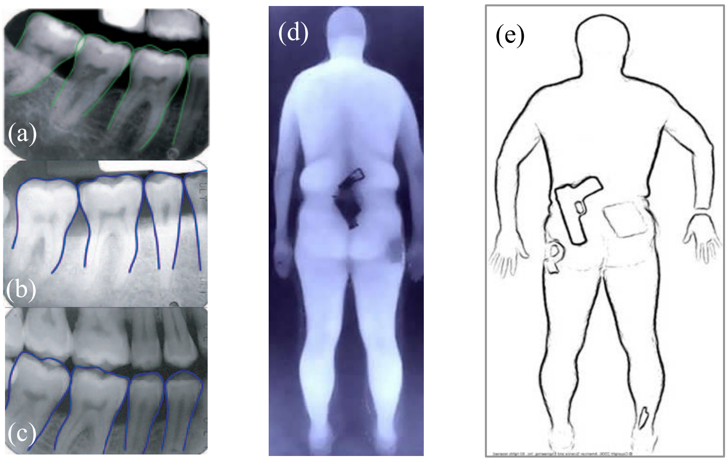

Fig. 3. (a-c) Dental radiographs used for human identification. (d) A backscatter XR image of a man, it shows the skin surface and objects hidden by clothing. (e) A backscatter XR image processed to ensure privacy. These figure insets are extracted from: [6] (a-c), [http://www.elpais.com] (d) and [http://www.as-e.com/] (e).

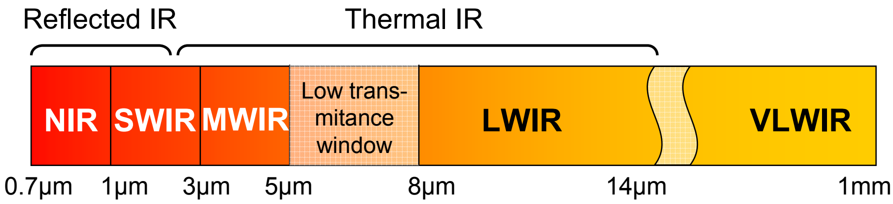

Fig. 4. Infrared band of the electromagnetic spectrum showing the different IR sub-bands.

different backscatter X-ray imaging systems available on the market to screen people (e.g. AS&E, Rapiscan Systems).

4 Infrared Imaging

The infrared band of the electromagnetic spectrum lies between the SMW and VIS regions, with wavelengths in the range of 0.7 µm - 1 mm (see Fig. 1). The human body emits IR radiation with a wavelength between 3-14 µm, hence both active and passive architectures can be used in IR imaging.

As indicated in Eq. (1), the radiation that is actually detected by an IR sensor depends on the surface properties of the object (ε, r, t) and on the trasmissivity of the medium (atmosphere). According to the properties of the medium and the spectral ranges of the currently available IR detectors, the IR spectrum is divided into five sub-bands, summarized in Fig. 4. The limits of these sub-bands are not completely fixed and depend on the specific application. In practice, IR imaging systems usually operate in one of the three following IR sub-bands: the near infrared (NIR), the medium wave infrared (MWIR) or the long wave infrared (LWIR), where the windows of high atmosphere transmissivity are located.

Table 1. Properties of the most important IR sub-bands.

IR Spectral bands	Range (µm)	Archi-tecture	IR camera cost	Image Properties	Applications in Biometrics
Near IR (NIR)	0,7-1	Active	Low, VIS camera also sensitive	Good quality, body condition invariant	Face [10] and Hand Vein [11] Recognition
Medium Wave IR (MWIR)	3 - 5	Passive	High	Good quality, sensitive to body conditions	Face [12] and Hand Vein [13] Recognition
Long Wave IR (LWIR)	8 - 14	Passive	Low	Low contrast, sensitive to body conditions	Face [14] and Hand Vein [11] Recognition

