Introduction to the Special Issue on Registration and Fusion of Range Images

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1 Introduction

This special issue contains nine high quality papers representative of the state-of-the art technologies used to acquire and process range image data. Following the call for papers, 23 manuscripts were received which were reviewed by a pool of 37 expert referees. We are thankful to these anonymous referees for their invaluable work which, as ever, is essential to maintain the high standards of CVIU. All selected papers carry an element of novelty, and we hope that this issue will be useful to theoreticians and practitioners alike.

Directly and indirectly, the papers deal with a central problem in working with 3D data sets, namely the fusion of single 2.5D range images into full 3D data sets describing all surfaces of an object or environment. In section 2 below we highlight what we perceive as the main issues and relevant approaches to this central task.

The issue opens with a paper by Wyngaerd and Van Gool on automatic pre-alignment of surfaces, a task that is usually done manually by current approaches. The method assumes Monge patch data from which subsequent good registration can be achieved. The paper by Krsek *et al.* also deals with automatic registration based on information from features found in the data which are determined from differential geometry. Robertson and Fisher also tackle automatic registration by using an evolutionary approach to estimate transformation parameters making it a pose search method as opposed to correspondence search. Assuming that data are pre-registered, Masuda presents the method of signed distance fields for iterative shape integration and registration. Also assuming pre-registration, Okatani and Deguchi deal with fine registration using measurement error properties as an alternative to the standard Iterative Closest Point (ICP) algorithm. Using acoustic data, Castellani *et al.* propose an ICP variant that is robust to noise and is based on the even distribution of registration errors and on the introduction of algebraic constraints on the transformations. Sablatnig and Kampel deal with the problem of registering front and back views of rotationally symmetric objects using a model based approach in connection with the ICP algorithm. Dalley and Flynn present a comparative study of ICP based algorithms aiming at testing their robustness at outlier classification. Finally, Gupta *et al.* take the ICP method to another dimension namely the compression of time-dependent 3D geometric data.

2 Issues and Approaches

Here we briefly summarize the issues that are driving the different research strands in the area of range data registration and fusion. From our perspective, registration is the key to fusion, so most of the issues and approaches discussed below are related to registration.

2.1 Range Data Registration

2.1.1 Initial Registration and Range of Convergence

Most registration algorithms use an iterative algorithm that ideally converges to the best multiple data set registration. Many algorithms only converge to a good solution if the initial relative pose estimate is sufficiently close to the optimal registration. So, one issue is how to find a good initial relative pose estimate. Further, different approaches have a wider range of tolerance about the optimal pose within which convergence occurs, so researchers are investigating methods for increasing the range and robustness. The main approaches can be classified as: 1) using special features or points for initial alignment (1; 12; 14; 23; 33; 40; 73; 76) 2) special circumstances, such as properties of the registered objects or of the imaging device (6; 19; 59; 74), 3) human assisted registration (54). It is interesting to note that even with good initialisation, algorithms may not find an optimal registration or even may not be able to refine the initial coarse registration. This is due to a large number of local minima due to noise, occlusion, appearance and disappearance of points, and general lack of knowledge about the distribution of points. Moreover, the distribution and characteristics of these local minima are dependent on image data of specific objects rendering it difficult to theoretically characterise these local minima. Consequently, finding an optimal solution is an unresolved issue and future research may have to focus on investigating trully general purpose registration techniques with a large convergence range without requiring good initialisation.

2.1.2 Inexact Correspondences

Two or more 3D data sets are unlikely to be acquired such that the 3D data points exactly correspond. For example, the sampling density might be different due to scanner settings, scanner distance or surface slopes. Thus, a point or feature in one data set will not have an exact correspondence in another data set, yet some sort of alignment between the elements in the two data sets will be needed. Hence, methods for finding appropriate correspondences is being researched (7; 13; 19; 49). However, it is observed that registration errors are a function of interpoint distances and thus, the resolution of the scanning. The smaller such distances, the larger the potential for accurate registration. This suggests that registration accuracy may be improved from fitted surfaces.

