Chapter I

An Overview of Image and Video Segmentation in the Last 40 Years

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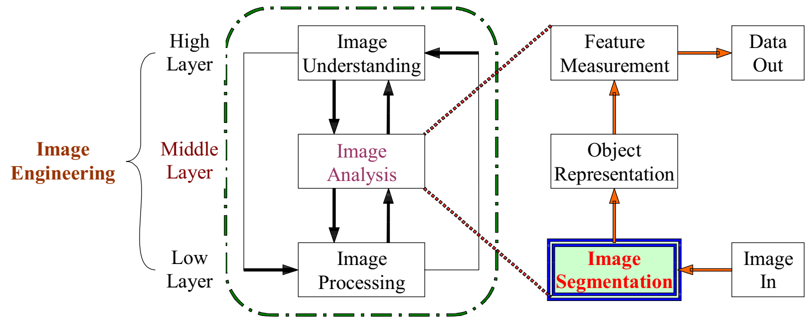
ABSTRACT

The history of segmentation of digital images using computers could be traced back 40 years. Since then, this field has evolved very quickly and has undergone great change. In this chapter, the position of image segmentation in the general scope of image techniques is first introduced; the formal definition and extension of image segmentation as well as three layers of research on image segmentation are then explained. Based on the introduction and explanations, statistics for a number of developed algorithms is provided, the scheme for classifying different segmentation algorithms is discussed and a summary of existing survey papers for image segmentation is presented. These discussions provide a general rendering of research and development of image segmentation in the last 40 years.

INTRODUCTION

Image, from its general sense, could embrace all media that can be visualized by human beings, such as still image, video, animation, graphics, charts, drawings and even text. From images, human beings obtain the majority of information from the real world. To better perceive images and to gain more information from these perceptions, various techniques have been developed and many applications have been discovered.

Figure 1. Image engineering and image segmentation



All image techniques can be grouped under a general framework—image engineering (IE), which consists of three layers: image processing (low layer), image analysis (middle layer) and image understanding (high layer), as shown in Figure 1 (Zhang, 2002a). In recent years, image engineering has formed a new discipline and made great progress (Zhang, in press).

Image segmentation is the first step and also one of the most critical tasks of image analysis. It has the objective of extracting information (represented by data) from an image via image segmentation, object representation and feature measurement (Figure 1). It is evident that the results of segmentation will have considerable influence over the accuracy of feature measurement (Zhang, 1995).

Image segmentation is often described as the process that subdivides an image into its constituent parts and extracts those parts of interest (objects). It is one of the most critical tasks in automatic image analysis because the segmentation results will affect all the subsequent processes of image analysis, such as object representation and description, feature measurement and even the following higher level tasks such as object classification and scene interpretation.

The first development of techniques for image segmentation can be traced back 40 years. In 1965, an operator for detecting edges between different parts of an image, the Roberts operator (also called the Roberts edge detector), was introduced (Roberts, 1965). This detector was the first step toward decomposing an image into its constitutional components. Since then, a large number of techniques and algorithms for image segmentation have been proposed, the result of much effort devoted to the research and application of image segmentation processes and development. In the meantime, concept and scope of images have been extended greatly. The extension of 2-D images to 3-D, still images to moving images or sequences of images (video), gray level images to color or multi-band images, etc. have also helped the concepts and techniques of image segmentation expand widely.

In spite of several decades of investigation, image segmentation remains a challenging research topic. Two bibliographical factors supporting this are:

1. Many conferences on image techniques have sessions for image segmentation. The number of papers on image segmentation increases steadily every year (Zhang, 2006).
2. Almost all books on image processing, analysis and understanding (computer vision) have chapters for image segmentation. However, to our knowledge, very few books (monographs) specialize in image segmentation (Mediode, 2000; Zhang, 2001a).

The first factor shows that the research on image segmentation is still evolving, and the second that the research is far from maturation. It is then evident that an overview of the progress of image segmentation would be useful for further development.

