ICP算法及其在建筑物扫描点云数据配准中的应用

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【摘 要】 ICP算法是三维激光扫描数据处理中点云数据配准的一种高水平的数学方法。本文全面地回顾了 ICP算法的研究背景, 并重点阐述了迭代最近点法 ICP的计算过程及其主要的改进算法; 通过建筑物三维激光扫描数据的采集, 对基于 ICP算法的点云数据配准过程进行了详细地分析。实验分析表明三维激光扫描数据配准后的点云数据质量较大程度上依赖于专业技术人员的数据处理经验和专业知识。

【关键词】 ICP算法; 建筑物扫描; 点云数据; 数据配准
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1 引言

数据配准(Data Registration)是将两个或两个以上坐标系中的大容量三维空间数据点集转换到统一坐标系统中的数学计算过程。在医学、工业制造、计算机视觉及土木工程应用中, 研究适用于三维激光扫描数据建模的配准方法是十分重要的。配准方法涉及到有理线性代数和 B-spline拟合等复杂问题, 以及非常复杂的非线性多变量最小化问题。

在 20世纪 80年代中期, 很多学者开始对点集数据的配准进行了大量研究。1987年, Horn, Arun等人用四元数法提出点集对点集配准方法。这种点集与点集坐标系匹配算法通过实践证明是一个解决复杂配准问题的关键方法。1992年, 计算计视觉研究者 Besl和 Mckay[1]介绍了一种高层次的基于自由形态曲面的配准方法, 也称为迭代最近点法 ICP(Iterative Closest Point)。以点集对点集(PSTPS)配准方法为基础, 他们阐述了一种曲面拟合算法, 该算法是基于四元数的点集到点集配准方法。从测量点集中确定其对应的最近点点集后, 运用 Faugera和 Hebert提出的方法计算新的最近点点集。用该方法进行迭代计算, 直到残差平方和所构成的目标函数值不变, 结束迭代过程。ICP配准法主要用于解决基于自由形态曲面的配准问题。

迭代最近点法 ICP最近点法经过十几年的发展, 不断地得到了完善和补充。Chen和 Medioni[2]及 Bergevin等人[3]提出了 point-to-plane搜索最近点的精确配准方法。Rusinkiewicz和 Levoy提出了 point-to-projection搜索最近点的快速配准方法。Soon-Yong和 Murali[4]提出了 Contractive-projection-point搜索最近点的配准方法。此外, Andrew和 Sing[5]提取了基于彩色三维扫描数据点纹理信息的数据配准方法, 主要在 ICP算法中考虑三维扫描点的纹理色彩信息进行搜索最近点。Natasha等人[6]分析了 ICP算法中的点云数据配准质量问题。

2 迭代最近点算法

2.1 迭代最近点算法基本原理

三维空间 R^3 存在两组含有 n 个坐标点的点集 P_L 和 P_R, 分别为: $P_L = \{p_{l1}, p_{l2}, \cdots p_{li}, p_{li} \in R^3\}$ 和 $P_R = \{p_{r1}, p_{r2}, \cdots p_{rn}, p_{ri} \in R^3\}$。三维空间点集 P_L 中各点经过三维空间变换后与点集 P_R 中点一一对应, 其单点变换关系式为:

$$P_{ri} = \boldsymbol{R} \cdot P_{li} + \boldsymbol{t} \quad (1)$$

上式中, $\boldsymbol{R}$ 为三维旋转矩阵, $\boldsymbol{t}$ 为平移向量。

在 ICP配准方法中, 空间变换参数向量 $\boldsymbol{X}$ 可表示为[1]: $\boldsymbol{X} = [q_0 \quad q_x \quad q_y \quad q_z \quad t_x \quad t_y \quad t_z]^{\mathrm{T}}$ 参数向量中四元数参数满足约束条件为: $q_0^2 + q_x^2 + q_y^2 + q_z^2 = 0$ (2)

根据迭代的初值 $\boldsymbol{X}_0$, 由式(1)计算新点集 P_i 为:

$$P_i = P_0(\boldsymbol{X}_0) = \boldsymbol{R}(\boldsymbol{X}_0)\mathrm{P} + \boldsymbol{t}(\boldsymbol{X}_0) \quad (3)$$

式中, P 表示原始未修改过的点集, P_i 的下标 i 表示迭代次数, 参数向量 $\boldsymbol{X}$ 的初始值 $\boldsymbol{X}_0$ 为 $\boldsymbol{X}_0 = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^{\mathrm{T}}$。

根据以上数据处理方法, ICP配准算法可以概括为以下七个步骤:

①根据点集 P_{lk} 中的点坐标, 在曲面 S上搜索相应最近点点集 P_{rk}; ②计算两个点集的重心位置坐标, 并进行点集中心化生成新的点集; ③由新的点集计算正定矩阵 N, 并计算 N的最大特征值及其最大特征向量; ④由于最大特征向量等价于残差平方和最小时的旋转四元数, 将四元数转换为旋转矩阵 R; ⑤在旋转矩阵 R 被确定后, 由平移向量 t 仅仅是两个点集的重心差异, 可以通过两个坐标系中的重心点和旋转矩阵确定; ⑥根据式(3), 由点集 P_{lk} 计算旋转后的点集 P'_{rk}。通过 P_{rk} 与 P'_{rk} 计算距离平方和值为 f_{k+1}。以连续两次距离平方和之差绝对值 $\Delta f = |f_k - f_{k+1}|$ 作为迭代判断数值; ⑦当 $\Delta f < \tau$ 时, ICP配准算法就停止迭代, 否则重复①至⑥步, 直到满足 $\Delta f < \tau$ 条件后停止迭代。

2.2 ICP搜索最近点的主要方法

1) Point to Point最近点搜索法

Point to Point最近点搜索法是 ICP算法中最经典的一种方法。如图 1a所示, Point to Point法根据源曲面上的一个点 p, 在目标曲面上找出对应于 p 点距离最近的 q 点。在这个方法中通常运用 kd-tree的方法实现最近点搜索。如图 1b所示, p_i 是源曲面点云数据中的一个点, V_i 是生成目标曲面点云数据中距 P_i 最近的点。根据 V_i 点搜索出在曲面上与 V_i 点相邻的点构成的三角形格网, 计算 P_i 点投影到每个三角形平面上的投影点 q_i 的坐标。对于每个三角形来说, 当投影点 q_i 位于三角形内部, 则距离最近点是搜索的最近点, 当投影点 q_i 位于三角形外部, 搜索的最近点应位于三角形的两条边界上, V_i 是该三角形到 P_i 点的最近距离点。将每个三角形确定的最近距离点进行比较可获得一个最近点。

2) Point to Plane最近点搜索算法

如图 2所示, Point to Plane法是根据源曲面上的一个点 p, 在目标曲面上找出对应于 p 点一个最近的 q 点。搜索算法是根据源曲面上 p 点的切平面的法线, 确定发现于目标曲面的交点 q'。根据目标曲面上 q' 点求出的过 q' 点切平面, 然后求源曲面上 p 点到过 q' 点切平面的垂线的交点 q。

3) Point to Projection最近点搜索算法

Point to Projection最近点搜索法是一种快速的配准方法。如图 3所示, 图中 O_q 是扫描目标曲面的透视点的位

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置。Point to Projection法是根据源曲面上的一个点 p 和透视点 O_q，在目标曲面上找出 q 点作为对应于 p 点的最近点。通过确定 O_q 点向 p 点方向的投影线与目标曲面的交点 q，作为搜索的最近点。

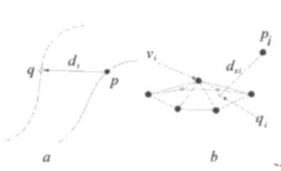

图1 点到点最近点搜索算法

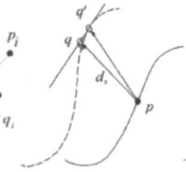

图2 Point to Plane 最近点搜索图

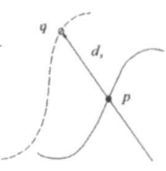

图3 Point to Projection 最近点搜索图

3 ICP迭代算法配准实例

ICP迭代法是一种优秀的三维配准方法，是三维激光扫描数据处理中普遍应用的一种算法。为了分析点云数据的 ICP配准的效果，某一座大楼作了一次三维激光扫描实验，实验中设置了两测站，从不同角度对建筑物进行了扫描并获得两幅三维激光扫描数据影像。利用三维激光扫描数据处理软件对扫描数据影像进行了三维配准处理。

3.1 扫描数据采集

实验所使用的三维激光扫描仪是加拿大 Optech公司生产的 ILRIS-3D扫描仪。首先在距离建筑物约 76m处设置测站 1，扫描平均间隔设置为 34mm，获得含有 1359692个点的距离图像数据。在数据预处理中，经过数据裁截后得到含有 953257个点的三维影像，见图 4。测站 2距离建筑物约 97m，扫描平均间隔设置为 44mm，获得含有 1059870个点的距离图像数据，数据经过有效裁截后得到含有 559293个点的三维影像见图 5。

