Lecture Notes in Mechanical Engineering

Caterina Rizzi · Angelo Oreste Andrisano · Francesco Leali · Francesco Gherardini · Fabio Pini · Alberto Vergnano *Editors*

Design Tools and Methods in Industrial Engineering

Proceedings of the International Conference on Design Tools and Methods in Industrial Engineering, ADM 2019, September 9–10, 2019, Modena, Italy

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Preface

The ADM 2019 International Conference, organized by the Italian Association of Design Methods and Tools for Industrial Engineering (ADM), brings the tradition of dissemination meetings back to life. The event in fact represents the reopening of the biennial international conferences organized by ADM in the years in which the JCM Conference (joint conference of ADM, INGEGRAF and S.mart) is not held.

The opportunity arose from the intention of all members of the Italian Association of Design Methods and Tools for Industrial Engineering to express gratitude to Prof. Angelo O. Andrisano, Rector of the University of Modena and Reggio Emilia.

As a member, adviser and President of the ADM board, Prof. Andrisano has with his skills, excellent professionalism, vision and passion offered a significant contribution to raising the works of the association to the highest levels.

As a very appreciated rector, Prof. Andrisano has moreover brought prestige to the association, stimulating the pride of all its members.

The ADM 2019 International Conference has been made possible with will and support of all the members of the ADM board, as well as the sensitivity of all the members of the Scientific Council, in particular the Coordinator, Prof. Caterina Rizzi. Moreover, a fundamental contribution was given by the Scientific Societies, INGEGRAF and S.mart, whom I sincerely thank.

I also thank all the members of the scientific and the organizing committees and Eng. Francesco Gherardini, who has effectively taken care of significant organizational aspects.

Special thanks go to all the authors and all the Italian and international reviewers for the high scientific level achieved by the papers, which has led to the publication of the research works in this prestigious book.

Finally, I thank all the ADM members. Their contribution has been fundamental for the organization of the ADM 2019 International Conference.

Vincenzo Nigrelli
ADM President

Letter to the Authors

Dear Attendees and Authors,

It is a great honour and a pleasure to welcome you to the ADM 2019 International Conference, held in Modena, Italy, 9–10 September 2019. The conference is hosted by the University of Modena and Reggio Emilia, a globally renowned university located in the heart of the Italian Motor Valley.

The conference aims at sharing knowledge, experience and up-to-date scientific information in the areas of design and manufacturing, with links between industry and academia. It provides a forum for researchers, educators and professional engineers for the dissemination and exchange of their latest research results.

Through the exchange of ideas, ADM 2019 intends to facilitate the creation of multidisciplinary cooperation and developments and discoveries for new product design and manufacture, health care, transportation and environment.

This book collects more than 80 scientific papers across a wide range of session topics that cover a broad spectrum of themes including theoretical issues, methods, tools, processes and case studies. The topics span from technical representation and geometric modelling to virtual/augmented reality, virtual ergonomics, human factors, human–machine interactions, knowledge management, additive manufacturing and many other subjects applied in different contexts, such as automotive, agriculture, cultural heritage and health care. They provide opportunities for interaction and for understanding how the application of emerging technologies impact on critical engineering issues activities such as product design, manufacturing, management and integration of information throughout the life cycle.

We have also the privilege to host three outstanding keynote speakers. The first is Prof. Angelo Oreste Andrisano (Rector of the University of Modena and Reggio Emilia, Italy) at the opening plenary session with a speech dealing with four decades of changes in the university and in our scientific sector. The others are two experts from industry: Dr. Massimo Giannozzi (Materials Engineering Manager, F1 Team Ferrari), with a speech on materials and processes for automotive design with a focus on additive manufacturing technologies, and Dr. Cécile Doan (Head of CATIA Strategy, Market Development and Finance—Dassault Systèmes, Vice President) with a speech on simulation-driven design in industry: tools and future trends.

