Digital Elevation Model: Registration and Quantification

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1. INTRODUCTION

With the advancements in imaging technologies, remote sensed images and their registration is a field of application that has gained immense attention and usage in the areas of medicine, cartography, climatology, archaeo-survey, hydrology and hydrogeology, pattern recognition, geographical information system, etc, [1], [7], and [16]. There are several areas of study in the field of remote sensed imaging – fusion and registration, classification techniques, extraction of data depending on application, mining of information, change detection, compression, enhancement and clustering and others. Amongst these, registration of images has attracted the scientific research for developing different techniques and for varied application.

Digital Elevation Models, henceforth called DEM, represent the earth's surface with horizontal coordinates of (x,y) and elevation or height (h). It characterizes the bare surface of the Earth. DEMs are generated from calibration from three basic sources - from topological maps, by photogrammetry of stereo-pairs of images, or from remote sensed images based on radar technique images [10]. Hence, DEMs are also considered as kind of remote sensed images which are 3D in nature. DEM is a generic name of a data set representing a surface, specifically earth's surface. DEMs have numerous applications and some of these include -

- extraction of parameters pertaining to terrains,
- modeling of flow of water and movement of land masses to depict landslides or avalanches, relief map depiction,
- 3D visualization and rendering of computer generated applications such as flight planning, physical model of ground surface creation, infrastructural designing, construction activities, etc.

DEMs of an area can vary in bulk, can be obtained using varied sensors, i.e., multi-modal, or recorded at different times, termed as multi-temporal, captured from different viewpoints, i.e., multi-viewpoint analysis, or have different resolutions, such as multi-resolution, and may also have different sizes. Such variations give rise to the need of a generalized approach for presenting these data in an application field.

Image registration is the process of transforming and synthesizing different images of the same area with varying parameters into one coordinate system and parameters. It is also said as the process of overlaying two or more images of the same scene taken at different times, from different viewpoints or from different sensors. Its primary aim is to geometrically align two images. Registration is usually used at the pre-processing phase for analysis of images received from one or more sensors having variable spatial or temporal variations.

Despite numerous techniques developed for image registration [1], [4], [7], [12],[14], [20], and [24], only a few have proved to be useful for registration of remote sensing images due to their being computationally heavy and having efficiency and robustness issues. Recent flux in technology has prompted a legion of approaches that may suit a particular remote sensing application.

Common image registration techniques follow a five-step procedure [7]. These are:

(a) Pre-processing,

(b) Feature Selection,

(c) Feature Correspondence,

(d) Determination of a transformation function and

(e) Resampling.

Of these afore mentioned steps, feature selection, correspondence and the transfer function determination are the ones in which numerous techniques, for manipulation, may be applied. These variations form the basis of classification included in this work.

Registration has many applications and more so for applications related to the uses of DEM scalar data files as the variability over the “bare” earth surface is not an exception, but is a common occurrence. These changes may be due to various reasons ranging from man-made, natural calamities to mass movements of lands. Presentation of these multi-temporal, multi-modal, multi-view and DEMs having different resolution in a unified model is a challenging problem. Though some specific application-oriented approaches have been proposed, however a generalized approach for multiple types of DEMs has remained elusive.

2. BRIEF LITERATURE SURVEY

Digital Elevation Models are realized from three sources, namely –

(i) Geodesic measurements of topological maps with contour line;

(ii) Photogrammetry wherein height values are evaluated from stereo-pairs of images;

(iii) Stereo-pairs of remote sensed images from Interferometric Synthetic Aperture Radar (InSAR) imaging, Light Detection and Ranging (LIDAR) imaging, Shuttle Radar Topography Mission (SRTM) imaging using interferometry techniques, etc [24].

In the literature, [1], [7], and [24], image registration techniques have been categorized as being

(i) feature-based or intensity-based;

(ii) using spatial or frequency domain methods;

(iii) Systems those are automatic or interactive.

