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Infrared face recognition: A comprehensive review of methodologies and databases

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ABSTRACT

Automatic face recognition is an area with immense practical potential which includes a wide range of commercial and law enforcement applications. Hence it is unsurprising that it continues to be one of the most active research areas of computer vision. Even after over three decades of intense research, the state-of-the-art in face recognition continues to improve, benefitting from advances in a range of different research fields such as image processing, pattern recognition, computer graphics, and physiology. Systems based on visible spectrum images, the most researched face recognition modality, have reached a significant level of maturity with some practical success. However, they continue to face challenges in the presence of illumination, pose and expression changes, as well as facial disguises, all of which can significantly decrease recognition accuracy. Amongst various approaches which have been proposed in an attempt to overcome these limitations, the use of infrared (IR) imaging has emerged as a particularly promising research direction. This paper presents a comprehensive and timely review of the literature on this subject. Our key contributions are (i) a summary of the inherent properties of infrared imaging which makes this modality promising in the context of face recognition; (ii) a systematic review of the most influential approaches, with a focus on emerging common trends as well as key differences between alternative methodologies; (iii) a description of the main databases of infrared facial images available to the researcher; and lastly (iv) a discussion of the most promising avenues for future research.

1. Introduction

In the last two decades automatic face recognition has consistently been one of the most active research areas of computer vision and applied pattern recognition. Systems based on images acquired in the visible spectrum have reached a significant level of maturity with some practical success [1]. However, a range of nuisance factors continue to pose serious problems when visible spectrum based face recognition methods are applied in a real-world setting. Dealing with illumination, pose and facial expression changes, and facial disguises is still a major challenge.

There is a large corpus of published work which has attempted to overcome the aforesaid difficulties by developing increasingly sophisticated models which were then applied on the same type of data – usually images acquired in the visible spectrum (wavelength approximately in the range 390–750 nm). Pose, for example, has been normalized by a learnt 2D warp of an input image [2], generated from a model fitted using an analysis-by-synthesis approach [3] or synthesized using a statistical method [4], while illumination has been corrected for using image processing filters [5] and statistical facial models [6], amongst others, with varying levels of success. Other methods adopt a multi-image approach by matching sets [7–10] or sequences of images [11,12]. Another increasingly active research direction has pursued the use of alternative modalities. For example, it is clear that data acquired using 3D scanners [13,14] is inherently robust to illumination and pose changes. However, the cost of these systems is high and the process of data collection overly restrictive for most practical applications.

1.1. Infrared spectrum

Infrared imagery is a modality which has attracted particular attention, in large part due to its invariance to the changes in illumination by visible light [15]. A detailed account of the relevant physics, which is outside the scope of this paper, can be found in [16]. In the context of face recognition, data acquired using infrared cameras has distinct advantages over the more common cameras which operate in the visible spectrum. For instance, infrared images of the faces can be obtained under any lighting condition, even in completely dark environments, and there is some evidence that thermal infrared (see Section 1.2) "appearance" may exhibit a higher

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degree of robustness to facial expression changes [17]. Thermal infrared energy is also less affected by scattering and absorption by smoke or dust than reflected visible light [18,19]. Unlike visible spectrum imaging, infrared imaging can be used to extract not only exterior but also useful subcutaneous anatomical information, such as the vascular network of a face [20]. Finally, in contrast to visible spectrum imaging, thermal vision can be used to detect facial disguises [21].

1.2. Spectral composition

In the existing literature, it has been customary to divide the infrared spectrum into four sub-bands: near IR (NIR; wavelength 0.75–1.4 μm), short wave IR (SWIR; wavelength 1.4–3 μm), medium wave IR (MWIR; wavelength 3–8 μm), and long wave IR (LWIR; wavelength 8–15 μm). This division of the IR spectrum is also observed in the manufacturing of infrared cameras, which are often made with sensors that respond to electromagnetic radiation constrained to a particular sub-band. It should be emphasized that the division of the IR spectrum is not arbitrary. Rather, different sub-bands correspond to continuous frequency chunks of the solar spectrum which are divided by absorption lines of different atmospheric gasses [16]. In the context of face recognition, one of the largest differences between different IR sub-bands emerges as a consequence of the human body's heat emission spectrum which is, in its idealized form, shown in Fig. 1. Specifically, note that most of the heat energy is emitted in LWIR sub-band, which is why it is often referred to as the thermal sub-band (this term is sometimes extended to include the MWIR sub-band). Significant heat is also emitted in the MWIR sub-band. Both of these sub-bands can be used to *passively* sense facial thermal emissions without an external source of light. This is one of the reasons why LWIR and MWIR sub-bands have received the most attention in the face recognition literature. In contrast to them, facial heat emission in the SWIR and NIR sub-bands is small and recognition systems operating on data acquired in these sub-bands require appropriate illuminators (invisible to the human eye) i.e. recognition is *active* in nature [22]. In recent years, the use of NIR also started received increasing attention from the face recognition community, while the utility of the SWIR sub-band has yet to be studied in depth.

