A Survey of Image Registration Techniques

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Registration is a fundamental task in image processing used to match two or more pictures taken, for example, at different times, from different sensors, or from different viewpoints. Virtually all large systems which evaluate images require the registration of images, or a closely related operation, as an intermediate step. Specific examples of systems where image registration is a significant component include matching a target with a real-time image of a scene for target recognition, monitoring global land usage using satellite images, matching stereo images to recover shape for autonomous navigation, and aligning images from different medical modalities for diagnosis.

Over the years, a broad range of techniques has been developed for various types of data and problems. These techniques have been independently studied for several different applications, resulting in a large body of research. This paper organizes this material by establishing the relationship between the variations in the images and the type of registration techniques which can most appropriately be applied. Three major types of variations are distinguished. The first type are the variations due to the differences in acquisition which cause the images to be misaligned. To register images, a spatial transformation is found which will remove these variations. The class of transformations which must be searched to find the optimal transformation is determined by knowledge about the variations of this type. The transformation class in turn influences the general technique that should be taken. The second type of variations are those which are also due to differences in acquisition, but cannot be modeled easily such as lighting and atmospheric conditions. This type usually effects intensity values, but they may also be spatial, such as perspective distortions. The third type of variations are differences in the images that are of interest such as object movements, growths, or other scene changes. Variations of the second and third type are not directly removed by registration, but they make registration more difficult since an exact match is no longer possible. In particular, it is critical that variations of the third type are not removed. Knowledge about the characteristics of each type of variation effect the choice of feature space, similarity measure, search space, and search strategy which will make up the final technique. All registration techniques can be viewed as different combinations of these choices. This framework is useful for understanding the merits and relationships between the wide variety of existing techniques and for assisting in the selection of the most suitable technique for a specific problem.

Categories and Subject Descriptors: A.1 [**General Literature**]: Introductory and Survey; I.2.10 [**Artificial Intelligence**]: Vision and Scene Understanding; I.4 [**Computing Methodologies**]: Image Processing; I.5 [**Computing Methodologies**]: Pattern Recognition

General Terms: Algorithms, Design, Measurement, Performance

Additional Key Words and Phrases: Image registration, image warping, rectification, template matching

CONTENTS

1. INTRODUCTION

A frequent problem arises when images taken, at different times, by different sensors or from different viewpoints need to be compared. The images need to be aligned with one another so that differences can be detected. A similar problem occurs when searching for a prototype or template in another image. To find the optimal match for the template in the image, the proper alignment between the image and template must be found. All of these problems, and many related variations, are solved by methods that perform image registration. A transformation must be found so that the points in one image can be related to their corresponding points in the other. The determination of the optimal transformation for registration depends on the types of variations between the images. The objective of this paper is to provide a framework for solving image registration tasks and to survey the classical approaches.

Registration methods can be viewed as different combinations of choices for the following four components:

(1) a feature space,
(2) a search space,
(3) a search strategy, and
(4) a similarity metric.

The *feature space* extracts the information in the images that will be used for matching. The *search space* is the class of transformations that is capable of aligning the images. The *search strategy* decides how to choose the next transformation from this space, to be tested in the search for the optimal transformation. The *similarity metric* determines the relative merit for each test. Search continues according to the search strategy until a transformation is found whose similarity measure is satisfactory. As we shall see, the types of variations present in the images will determine the selection for each of these components.

For example, consider the problem of registering the two x-ray images of chest taken of the same patient at different times shown in Figure 1. Properly aligning the two images is useful for detecting, locating, and measuring pathological and other physical changes. A standard approach to registration for these images might be as follows: the images might first be reduced to binary images by detecting the edges or regions of highest contrast using a standard edge detection scheme. This removes extraneous information and reduces the amount of data to be evaluated. If it is thought that the primary difference in acquisition of the images was a small translation of the scanner, the search space might be a set of small translations. For each translation of the edges of the left image onto the edges of the right image, a measure of similarity would be computed. A typical similarity measure would be the correlation between the images. If the similarity measure is computed for all translations then the search strategy is simply exhaustive. The images are registered using the translation which optimizes the similarity criterion. However, the choice of using edges for features, translations for the search space, exhaustive search for the search strategy and correlation for the similarity metric will influence the outcome of this registration. In fact, in this case, the registration will undoubtably be unsatisfactory since the images are misaligned in a more complex

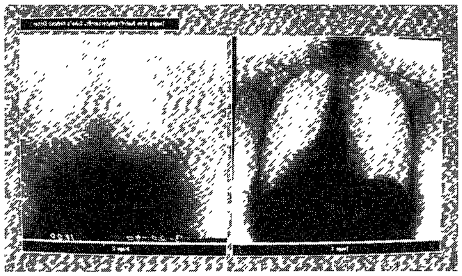

Figure 1. X-ray images of a patient's chest, taken at different times. (Thanks to A. Goshtasby.)