BACKGROUND

Formal Definition

Considering image segmentation as the partition of an image into a set of non-overlapping regions whose union is the entire image, some rules to be followed for regions resulting from the image segmentation can be stated as (Haralick, 1985):

1. They should be uniform and homogeneous with respect to some characteristics;
2. Their interiors should be simple and without many small holes;
3. Adjacent regions should have significantly different values with respect to the characteristic on which they are uniform; and
4. Boundaries of each segment should be simple, not ragged, and must be spatially accurate.

A formal definition of image segmentation, supposing the whole image is represented by R and R_i, where $i = 1, 2, \ldots, n$ are disjoint non-empty regions of R, consists of the following conditions (Fu, 1981):

1. $\bigcup_{i=1}^{n} R_i = R$;
2. for all i and j, $i \neq j$, there exits $R_i \cap R_j = \varnothing$;
3. for $i = 1, 2, \ldots, n$, it must have $P(R_i) = TRUE$;
4. for all $i \neq j$, there exits $P(R_i \cup R_j) = FALSE$;

where $P(R_i)$ is a uniformity predicate for all elements in set R_i and $\varnothing$ represents an empty set.

Some have thought the following condition is also important:

5. For all $i = 1, 2, \ldots, n$, R_i, is a connected component.

In the above, condition (1) points out that the summation of segmented regions could include all pixels in an image; condition (2) points out that different segmented regions could not overlap each other; condition (3) points out that the pixels in the same segmented regions should have some similar properties; condition (4) points out that the pixels belonging to different segmented regions should have some different properties; and finally, condition (5) points out that the pixels in the same segmented region are connected.

Definition Extension

As mentioned in the introduction, the concept and scope of image have been extended widely. If the basic 2-D still gray level image is represented by $f(x, y)$, then the extension of 2-D images to 3-D can be represented by $f(x, y) \Rightarrow f(x, y, z)$; the extension of still images to moving images or sequences of images can be represented by $f(x, y) \Rightarrow f(x, y, t)$; a combination of the above extensions can be represented by $f(x, y) \Rightarrow f(x, y, z, t)$; and the extension of gray level images to, for example, color images or multi-band images (in combining all the above extensions) can be represented by $f(x, y) \Rightarrow \boldsymbol{f}(x, y, z, t)$.

Considering the extension of images, the definitions of image segmentation may also need to be extended. With the extension of $f(x, y) \Rightarrow f(x, y, z)$, $f(x, y) \Rightarrow f(x, y, t)$ and $f(x, y) \Rightarrow f(x, y, z, t)$, the regions in all the above conditions should be extended to some high-dimensional blobs. With the extension of $f(x, y) \Rightarrow \boldsymbol{f}(x, y, z, t)$, the properties of image elements become vectors, so the logic predicate defined for conditions (3) and (4) should be modified to incorporate vector information. Once done, the above five conditions can still be used to define the image segmentation.

Two notes that relate to the extension of the concepts of images and image segmentation are as follows: First, when 2-D images are extended to 3-D images, i.e., $f(x, y) \Rightarrow f(x, y, z)$, the original pixel should be replaced by a 3-D voxel (volume element). For even higher dimensional images, no universal image element has been defined. Second, when in cases of $f(x, y) \Rightarrow f(x, y, t)$ and $f(x, y) \Rightarrow f(x, y, z, t)$, the extended images can be segmented either in space (i.e., x, y, z) or in time domain (i.e., temporal segmentation). In both cases, the principle indicated by conditions (3) and (4) is still the similar properties inside each component and the different properties for adjacent components.

Three Levels of Research

Research on image segmentation began with developing techniques for segmenting images. However, there is yet no general theory for image segmentation. So, this development has traditionally been an *ad hoc* process. As a result, many research directions have been exploited, some very different principles have been adopted and a wide variety of segmentation algorithms have appeared in the literature. It has been noted by many that none of the developed segmentation algorithms are generally applicable to all images and different algorithms are not equally suitable for particular applications.

