Millimeter- and Submillimeter-Wave Imaging Technologies for Biometric Purposes

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***Abstract*- The inherent restrictions of human body images acquired at visible spectrum hinder the performance of person recognition systems built using that kind of information (e.g. scene artifacts under varying illumination conditions). One promising approach for dealing with those limitations is using images acquired out of 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 pros and cons of each technology and their biometric applications are presented, with special attention to Millimeter and Submillimeter Wave imaging.**

I. 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 several 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 the body occlusion (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 areas [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.

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, we will concentrate on the potential application of images acquired at GHz-THz frequencies for biometric purposes. We stress the importance of this radiation range because of its ability to pass through cloth and other occlusions, its health safety, its low intrusiveness, and the recent deployment and rapid progress of GHz-THz systems in screening applications.

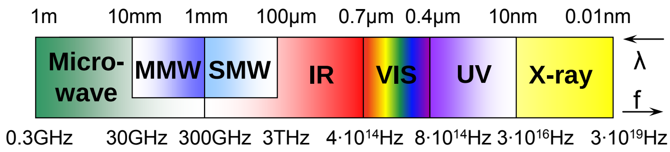

Fig. 1. Electromagnetic spectrum showing the different spectral bands between the microwaves and the X-rays. IR band is sometimes considered to extend to 1 mm including the SMW region.

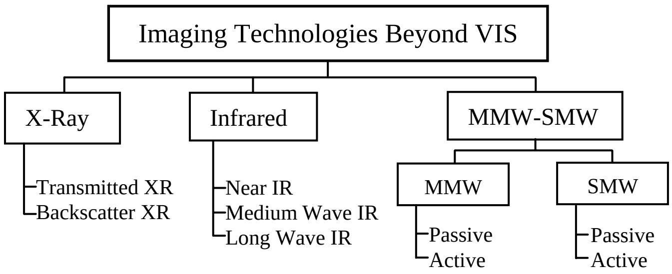

Fig. 2. A taxonomy of imaging technologies beyond visible spectrum. The figure only shows the technologies adequate for biometrics.

II. 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-, 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.

A. *X-ray Imaging*

X-radiation has 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. The first one is the technique used in conventional X-ray radiographic systems, where XR photons transmitted through the body are detected to form the image. In the backscatter XR, the scattered photons are used to construct the image providing mainly a view of the surface of the scanned person [3]. Backscatter XR imaging technology has no tissue penetration.

There are very few works on biometric identification making use of XR imaging: Shamir *et al.* [4] perform biometric identification using knee X-rays while Chen *et al.* [5] present an automatic method for matching dental radiographs. According to our knowledge, there are no works on biometrics using backscatter X-ray images. The application of this technique includes medical imaging [6] and passenger screening at airports and homeland security [7]. There are currently different backscatter X-ray imaging systems available on the market (e.g. AS&E, Rapiscan Systems) to screen people.

B. Infrared Imaging

The infrared band of the electromagnetic spectrum lies between the SMW and VIS regions, its wavelength is in the range of 0.7 µm - 1 mm. 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.

The radiation that is actually detected by an IR sensor depends on the surface properties of the object and 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 parts. However IR imaging systems usually operate in one of the three following IR bands: the near infrared (NIR), the medium wave infrared (MWIR) or the long wave infrared (LWIR), where the high transmissivity atmosphere windows are located. Imaging objects within these IR-bands presents different characteristics. A summary of the properties of these bands is showed in Table 1.

Many biometric research works have been developed using NIR, MWIR and LWIR imaging systems. 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 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 [9], 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 [10, 11], 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 [9].

C. Millimeter and Submillimeter Wave Imaging

MMW and SMW radiation fill the gap between the IR and the microwaves (see Fig. 1). Specifically, millimeter waves lie in the band of 30-300 GHz (10-1 mm) and the SMW regime lies in the range of 0.3-3 THz (1-0.1 mm).

