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An experimental study on fuzzy distances for skull–face overlay in craniofacial superimposition

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Abstract

Skull–face overlay is the most time-consuming and error-prone stage in craniofacial superimposition, an important skeleton-based forensic identification technique. This task focuses on achieving the best possible overlay of an unknown skull found and a single ante-mortem image of a candidate missing person. The process is influenced by some sources of uncertainty since two objects of different nature are involved, i.e. a skull and a face. In previous works we have developed a computer-aided craniofacial superimposition system aimed to assist forensic anthropologists in obtaining the best possible skull and face overlay. The system has successfully allowed us to reduce the processing time, simplify the forensic anthropologists' work, and make the process more objective and reproducible. Our approach is based on automatically overlaying a skull three dimensional model onto a facial photograph by minimizing the distance between two subsets of corresponding cranial and facial landmarks. The proposed method properly deals with the inherent uncertainty sources to the skull–face overlay process by considering fuzzy sets to model imprecise landmark location, and imprecise cranial and facial landmarks spatial correspondence (resulting from the presence of soft tissues in the face). Accordingly, our methodology requires computing two kinds of distance metrics: between a point and a fuzzy set, and between two fuzzy sets. This contribution is devoted to study the performance and influence of the most significant and suitable fuzzy distances proposed in the specialized literature, as well as other new ones proposed, on our skull–face overlay system. In particular, we have tested the behavior of our automatic method when considering eight different distance measurements. The system performance has been objectively evaluated considering 18 case studies resulting from a ground truth dataset following a rigorous statistical experimental setup. The fact that the choice of a good distance metric is crucial to our method has been demonstrated since it significantly affects the quality of the final solutions. It has been shown that our skull–face overlay approach presents the best performance using the weighted mean distance in most of the cases and that the results are both more accurate and robust than the other studied metrics.

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1. Introduction

Craniofacial superimposition (CFS) [1], one of the approaches in craniofacial identification [2,3], is a forensic process where a number of ante-mortem images of a missing person are superimposed with the skull that is found to determine if they belong to the same subject. The appropriate projection of the skull onto the facial photograph, known as skull face overlay (SFO) [4], is a very challenging and time-consuming part of the CFS technique [5]. There is a strong interest in designing automatic methods to support the forensic anthropologist to put it into effect [6]. In particular, the design of computer-aided CFS methods has experienced a boom over the past twenty years [7]. The most recent approaches consider the use of skull 3D models, as it is the case in the current contribution.

The SFO process is influenced by inherent uncertainty since two objects of different nature are involved (a skull and a face) [8]. Other limitations associated with the different sources of uncertainty in this problem are related with the difficult task to locate landmarks, both in the skull and in the face [9,10]. Namely, the difficulty to precisely positioning facial landmarks in photographs, specially with a poor quality, and the inability to locate a large set of (noncoplanar) landmarks due to occlusions [8]. Hence, there is a need for an appropriate automatic SFO method able to model this imprecision.

Computer vision (CV) and soft computing (SC) methods can be extremely useful for this aim. Computer vision includes techniques for processing, analyzing, segmenting, and registering image data in an automatic way [11]. Within CV, image registration (IR) aims to find a geometric transformation that overlays two images taken under different conditions (at different times, from different viewpoints, and/or by different sensors) [12]. Soft computing is aimed to design intelligent systems to process uncertain, imprecise and incomplete information [13]. Two of the main SC techniques are fuzzy logic (FL) [14] and evolutionary algorithms (EAs) [15]. The former extends classical logic to provide a conceptual framework for knowledge representation under imprecision and the consequent uncertainty. Specifically, fuzzy sets have largely demonstrated their capability to deal with vagueness and imprecise information. The latter comprises powerful bio-inspired search and optimization tools to automate problem solving in areas such as modeling, simulation, or global optimization [15].

Our previous works tackle SFO in an automatic way using EAs and fuzzy sets [8,16,17]. These approaches are based on overlaying a skull 3D model on a facial photograph by minimizing the distance among pairs of landmarks as well as handling the imprecision due to the facial landmarks location [9,10]. Fuzzy landmarks in photographs are used to jointly deal with the imprecise landmark location and the coplanarity problem [8]. Besides, since the correspondence between facial and cranial landmarks is not always symmetrical and perpendicular [18], cranial landmarks are also modeled by fuzzy sets in our previous approach [19], taking into account the available information concerning soft tissue depths [20,21].

This methodology thus requires computing distances between pairs of cranial and facial landmarks. The registration transformation leading to the overlay corresponding to the minimum distance should be the best solution to the SFO problem. Since both kinds of landmarks can be represented as fuzzy sets, the need to compute distance measures between fuzzy sets arises. In fact, cranial landmarks are always represented by fuzzy sets in order to account for the soft tissue depths while facial landmarks can sometimes be modeled by crisp points and others by fuzzy landmarks, depending on the landmark location conditions. Hence, two kinds of fuzzy distances are involved in this problem: between a crisp point and a fuzzy set, when facial landmarks are located using a precise point (one pixel on the image); and between two fuzzy sets, when facial landmarks are located using an imprecise region (an ellipse on the image). Regardless the distance nature, the choice of a particular distance measure is expected to have an impact on the performance and robustness of our automatic SFO method.

In the literature, many fuzzy distance measures have been proposed. These distances have been classified depending on the type of information they convey and the application they attend. In this contribution, we aim to study the performance and influence of the most significant, and, *a priori*, most appropriate distance definitions on our SFO method. We will also propose and test a few new metrics. To do so, we have tested our 3D-2D automatic approach using all these distances on 18 skull–face overlay instances from a ground truth dataset [22].

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