With the increase in the number of algorithms for image segmentation, evaluating the performance of these algorithms becomes indispensable in the study of segmentation. Considering the various modalities for acquiring different images and the large number of applications requiring image segmentation, selecting appropriate algorithms becomes an important task. A number of evaluation techniques have been proposed; for those published in the last century, see Zhang (1996, 2001b) for survey papers.

The technique of evaluation of image segmentation can be categorized into two types: characterization and comparison. Characterization may be seen as an intra-technique process while technique comparison as an inter-technique one. Both emphasize the evaluation of an algorithm's performance but not its development. In other words, not the design but the behavior of an algorithm is taken into account.

While evaluation techniques have gained more and more attention, with numerous evaluation methods newly designed, how to characterize the different existing methods for evaluation has also attracted interest. In fact, different evaluation criteria and procedures, their applicability, advantages and limitations need to be carefully and systematically studied.

According to the above discussion, the research for image segmentation is carried on at three levels. The first, and also the most basic, is the level of algorithm development. The second, at the middle, is the level of algorithm evaluation, and the third, at the top, is the systematic study of evaluation methods.

The present chapter will concentrate on the first level of segmentation, while discussion of the state-of-art in second and third levels will be given in Chapter XX.

MAIN THRUST

The current study focuses on statistics about the number of segmentation algorithms developed, how different segmentation techniques are classified and on a general overview of survey papers published in the last 40 years.

Number of Developed Algorithms

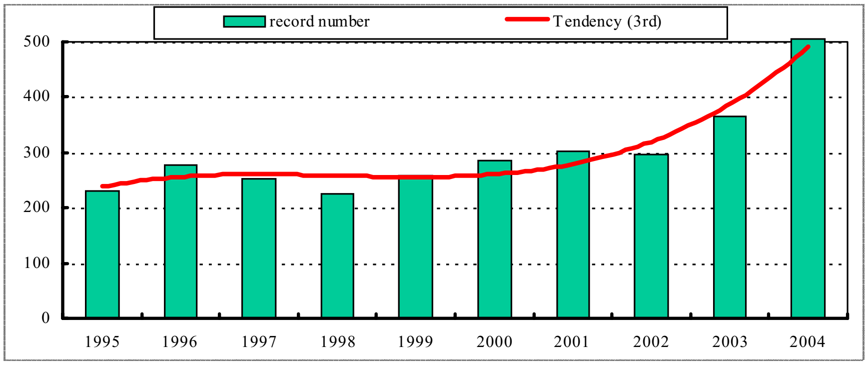
Over the last 40 years, the research and development of segmentation techniques has gone on steadily. A great number of segmentation algorithms have been developed and this number is continually increasing. More than 10 years ago, an estimation of the number of internationally proposed algorithms for image segmentation had been made (Zhang, 1994). It was first pointed out that the cumulative number should approach one thousand (instead of "hundreds" as some were still predicting) at that time. Now, with the advent of network search engines, a search using the term "image segmentation" in title field from EI Compendex provides the list of English records (papers) as shown in Table 1. These records were collected in April 2006.

From Table 1, it is obvious that the estimation made more than 10 years ago has been verified. The record of numbers in the last 10 years is plotted in Figure 2, together with a tendency curve (third order polynomial).

Table 1. List of image segmentation records found in EI Compendex

1965-1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	Total
965	232	278	253	226	258	287	303	298	365	506	326	4297

Figure 2. Number of records and the tendency of development in 1995~2004



It can be seen from Figure 2 that the curve is flat for the first 5 years and increases quickly for the last 5 years. A related but distinct study can be found in Zhang (2006), from which some statistics for an even wider scope of image techniques (including image segmentation) over the last 10 years may be found, and a comparison of the developmental tendency of image segmentation with that of another popular image technique—image coding—is also provided.