2.1.3 Outliers/Partial Overlap

When registering two (or more) data sets, there are usually 3D data points or other features that do not have any correspondence between the data sets. The two main causes of this are: 1) regions of the data where there is no overlap (a natural consequence of extending the data description by incrementally fusing partially overlapping data) and 2) noise outliers (10; 18; 51; 62; 79). Hence, great effort has been made to identify outliers and partial overlap based on techniques such as high dimensional distance measurement (37; 24; 63), orientation consistency (79), interpoint distance (20), boundary points removal (57; 72), threshold (62), and motion properties (42; 43; 56). It has been shown that the identification of outliers and partial overlap are essential steps to the estimation of motion parameters. Moreover, these two steps are often interweaved and affect each other especially when no exact information is available about the distribution of points, occlusion, appearance and disappearance of points. This implies that assuming image data as a black or grey box, the development of techniques to register such data is still a challenging task and prone to local minimum convergence as pointed out above. Future research may focus on the use of structural data information, motion properties, special information on objects, or special imaging configurations for a more accurate estimation of image correspondences.

2.1.4 Pose versus Correspondence Search

Most registration algorithms align data sets by finding approximately corresponding data features and then estimating the pose that aligns these. A problem that arises from this approach is the convergence to significantly misaligned local minima, which can happen when the data sets are initially far from correct alignment or slight misalignment when near to the global optimum. More recent research has started search in the pose space instead of the correspondence space and seem to be finding a broader range of initial poses that still lead to convergence near the correct alignment (9; 11; 25; 55). So here essentially we have to make clear how to measure the quality of correspondences independent of the algorithms used to estimate the pose. At the beginning of the registration most correspondences are not correct, and the converse problem arises as how to measure the quality of the pose from such inaccurate correspondences. In fact, we may never know whether estimated correspondences are exactly right or not and this has an obvious effect on the quality of the estimated pose parameters.

2.1.5 Registerable Feature Type

When searching for corresponding features in the two data sets, there are a variety of criteria that one can use for classifying points as being similar or interesting or key points, such as colour, local surface normals, local curvature shape, edgeness, texture, etc. (1; 8; 14; 22; 26; 36; 37; 38; 62; 66; 70; 73; 78). All such features are to varying degrees sensitive to noise and other conditions such as occusion and thus, the extraction of such features is also a challenging task. This contrasts with using the points directly (5; 19; 21) with the shortcoming that such algorithms often require good initialisation.

2.1.6 Performance Acceleration

The correspondence search algorithms generally have a large potential space to search through in order to find corresponding features. There are several approaches to reducing the computational complexity of this search, including coarse-to-fine strategies (12; 29; 41; 57; 69). The use of k-D trees is particularly popular (*e.g.* (21; 62)).

2.1.7 Improving Registration Accuracy

Accurate 3D object reconstruction requires accurate data alignment as well as having accurate data to begin with. Given the iterative nature of many of the alignment algorithms, researchers are investigating methods of avoiding local minima in the search space (9; 11; 12; 44; 55). A second statistical approach uses better information about the uncertainty of measurements themselves for the alignment and fusion (10; 18; 27; 30; 45; 50; 52; 67; 68; 69; 71).

2.1.8 Multiple View Registration

If more than two data sets are to be fused, then one can merge the data sets incrementally (*e.g.* (5; 61; 13) and many others) or simultaneously (2; 3; 4; 7; 15; 16; 21; 28; 39; 47; 48; 49; 54; 77). The incremental method is efficient and requires less computer memory but the registration error can accumulate and redundant data are not fully utilised to improve registration. The simultaneous method makes full use of redundant data, but it often involves more intensive computation for optimisation and requires a huge amount of computer memory and, at least theoretically, yields more accurate registration results.

2.2 Range Data Fusion

There is still considerable research into the different approaches to fusing multiple 3D data sets, with no clearly superior approach so far. The two main classes are based on fusing surface-based representations such as triangulation (33; 64; 65; 72) or fusing multiple point sets into volumes or fusing the volumes created from the multiple point sets individually (17; 34; 35; 48; 46; 60; 75). An important issue is how to manage the fusion of data in the overlap region (53; 58; 64; 72). Many researchers do registration first and then fuse the data as a final step, but iterative registration and fusion processes are being investigated (7; 48).

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