To conclude, I would like to thank all the authors for their valuable contribution to the book and each and every one of you for making ADM 2019 successful with your expertise, commitment and active engagement. Special thanks go to the Program Chair, Prof. Francesco Leali, and to the members of the Organizing Committee for their tremendous efforts for making this conference possible.

We sincerely hope that you will enjoy the conference, the Gala Dinner @ MEF—Museo Enzo Ferrari—and the beautiful Modena city.

Caterina Rizzi
Conference Chair

Introduction

This book collects the proceedings of the ADM 2019 International Conference, entitled “Design Tools and Methods in Industrial Engineering”, held in Modena, Italy, on 9–10 September 2019.

This is not the first time that an event organized by ADM (formerly known as Italian Association of Machines Design, today renamed the Italian Association of Design Methods for Industrial Engineering) or by our scientific sector (ING-IND/15) takes place in Modena. I am pleased to remember the “ADM day” held at the Military Academy of Modena in 2008, as well as the ING-IND/15 workshop organized in 2009 in the hills of Bologna, not far from Modena.

However, this conference is particularly significant, for the reasons I wish to summarize here.

Firstly, the ADM Conference constitutes a new international, permanent event held in Italy, aimed at disseminating cutting-edge research to a national and international audience. For several years, our association has had a collaborative relationship with the Spanish members of INGEGRAF and the French members of S.mart (formerly AIP-PRIMECA), with whom we organize the International Joint Conference on Mechanics, Design Engineering and Advanced Manufacturing (JCM) every two years. This event is hosted alternately by one of our three countries. Therefore, the ADM International Conference was born from the need for an event “in the middle”, to strengthen the international research network and to meet our colleagues in Italy. As a matter of fact, the ADM 2019 scientific committee was joined by Spanish and French colleagues, as well as German, Swedish, Norwegian and American ones, thanks to partnerships created by our “Enzo Ferrari” Department of Engineering (Modena) over the years.

Secondly, I am honoured to play the role of conference chair, a position that has led me to be one of the editors of this book. In more than 45 years of experience in this sector, I have seen many developments and evolutions. From the first use of CAD in the industrial sector, today we have reached a high multidisciplinary level and integration with information technology and electronics. The integration of novel tools and approaches in the industrial world is also due to the activity of our scientific sector, capable of developing and integrating innovative tools and methodologies with the traditional themes of industrial engineering.

Finally, this conference is held in 2019, an important year for me, marking the conclusion of my mandate as Rector of the University of Modena and Reggio Emilia, as well as that of Full Professor for our scientific sector. As the Dean of the ADM association and the scientific sector, I enthusiastically accepted the proposal of Francesco Leali, my collaborator for years and now my colleague, to nominate the University of Modena and Reggio Emilia, and in particular our "Enzo Ferrari" Department of Engineering, as the location for the ADM 2019 International Conference. I would like to thank both him and my departmental colleagues, in particular the researchers of my lab, LaPIS lab, for organizing this event at the "Enzo Ferrari" Department of Engineering, so dear to me, having been one of its first promoters and founders.

Equally, I would like to thank the ADM President Prof. Vincenzo Nigrelli, and Prof. Caterina Rizzi, Coordinator of the ADM Scientific Council, whose members, in turn, I gratefully thank. Further thanks go to the publisher, Springer, who honoured us by publishing the proceedings of this first ADM International Conference in the series "Lecture Notes in Mechanical Engineering".

Therefore, as editor of this first book, I hope that it will be the first of a new series of international conference proceedings underlining the leading role of our scientific sector in the international scene. The colleagues who will be hosting the next ADM conferences will have the burden, but above all the honour, of continuing this project that today we have started in Modena.

Angelo Oreste Andrisano
Honorary Conference Chair

Organization

ADM 2019 is organized by ADM—Italian Association of Design Methods and Tools for Industrial Engineering—in cooperation with the "Enzo Ferrari" Department of Engineering of the University of Modena and Reggio Emilia, Italy.