The approaches are usually application or data specific. There is no single solution approach to the problem of DEM registration having varied data types. Various techniques so developed have their own foci like computation time, accurateness of the model, feature space, search strategy, etc. Many such works have been discussed in [1], [4], [7], and [14]. Also image registration is considered an ill-posed problem, so much so that, very minor changes in the candidate image can result in a very different registration output [6].

Registration becomes crucial when spatial data, described as surfaces, need to be mapped to one another [1]. DEM registration is an approach to represent DEMs in-line with either another DEM or a map or an image. DEM-to-DEM registration remains much elusive and its generalizations, including variations in their resolutions as well, are difficult to map in terms of transformation functions, and to automate as well. Elevation model registration is almost obligatory due to the presence of many multi-modal, multi-viewpoint and multi-temporal models of the corresponding terrains. Also multi-resolution DEMs may be required to be registered to give more valuable information. Re-sampling is very commonly required in case of multi-resolution DEM registration. Many-a-time multi-temporal registration and its processing is also mandated due to man-made afflictions, natural disasters, or notable features of the places themselves may alter, leading to substantial changes in the terrain over a period of time.

An existing method for registration includes using the concept of Ground Control Points (GCPs), a feature based technique that was used in references [9]. Li and Bethel, in [9], used reduction of the sum of squares of the Euclidean distances between the surfaces based on arbitrarily orientation of 3D surface patches. However, initial approximations of the parameters were provided by interactive selection and common points on both surfaces before matching was used. Various parameters for similarity checking are in-vogue. These include - Euclidean distance between the template and search surface elements, number of points or vertices required, number of iterations required, time requirement, and RMS error. Statues and architectural images have been used for experimentation. Rigid transformation technique was used and experimentation data included DTM images, airborne remote sensed data, DEM data and multi-temporal data have been used.

Multi-step matching strategy based on probability relaxation and Least Square Matching (LSM) has been dealt by Liao, Lin and Zhang, in [10]. Certain contemporary and existing proposals use least trimmed squares estimator with the least Z-difference (LZD) in which the algorithm is able to detect deformation areas of no more than 50%. A similar method using both LSM and LZD was proposed by Zhang and Cen, in [8]. Their work focused towards co-registration of DEMs for assessment of terrain changes. 3D Least Square Matching technique for co-registration of surfaces has been explained by Akca in [2].

Iterative Closest Point (ICP) based matching was used for automatic range image registration and matching. This method used by Y. Liu [11] extended the basic ICP for area-based matching algorithm. In addition, a different method for automatic co-registration of 3D point clouds using generalized least square image matching concepts exists and is based on the application of generalized Gauss-Markoff model. Rigid body based transformation were also employed by Rodrigues and Liu in [17] which used modified ICP and free-form shapes. They employed the constraints that for maximum registration accuracy, maximum overlapping was required and tested for 100% overlapped data. Rigid constraints were required for establishment of correspondence and proper initialization of the algorithm was deemed mandatory.

An alternative technique adopted the approach of ortho-rectification and geo-positioning of LIDAR DEMs for automated cross-sensor registration. It was considered by Pritt, Gribbons and LaTourette [15]. However certain constraints that needed to be observed for experimentation included Camera/sensor model data and Illumination condition data. Aguilar *et al* [19], used shaded-relief matching for geo-referencing of DEMs. Quality related issues were considered and elaborated in [18]. Certain parameters for evaluation that were used include average registration error, standard deviation, number of established correspondence points, number of iterations, and total time required. Many of these above mentioned methods have used apriori knowledge-based algorithms.

A class of techniques that is being lauded for its proliferation includes the usage of non-rigid techniques for mapping and registration [22]. These non-rigid transformations have been shown using a computer-graphics technique of free-form deformation [5], [6], [7], [22] and [23]. Many works have used free-form deformation based on splines as the transformation model. Some drawbacks of that methodology include under or over-shooting, commonly known as Gibb's phenomenon, and higher computation time [21]. A criterion that may be of immense importance is, the more the overlapped area's common features, the better are the results of registrations.

