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Point set augmentation through fitting for enhanced ICP registration of point clouds in multisensor coordinate metrology

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A B S T R A C T

In multisensor coordinate metrology scenarios involving the fusion of homogenous data, specifically 3D point clouds like those originated by CMMs and structured light scanners, the problem of registration, i.e. the proper localization of the clouds in the same coordinate system, is of central importance. For fine registration, known variants of the Iterative Closest Point (ICP) algorithm are commonly adopted; however, no attempt seems to be done to tweak such algorithms to better suit the distinctive multisensor nature of the data. This work investigates an original approach that targets issues which are specific to multisensor coordinate metrology scenarios, such as coexistence of point sets with different densities, different spatial arrangements (e.g. sparse CMM points vs. gridded sets from light scanners), and different noise levels associated to the point sets depending on the metrological performances of the sensors involved. The proposed approach is based on combining known ICP variants with novel point set augmentation techniques, where new points are added to existing sets with the purpose of improving registration performance and robustness to measurement error. In particular, augmentation techniques based on advanced fitting solutions promote a paradigm shift for registration, which is not seen as a geometric problem consisting in moving point sets as close as possible to each other, but as a problem where it is not the original points, but the underlying geometries that must be brought together. In this work, promising combinations of ICP and point augmentation techniques are investigated through the application to virtual scenarios involving synthetic geometries and simulated measurements. Guidelines for approaching registration problems in industrial scenarios involving multisensor data fusion are also provided.

1. Introduction

1.1. Data registration in multisensor coordinate metrology

The combined use of multiple measurement sensors is increasingly becoming commonplace in coordinate metrology for reverse engineering and quality inspection [1–3]. Multisensor architectures are recognized as a promising solution for improving the overall quality of measurement by reducing uncertainty, improving reliability, increasing coverage, and increasing execution speed.

In coordinate metrology, multisensor data fusion refers to the process of combining measurement data coming from different sensors into a single, coherent representation, which can provide benefit to metrological assessment [3]. This work focuses in particular on the integration of homogeneous (i.e. same output) sensors producing 3D point sets (also known as point clouds). A typical scenario is an instrument where multiple touch and/or optical probes are mounted onto the same frame; another common scenario consists in multiple, separate CMMs operating on the same measurand. In general, depending on how the measurement is planned, the point clouds may be characterized by different densities, different coverage of the measurand surface, and different measurement accuracies and precisions.

The fusion of 3D point clouds is comprised of two main aspects: registration, i.e. transferring the point clouds acquired by different sensors into the same common coordinate system, and merging, i.e. combining the information coming from multiple, registered clouds to elicit the synergic effects of data fusion. If the point clouds are not correctly registered, the quality of their merging may be negatively affected. Therefore it becomes important to achieve the best registration possible.

In commercial solutions where multiple sensors are mounted onto the same instrument frame and are rigidly connected with

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each other (e.g. at the end of the same kinematic chain), an extrinsic calibration procedure run once in a while may be deemed enough to obtain the roto-translation matrix needed for registering sensor outputs. In architectures where the sensors are mounted at the end of different kinematic chains, but ultimately rooted to the same instrument base, encoder readouts can be used to obtain the current relative position of the sensors. Finally, if the sensors are entirely unrelated from a physical standpoint (e.g. different instruments altogether, or different measurement sessions with loss of reference frame in-between), registration through alignment of physical landmarks or properly placed markers could be done.

In nearly all the situations described above, the illustrated registration solution is usually only good enough for obtaining a coarse result and additional registration efforts are necessary.

While recent work illustrating a specific application involving the registration of data from multiple optical sensors can be found in [4]; the literature on the general problem of registering multiple point sets is quite vast. The Iterative Closest Point (ICP) algorithm and its variants form one of the most widely known and widespread approaches to registration, and will be specifically addressed in this work. Amongst the most notable alternative approaches, those based on the Random Sample Consensus (RANSAC) method [5] deserve special mention: the RANSAC method provides a solution for fitting a mathematical model to observed data in presence of outliers and can be used to implement fast and outlier-robust registration processes. RANSAC-based algorithms can either form the basis of complete registration solutions, in particular to rapidly obtain an initial coarse registration solution [6–8], or they can be integrated into ICP to develop outlier-robust ICP variants [9].