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Shape and Texture Analysis of Radiomic Data for Computer-Assisted Diagnosis and Prognostication: An Overview

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Abstract. There is increasing evidence that shape and texture descriptors from imaging data could be used as image biomarkers for computer-assisted diagnosis and prognostication in a number of clinical conditions. It is believed that such quantitative features may help uncover patterns that would otherwise go unnoticed to the human eye, this way offering significant advantages against traditional visual interpretation. The objective of this paper is to provide an overview of the steps involved in the process – from image acquisition to feature extraction and classification. A significant part of the work deals with the description of the most common texture and shape features used in the literature; overall issues, perspectives and directions for future research are also discussed.

Keywords: Shape · Texture · Radiomics · Computer-assisted medicine

1 Introduction

Recent technological advances including new imaging modalities as well as storing, sharing and computing resources have facilitated the collection of very large amounts of three-dimensional medical data [1]. In this scenario shape and texture analysis of such data has been receiving increasing attention during the last few years. The overall objective is that of extracting quantitative parameters from the imaging data (*biomarkers*) capable of correlating with clinical features such as disease phenotype and/or survival. The whole process, usually referred to as *radiomics*, can be regarded as an improvement on the traditional

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practice wherein medical images were mostly used as pictures for qualitative visual interpretation only [2,3]. In the management of oncologic disorders, for instance, a number studies have supported the use of radiomics for a variety of tasks including prediction of outcome [4,5] and response to treatment [6,7]; discrimination between benign, malignant, primary and metastatic lesions [8–10]; and classification of hystologic subtypes [11].

Radiomics, however, is still a new discipline and definitely far from being mature. There are significant obstacles that prevent the application on a large scale – chief among them the lack of large enough datasets for building models and classifiers, and the absence of standards establishing how the biomarkers should be computed [12]. The objective of this paper is to provide an overview of the steps involved, discuss the open issues and indicate directions for future research. A significant part of the paper deals with the description of the most common texture and shape features used in the literature.

2 Methods

The flow-chart of Fig. 1 summarises the overall workflow in radiomics. Image acquisition is always the first step and can optionally be followed by a post-processing phase. Segmentation is then required to separate the region of interest (ROI) from the background. Feature extraction is the core of the procedure and consists of extracting a set of meaningful parameters (*features*) from the ROI. The features can undergo some post-processing step as for instance selection and/or reduction. Finally, the resulting data are fed to some classifier or regression model suitable for the required task.

2.1 Image Acquisition

There are three main classes of medical imaging modalities providing three-dimensional data [13]: Computed Tomography (CT), Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI).

Computed Tomography is based on the unlike absorption of X-rays by different tissue types, therefore the signal is proportional to the tissue density in this case [14]. Positron Emission Tomography estimates the metabolic activity of the tissue by measuring the radioactive decay of some specific radio-tracers. Those used in PET contain isotopes (e.g. ^{11}C, ^{15}O and ^{18}F) which emit positrons through $\beta+$ decay. The positrons collide and annihilate with the electrons in the tissue, this way emitting two γ rays 180° apart that are detected by the sensors [15]. Finally, in Magnetic Resonance Imaging the signal comes from positrons (hydrogen nuclei) contained in water and lipids. The signal in this case is proportional relaxation time – i.e. the time to return to the equilibrium magnetization state once the external magnetisation field is switched off [16].

In all the imaging modalities the scanning usually proceeds axially (head to feet), this way producing, as a result, a variable number of axial cross-sections with fixed size (slices). A three-dimensional voxel model is eventually reconstructed by piling up all the slices.