A common information-theoretic measure, Mutual Information, has been considered as a registration step some studies [3], [13], [15]. Also, similarity measure has been used for measuring the registration algorithms [1], [4], [7], [18], [20]. In some of the literatures, certain measures have been used as a part of the registration algorithm itself whereas sometimes they have been used as metrics only. However, throughout this study there was an erring gap in using any measure for quantification of the images involved in registration for their better understanding.

3. GENERIC REGISTRATION FUNCTION

DEM data files have been considered as a grid of (x,y,h) values. They represent (x,y) pair that corresponds on the ground and h, elevation or height to represent a three-dimensional data sets. We have carried out our work in 3D where we have considered DEM as a 3D point cloud. The surface topology of a given area is demonstrated by visual inspection of the data files. However, their registration is much tedious due to the presence of unknown and random errors. To register the candidate and the reference scalar values of DEM files, the correspondence between these need to be substantiated and evaluated. The matching correspondence between the reference and the candidate data files is stated as:

$$f(x,y,h) = T\big(g(x,y,h)\big) + e(x,y,h), \quad \ldots\ldots.. \quad (1)$$

where $f(x, y, h)$ is the reference data, $g(x, y, h)$ is the candidate data, T is the transformation function and $e(x, y, h)$ is the error function. These errors cover random errors between the candidate and reference data files that are *prima facie* uncorrelated.

The major implication of the work is to propose a registration which would be symmetric and consistent in nature. The manifestation of this mapping function using non-rigid symmetric and consistent registration is to minimize the cost or energy function that may be defined in terms of certain geometric or particular parameter-based difference between the two images. In other terms, the objective of registration may be stated as - to find an optimal transformation whose cost in terms of measurements like similarity or difference is maximum or minimum respectively. Registration leads to finding a deformation field that spatially aligns the overlapping areas of the candidate DEM with respect to that of reference DEM. This may be written as

$$\mu = \begin{cases} Max[Similarity - metric(DEM_{ref}, DEM_{registered}), \; or \\ Min[Difference - metric(DEM_{ref}, DEM_{registered}), \end{cases} \qquad \ldots\ldots\ldots\ldots \qquad (2)$$

wherein, $DEM_{registered}$ is the final DEM got after the task of registration of DEM_{ref} and DEM_{cand} is completed. DEM_{ref} is the reference DEM model considered, the model against which the similarity has been calculated. μ is the similarity or difference measure, DEM_{cand} is the template or the moving DEM image which is to be registered with the DEM_{ref}.

4. SOME IDENTIFIED KNOWLEDGE GAPS

DEMs may be either multi-modal or multi-temporal or have different resolutions. Throughout the literature, studied related to this work, the registration seem to be applied to either multi-modal data or multi-temporal data only. A registration technique encompassing all these varied data types was not considered. This raised an issue so as to have a registration approach to accommodate a variety of DEM data types being available for registration – multi-temporal, multi-modal, multi-viewpoint and multi-resolution.

Another issue that is a cause of inconvenience to all registration techniques is the handling of errors. Since DEMs, as stated in Section 2, can be procured from multiple sources such as from topographic maps, or stereo-pairs, or from remote sensed images [24]. They may be represented as three-dimensional model or grid values. These factors may be sources of errors. Existence of minor errors is quite common in DEMs as these are calibrated from

LIDAR, SRTM and other remote sense imaging techniques. These errors may be periodic or uniform error that may exist due to the calibration error of instruments or sensors. Such errors are easy to handle and usually require simple pre-processing such as reduction of the error factor from each value or at a uniform interval. Error due to noise or signal errors are random in nature and are more difficult to handle. Their mapping is difficult and is one of the reasons of using non-rigid transformation functions for registration tasks. Non-existence of data or data holes is another class of error where data might be missing. Though random errors are managed by some registration algorithm to a certain extent, handling of data holes is not shown by any of the studied literature. Generally the error areas are not large in sizes, however, there existence is typical and must be handled sensitively.