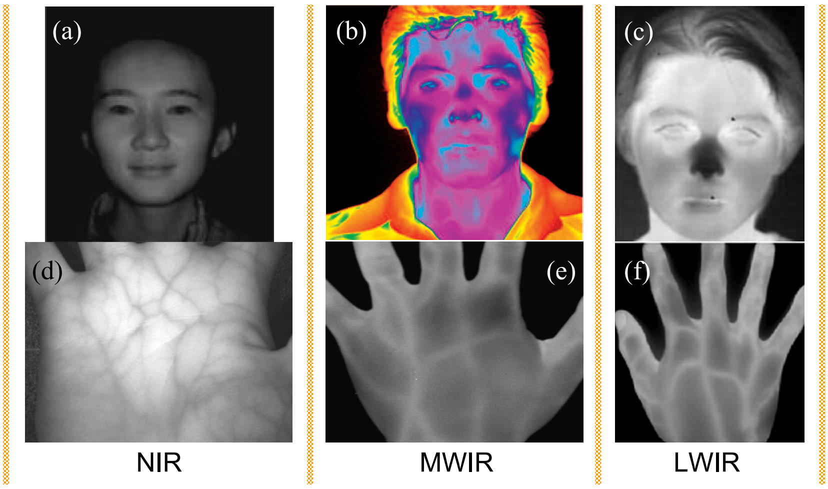

Fig. 5. Face and hand images acquired at NIR, MWIR and LWIR: (a) face at NIR, (b) face at MWIR, (c) face at LWIR, (d) palm at NIR, back of the hand at MWIR (e) and at LWIR (f). The images are extracted respectively from [10], [12], [14], [11]. [13] and [11].

In Fig. 4 the IR band is split in two sub-bands: *Reflected IR* band (0.7-2.4 µm) and *Thermal IR* band (beyond 2.4 µm). The Reflected IR band is associated with reflected solar radiation that contains no information about the thermal properties of materials. The Thermal IR band is associated with the thermal radiation emitted by the objects. This division in two bands is also related to the two kind of imaging architectures: active and passive imaging. In the Reflected IR band external illumination is needed while in the Thermal IR band passive imaging is preferred (natural IR radiation emitted by the person is captured).

The three mentioned practical IR sub-bands (i.e. NIR, MWIR and LWIR) present different characteristics. A summary of the properties of these sub-bands is given in Table 1 while Fig. 5 shows face and hand images acquired at NIR, MWIR and LWIR.

Many research works have been developed using NIR, MWIR and LWIR imaging systems for biometrics. Face and hand vein pattern recognition are the most important biometric modalities investigated in these three bands (see references in Table 1). Images acquired at any of these bands (see Fig. 5) are, to some extent, environmental illumination invariant. Specifically, images at NIR are body condition invariant and can provide good quality vein patterns near the skin surface [11], but external NIR illumination is required. Images acquired at MWIR and LWIR show patterns of radiated heat from the body's surface (often called thermograms). Very few biometric works have been developed in MWIR [12, 13], probably due to the high cost of MWIR cameras. LWIR cameras are much cheaper but, in contrast with NIR, LWIR can only capture large veins. Additionally, most of the LWIR images have low levels of contrast, being also sensitive to ambient and body condition [11].

5 Millimeter and Submillimeter Wave Imaging

MMW and SMW radiation fill the gap between the IR and the microwaves (see Fig. 1). Specifically, MMW band spreads from 30 to 300 GHz (10-1 mm) while the SMW band lies in the range of 0.3-3 THz (1-0.1 mm) [4].

The use of MMW/SMW of radiation within imaging systems is currently an active field of research due to some of its interesting properties [15-20]. The penetration through clothing and other nonpolar dielectric materials even at stand off ranges is one of the most important MMWs and SMWs abilities. Hence, security screening (detection of concealed weapons under clothing), nondestructive inspection and medical and biometric imaging are the most relevant applications of MMW/SMW imaging. Another application of MMW imaging is low visibility navigation (due to the low attenuation of MMWs under adverse weather).

Images acquired at MMW/SMW frequencies have lower resolution than IR or VIS images due to larger wavelength. Further, MMW and, specially, SMW imaging technologies are not as mature as the IR or VIS imaging technologies, which restricts the quality of the resulting images. On the other hand, SMW images have better spatial resolution than MMW images (SMW wavelength is smaller), but SMW clothing penetration is lower compared to MMW. In any case, images acquired with passive or with active systems present different characteristics (see Table 2). Different Passive MMW (PMMW), Active MMW (AMMW), Passive SMW (PSMW) and Active SMW (ASMW) images are shown in Fig. 6. As MMW and SMW images

Table 2. Properties of MMW and SMW imaging operating with passive or active architecture. The spatial resolution depends on some conditions such as the distance between the target and the detector, the given resolution corresponds to a target-detector distance of some meters.