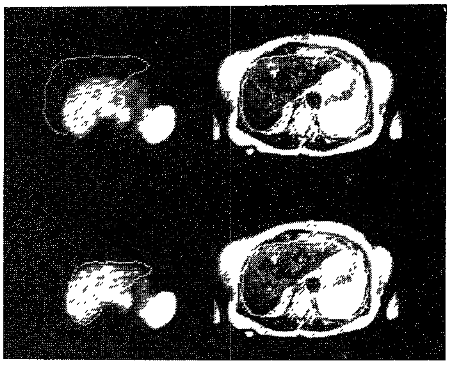

Figure 2. The top left image is a SPECT image of a patient's liver. The top right shows the same region viewed by MRI. A contour was manually drawn around the liver in the MRI image. The location of this contour in the SPECT image shows the mismatch between the two images. At the bottom right the MRI image has been registered to the SPECT image, and the location of the transformed contour is shown on the SPECT image, bottom left. A brief description of the registration method employed is in Section 3.3.3. (Courtesy of QSH, an image display and processing toolkit [Noz 1988] and New York University; I would like to thank B. A. Birnbaum, E. L. Kramer, M. E. Noz, and J. J. Sanger of New York University, and G. Q. Maguire, Jr. of Columbia University.)

way than translation. By establishing the relationship between the variations between the images and the choices for the four components of image registration, this paper provides a framework for understanding the exisiting registration techniques and also a methodology for assisting in the selection of the appropriate technique for a specific problem. By establishing the relationship between the variations among the images and the choices for the four components of image registration, this paper provides a framework for understanding the existing registration techniques and also a methodology for assisting in the selection of the appropriate technique for a specific problem.

The need to register images has arisen in many practical problems in diverse fields. Registration is often necessary for (1) integrating information taken from different sensors, (2) finding changes in images taken at different times or under different conditions, (3) inferring three-dimensional information from images in which either the camera or the objects in the scene have moved, and (4) for model-based object recognition [Rosenfeld and Kak 1982].

An example of the first case is shown in Figure 2. In this figure the upper right image is a Magnetic Resonance Image (MRI) of a patient's liver. From this image it is possible to discern the anatomical structures. Since this image is similar to what a surgeon will see during an operation, this image might be used to plan a medical procedure. The upper left image is from single photon emission computed tomography (SPECT). It shows the same anatomical region after intravenous administration of a Tc-99m (a radionuclide) labeled compound. This image depicts some of the functional behavior of the liver (the Tc-99m compound binds to red blood cells) and can more accurately distinguish between cancers and other benign lesions. Since the two images are taken at different resolutions, from different viewpoints, and at different times, it is not possible to simply overlay the two images. However, if the images can be registered, then the functional information of the SPECT image can be structurally localized using the MRI image. Indeed, the registration of images which show anatomical structures such as MRI, CT (computed tomography) and ultrasound, and images which show functional and metabolic activity such as SPECT, PET (positron emission tomography), and MRS (magnetic resonance spectroscopy) has led to improved diagnosis, better surgical planning, more accurate radiation therapy, and countless other medical benefits [Maguire et al. 1990].

In this survey, the registration methods from three major research areas are studied:

(1) Computer Vision and Pattern Recognition—for numerous different tasks such as segmentation, object recognition, shape reconstruction, motion tracking, stereomapping, and character recognition.

(2) Medical Image Analysis—including diagnostic medical imaging, such as tumor detection and disease localization, and biomedical research including classification of microscopic images of blood cells, cervical smears, and chromosomes.

(3) Remotely Sensed Data Processing—for civilian and military applications in agriculture, geology, oceanography, oil and mineral exploration, pollution and urban studies, forestry, and target location and identification.