Another constraint is the fact that usual registration approaches are directional. This implies that the result of registration is dependent on the choice of reference and candidate images. In case of non-rigid registration [22], the direction of registration i.e. the estimated transformation from DEM_A to be registered with DEM_B or vice-versa is not equal to the inverse of the estimated transformation correspondence function from DEM_B to be registered with DEM_A. The results of the similarity metric are not consistent and may differ with varying results. The resultant registration output would differ if the reference and candidate images are interchanged. This causes a predicament, as in some applications, though using the same set of images, may require the choices of data of reference and candidate to be interchangeable e.g., due to natural calamity, a elevations of the earth surface may change and the requirement may be to have the latest large DEM surface data of that particular area and its nearby areas. Another application may be to depict the changes in the surface, from recent times to some past era. In such cases the data sets remain same; however the choice of candidate and reference may be interchangeable.

Also, many-a-times, registrations involving multiple candidates may be required. The projection of this issue is the requirement of extending the application of registration to include multiple registrations wherein the common area may be shared amongst various candidate data files or the overlap may be partial with multiple candidate data files. These asymmetric constraints may lead to registration inconsistency since the result of registration may differ based on the direction. Hence, if an inverse-consistent transformation correspondence is formed, it would lead to better registration mapping since it would remove the emphasis on the direction of registration [23]. The problem of registration, with relation to the above mentioned, may be stated as find the transformation t_{AB} and t_{BA} such that t_{AB}

maps DEM_{ref} to DEM_{cand} and t_{BA} maps DEM_{cand} to DEM_{ref} such that t_{AB} = t_{BA}^{-1}, where DEM_{ref} is the reference data file and DEM_{cand} is the candidate data file. Also the transformation must incorporate all the transformations of the multiple candidates also i.e., $T = T_1 + T_2 + \cdots + T_n$ where T_i refers to the individual mapping between the reference and the i^{th} candidate data files.

Further reflection on the study reveals another deficiency in the analysis of the research works being related to lack of quantification of the images and their dissimilarity, and effect of DEM registration. The use of information-theoretic measures finds relevant application based on the distribution of the voxels. These measures are related to – distances, divergence and similarity measures. This absence of investigation has propelled the need to probe their quantifying elements. The examination may be performed at individual level i.e., individual data's energy level as well as with relation to all the three concerned data files. For tackling this, some well-known measures such Shannon's and Sharma-Mittal entropy measure and other parametric generalization have been used for exercising individual energy volume, and Kullback-Liebler and its symmetric form, J-divergence, for dissimilarity, and Theil's measure for effect of registration. Individual data files' entropy also revealed the topological variations within the data files. The study also revealed about the construction of the histogram graph being a combination of certain homogeneous and heterogeneous parts. The relative information between the three data files – reference, candidate and registered data sets were missing and this too has been performed in this work.

Based on the literature survey of various works, the following issues were recognized as identified knowledge gaps that have been resolved in this thesis.

ISSUE 1: Lack of approaches to accommodate for registration of variety of DEM data types being available for registration – multi-temporal, multi-modal, multi-view, multi-resolution.

ISSUE 2: Insufficiency of transformation functions to map the behavior of errors. There exist various types of errors, including those of missing data or *data-holes*. The registration mapping function should aim to reduce the effects of these errors on registration between the reference-candidate DEM data pairs. Though some techniques for mapping the behavior of inherent errors are present, no particular work focuses on the existence of explicit noise and their behavior.

ISSUE 3: Another shortcoming of common registration function is that they are directional i.e., the choice of reference and candidate data files dictates the outcome of the registration. Most works lack in having one or both the criteria of symmetricity, and consistency.

ISSUE 4: Absence of mechanism to register a series of candidate DEMs, given a single reference DEM. Usual works studied in this domain involve a pair-wise registration, however, wherever registration involving a series of DEMs is not presented. For, such cases, incorporating presence of some common overlapping area, mapping of the data in a given group has not been found.

ISSUE 5: There has been no consistent study on the quantitative analysis and inferences of some measures and the study of their effects on registration in general. Hence, there is a need to seek some quantitative measures of the images related to registration and to suitably quantify their differences as well as to quantify the effect of DEM registration.