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 [8] and Hand Vein [9] Recognition
Medium Wave IR (MWIR)	3 - 5	Passive	High	Good quality, sensitive to body conditions	Face [10] and Hand Vein [11] Recognition
Long Wave IR (LWIR)	8 - 14	Passive	Low	Low contrast, sensitive to body conditions	Face [12] and Hand Vein [9] Recognition

Table 1. Properties of the most important IR bands.

MMW and SMW radiation can penetrate through many commonly used nonpolar dielectric materials such as paper, plastics, wood, leather, hair and even dry walls with little attenuation [13, 14]. Clothing is highly transparent to the MMW radiation and partially transparent to the SMW radiation [15]. Above 30 GHz, the transmission of the atmosphere varies strongly as a function of frequency due to water vapour and oxygen [16, 17]. There are relatively transparent windows centered at 35, 94, 140 and 220 GHz in the MMW range and less transparent windows in the SMW region located at: 0.34, 0.67, 1.5, 2, 2.1, 2.5, 3.4 and 4.3 THz. Atmosphere attenuation is further increased in poor weather. Liquid water extremely attenuates submillimeter waves while MMW radiation is less attenuated (millions of times) in the presence of clouds, fog, smoke, snow, and sand storms than VIS or IR radiation.

Consequently, natural applications of MMW and SMW imaging include security screening, non-destructive inspection, and medical and biometrics imaging. Low visibility navigation is another application of MMW imaging [18]. The detection of concealed weapons has been the most developed application of MMW/SMW imaging systems so far, in contrast to the biometrics area, where no research works have been produced.

Although most of the radiation emitted by the human body belongs to the MWIR and LWIR bands, it emits radiation in the SMW and MMW regions as well. This allows passive imaging. A key factor in MMW and SMW passive imaging is the sky illumination. This makes images acquired in indoor and outdoor environments to have very different contrast when working with passive systems. Outdoors radiometric temperature contrast can be very large, but it is very small indoors. In passive imaging operating indoors the signal to noise ratio (SNR) of the existing cameras is barely enough for coarse object detection, being usually insufficient for identification (as needed for biometrics). There are two solutions to overcome this problem: (i) cooling the detector or alternatively (ii) using active imaging. Cooling the detector improves the sensitivity but it makes the camera more expensive and difficult to use.

In active imaging, the source that illuminates the scene produces much higher power level than the emitted from the scene, so it can be considered as an object at very high temperature. If the source is incoherent and physically large, active imaging is equivalent to passive imaging with the surroundings at very high temperature, and hence results in much greater contrast within the image. If the source is small, active imaging becomes more complicated. In any case, the power level of the radiation source in active imaging strongly affects the detection resolution. In addition to higher resolution than passive imaging, active imaging provides higher SNR, higher signal levels, and the ability to obtain depth information in the scene.

C.1. Millimeter Wave Imaging

- **Passive MMW Imaging**

There have been many research groups working on passive MMW imaging (PMMW) since its early developments. Most of them have constructed prototype radiometers that work at a frequency range centered at 35 GHz [19] or at 94 GHz [13, 20-22].

The images obtained with PMMW imaging systems have low resolution compared to VIS and IR images. This low resolution is a consequence of the longer wavelengths used relative to the aperture size of the sensor's collection optics. Further, images acquired indoors will present less contrast than those acquired outdoors, as it is shown in Fig. 3a and 3b.

The applications of most of the cited works are the detection of concealed weapons or vision under adverse weather conditions. No biometrics applications have been found yet in PMMW imaging in spite of its ability to penetrate cloth and the availability of multiple commerical PMMW cameras (e.g. Quinetiq, Brijot, Alfa Imaging, Sago Systems, Millivision, and View Systems).

