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Towards terrestrial 3D data registration improved by parallel programming and evaluated with geodetic precision

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ABSTRACT

In this paper a quantitative and qualitative evaluation of proposed ICP-based data registration algorithm, improved by parallel programming in CUDA (compute unified device architecture), is shown. The algorithm was tested on data collected with a 3D terrestrial laser scanner Z + F Imager 5010 mounted on the mobile platform PIONNER 3AT. Parallel implementation enables data registration on-line, even using a laptop with a standard hardware configuration (graphic card NVIDIA GeForce 6XX/7XX series). Robustness is assured by the use of CUDA-enhanced fast NNS (nearest neighbor search) applied for ICP (iterative closest point) with SVD (singular value decomposition) solver. The evaluation is based on the reference ground truth data registered with geodetic precision. The geodetic approach extends our previous work and gives an accurate benchmark for the algorithm. The data were collected in an urban area under a demolition scenario in a real environment. We compared four registration strategies concerning data preprocessing, such as subsampling and vegetation removal. The result is the analysis of measured performance and the accuracy of the geometric maps. The system provides accurate metric maps on-line and can be used in several applications such as mobile robotics for construction area modelling or spatial design support. It is a core component for our future work on mobile mapping systems.

1. Introduction

The 6D-SLAM (simultaneous localization and mapping) algorithm, apart from solving the simultaneous localization and mapping problem, allows for the quick and reliable creation of digital models of large environments without the need for direct intervention. The 6D comes from the six dimensions of the robot motion model, which integrates 3D position coordinates (x, y, z) with orientation information (yaw, pitch, and roll). Such a model is a natural choice for an outdoor environment. There is no limitation in using 6D-SLAM in indoor environments, but using pitch and roll angles on flat surfaces is not always necessary. The output of the algorithm, in most cases, is a map in one of two forms — dense or sparse. Dense maps are related with 3D point clouds [1] obtained typically with 3D laser scanners; sparse maps are related with features extracted mostly from images. The 3D data registration problem was introduced by Besl and McKay in Ref. [2]; from that moment on, many researchers have been trying to solve the problem of augmenting the accuracy and the performance of aligning two clouds of points. Based on the State of the Art, we can state that the solutions to key issues of 3D GPGPU (general purpose computing on graphics processing units) data registration proposed in the important contributions are very close to optimum, but may still be improved upon. An approach that is widely used for 3D data registration is the iterative closest point (ICP) algorithm. The goal of the ICP is to find the transformation matrix that minimizes the sum of distances between the corresponding points in two different data sets. The method's effectiveness depends mostly on solutions to two important problems:

- the nearest neighbor search (NNS) and
- choosing the proper optimization technique for the minimization of the mentioned function (estimation of the 3D rigid transformation).

The NNS procedure is dominant compared to the rest of the ICP algorithm; therefore, many researchers are trying to optimize the time of its execution. The SoA provides several CUDA based approaches for the NNS problem in the ICP algorithm. An approach from Ref. [3] uses regular grid decomposition [4], whereas in Ref. [5] kd-tree is used. The second problem, choosing the proper optimization technique, has been a research topic in recent decades. A comparison of four algorithms for estimating 3D rigid transformation is shown in Ref. [6]. The first algorithm proposed in Ref. [7] uses singular value decomposition (SVD) for derive matrix. The second approach, based on orthonormal matrices and the computation of an eigensystem of a derived matrix, is proposed in Ref. [8]. The third algorithm is shown in Ref. [9]. It finds the transformation for the ICP algorithm by using unit quaternions. The fourth algorithm, shown in Ref. [10], uses the so-called dual

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quaternions. Apart from these four closed-form solution methods, a novel linear solution to the scan registration problem is shown in Ref. [11]. The advantage of these new linear solutions is that they can be extended straightforwardly to n-scan registrations. It was stated that under the assumption that the transformation (**R**,**t**) that has to be calculated by the ICP algorithm is small, it can be approximated by applying instantaneous kinematics. This solution was initially given in Refs. [12, 13]. Reported experiments have shown that the helix transform performs qualitatively as well as the uncertainty-based algorithm using Euler angles. The paper is composed of 11 chapters. The current one provides an introduction and short state of the art summary. The second explains the motivation behind the research. In the real task scenario details of the experiment are explained. Chapter 4 describes the data acquisition and processing. In chapter 5, the methodology for evaluation is described, followed by algorithm modifications, vegetation removal and sub-sampling. Chapter 8 provides a detailed description of the experiment, with the analysis of the results in chapter 9. The article in chapter 10 introduces the end-user case study, and chapter 11 closes with a summary and conclusions.

2. Problem formulation

The goal of this work is to benchmark the 3D data registration method, improved by CUDA parallel programming, shown in the previous work [14] within the scope of quantitative spatial design support. The benchmark is analyzed using reference data of geodetic precision. The approach extends the state of the art by providing qualitative information concerning the accuracy of the proposed method. The secondary goal is to test the system in the real task scenario with an assumption of the on-line performance. The resulting maps can be used for numerous applications: urban area modeling, spatial design support, basic space design, etc.

3. Real task scenario

To assure the real-life conditions for the experiment, a proper environment has to be chosen. Fig. 1a shows an object of interest: a building in village Klomino (Poland), abandoned since 1993. The choice is motivated by the hard terrain conditions of the area. The goal of the experiment is to create a metric model of this building. Data for the model are gathered with a geodetic laser range finder mounted onto a robotic platform (Fig. 1c). This scenario simulates a potential real robotic application: deployment of a mobile platform in a hazardous environment for gathering data and providing a metric map in an on-line fashion. Similar equipment (RIEGL LMS-Z210) was involved in disaster assessment at Fukushima 1 in 2011. The key factor is the accuracy of scan matching, which has to be as high as possible to increase the fidelity of the produced metric map.

4. Data registration

The ICP algorithm, with its variations, point to point and point to plane, has become a well-known method since it appeared in Ref. [2]. The fastest implementation that can be found in literature needs 60 ms to align two point clouds, each of 320 × 240 data points [15], but the authors unfortunately did not discuss the scalability of proposed method. The key concept of the standard ICP algorithm can be summarized in two steps [16]:

1. Compute correspondences between the two scans (nearest neighbor search).
2. Compute a transformation which minimizes distance between corresponding points.

Iteratively repeating these two steps should result in convergence to the desired transformation. Range images (scans) are defined as model set M where

$$|M| = N_{\mathrm{m}} \quad (1)$$

and data set D where

$$|D| = N_{\mathrm{d}}. \quad (2)$$

The alignment of these two data sets is solved by minimizing the following cost function:

$$E(\mathbf{R}, \mathbf{t}) = \sum_{i=1}^{N_{\mathrm{m}}} \sum_{j=1}^{N_{\mathrm{d}}} w_{ij} \left\| \mathbf{m}_i - \left(\mathbf{R}\mathbf{d}_j + \mathbf{t} \right) \right\|^2 \quad (3)$$

w_{ij} is assigned 1 if the ith point of M corresponds to the jth point in D. Otherwise $w_{ij} = 0$. $\mathbf{R}$ is the rotation matrix, $\mathbf{t}$ is the translation matrix, $\mathbf{m}_i$ corresponds to points from the model set M, and $\mathbf{d}_j$ corresponds to

(a) Location of scenario. (b) Object of interest. (c) Mobile robot and geodetic equipment.

Fig. 1. Real task scenario.