Classification of Algorithms

With so many algorithms having been developed, classification of various techniques for image segmentation becomes an essential task. Different schemes have been proposed. For example, segmentation algorithms have been divided into three groups (Fu, 1981):

1. Thresholding or clustering (the latter is the multi-dimensional extension of the former)
2. Edge detection
3. Region extraction

The problem with this classification is that as thresholding is also a region extraction approach in reality, group (1) is just a special sub-group of group (3).

Another study considers various segmentation algorithms in six groups (Pal, 1993):

1. Thresholding
2. Pixel classification (including relaxation, Markov random field based approaches and neural network based approaches)
3. Range image segmentation
4. Color image segmentation
5. Edge detection

6. Methods based on fuzzy set theory (including fuzzy thresholding, fuzzy clustering and fuzzy edge detection)

It is clear that the above six groups are somehow overlapping from the technique point of view. For example, the groups of range image segmentation and color image segmentation emphasize how images are to be segmented. However, the algorithms for segmenting these images are still based on thresholding, pixel classification or edge detection, as indicated by the authors (Pal, 1993). On the other hand, the group of algorithms based on fuzzy set theory is a combination of fuzzy set theory with groups (1), (2) and (5). Thus, in fact, only three groups of segmentation algorithms are distinguishable here. Lastly, the algorithms in groups (1) and (2) have many similarities (Fu, 1981), while commonly employed region-growing techniques, for example, cannot be included among these groups.

A classification of algorithms into groups, in principle, is a problem of set partition into subsets. With reference to the definition of segmentation (Fu, 1981), it was believed that the resultant groups, after an appropriate classification of segmentation algorithms according to the process and objective, should satisfy the following four conditions (Zhang, 1997):

1. Every algorithm must be in a group
2. All groups together can include all algorithms
3. Algorithms in the same group should have some common properties
4. The algorithms in different groups should have certain distinguishable properties

Classifications of algorithms are performed according to specific classification criteria. The first two conditions imply that the classification criteria should be suitable for all algorithms. The last two conditions imply that the criteria should determine the representative properties of each algorithm group. Keeping these conditions in mind, the following two criteria appear to be suitable for the classification of segmentation algorithms.

Gray level image segmentation is generally based on one of two basic properties of gray level values in images: discontinuity and similarity (Conzalez, 2002). Thus, two categories of algorithms can be distinguished: the boundary-based ones that detect object contours explicitly by using the discontinuity property and the region-based ones that locate object areas explicitly according to the similarity property. These two categories may be considered as complementary. On the other hand, according to the processing strategy, segmentation algorithms can be divided into sequential and parallel classes (Rosenfeld, 1981). In the former, some cues from the early processing steps are taken for the subsequent steps. While in the latter, all decisions are made independently and simultaneously. Both strategies are also complementary from the processing point of view.

Combining the two types of categorizations, four groups of techniques: G1, G2, G3 and G4 can be defined as shown in Table 2.

It can be verified that such a classification scheme satisfies the above four conditions for algorithms. These four groups can cover/include all existing segmentation algorithms, such as those surveyed by Fu (1981) as well as Pal (1993). Most edge detection based segmentation procedures can be categorized as belonging to group G1,

Table 2. General classification of segmentation algorithms

Classification	Edge-based (discontinuity)	Region-based (similarity)
Parallel process	G1: Edge-based parallel process	G3: Region-based parallel process
Sequential process	G2: Edge-based sequential process	G4: Region-based sequential process

while other edge-based algorithms using processes such as edge linking and boundary following, which are inherently sequential, could be better classified in the G2 group. All thresholding and clustering techniques and many procedures considering segmentation as a pixel/voxel classification problem belong to the G3 group. Methods based on multi-resolution structure, region growing as well as region split and merge are often labeled under the group G4.