5. OBJECTIVES OF THE STUDY

We have proposed a novel registration scheme based on symmetric difference of the various images under consideration using non-rigid, inverse-consistent mapping. It has been tested for multimodal, multi-temporal and multi-resolution images of the same area, and for overlapping areas. Based on the reviewed literature and the various issues that have been identified therein, this thesis focuses on the below goals:

Objective 1: To propose an environment to encompass registration of multi-modal, multi-view, multi-temporal and multi-resolution DEMs. This objective aims to resolve the first issue as enumerated in the section above (ISSUE 1). In Chapter 2 we have experimented with some common image processing techniques for usage for DEM registration including segmentation, classification, and morphological operations, for multi-temporal and multi-modal DEMs. Next, in Chapter 3, a novel method for registration using landmarks, which is based on cognitive learning of route- or way-finding for multi-view and multi-resolution DEMs, has been proposed. The mapping has been evolved to relate to ISSUE 1 such that it would incorporate registration of multi-modal, multi-temporal, multi-view and multi-resolution DEMs.

Objective 2: To address the issue of robustness of the DEM registration technique to give acceptable results with the DEMs having some errors and / or missing data i.e., data holes. Also, studying their nature and effects with respect to DEM registration is an objective of this thesis. We have tested our work for robustness to various noises and errors - not only for implicit but also explicit errors. We have also tested with DEM files wherein some data is missing or data-holes exist and the proposed methodology has been found to be able to compensate for such data holes with sizes ±30 – 50 pixels in radius. This objective satisfies the second issue identified (ISSUE 2). Though the issue of robustness of the DEM registration against errors has been checked in each of the chapters of 2, 3 and 4, the issue of data holes have been specifically dealt in Chapter 4.

Objective 3: To reduce the effect of directional registration by introducing symmetric and consistent mapping and transformation. Our final work is symmetric, and consistent, implying that the direction and choice of candidate and reference data files would not affect the outcome of the registration. This addresses the third issue so identified above (ISSUE 3). This issue has been specifically dealt with in Chapter 4.

Objective 4: To handle single-reference-to-multiple-candidate registrations. The approach used for the registration task must be able to handle multiple candidates for registration with a single reference data file having a common overlapping area or some multiple sections of overlapping areas. Our work is extendable to registration of multiple DEM scalar data files wherein, there might be some common or overlapped area between the various candidate data files. This work is towards resolving ISSUE 4. Experimental results relating to single-reference-to-multiple-candidate registrations have been shown in Chapter 4.

Objective 5: To suitably quantify the whole process of DEM, there is need to quantify various images involved in registration by measuring their individual content, measuring their differences and quantifying the registration output. The measures that fit for this purpose are the information theoretic measures and are studied in Chapter 5. This is related to resolution of ISSUE 5.

6. THESIS ORGANIZATION

The chapter-wise organization of the thesis is as described below.

Chapter 1: Introduction

In Chapter 1, the general topic of image registration, DEM and DEM scalar data registration are introduced. This chapter establishes the research described in the consequent chapters in the context of the present state-of-the-art of the investigation of registration techniques. The need and necessity of such a transformation functions has been stressed upon. The problem domain, the issues related to it, their general solution approach, and the objectives have also been described. The motivation behind the work and related research issues have been stated in this chapter. The overview and basic study of the domain along with core component study, classification and registration related models for mapping transformations and measures and metrics for similarity have been presented. Reviews of the relevant study of methods for remote sensed image registration are also reported.

Some details have been included in my work:

- S. Dawn, V. Saxena, and B.D. Sharma, "Remote Sensing Image Registration Techniques: A Survey", Proceedings of International Conference on Image and Signal Processing, ICISP 2010, LNCS 6134, pp. 103–112, 2010.

Chapter 2: DEM registration using SVD and Watershed techniques

Common image processing techniques are simple to use and form the backbone of many processes. The work uses many such techniques which have been described. Feature finding and matching is a very important step in any image registration which may be applied implicitly or explicitly. Chapter 2 provides a detailed analysis of commonly used image processing techniques such as segmentation, classification, usage of morphological operations. Techniques such as singular value decomposition (SVD) can be conveniently used for completion of registration. The experiments prove that simple techniques such as segmentation, classification and using morphological operations can be implemented easily and their resultants can be smoothly used for the purpose of registration with some level of user interventions.