Another special mention goes to Maximum Likelihood Registration (MLR) methods. These approaches are based on considering the problem of finding the optimal registration solution as a parameter estimation problem handled by a maximum likelihood estimation (MLE) procedure [10,11]. MLR methods have been recently gaining increased popularity in multisensor coordinate metrology [12–14].

1.2. ICP for fine registration of multiple point sets

The Iterative Closest Point (ICP) algorithm, originally proposed in [15,16], has become the de-facto standard for fine registration of point clouds in reverse engineering and quality inspection. However, under the term ICP, numerous variants have gradually been included during the years and, as several authors have demonstrated, such variants do not perform identically [17–20]. Discrepancies may not only be due to differences in the algorithmic details, but also to the fact that some variants may perform better in certain applications, and not so well in others.

However, in current industrial practice there is still a widespread tendency to use ICP as a black box, regardless of whether the specific implementation available is actually optimal for the specific scenario, and without investigating how the original data may be preprocessed to improve performance, or at least for reducing the risk of drift, or poor convergence to suboptimal solutions.

1.3. Premises and goals of this work

This work deals with the problem of applying ICP to the registration of two point sets specifically addressing issues typical to multisensor scenarios. The two point sets are assumed as having a different number of points, different density, different spatial organization, different associated noise (due to different metrological performance of the sensors) and different coverage on the measurand surface.

For the above reasons it is safe to assume that–in general–single points belonging to different datasets may not fall into the same exact locations on the measurand. This observation, which is referred to as lack of co-localization, seems to be conflicting with the most basic formulation of ICP, which aims at bringing points belonging to different datasets as close as possible to each other. This line of thought leads to one of the main underlying assumptions of this work: registration approaches that are aware of the lack of co-localization problem and that do not try to force point alignment at any cost should perform better in multisensor scenarios.

The other strong motivation for this work comes from the understanding that ICP blindly operates on the points of the two datasets, without taking into considerations the fact that part of their positions is determined by measurement error. Again, novel approaches aimed at increasing the robustness of registration solutions to such issues may be worth investigating.

Given the premises, the main goal of the work is therefore to investigate innovative registration solutions based on ICP, which specifically target multisensor data fusion scenarios. The focus is in finding effective solutions for handling the lack of co-localization of the points belonging to the two sets, and in improving robustness to various degrees of measurement error.

As a final consideration, this work specifically addresses registration problems involving two point sets only. The extension to more than two sets may be naively implemented by sequentially registering one point set at a time with the techniques proposed in this work. Alternative solutions, implemented to make optimal use of the higher amount of simultaneously available information, are beyond the scope of this work.

1.4. Multisensor scenario

This work focuses on a specific family of multisensor scenarios commonly found in industrial practice, and is comprised of the following main aspects:

- the measurand geometry is a smooth freeform surface; optionally, a delimited, sharp feature may provide a local discontinuity;
- the measurand surface is acquired by means of a structured light scanner first, which leads to a large set of points arranged as a regular grid (structured point set), and characterized by high spatial density and low precision;
- a smaller set of sparse points is acquired by means of a CMM equipped with a touch probe; the points are localized within the boundaries of the area acquired by means of the structured light scanner. In a real case scenario, such second set of points would be acquired to provide additional, more precise, information concerning specific regions of the measurand. The CMM points form an unstructured set (i.e. points are not arranged along a regular grid, but scattered as chosen by the operator), they have lower density but much higher precision than the other point set.

The proposed scenario is quite common in multisensor coordinate metrology: many currently available commercial instruments include a structured light scanner mounted onto the frame of a touch-probe CMM. Other compatible configurations may involve physically separate CMM and laser scanners, and in general any case where the reference frame is lost between measurements (e.g. due to part refixturing). In scenarios involving laser scanners, registration implemented through alignment of marker points is almost never sufficient for a precise registration of the point sets. In particular because it is difficult to match