The algorithms in each group have some common characteristics. In the study of segmentation algorithms, typical examples are often selected as representative of the group. For example, in an evaluation of different groups of segmentation algorithms (Zhang, 1997), two algorithms, the Canny operator edge detecting and boundary closing, have been taken from group G1; the algorithm using dynamic programming techniques for contour searching is taken from group G2; the algorithm based on improved histogram concavity analysis is taken from group G3; while the algorithm employs split, merge and group approach is taken from group G4. Recently, a number of researchers have combined the primitive algorithms in diverse groups to form new composite ones. Though different strategies can be used (Munoz, 2002), the fundamental principles of basic algorithms are unaffected.

New algorithms based on many different mathematical theories and models, such as Bayesian theory, Brownian string, expert system, fractal, Gabor filtering, Gaussian mixture models, generic algorithms, Gibbs Random Field, hidden Markov models, Markov random field (MRF), multi-scale edge detection, simulated annealing, wavelet modulus maxima, and so forth, have attracted the consideration of many researchers. The above general classification scheme is still applicable for these new algorithms. For example, algorithms based on the SUSAN operator belong to group G1; ACM and ASM belong to group G2; different thresholding techniques, no matter what they are based on wavelet transformation, maximum/minimum entropy or fuzzy divergence, or even fuzzy C-means, belong to group G3; watershed algorithms correspond to the boundary of object, but segmentation techniques using watershed are usually based on region attributes (Roerdink, 2000); like region-growing techniques, watershed uses region-based properties to determine the region boundary and thus could be categorized into group G4.

Compared to the spatial-nature of (static) images, video has both spatial nature and temporal nature. Segmenting a frame of video in spatial domain is just like segmenting a static image. Segmenting a sequence of video frames in temporal domain is called temporal segmentation or shot detection (Zhang, 2002b). The purpose is to divide a video sequence into its constitute units—shots. The principle used in this segmentation is still like that in spatial domain. In fact, the difference between adjacent frames and the similarity among consecutive frames could be used to determine the frontier of shots. The former corresponds to edge-based techniques while the latter corresponds to region-based techniques. In edge-based image segmentation, the inter-region disparity between one region and its comparison to their neighbors is considered. In edge-based video segmentation, neighbors should be adjacent frame and most temporal segmentation, shot-detection methods are dependent on discrepancy between frames. In region-based image segmentation, the intra-region homogeneity is taken into account. In region-based video segmentation, motion uniformity across frames or the temporal stability of certain region features can be used.

In Table 2, the classification is shown for the top group level. For each group, sub-group level classification is still possible. For example, thresholding is a popular tool used in image segmentation and a wide range of thresholding techniques has been developed—a survey of them can be found in Sahoo (1988). Determination of appropriate threshold values is the most important task involved in thresholding techniques. Threshold values have been determined in different techniques by using rather different criteria. A classification of thresholding techniques can be based on how the threshold values are determined (Zhang, 1990). The threshold T is a function of the form $T = T[x, y, f(x, y), g(x, y)]$, where $f(x, y)$ is the gray level of a point located at (x, y), and $g(x, y)$ denotes some local properties of this point. When T depends solely on $f(x, y)$, the thresholding technique is point-dependent. If T depends on both $f(x, y)$ and $g(x, y)$, then the thresholding technique is region-dependent. If, in addition, T depends also on the spatial coordinates x and y, the thresholding technique will be coordinate-dependent.

Another classification of thresholding techniques takes into account the application range of thresholds. The thresholds obtained by both point-dependent and region-dependent techniques will be applied to the whole image, so these techniques could be called global techniques. The thresholds obtained by coordinate-dependent techniques, on the other hand, will be applied to each pixel of each sub-image, so these techniques could be called local techniques.