图4 建筑物的扫描点云图之一(测站1)

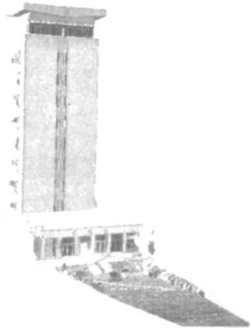

图5 建筑物的扫描点云图之二(测站2)

3.2 点云影像的近似配准

为表示 ICP迭代的过程与效果，将两个测站的扫描点云图可用方格网表示。从方格网中选择三组对应点，可直接得到近似配准的格网效果图，如图 6所示。近似配准由于选择三组对应点不是十分准确，所以每次近似配准的效果都不一定相同。近似配准的方法主要使用点集到点集的配准方法，配准的结果使得两个曲面的重复区域比较接近，因此可以作为 ICP迭代法配准的初始配准条件。

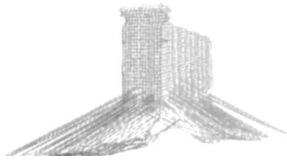

图6 PSTPS近似配准的格网效果

3.3 点云影像基于 ICP迭代法的配准

在进行 ICP迭代法配准前，首先需要设定容差、收敛值等配准参数，当迭代结果满足设置条件时则停止迭代计算。

在容差为 4.0m时，在 ICP处理时间到 48分钟后，迭代了 287850次，收敛条件到 0.000075后不再收敛，残差的均值为 0.007576m时，最近点距离差的标准差为 0.316024m。由于迭代不收敛和容差设置过大，配准的结果不佳。

对配准所用的参数设置进行修正，设容差为 0.05m时，用 ICP法计算处理时间很短，迭代了 42次，收敛条件到 0.0000089后，残差的均值为 0.000035m，最近点距离差的标准差为 0.011740m。从图 7a和图 7b可以看出，配准的结果较为理想。ICP迭代法配准的实际效果与配准初始设置参数存在十分复杂的关系，容差值与收敛值设置的是否合理，直接关系到配准的实际效果。因此，三维激光扫描数据配准后的点云数据质量很大程度上依赖于专业技术人员的数据处理经验和专业知识。图 7c为采用合适的配准初始设置得到的 ICP迭代法配准的点云影像图。

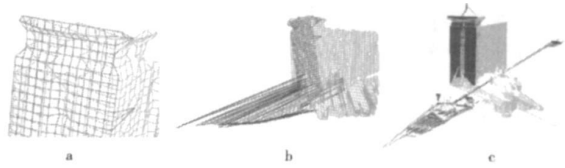

图7 ICP配准效果图

以点云数据表示 ICP配准算法的效果见图 7c，图中淡红色(浅色)为测站 1扫描所得的点云，蓝色(深色)为测站 2扫描所得的点云。配准后的图形质量、配准残差均值及最近点距离标准差表明采用 ICP配准过程可以得到较为精确的建筑物配准点云。

4 结束语

三维激光扫描技术可以高效地获得高密度三维点云数据，点云数据的配准方法是三维激光扫描数据处理中一项极其重要的研究内容。目前，国外的三维激光扫描仪随机后处理软件中都提供了点云数据的配准功能，它们在点云数据配准中主要使用了两种配准方法，即迭代最近点 ICP算法和点集到点集(PSTPS)的配准方法。本文通过对 ICP算法的阐述，可以使国内三维激光扫描数据处理软件使用者了解其计算步骤、数据处理过程，并为 ICP算法的分析和改进提供了基础。国外学者对 ICP算法作了大量的研究，在搜索最近点以及计算的收敛性方面作了较大的改进，提高 ICP算法的配准精度和配准速度。此外，还对 ICP算法的稳定性、收敛性和可靠性方面作了更细致的研究分析。目前，国内学者对 ICP算法的研究处于初级阶段，但由于数据配准是三维激光扫描数据处理软件中的一项重要处理过程，所以研究和改进 ICP配准算法是开发国产三维激光扫描数据处理软件的必然过程。

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intensity map which build from point cloud, and the picture's external orientation parameters are determined by the coplanar condition. The framework of the building and the texture are created from the aligned data sets. At last, an experiment provides the result of construction of old library of Wuhan University.