For more information specifically related to each of these fields, the reader may consult Katuri and Jain [1991] or Horn [1989] in computer vision, Stytz et al. [1991] and Petra et al. [1992] in medical imaging, and Jensen [1986] and Thomas et al. [1986] in remote sensing. Although these three areas have contributed a great deal to the development of registration techniques, there are still many other areas which have developed their own specialized matching techniques, for example, in speech understanding, robotics and automatic inspection, computer-aided design and manufacturing (CAD/CAM), and astronomy. The three areas studied in this paper include many instances from the four classes of problems mentioned above and a good range of distortion types including:

- sensor noise
- perspective changes from sensor viewpoint or platform perturbations
- object changes such as movements, deformations, or growths
- lighting and atmospheric changes including shadows and cloud coverage
- different sensors.

Tables 1 and 2 contain examples of specific problems in registration for each of the four classes of problems taken from computer vision and pattern recognition, medical image analysis, and remotely sensed data processing. The four classes are (1) multimodal registration, (2) template matching, (3) viewpoint registration, and (4) temporal registration. In classes (1), (3), and (4) the typical objective of registration is to align the images so that the respective changes in sensors, in viewpoint, and over time can be detected. In class (2), template matching, the usual objective is to find the optimal location and orientation, if one exists, of a template image in another image, often as part of a larger problem of object recognition. Each class of problems is described by its typical applications and the characteristics of methods commonly used for that class. Registration problems are by no means limited by this categorization scheme. Many problems are combinations of these four classes of problems; for example, frequently images are taken from different perspectives *and* under different conditions. Furthermore, the typical applications mentioned for each class of problems are often applications in other classes as well. Similarly, method characteristics are listed only to give an idea of some of the more common attributes used by researchers for solving these kinds of problems. In general, methods are developed to match images for a wide range of possible distortions, and it is not obvious exactly for which types of problems they are best suited. One of the objectives of these tables is to present to the reader the wide range of registration problems. Not surprisingly, this diversity in problems and their applications has been the cause for the de-

Table 1. Registration Problems — Part I

MULTIMODAL REGISTRATION
Class of Problems: Registration of images of the same scene acquired from different sensors.
Typical Application: Integration of information for improved segmentation and pixel classification.
Characteristics of Methods: Often use sensor models; need to preregister intensities; image acquisition using subject frames and fiducial markers can simplify problem.
Example 1
Field: Medical Image Analysis
Problem: Integrate structural information from CT or MRI with functional information from radionucleic scanners such as PET or SPECT for anatomically locating metabolic function.
Example 2
Field: Remotely Sensed Data Processing
Problem: Integrating images from different electromagnetic bands, e.g., microwave, radar, infrared, visual, or multispectral for improved scene classification such as classifying buildings, roads, vehicles, and type of vegetation.
TEMPLATE REGISTRATION
Class of Problems: Find a match for a reference pattern in an image.
Typical Application: Recognizing or locating a pattern such as an atlas, map, or object model in an image.
Characteristics of Methods: Model-based approaches, preselected features, known properties of objects, higher-level matching.
Example 1
Field: Remotely Sensed Data Processing
Problem: Interpretation of well-defined scenes such as airports; locating positions and orientations of known features such as runways, terminals, and parking lots.
Example 2
Field: Pattern Recognition
Problem: Character recognition, signature verification, and waveform analysis.

Table 2. Registration Problems — Part II

VIEWPOINT REGISTRATION
Class of Problems: Registration of images taken from different viewpoints.
Typical Application: Depth or shape reconstruction.
Characteristics of Methods: Need local transformation to account for perspective distortions; often use assumptions about viewing geometry and surface properties to reduce search; typical approach is feature correspondence, but problem of occlusion must be addressed.
Example 1
Field: Computer Vision
Problem: Stereomapping to recover depth or shape from disparities.
Example 2
Field: Computer Vision
Problem: Tracking object motion; image sequence analysis may have several images which differ only slightly, so assumptions about smooth changes are justified.
TEMPORAL REGISTRATION
Class of Problems: Registration of images of same scene taken at different times or under different conditions.
Typical Applications: Detection and monitoring of changes or growths.
Characteristics of Methods: Need to address problem of dissimilar images, i.e., registration must tolerate distortions due to change, best if can model sensor noise and viewpoint changes; frequently use Fourier methods to minimize sensitivity to dissimilarity.
Example 1
Field: Medical Image Analysis
Problem: Digital Subtraction Angiography (DSA)—registration of images before and after radio isotope injections to characterize functionality, Digital Subtraction Mammiography to detect tumors, early cataract detection.
Example 2
Field: Remotely Sensed Data Processing
Problem: Natural resource monitoring, surveillance of nuclear plants, urban growth monitoring.

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