Radiation	Architecture	Image Properties	Relative Spatial Resolution	Operating Frequencies	Commercial Systems
MMW	Passive	▪ Low resolution compared to VIS and IR ▪ Highly affected by sky illumination	Very Low (indoors) Low-Medium (outdoors)	▪ 35 GHz ▪ 94 GHz	▪ Qinetiq ▪ Brijot ▪ Alfa Imaging ▪ Sago Systems
	Active	▪ Higher quality than Passive MMW images	Medium	▪ 30 GHz ▪ 60 GHz ▪ 190 GHz	▪ Agilent ▪ L-3 Communications
SMW	Passive	▪ Good quality ▪ Partial clothing opacity	Medium-High	▪ 0.1-1 THz ▪ 1.5 THz	▪ Thruvision
	Active	▪ Higher quality than Passive SMW images ▪ Partial clothing opacity	High (at a distance) Very high (near)	▪ 0.6-0.8 THz ▪ 310 GHz ▪ > 1 THz	▪ Picometrix ▪ Teraview

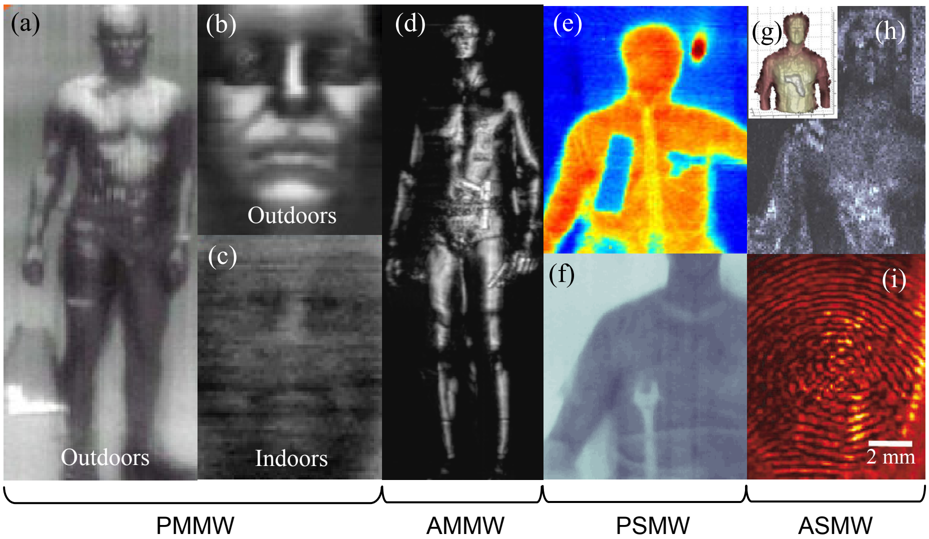

Fig. 6. Images acquired with MMW and SMW imaging systems. (a) Outdoors PMMW image (94 GHz) of a man carrying a gun in a bag. (b-c) Indoors and outdoors PMMW image of a face. (d) AMMW image of a man carrying two handguns acquired at 27-33 GHz. (e) PSMW image (0.1-1 THz) of a man with concealed objects beneath his jacket. (f) PSMW image (1.5 THz) of a man with a spanner under his T-shirt. (h) ASMW image (0.6 THz) of a man hiding a gun beneath his shirt. (g) Full 3-D reconstruction of the previous image after smoothing of the back surface and background removal. (i) Terahertz reflection mode image of a thumb. These figure insets are extracted from: www.vision4thefuture.org (a-c), [16] (d), [17] (e), [18] (f), [19] (g-h) and [20] (i).

measure the different radiometric temperatures in the scene, see Eq. (1), images acquired indoors and outdoors have very different contrast when working in passive mode, specially with MMW (see Fig. 6b and c).

In spite of the significant advantages of MMW and SMW radiation for biometric purposes (cloth penetration, low intrusiveness, health safety), no biometric applications have been developed yet.

3 Conclusions

We have provided a taxonomy of the existing imaging technologies operating at frequencies beyond the visible spectrum that can be used for biometrics purposes. The advantages and challenges of each imaging technology, as well as their image properties have been presented. Although only X-ray and Infrared spectral bands have been used for biometric applications, there is another kind of radiation with promising applications in the biometric field: millimeter and submillimeter waves. However MMW and SMW technology is not completely mature yet.

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