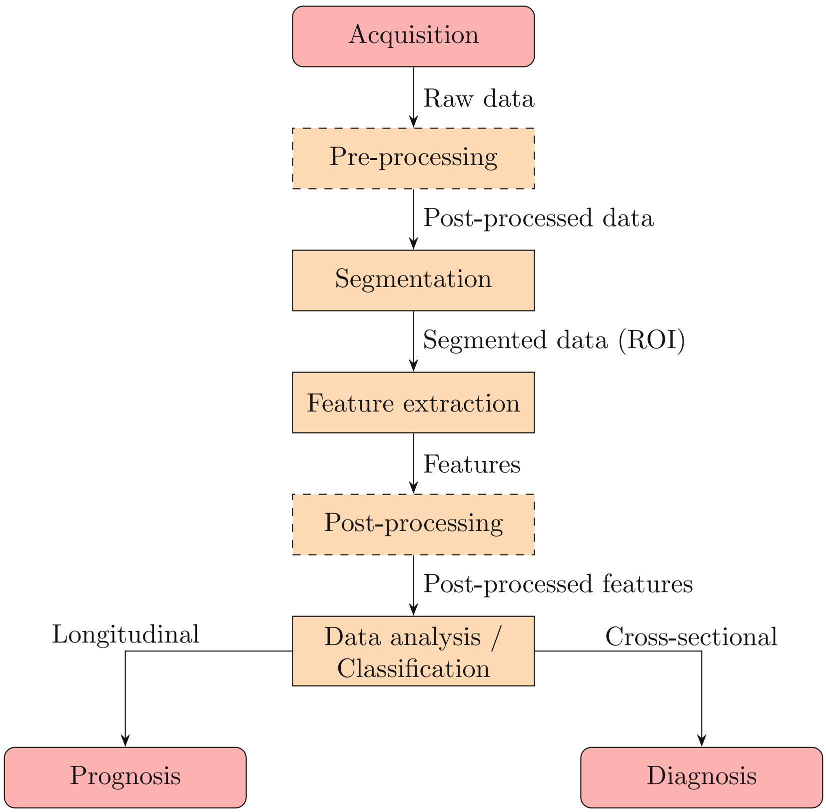

Fig. 1. The overall pipeline. Dashed lines indicate optional steps.

2.2 Pre-processing

Pre-processing usually involves one or more of the following operations: (1) *windowing* (rescaling), (2) *filtering* and (3) *resampling*. Although frequently overlooked, pre-processing is a fundamental step in the pipeline with significant effects on the overall results, as for instance shown in [17,18].

Windowing consists of applying an upper and lower threshold to the raw intensity values returned by the scans, this way excluding from the analysis those values that fall outside the range. In CT, for instance, windowing is routinely used to exclude from the analysis those anatomic parts (e.g. bones) that are reputed not relevant to the disease investigated.

Filtering can be carried out either to reduce noise and/or highlight features at different spatial scales. A variety of methods can be used for this purpose, as for instance Butterworth smoothing [18], Gaussian [19] and Laplacian of Gaussian [7,20] filters.

Resampling involves changing the number of bits (*bit depth*) used for encoding the intensity values. The bit depth of the raw data depends on the scanning device and settings used (12 and 16 bit are standard values in the practice). These are usually reduced to lower values (*downasmpling*) before feature extraction: eight, six and four bit and are common choices [6,18,21,22].

2.3 Segmentation

The objective of segmentation is that of identifying the part of the scan (ROI) that is considered relevant to the analysis. A ROI usually represents a clinically relevant region, as for instance a potentially cancerous lesion (Fig. 2). Segmentation is a crucial step, for it provides the input to the subsequent phases. Unfortunately, this is also a tedious and time-consuming procedure. Although a number of methods have been investigated for automatising the process – these include, among the others thresholding [23,24], region growing [23–25], edge detection [23,24] and convolutional networks [26,27] – segmentation remains by and large a manual procedure in which the experience and sensitivity of the physician play a major role. Besides, the decision whether to include or exclude dubious areas such as necrosis, atelectasis, inflammation and/or oedema is essentially the clinician's responsibility and, as such, hard to automatise.

CT			PET		
Axial	Coronal	Sagittal	Axial	Coronal	Sagittal

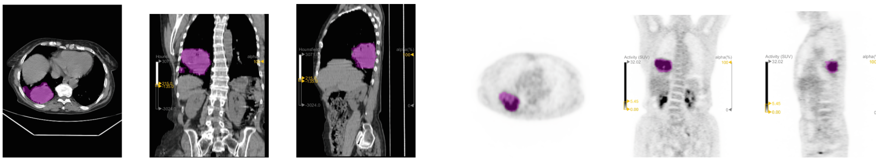

Fig. 2. CT (left) and PET (right) scans of a lung lesion with manually delineated ROI.