Further classification could still be made. For example, according to the information exploited (Marcello, 2004), the above mentioned global techniques have been classified into the following groups (this list could be and in fact is being augmented):

1. Histogram shape-based methods (where the peaks, valleys, curvatures, etc., of the smoothed histogram are analyzed)
2. Clustering-based methods (where the grey level samples are clustered in two parts as background and foreground or, alternately, are modeled as two Gaussian distributions)
3. Entropy-based methods (where the entropy of the foreground-background regions, the cross-entropy between the original and segmented image, etc., are calculated)
4. Object attribute-based methods (where a measure of similarity between the grey-level and segmented images, such as fuzzy similarity, shape, edges, number of objects, etc., are investigated)
5. Spatial relation-based methods (where probability mass function models take into account correlation between pixels on a global scale are used)

Summary of Survey Papers

Along with the development of image segmentation algorithms, a number of survey papers for general image segmentation algorithms have been presented in the literature over the last 40 years (Davis, 1975; Zucker, 1976; Riseman, 1977; Zucker, 1977; Weszka, 1978; Fu, 1981; Rosenfeld, 1981; Peli, 1982; Haralick, 1985; Nevatia, 1986; Pavlidis, 1986; Borisenko, 1987; Sahoo, 1988; Buf, 1990; Sarkar, 1993; Pal, 1993), though they only partially cover the large number of techniques developed. In partitioning the last 40 years into four decades, it is interesting to note that all these survey papers are dated in the second and third decades. The reason for a lack of surveys in the first decade is because the research results were just cumulating during that period. The reason for no survey results in the last decade may be attributed to the factor that so many techniques have already been presented, that a comprehensive survey becomes less feasible.

Though no general survey for the whole scope of image segmentation has been made in the last 10 years, some specialized surveys have nevertheless been published in recent years. These survey papers can be classified into two sub-categories:

1. Survey focused on particular group of segmentation algorithms:

Many segmentation algorithms have been developed by using certain mathematical/theoretical tools, such as fuzzy logic, genetic algorithms, neural networks (NN), pattern recognition, wavelet, and so forth, or based on unique frameworks, such as active contour models (ACM), thresholding, watershed, and so forth. Some surveys for algorithms using the same tools or based on the same frameworks have been made, for example:

Because using fully automatic methods sometimes would fail and produce incorrect results, the intervention of a human operator in practice is often necessary. To identify the patterns used in the interaction for the segmentation of medical images and to develop qualitative criteria for evaluating interactive segmentation methods, a survey of computational techniques involving human-computer interaction in image segmentation has been made (Olabarriaga, 2001). This survey has taken into account the type of information provided by the user, how this information affects the computational part of the method and the purpose of interaction in the segmentation process for the classification and comparison of a number of human-machine dialog methods.

Algorithms combining edge-based and region-based techniques will take advantage of the complementary nature of edge and region information. A review of different segmentation methods which integrate edge and region information has been made (Freixenet, 2002). Seven different strategies to fuse such information have been highlighted.

Active shape model (ASM) is a particular structure for finding the object boundary in images. Under this framework, various image features and different search strategies can be used, which makes for a range of ASM algorithms. A number of these variations for the segmentation of anatomical bone structures in radiographs have been reviewed in Behiels (2002).

Thresholding technique is a relative simple and fast technique. A survey of thresholding methods with a view to assess their performance when applied to remote sensing images has been made recently (Marcello, 2004). Some image examples are taken from oceanographic applications in this work.

2. Surveys focused on a particular application of image segmentation:

Image segmentation has many applications. For each application, a number of segmentation algorithms could be developed. Some surveys for particular applications have been made. In medical imaging applications, image segmentation is used for automating or facilitating the delineation of anatomical structures and other regions of interest. A survey considering both semi-automated and automated methods for the segmentation of anatomical medical images has been done (Pham, 2000), wherein their advantages and disadvantages for medical imaging applications are discussed and compared.

While video could be considered as a particular type of general image, its segmentation is an extension of image segmentation. For video data, a temporal segmentation is used for determining the boundary of shots. A survey is made for techniques that operate on both uncompressed and compressed video streams (Koprinska, 2001). Both types of shot transitions, abrupt and gradual, are considered. The performance, relative merits and limitations of each approach are comprehensively discussed.

