Intuitionistic Fuzzy Image Processing

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INTRODUCTION

Since its genesis, fuzzy sets (FSs) theory (Zadeh, 1965) provided a flexible framework for handling the indeterminacy characterizing real-world systems, arising mainly from the imprecise and/or imperfect nature of information. Moreover, fuzzy logic set the foundations for dealing with reasoning under imprecision and offered the means for developing a context that reflects aspects of human decision-making. Images, on the other hand, are susceptible of bearing ambiguities, mostly associated with pixel values. This observation was early identified by Prewitt (1970), who stated that "a pictorial object is a fuzzy set which is specified by some membership function defined on all picture points", thus acknowledging the fact that "some of its uncertainty is due to degradation, but some of it is inherent". A decade later, Pal & King (1980) (1981) (1982) introduced a systematic approach to fuzzy image processing, by modelling image pixels using FSs expressing their corresponding degrees of brightness. A detailed study of fuzzy techniques for image processing and pattern recognition can be found in Bezdek et al and Chi et al (Bezdek, Keller, Krisnapuram, & Pal, 1999) (Chi, Yan, & Pham, 1996).

However, FSs themselves suffer from the requirement of *precisely* assigning degrees of membership to the elements of a set. This constraint raises some of the flexibility of FSs theory to cope with data characterized by uncertainty. This observation led researchers to seek more efficient ways to express and model imprecision, thus giving birth to higher-order extensions of FSs theory.

This article aims at outlining an alternative approach to digital image processing using the apparatus of Atanassov's intuitionistic fuzzy sets (A-IFSs), a simple, yet efficient, generalization of FSs. We describe heuristic and analytic methods for analyzing/synthesizing images to/from their intuitionistic fuzzy components and discuss the particular properties of each stage of the process. Finally, we describe various applications of the intuitionistic fuzzy image processing (IFIP) framework from diverse imaging domains and provide the reader with open issues to be resolved and future lines of research to be followed.

BACKGROUND

From the very beginning of their development, FSs intrigued researchers to apply the flexible fuzzy framework in different domains. In contrast with ordinary (crisp) sets, FSs are defined using a characteristic function, namely the *membership function*, which maps elements of a universe to the unit interval, thereby attributing values expressing the *degree of belongingness* with respect to the set under consideration. This particular property of FSs theory was exploited in the context of digital image processing and soon turned out to be a powerful tool for handling the inherent uncertainty carried by image pixels. The importance of fuzzy image processing was rapidly acknowledged by both theoreticians and practitioners, who exploited its potential to perform various image-related tasks, such as contrast enhancement, thresholding and segmentation, de-noising, edge-detection, and image compression.

However, and despite their vast impact to the design of algorithms and systems for real-world applications, FSs are not always able to directly model uncertainties associated with imprecise and/or imperfect information. This is due to the fact that their membership functions are themselves crisp. These limitations and drawbacks characterizing most ordinary fuzzy logic systems (FLSs) were identified and described by Mendel & Bob John (2002), who traced their sources back to the uncertainties that are present in FLSs and arise from various factors. The very meaning of words that are used in the antecedents and consequents of FLSs can be uncertain, since some words may often mean different things to different people. Moreover, extracting the knowledge from a group of experts who do not all agree, leads in consequents having a histogram of values associated with them. Additionally, data presented as inputs to an FLS, as well as data used for its tuning, are often noisy, thus bearing an amount of uncertainty. As a result, these uncertainties translate into additional uncertainties about FS membership functions. Finally, Atanassov et al. (Atanassov, Koshelev, Kreinovich, Rachamreddy & Yasemis, 1998) proved that there exists a fundamental justification for applying methods based on higher-order FSs to deal with everyday-life situations. Therefore, it comes as a natural consequence that such an extension should also be carried in the field of digital image processing.

THE IFIP FRAMEWORK

In quest for new theories treating imprecision, various higher-order extensions of FSs were proposed by different scholars. Among them, A-IFSs (Atanassov, 1986) provide a simple and flexible, yet solid, mathematical framework for coping with the intrinsic uncertainties characterizing real-world systems. A-IFSs are defined using two characteristic functions, namely the *membership* and the *non-membership* that do not necessarily sum up to unity. These functions assign to elements of the universe corresponding *degrees of belongingness* and *non-belongingness* with respect to a set. The membership and non-membership values induce an *indeterminacy index*, which models the *hesitancy* of deciding the degree to which an element satisfies a particular property. In fact, it is this additional degree of freedom that provides us with the ability to efficiently model and minimize the effects of uncertainty due to the imperfect and/or imprecise nature of information.

Hesitancy in images originates out of various factors, which in their majority are caused by inherent weaknesses of the acquisition and the imaging mechanisms. Distortions occurred as a result of the limitations of the acquisition chain, such as the quantization noise, the suppression of the dynamic range, or the nonlinear behavior of the mapping system, affect our certainty regarding the "*brightness*" or "*edginess*" of a pixel and therefore introduce a degree of hesitancy associated with the corresponding pixel. Moreover, dealing with "*qualitative*" rather than "*quantitative*" properties of images is one of the sound advantages of fuzzy-based techniques. Qualitative properties describe in a more natural and human-centric manner image attributes, such as the "*contrast*" and the "*homogeneity*" of an image region, or the "*edginess*" of a boundary. However, as already pointed out, these terms are themselves imprecise and thus they additionally increase the uncertainty of image pixels. It is therefore a necessity, rather than a luxury, to employ A-IFSs theory to cope with the uncertainty present in real-world images.

In order to apply the IFIP framework, images should first be expressed in terms of elements of A-IFSs theory. Analyzing and synthesizing digital images to and from their corresponding intuitionistic fuzzy components is not a trivial task and can be carried out using either heuristic or analytic approaches.

Heuristic Modelling

As already stated, the factors introducing hesitancy in real-world images can be traced back to the acquisition stage of imaging systems and involve pixel degradation, mainly triggered by the presence of quantization noise generated by the A/D converters, as well as the suppression of the dynamic range caused by the imaging sensor. A main effect of quantization noise in images is that there exist a number of gray levels with zero, or almost zero, frequency of occurrence, while gray levels in their vicinity possess high frequencies. This is due to the fact that a gray level g in a digital image can be either (g+1) or (g-1) without any appreciable change in the visual perception.

An intuitive and heuristic approach to the modelling of the aforementioned sources of uncertainty in the context of A-IFSs was proposed by Vlachos & Sergiadis (Vlachos & Sergiadis, 2005) (Vlachos & Sergiadis, 2007 d) for gray-scale images, while an extension to color images was presented in Vlachos & Sergiadis (Vlachos & Sergiadis, 2006). The underlying idea involves the application of the concept of the *fuzzy histogram* of an image, which models the notion of the gray level "*approximately g*". The fuzzy histogram takes into account the frequency of neighboring gray levels to assess the frequency of occurrence of the gray level under consideration. Consequently, a quantitative measure of the quantization noise can be calculated as the normalized absolute difference between the ordinary (crisp) and fuzzy histograms.