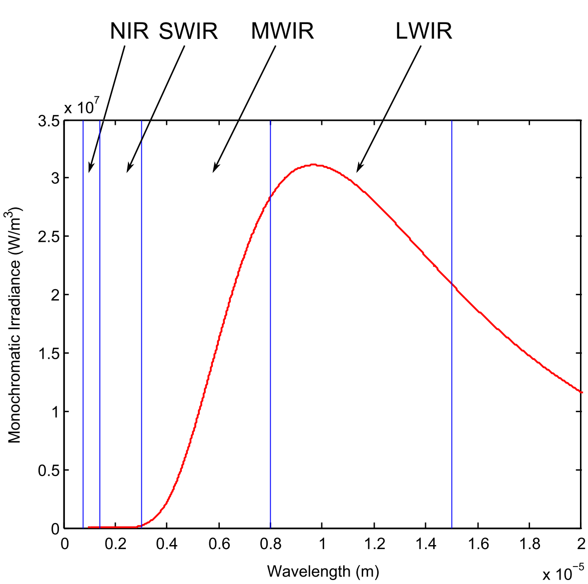

Fig. 1. The idealized spectrum of heat emission by the human body predicted by Planck's law at 305 K, with marked boundaries of the four infrared sub-bands of interest in this paper: near-wave (NIR), short-wave (SWIR), medium-wave (MWIR) and long-wave (LWIR). Observe that the emission in the NIR and SWIR sub-bands is nearly zero. As a consequence, imaging in these bands is by necessity active i.e. it requires an illuminator at the appropriate wavelengths.

1.3. Challenges

The use of infrared images for automatic face recognition is not void of challenges. For example, MWIR and LWIR images are sensitive to the environmental temperature, as well as the emotional, physical and health condition of the subject, as illustrated in Fig. 2. They are also affected by alcohol intake. Another potential problem is that eyeglasses are opaque to the greater part of the IR spectrum (LWIR, MWIR and SWIR) [23]. This means that a large portion of the face wearing eyeglasses may be occluded, causing the loss of important discriminative information. Unsurprisingly, each of the aforementioned challenges has led to and motivated a new research direction. Some researchers have suggested fusing the information from IR and visible modalities as a possible solution to the problem posed by the opaqueness of eyeglasses [1]. Others have described methods which use thermal infrared images to extract a range of invariant features such as facial vascular networks [20,24] or blood perfusion data [25] in order to overcome the temperature dependency of thermal “appearance”. Another consideration of interest pertains to the impact of sunlight if recognition is performed outdoors and during daytime. Although invariant to the changes in the illumination by visible light itself (by definition), the infrared “appearance” in the NIR and SWIR sub-bands *is* affected by sunlight which has significant spectral components at the corresponding wavelengths. This is one of the key reasons why NIR and SWIR based systems which perform well indoors struggle when applied outdoors [26,27].

1.4. Aims and organization

The aim of this paper is to present a thorough literature review of the growing and increasingly important problem of infrared face recognition. In comparison with the already published reviews of the field, by Kong et al. [1], Akhloufi et al. [28] and Ghiass et al. [29,30], the present paper makes several important contributions. Firstly, we survey a much greater corpus of relevant work. What is more, we include and give particular emphasis to the most recent advances in the field. As such, our review is both the most comprehensive and the most up-to-date review of infrared based face recognition to date. Finally, our work is distinguished from other reviews of the field also by its original categorization of different methodologies, which adds further insight into the evolution of dominant research trends.

The remainder of this paper is organized as follows. Firstly, the inherent advantages and disadvantages of infrared data in the context of face recognition are discussed in Section 2. Section 3 comprises the main part of the paper. This is where we describe different recognition approaches proposed in the literature, grouped by the methodology or the type of features employed for recognition. Section 4 which follows aims to survey various databases of infrared facial images. Our focus was on free databases, but a number of proprietary databases which have gained prominence through important peer-reviewed publications are included as well. Finally, the most important conclusions and trends in the field to date are summarized in Section 5.

2. Infrared data: advantages and disadvantages

Many of the methods for infrared based face recognition have been inspired by or are verbatim copies of algorithms which were initially developed for visible spectrum recognition. In most cases, these methods make little use of the information about the spectrum which was used to acquire images. However, the increasing appreciation of