2.4 Feature Extraction

Feature extraction can be considered the 'core' of the whole procedure and consists of computing meaningful parameters from the regions of interest. There are two main strategies to feature extraction: the 'hand-designed' or 'hand-crafted' paradigm one the hand, and Deep Learning on the other.

In the hand designed approach the functions for feature extraction (also indicated as *image descriptors*) are mostly designed by hand, the design process being based on some prior knowledge about filtering, perceptual models and/or relatively intuitive visual properties (e.g. coarseness, business, contrast, etc.) This model-driven, 'a priori' paradigm is independent on the data to analyse. By contrast, Deep Learning is a data-driven, 'a posteriori' strategy in which the descriptors are essentially shaped by the data. The feature extractors, in this case, are based on sets of combinable blocks (layers) of which only the overall skeleton is defined a priori, and their behaviour depends on lots of free parameters whose values need to be determined by training over huge sets of data. In this paper we are mostly concerned with the hand-design paradigm; for an overview of Deep Learning and its potential applications in the field we refer the reader to Refs. [28–30].

Regardless the method used, there are some desirable properties that one would always expect from features. First, they should be *discriminative*, i.e.: they should enable good separation among the classes involved in the problem investigated (e.g. classification benign vs. malignant). Second, they should be *interpretable* on the basis of some physical characteristics (e.g. round/elongated, coarse/fine, etc.) Third, they should be *few*: this, again, facilitates interpretation, limits the computational overhead and reduces the chances of overfitting. Here below we briefly review some of the most common shape and texture features used in radiomics.

Shape Features. Shape features have been investigated as potential biomarkers for a range of diseases. In oncologic disorders, for instance, lesions presenting ill-defined ('spiculated') borders are considered suggestive of malignancy, aggressiveness and in general worse prognosis; whereas those with regular, well defined margins are more frequently indicative of benign or less aggressive lesions [31–33]. For a quantitative evaluation of shape different parameters have been proposed – among them *compactness*, *spherical disproportion*, *sphericity* and *surface-to-volume ratio* (Eqs. 1–4). In formulas, indicated with A the surface area of the ROI, V the volume and R the radius of a sphere with volume V we have:

$$\text{compactness} = \frac{V}{\sqrt{\pi} A^{2/3}} \tag{1}$$

$$\text{spherical dispr.} = \frac{A}{4\pi R^2} \tag{2}$$

$$\text{sphericity} = \frac{\pi^{1/3} (6V)^{2/3}}{A} \tag{3}$$

$$\text{surface-to-vol. ratio} = \frac{A}{V} \tag{4}$$

Compactness, spherical disproportion and surface-to-volume ratio from CT, for instance, were found predictive of malignancy in lung lesions [34]; surface-to-volume ratio from MRI showed potential to differentiate between clinically significant and non-significant prostate cancer [31]; and functional sphericity from PET images correlated with clinical outcome in non-small-cell lung cancer [32].

Texture Features

Basic Statistics. These are parameters that can be computed directly from the raw data with no further processing. Resampling is not required. They include: *mean*, *maximum*, *median*, *range*, *standard deviation*, *skewness* and *kurtosis* (for definitions and formulae see also [35]). All these features are by definition invariant to geometric transformations of the input data such as rotation, mirroring, scaling and/or voxel permutation. Most of these features are also rather intuitive and their implementation straightforward.