- **Active MMW Imaging**

Active MMW imaging (AMMW) has gained more and more attention during the last few years for indoor security applications [23-25]. Sheen *et al.* [23] demonstrated an AMMW imager operating at 27-33 GHz and good quality images were obtained (see Fig. 3c). Derham *et al.* [24] showed the performance of a prototype AMMW imaging system operating at 60 GHz that uses the frequency–encoding technique. Timms *et al.* [25] developed a 190 GHz active imaging system.

An image obtained with AMMW is shown in Fig. 3c together with two PMMW images. The higher quality of the images acquired with active systems is clearly noticeable.

Again, most of AMMW imaging systems are used as security portals. Some AMMW imagers are currently available on the market (Agilent and L3-Communications). Agilent's MMW imaging system works at 30 GHz and has a transverse resolution of 1 cm. L-3 Provision MMW body screening portal has been used since 2007 at some airports. However, no biometric application of AMMW imaging has emerged so far.

C.2. Submillimeter Wave Imaging

The shorter the radiation wavelength is, the better image resolution is available, and hence SMW imaging would provide better resolution than MMW imaging. On the other hand, as the wavelength decreases, the penetration capability decreases. Further, the technology needed in the SMW imaging systems is much less mature than the MMW technology.

- **Passive SMW Imaging**

In passive SMW imaging (PSMW) the contrast in the image depends on the operation frequency: at frequencies below 0.5 THz it will be dominated by the reflectivity of the items, while at frequencies of 0.5 THz and above, it will be dominated by the emissivity of the objects and their physical temperature (similar to thermography).

Some of the more relevant and recent research works on PSMW imaging include [26] and [27]. Luukanen *et al.* [26] developed an imaging system working at 0.1-1 THz. Shen *et al.* [27] performed detection and segmentation of concealed objects in images acquired with the imaging system described in [26]. They obtain good quality images as it can be seen in Fig. 4a. Fig. 4b shows another PSMW image of a man with a spanner hidden under his T-shirt (acquired at 1.5 THz [28]). These two images show that cloth is less transparent to submilliter waves than to MMW radiation (collar and folds of the weave are visible). A passive system required to penetrate all type of clothing should operate below 0.3-0.5 THz [15, 16].

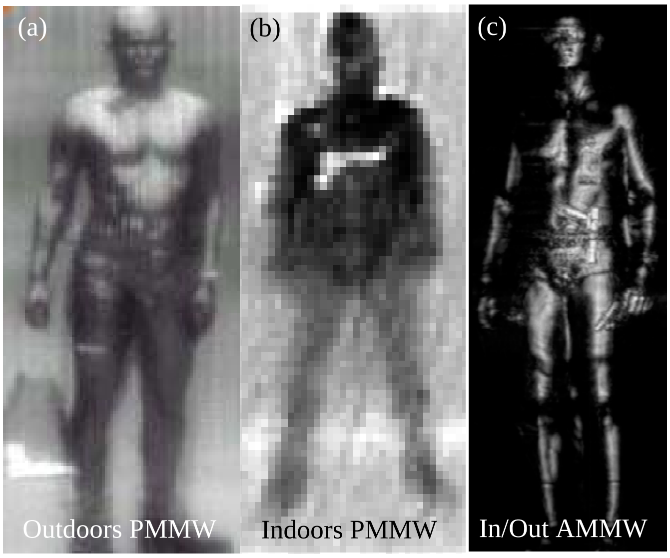

Fig. 3. Images acquired with MMW imaging systems. (a) Outdoors PMMW image (94 GHz) of a man carrying a gun in a bag. (b) Indoors PMMW image (94 GHz) of a man with a gun concealed under clothing. (c) AMMW image of a man carrying two handguns acquired at 27-33 GHz. These figure insets are extracted from: www.vision4thefuture.org (a), www.alfaimaging.com (b) and [23] (c).

The higher resolution of SMW images compared to MMW makes SMW more suitable to biometric recognition applications. However the partial clothing opacity to SMW radiation would hinder the performance of biometric systems. To the best of our knowledge, no biometric works have been performed using PSMW imaging.