Key words: 3D reconstruction; old architecture survey; laser scanner; data processing

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ICP algorithm and application in the data registration of building scanning point cloud

Abstract: ICP algorithm is a level of art registration in data processing of 3D laser scanning point cloud. The background of ICP algorithm is reviewed in detail. The calculation course of ICP algorithm and its improved ICP algorithm are introduced in the paper. Through point cloud data acquired from the building, the course of registration based ICP algorithm is provided. The conclusion of experiment is that *the quality of registration relies on the experience and knowledge of* skilled worker.

Key words: ICP algorithm; building scanning; point cloud; data registration

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Calibration of nikon D1X camera

Abstract: The paper adopts space resection to calibrate Nikon D1X camera (with NIKKOR 17 lens) in indoor test field. The precision of calibration results is analyzed and its reliability testified using a method of space intersection with multi - image in this paper. The conclusion shows that space resection with multi - image is a reliable method for digital camera calibration. The calibration results of Nikon D1X camera are correct and reliable in the paper.

Key words: digital camera calibration; indoor test field; space resection; space intersection with multi - image

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Automated name placement of area map feature by center array method

Abstract: The paper mainly expounds the principle of automatic name placement of area element by center array method, the algorithm of polygon pretreatment, the method of getting array rotating center and the algorithm of name placement positioning line. Then, an experiment, made to test the feasibility of center array method, proves that it can deal with not only all polygons with general shape, but also some irregular polygons with special shape.

Key words: center array method; offset; automatic name placement; convex hull

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A virtual observational approach to ill - conditioned problem

Abstract: To resolve the ill conditioned problem exists in geodesy data processing, there are many methods such as ridge estimation, singular value decomposition, Tihonov regularization. Most of these methods pay attention to the mathematic theory while lack the true physical meaning. These lead to difficulties in understanding and study of the ill - conditioned problem. In order to set real meaning to the method for ill - conditioned problem, a new method of ridge estimation based on virtual observation is developed in this paper. The apriori information was taken as one class of virtual independent observations, and then the ill - conditioned problem was translated to a problem of adjustment. So the ridge parameter can be resolved using Helmert variance components estimation which is a very common method in adjustment. And the weight matrix between the parameters can be derived from this method. The new method also can be used in general ridge estimation when the weight matrix of the virtual observations was replaced by the weight matrix between the parameters. The result of the examples show the new method is much simpler and more effective than the traditional methods.

Key words: ill - conditioned problem; ridge estimation; virtual observation; Helmert variance components estimation.

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Research of fitting and transforming GPS height into normal height

Abstract: Aiming at the pertinent problems of the Hulin existing elevation systems, technical problems, such as converting ellipsoidal heights to normal heights of the region, are discussed in this paper. After systematically introducing the theory of GPS and leveling measuring height system and their similarities and discrepancies, the principles and methods of determining geoid are emphatically explained. Then using mathematic model, the scheme achieving height transformation with a cm - level precision by a few GPS/leveling points is searched. Finally, an approximate solution of the geoid computation with a cm - level precision in Hulin is proposed based on analyzing the approaches and corresponding errors of computing normal heights in cm - level for different areas. Taking the terrain characteristics of the Hulin region in account, the approaches adapted to different surveying projects are used to realize height transform here. Proved by practice, the normal heights with a cm - level precision for the region can be achieved by a few but reasonably distributed leveling points and such precision can meet the demand of general surveying projects.

Key words: GPS; quasi - geoid; normal height; precise model; isoline of height anomaly; deflection of the vertical

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The effect of ill - condition equations of GPS rapid positioning on the GPS baseline solution

Abstract: The data processing of GPS rapid positioning is usually based on integer least - squares principle, and parameter estimation consists of three steps: float - solution, search of integer ambiguities and fixed - solution. But in case of short observational time spans, the normal equations are seriously ill - conditional, which cause float - solution has large deflection compared with accurate solution. *In this paper, the ill - condition extent of normal equations* and the effect on the GPS baseline solution in different observational time spans is studied by examples. The results show that it is difficult to acquire reliable solution with LS and LAMBDA method in case of less than two minutes spans.

Key words: GPS rapid positioning; ambiguities; LAMBDA; ill - condition equation

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High - speed Position Orientation

A Raster - based method of counting the center and buffer of network

Abstract: The importance of raster - based network analysis method is firstly discussed in this paper. Then, on the basis of the stipulation of basic factors to describe raster - based method network analysis, this paper gives a new raster - based method to counting the center and the buffer of any node of a network through grid expanding model. Finally, It is proved by the example that it is a simple, effective and accurate method.

Key words: Raster - based network; network center counting; buffer analysis of network

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Study on topographical map update using electronic map for navigation

Abstract: On the characteristic of electronic map for navigation, this paper firstly presents a method using electronic map for navigation to

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