Histogram-Based Features. This kind of features are derived from the probability distribution (histogram) of the intensity levels within the ROI. Features like *energy* (Eq. 5 – sometimes also referred to as *uniformity*) and *entropy* (Eq. 6) are routinely used for assessing the 'heterogeneity' of tumour lesions. There is indeed evidence that higher heterogeneity may correlate with worse overall prognosis and response to treatment [36–39]. Histogram-based statistics are invariant to geometric transformations of the input data – just as basic statistics are – but they heavily depend on the resampling scheme used. In formulas, given N the number of quantisation levels and p the probability of occurrence of the i-th intensity level, we have:

$$\text{energy}_{\text{H}} = \sum_{i=0}^{N-1} \left[p\left(i\right)\right]^2 \tag{5}$$

$$\text{entropy}_{\text{H}} = \sum_{i=0}^{N-1} p\left(i\right) \log_2 \left[p\left(i\right)\right] \tag{6}$$

where entropy is expressed in bits in this case. Subscript 'H' is used to indicate that the features are computed from histograms and to differentiate them from those computed from co-occurrence matrices (see below).

Grey-Level Co-occurrence Matrices. Co-occurrence matrices (GLCM) represent the two-dimensional joint distribution of the intensity levels between pairs of voxels separated by a given displacement vector. By changing the orientation and the length of the vector GLCM can probe the local signal variation at different scales and orientations. Co-occurrence matrices, a classic tools in texture analysis, were originally designed for planar images [40] but their extension to three-dimensional data is straightforward [41]. In this case there are 26 possible orientations for a given scale and as many GLCM, of which, however, only 13 non-redundant. A GLCM with values mainly clustered around the main diagonal will indicate a texture with low variability; a highly dispersed matrix will be characteristic of a variable texture. To capture this behaviour one usually extracts some global parameters from the GLCM, as for instance *contrast*, *energy*, *entropy* and *homogeneity* (Eqs. 7–10). Again, these have shown potential as clinical biomarkers in a number of studies [5,6,22,42]. Indicated with i and j the indices of the two voxels separated by a given displacement vector, we have:

$$\text{contr.}_{\text{CM}} = \frac{\sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \left(i-j\right)^2 p\left(i,j\right)}{\left(N-1\right)^2} \tag{7}$$

$$\text{energy}_{\text{CM}} = \sum_{i=0}^{N-1} \sum_{i=0}^{N-1} \left[p\left(i,j\right) \right]^2 \tag{8}$$

$$\text{entr.}_{\text{CM}} = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} p\left(i,j\right) \log_2 \left[p\left(i,j\right) \right] \tag{9}$$

$$\text{hom.}_{\text{CM}} = \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \frac{p\left(i,j\right)}{1 + |i-j|} \tag{10}$$

Other Texture Features. Texture analysis has been an area of intense research for more than forty years, and, as a results, the amount of available methods is huge. Among those that have received attention in the field of radiomics are: neighbourhood grey-tone difference matrices (NGTDM [6,21,22,43]), grey-level run-length matrices (GLRLM [21,22,44]), Local Binary Patterns (LBP [17,45]), Laws' masks [46,47] and wavelets [48,49]. For definitions and further details we refer the reader to the given references.

2.5 Post-processing

The features returned by the extraction phase can undergo further processing to (a) reduce their number and (b) increase their discrimination capability. The main strategies to achieve this goal are *feature selection* and *feature generation* [50]. The first aims at identifying the most discriminative features so as to reduce their overall number while retaining as much information as possible. This is particularly important in radiomics, where some shape and texture features tend to be highly correlated to each other, as recently shown in [51]. The second consists of generating new features from the original ones via some suitable transformation, as for instance Principal Component Analysis (PCA) and Independent Component Analysis (ICA) [50].

2.6 Data Analysis/Classification

The last step consists of feeding the features to a classifier to make predictions about the disease type (*computer-assisted diagnosis*) and/or the clinical outlook (*prognostication*). To this end suitable machine learning models and large enough sets of labelled data (*train set*) are required. As for the model, one can choose among a number of different solutions (e.g. linear classifiers, Support Vector Machines, Classification Trees, neural networks and/or a combination of them [50,52]): the main problem is selecting the right model for the specific task. Getting the right data for training, however, can be rather hard, for it requires finding large enough sets of manually classified/annotated clinical records. For prognostication the data need also to be longitudinal, which implies following up on a cohort of patients for a long period of time.