Regarding commercial PSMW imaging systems, Thruvision currently produces what it seems to be the only commercially available passive THz imaging system.

- **Active SMW Imaging**

Research works on active SMW imaging (ASMW) have only appeared recently [29-31]. Some of them can image a body part at a distance [29] at 0.6-0.8 THz with a spatial resolution of less than 1 cm, while the rest present much better resolution (< 2 mm) working with relatively close targets at 310 GHz [30], or beyond 1 THz [31].

Fig. 4 c-f shows images acquired at SMW with the active architecture. An image of a man hiding a gun beneath his shirt acquired with a 0.6 THz radar [29] is shown in Fig. 4d while the inset 4c is a full 3-D reconstruction of the same image after some additional smoothing. The two images at the bottom right, insets 4e and 4f, show, respectively, a visible frequency ink thumb print and a reflected terahertz 20-frame average image of the same thumb flattened against a polyethylene wedge [31].

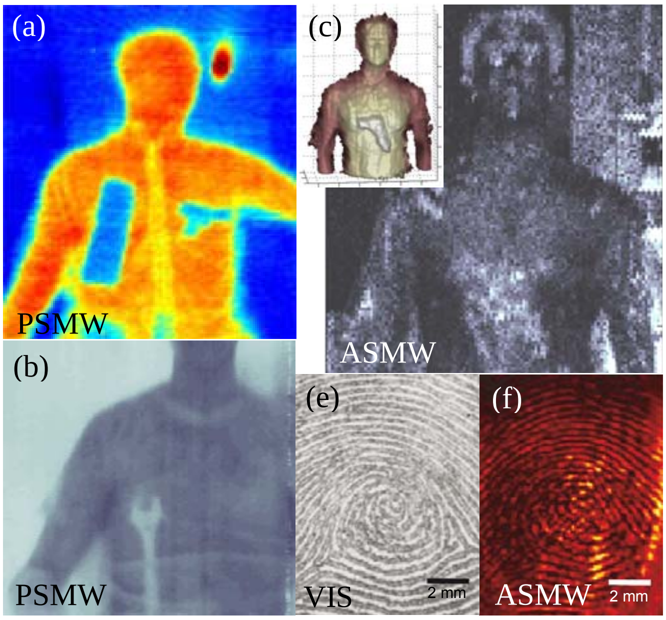

Fig. 4. Images acquired with SMW imaging systems. (a) PSMW image (0.1-1 THz) of a man with concealed objects beneath his jacket. (b) PSMW image (1.5 THz) of a man with a spanner under his T-shirt. (d) ASMW image (0.6 THz) of a man hiding a gun beneath his shirt. (c) Full 3-D reconstruction of the previous described image after smoothing of the back surface. (e) White light image of a thumb print. (f) Terahertz reflection mode image of thumb. These figure insets are extracted from: [27] (a), [28] (b), [29] (c and d) and [31] (e and f).

Although images acquired at a distance with ASMW imaging systems present not very high spatial resolution, extracting signals from the noisy scene clutter is possible [29]. Furthermore, images acquired from targets near the system present a reasonable resolution for biometric applications, as it is shown in Fig. 4f. This fingerprint acquired at 4.3 THz has enough quality to allow the identification of an individual. On the other hand, the imaging system is quite complicated, and it works only in laboratory environments. Active terahertz imaging systems are available providing high resolution (Picometrix) and additional spectroscopic information (Teraview).

III. Conclusions

We have provided a taxonomy of the existing imaging technologies operating at frequencies out of the visible spectrum that can be used for biometrics purposes. Although only X-ray and Infrared spectral bands have been used for biometric applications, we have focused our attention in MMW and SMW bands, which provide interesting advantages over the other kind of radiation (e.g. transmission through common garment, no health hazard and low intrusiveness). However the imaging technology operating at these frequencies (GHz-THz) is not completely mature yet.

Acknowledgments

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