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Fast glacier volume change detection based on least squares 3D surface matching of DEM

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Abstract. In this paper, a new fast detection method on glacier volume change has been adopted and analyzed to solve shortages of low precision and inefficiency in traditional algorithms. High-precision Digital Elevation Model (DEM) has been used in this method to improve the accuracy of the result. Besides, GCPs are unnecessary in this new method so that it can be widely applied in glacier districts where GCPs are hard to be set. Furthermore, Least squares 3D surface matching method has also been improved in this paper in that blocking computing has been added to strengthen the speed and accuracy of this method. Multitemporal images in Xinjiang Province, China have been used to test the accuracy and efficiency of this proposal method: iterations are 12 and D-values are small. The test results show that this method has the advantages of Least squares 3D surface matching so that it can be widely used to satisfy the speed and accuracy of fast changing detection of Glacier Volume.

1. Introduction
Glacier volume change has a tremendous role in global water cycle, regional water cycle and global climate change. Since 1900s, glaciers in mountainous districts around the world have been in melt state, which has become a hot area of research [1]. In this background, a lot of innovate Glacier volume change detection methods have been applied in this field. In traditional method, multitemporal optical remote sensing images have been acquired for the detection of glacier change areas [2]. Digital Elevation Model (DEM) data from various sources have also been used for glacier volume detection [2, 3]. However, traditional methods focus on the applications of optical remote sensing data, which are unlikely to satisfy the accuracy and efficiency requirement in that GCPs are difficult to be acquired and DEM accuracy becomes higher and higher.

The least squares 3D Surface Matching Method is put forward by Armin Gruen for the problem statement of surface patch matching and its solution method in photogrammetry in 1985 [4, 5]. Based on the Generalized Gauss-Markoff model, the proposed method estimates the seven transformation parameters among different surfaces and minimizes the sum of squares of the Euclidean distances [5]. It has been widely used among terrain change monitoring, commercial measurement and Photogrammetry. Based on this method, Pauline Miller (2009) also successes in acquiring glacier volume change results in Slakbreen district in Norway, using ASTER data and LIDAR data [6].
2. 3D Surface Matching Method

2.1 Outline of the method

The Least Squares 3D matching method is to minimize the sum of squares of the Euclidean distances between the surfaces $f(x, y, z)$ and the matching surface $g(x, y, z)$. By calculating the distance between the template surface $f(x, y, z)$ and the matching surface $g(x, y, z)$, 7 parameters for transformation: the uniform scale factor ($m$), translation parameters ($t_x$, $t_y$, $t_z$) and rotation parameters ($\omega$, $\rho$, $\kappa$) can be acquired. Therefore, matching coordinates in two surfaces can be achieved.

The Least Squares 3D matching method has the advantages as follows: (1) Accuracy for detection can be improved by iterative computations; (2) GCPs are unnecessary in this method, which can overcome the difficulty in acquiring GCPs in glacier districts. (3) It can eliminate the coordinate deviations between different DEM data, which would bring about errors in detecting glacier volume changing.

2.2 Principle of the method

Assuming the template surface is $f(x, y, z)$ and the matching surface is $g(x, y, z)$, a true error vector $e(x, y, z)$ is added because of the existing of random errors.

$$f(x, y, z) - g(x, y, z) = e(x, y, z)$$

(1)

In order to perform the Least Squares estimation, Equation (1) is expanded by the Taylor series, of which only the linear terms are reserved:

$$f(x, y, z) - e(x, y, z) = g_0(x, y, z) + \frac{\partial g_0(x, y, z)}{\partial x} \cdot dx + \frac{\partial g_0(x, y, z)}{\partial y} \cdot dy + \frac{\partial g_0(x, y, z)}{\partial z} \cdot dz$$

(2)

In the 3D transformation, assuming $(X_t, Y_t, Z_t)$ is the geometric coordinates of $f(x, y, z)$ and $(X_m, Y_m, Z_m)$ is geometric coordinate of $g(x, y, z)$. $R$ is the rotation matrix.

$$\begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} = m \times R \times \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$$

(3)

Differentiation of Equation (3) gives:

$$dx = dx + a_{10} \cdot dm + a_{11} \cdot d\psi + a_{12} \cdot d\omega + a_{13} \cdot dx$$

(4)

$$dy = dy + a_{20} \cdot dm + a_{21} \cdot d\psi + a_{22} \cdot d\omega + a_{23} \cdot dx$$

(5)

$$dz = dz + a_{30} \cdot dm + a_{31} \cdot d\psi + a_{32} \cdot d\omega + a_{33} \cdot dx$$

(6)

where $a_{ij}(i,j=1,2,3)$ are derivations of $\omega$, $\rho$, $\kappa$ from equation (3).