Matter of this chapter is based on my following research papers:

- S. Dawn, V. Saxena, and B.D. Sharma, " DEM Registration and Error Analysis using ASCII values", Proceeding of International Conference on Signal Processing and Imaging Engineering 2010, San Francisco, USA, 20-22 October 2010.
- S. Dawn, V. Saxena, and B.D. Sharma, "SVD Based Digital Elevation Model Registration", International Conference on Microwaves, Antenna, Propagation & Remote Sensing 2011, pp. 197, Organized by International Centre for Radio Science, Jodhpur, Dec 2011.
- S. Dawn, V. Saxena, and B.D. Sharma, "DEM Registration using Watershed algorithm and Chain Coding", Compute '11, ACM, Mar 25-26 2011, Bangalore, India.

Chapter 3: Cognition-based DEM registration

Chapter 3 has been dedicated to the study of use of cognition related tasks-based DEM registration. This chapter provides a detailed reasoning of how various landmarks, that are cognitively used for way-finding and route-forming, can be used for registration. Landmarks, in this work have been used as features and their corresponding finding and mapping was the main task that was undertaken in this chapter. These landmarks were formed by applying segmentation and then thresholding in the contextual pyramid formation. Landmark correspondences were achieved by applying sub-graph matching. Experimentation conclusions were found to be competent for DEM registration. This method was shown to be extendable to route-finding as well. This method of DEM registration based on human spatial cognition of recollection was also checked for robustness against noise too. This work is reported in:

- S. Dawn, V. Saxena, and B.D. Sharma, "Cognitive-mapping and Contexual Pyramid based Digital Elevation Model Registration and its Effective Storage using Fractal based Compression", International Journal of Computer Science Issues, IJCSI, Vol. 10, Issue 3, No.1, pp.126 – 135, May 2013.

Chapter 4: Inverse Consistent Non-rigid DEM registration

In Chapter 4, the issues of symmetricity and consistency related to the registration direction and the non-rigid nature of the DEM data files have been dealt with. The chapter describes the use of B-splines for achieving these goals. Diffeomorphic image registration for the task of DEM scalar registration has been introduced and discussed based on the results of experimentation so accomplished. Furthermore, inverse consistency and its regularization optimization criteria have been introduced and their effects have been discussed. This chapter also showcases the extension of the usual pair-wise technique to include multiple reference data – candidate data registration by establishing not only a common correspondence between the various images also displaying the vivacity of the work wherein all the data files may not have a single overlapping area but multiple sections of overlapped field of study. Performance gain, in terms of number of internal markers, file size being handled, and the percentage of overlapped area, were seen. Experiments with not only DEM data files however with other 3D data model files have also been conducted. Metrics such as MI, CC, and SSD were used for evaluating the proposed scheme against other techniques as well. The following publications refer to the works:

- S. Dawn, V. Saxena, and B.D. Sharma, "Advanced Free-form Deformation and Kullback-Liebler Divergence Measure for Digital Elevation Model Registration", Springer Journal of Signal, Image and Video Processing. DOI: 10.1007/s11760-014-0621-z
- S. Dawn, B.D. Sharma and V. Saxena, "A Novel Non-Rigid Free-form Deformation for Consistent Registration of Digital Elevation Models", under review in ICVGIP. (Communicated)

Chapter 5: Quantification of DEMs using Information-Theoretic concepts

Chapter 5 takes up the problem of quantification of the various DEM scalar data used in registration algorithm both at individual level as well as in a relative manner. Considering the distribution of the voxels in the DEMs as the probability distribution, quantification has been done using measures from the field of Information Theory. Individual content is measured using Shannon's and Sharma-Mittal entropy. Their quantification leads to much understanding of the related images. Divergence between two images has been measured using J-divergence arising from Kullback-Liebler's relative information measure and the overall registered data's content improvement has been quantified by Theil's measure. Information-theoretic measure inferences with respect to the DEM registration i.e. the common measures used for quantifying the quality of registration method have been studied. Some inferences have been derived from their study and these have been presented in this chapter that includes several criteria that can measure and quantify the quality of the obtained result and the approach in general. Critical analysis has also been carried out based on the numerous experiments conducted on actual 3D data models as well that are easily available in the public domain with respect to the registration method so proposed. This work has been communicated to:

- S. Dawn, B.D. Sharma and V. Saxena, "DEM Registration and its Quantification based on Information-Theoretic Measures", under review to Informatica - An International Journal of Computing and Informatics. (Communicated)

Chapter 6: Conclusion and Future Works

In this chapter, the thesis work has been concluded to its summary. The novelty of the work, so justified in the thesis, has been presented in a concise manner. The study's merits and some of the further possible extensions have been proclaimed as outlines. This chapter concludes the overall work undertaken in this thesis.

To briefly summarize, in this work we have presented a novel technique for non-rigid registration of pairs of candidate and reference DEM data sets. The method here proposed deals with solving the spatial misalignment problem between DEM pairs. The method is presented in pairwise mode; and is also extended to using triplets or multiple scalar field registration as well. In our work, we examine the registration task to also include actual mapping and fusion of the image pairs/groups under consideration. These data sets have been cross-verified with their reference DEM data. Summarily, we may state that our main contributions are (i) developing an efficient and robust non-rigid registration approach for aligning partially overlapping DEM models that may be multi-temporal, multi-modal or having multiple-resolutions; (ii) creating an adaptive deformation model that allows for stable deformations also for parts of the surface for which good correspondences may not be available due to major variations in their values or due to presence of random errors and data holes; (iii) presenting a scheme that would perform consistent registration in forward as well as reverse directions, (iv) handling of multiple or series of candidate DEMs for registration with a single reference data, and (v) studying the nature of the DEMs with respect to certain information-theoretic factors for the purpose of quantifying them. We initially started by using the formulation of mapping of residuals of corresponding candidate and reference data sets by using symmetric difference and getting their actual overlapping areas. These are then subjected to non-rigid diffeomorphic registration algorithm. We have also used optimized regularization so as to have an accurate and smooth mapping. Inaccurate mapping and overly constrained registration may be resulted due to over-regularization, convergence at poor local minima, and image folding. Also, incorrect registration may happen due to under-regularization. Thus, regularization plays a very important role in our registration technique.

We have proposed a generic registration approach and through experiments have demonstrated its usability. For the purpose of testing, we have used certain common evaluation parameters such as SSD, CC, and MI. Our work in comparison with other existing works is quite generic in nature and compares well. We have been able to map small scale as well as large scale deformations using the proposed technique and have experimented for various terrain types. We have verified through various test cases. When candidate DEM data file is not provided to the system, the system chooses from a given folder based on histogram-based matching. We have tested with data of varying sizes and varying noise types. As is depicted through our experimentation, the proposed method for the registration of DEMs can be successfully completed and can give favourable results when compared to existing techniques. The results are good even when the candidate DEM data file have data holes (up till 10% of the total size). A major strength of this model is its comprehensiveness to work even on partially incomplete and noisy data sets. The algorithm of DEM registration is extendable and is easily able to register more than 2 candidate data files at a time. We have also tested for 3D model data files and the algorithm is shown to be able to successfully map the reference and candidate files even in these cases.

We have also studied the content of the images involved in registration. This included measuring content of individual images, measuring their differences and quantifying the content improvement of the registered output image. These quantifications have been performed using information-theoretic measures. Shannon's Entropy and Sharma-Mittal Entropy has been used for quantifying individual content. Symmetric distance is measured using J-divergence measure. Content improvement has been factored using Theil's measure. Such measures would help in increasing the understanding of the images involved with the task of registration.

Keywords: **DEM, Registration, Inverse Consistency, Diffeomorphism, Non-rigid registration, Information-Theoretic measures, Similarity Measure, Shannon's Entropy, Sharma-Mittal Entropy, Parametric Measures, J-divergence, Theil's information improvement measure.**

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