For temporal video segmentation, excepting the ability and correctness of shot detection, the computation complexity is also a criterion that should be considered, especially for real-time application. A review of real-time segmentation of uncompressed video sequences for content-based search and retrieval has been made (Lefèvre, 2003). Depending on the information used to detect shot changes, algorithms based on pixel, histogram, block, feature and motion have been selected.

Vessel extraction is essentially a segmentation process. A survey for related algorithms to this process has been made (Kirbas, 2003). Six groups of techniques proposed for this particular application are involved: (1) pattern recognition techniques; (2) model-based approaches; (3) tracking-based approaches; (4) artificial intelligence-based approaches; (5) neural network-based approaches; and (6) miscellaneous tube-like object detection approaches.

In many vision applications, moving shadows must be detected. Moving shadows can be considered as objects in video streams and the detection of moving shadows is basically a video segmentation problem. A survey has been made for four classes of techniques (two statistical and two deterministic) that are specially designed for detecting moving shadows (Prati, 2003).

FUTURE TRENDS

The subject of image and video segmentation covers a very large area, and further developments could move in many directions; a few of them are indicated as follows:

1. Mathematical models and theories

It is said there is yet no general theory for image and video segmentation. However, this does not prevent the introduction of various mathematical theories into the research of image and video segmentation. Many novel models have also been created over the years which have had certain success. To further push the research on image and video segmentation, and to drive the research beyond being *ad hoc* process, more mathematical models and theories would be required and used in the future.

2. High level study

As discussed in the beginning of this chapter, the research on image and video segmentation is currently conducted in three levels: the development of segmentation algorithms, the evaluation of segmentation quality and performance as well as the systematic study of evaluation methods. With a large number of segmentation algorithms being developed, the performance evaluation of these algorithms has attracted more research efforts (see Chapter XX). The results obtained from high-level study could greatly help the development of new segmentation algorithms and/or the effective utilization of the existing segmentation algorithms (Zhang, 2000).

3. Incorporating human factors

Image (and video) segmentation is a critical step of image analysis occupying the middle layer of image engineering, which means it is influenced not only from data but also from human factors. It seems that the assistance of humans, knowledgeable in the application domain, will remain essential in any practical image segmentation method. Incorporating high-level human knowledge algorithmically into the computer remains a challenge.

4. Application-oriented segmentation

Image and video segmentation have been proved necessary in many applications. Though the general process of segmentation is well defined in all applications, the particular requirements for segmentation can be different, and this difference leads to a variety of application-oriented segmentation. For example, in target detection, capturing a recognizable target, instead of segmenting it precisely, would be more significant. Another example is that the extraction of meaningful regions (Luo, 2001), instead of precisely segmenting objects, has proved to be effective in content-based visual information retrieval tasks (Zhang, 2005).

CONCLUSION

Image segmentation, forty years' old, is a critical task for image analysis which is at the middle layer of image engineering. The concepts of image and image segmentation have been extended widely since their initial appearance. The research on image and video segmentation is currently conducted at three different levels: developing segmentation algorithms, evaluating algorithm performance and studying the behavior of evaluation methods.

An overview of the development of image and video segmentation in the last 40 years is provided in this chapter. Several thousands of segmentation algorithms have been designed and applied for various applications, and this number has increased steadily at a rate of several hundreds per year since 2000. This increase makes it quite hard to work out a comprehensive survey on the techniques of image and video segmentation, and a suitable classification scheme for hierarchical cataloging the whole technique.

After 40 years' growth, the domain of image and video segmentation is still immature. Many research topics, such as introducing more mathematical theories into this field, using high-level research results to guide low-level development, incorporating human factors and working toward application-oriented segmentation, need to be exploited. Even more, many unsettled problems need to be defined and solved in this area. However, as a Chinese saying states: "A person will not be puzzled after 40 years of age." Due to the accumulation of solid research results and the progress of science and technology comprising the 40 years' experience, further directions have become clearer. It is firmly believed that the domain of image and video segmentation will be greatly advanced in the future.

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