Equation (2) can be substituted as followed:

$$-e(x, y, z) = gx \cdot dx + gy \cdot dy + gz \cdot dz + (gx \cdot a_{10} + gy \cdot a_{20} + gz \cdot a_{30}) \cdot dm$$

$$+ (gx \cdot a_{12} + gy \cdot a_{22} + gz \cdot a_{32}) \cdot d\psi + (gx \cdot a_{11} + gy \cdot a_{21} + gz \cdot a_{31}) \cdot d\omega$$

$$+ (gx \cdot a_{13} + gy \cdot a_{23} + gz \cdot a_{33}) \cdot dx + f(x, y, z) - g_0(x, y, z)$$

(7)

Which can be simplified as:

$$-e = AX - L$$

(8)

With $gx = \frac{\partial g_0(x, y, z)}{\partial x}$, $gy = \frac{\partial g_0(x, y, z)}{\partial y}$, $gz = \frac{\partial g_0(x, y, z)}{\partial z}$. $A$ is the design matrix, $X$ is parameter vector and $L$ is the discrepancy vector that consists of the Euclidean distances between the template and correspondent search surface.

3. Glacier Volume Detection

3.1 Glacier Volume Changing Calculation

Glacier Volume Changing can be calculated after the coordinate deviations have been eliminated by 3D matching method.

$$\Delta H_{average} = \Sigma (\Delta H/\text{num})$$

(9)
Where $\Delta H$ is the thickness changing in glacier district and num is the pixel points of glacier district. $\Delta H_{\text{average}}$ is the average thickness changing quantity.

The glacier volume changing quantity can be calculated by the thickness changing one.

$$
\Delta V = \sum (\Delta H \times S) \times \frac{1}{t_{\text{diff}}}
$$

Where $S$ is area of glacier district and $t_{\text{diff}}$ is span of time series. $\Delta V$ is the glacier changing volume.

3.2 Method flow

The following steps can be concluded as the procedures for the proposed method and Figure 1 is the flow chart.

![Flow chart of the method.](image)

**Figure 1.** Flow chart of the method.

- **Step 1:** DEM data will be acquired and resampled into the same size and resolution. Bilinear Interpolation method will be adopted for data preprocessing.
- **Step 2:** DEM data exist in (B,L,H) coordinate system and should be converted into (X,Y,Z) coordinate system for 3D surface matching.
- **Step 3:** Grade of each point will be calculated with the nearby points, which can be regarded as surface vector and used for surface fitted function calculation.
- **Step 4:** Mask files will be constructed to eliminate the influence of glacier volume changing information, which distinguishes glacier and non-glacier districts.
- **Step 5:** Design matrix and parameter vector will be built up according to equation (7). The proposed method will calculate the parameters for 3D transformation between two surfaces and coordinate deviations will be eliminated.
- **Step 6:** Glacier changing information can be acquired based on equation (9) and (10).

4. Test and Analyst

4.1 Test site and data

The template surface is the SRTM (Shuttle Radar Topography Mission) DEM DATA VERSION 4.1. It covers an area of 1 degree x 1 degree and its resolution is about 90 meters. The image acquisition time is 2009. The matching surface is ASTER (The Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM (GLOBAL DIGITAL ELEVATION MODEL) Version 2 data. It is 1 degree x 1 degree tile and its resolution is 30 meters. It is acquired in 2002.
4.2 Results and Analysis

SRTM DEM and ASTER GDEM in Fig 3 are used to verify the proposed method. Table (1) shows the Root-Mean-Square error (RMSE) and the average D-values between two surfaces in X, Y, Z and height. It shows that least Squares 3D matching method can eliminate the coordinate errors efficiently.

| Index                        | X       | Y       | Z       | Height  |
|------------------------------|---------|---------|---------|---------|
| Standard Deviation Before Matching | 4.437284 | 51.319075 | 49.383870 | 71.351162 |
| D-values Before Matching     | -16.133163 | -57.989594 | 50.158625 | -7.874419 |
| D-values After Matching      | 0.000342   | 0.005977   | 0.006055  | -0.008341 |

Table 2 is the transformation solution for 3D surface matching. 7 parameters and number of iteration have been listed. The proposed method achieves the accuracy requirement after 12 iterations which proves that it is a fast and efficient strategy.
Table 2. Transformation solution for 3D surface matching

| Parameter (unit) | Value          | Parameter (unit) | Value          |
|------------------|----------------|------------------|----------------|
| m                | 0.999999       | No. Iterations   | 12             |
| ψ (degree)       | 8.643074e-011  | tx (meter)       | -16.132967     |
| ω (degree)       | 5.86946e-010   | ty (meter)       | -57.987025     |
| κ (degree)       | -4.192891e-011 | tz (meter)       | 50.156115      |

Table 3 is the Volumetric Change Indexes for test site. It shows that the glacier volume in test site has decreased about 206 353 635 m³ during 2002 to 2009.

Table 3. Volumetric Change for Glacier Region

| Change Index      | Value                        |
|-------------------|------------------------------|
| Surface Area(m²)  | 115325100                    |
| Gain(m³)          | 1362312811.460363            |
| Loss(m³)          | -1568666446.543645           |
| Net change(m³)    | -206353635.083282            |

5. Conclusion
This paper presents a novel solution for the reliable determination of volumetric change in glacial environments. At the core of the method lies a least squares surface matching algorithm, facilitating the robust registration of multitemporal DEM data from different sources. DEM data have been resampled and converted into geodetic coordinate system. The test results show that it can satisfy the accuracy requirement of glacier volume change detection.

3D surface matching has the advantages of high matching accuracy, fast iterative speed and being unnecessary of GCP. Due to multitemporal DEM which are from different sources becoming easier to be acquired, the proposed method can be widely used in glacier changing detection and researches of influences bringing about global climate changes.

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