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A method for compensating platform attitude fluctuation for helicopter-borne LiDAR: Performance and effectiveness

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ABSTRACT

Attitude fluctuation of helicopter-borne platform is an important factor influencing the quality of point cloud products from airborne LiDAR, especially the roll and pitch parts. Therefore, we proposed a method to compensate the attitude fluctuation for helicopter-borne laser scanning; an attitude compensation prototype was designed, to eliminate the impact of both the roll and pitch fluctuations on point cloud products. The mechanical structure and control system of the prototype were designed. In order to test the dynamic compensation effectiveness of the prototype for airborne LiDAR, we established a semi-physical simulation system. In the experiment setup, the prototype, a laser rangefinder as well as a position and orientation system (POS) were all mounted on the platform of a three-axis turntable. The inner and middle shafts of the three-axis turntable rotated with sinusoidal movements to simulate the roll and pitch fluctuations of helicopter-borne platform. The x-axis and y-axis frameworks of the prototype were controlled to rotate inversely halves of the measured rotation angles of the simulated attitude fluctuations by the POS. Hence, the emitting orientations of the pulsed laser beams reflected by the scanning mirror embedded in the prototype would not be affected by the dynamic changing of the roll and pitch fluctuations. Total 11 groups of experiments were carried out to verify the control performance and dynamic compensation effectiveness of the compensation prototype under 11 sets of sinusoidal attitude fluctuations with different frequencies and amplitudes. Experimental results show that, under the impact of different frequencies and amplitudes sinusoidal attitude fluctuations, the attitude compensation prototype can always significantly decrease the unfavorable influence of the attitude fluctuations and have good dynamic compensation effectiveness.

1. Introduction

Helicopter-borne LiDAR (or laser scanning) as an efficient topographic mapping technology, has obvious advantages as compared with the other traditional surveying technologies, such as Photogrammetry and Interferometric Synthetic Aperture Radar (InSAR) [1]. Using airborne LiDAR, laser point clouds, high-quality digital elevation model (DEM) and digital surface model (DSM) reflecting the measured terrain surface can be obtained in real time or semi real-time [2–5]. Therefore, at present, helicopter-borne LiDAR has been widely used in lots of fields, such as city modeling, topographic mapping, virtual reality, reverse engineering, and so on [6,7].

According to the working principle of airborne LiDAR, the measurement errors of various sensors, such as global positioning system (GPS), inertial measurement unit (IMU), laser rangefinder, and optoelectronic angular encoder, can directly influence the positioning accuracy of measured laser points and the quality of reconstructed DSM. Therefore, many researches have focused on analyzing and eliminating these kind of errors [8–11]. But actually, the measurement errors of various sensors are only one of the factors affecting the accuracy of laser points and the DSM. There is also another important error source, that is, the attitude fluctuations of helicopter-borne platform. It is known that the terrain mapping procedure

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of helicopter-borne LiDAR is a two-dimensional (2-D) sampling procedure. Hence, in order to reconstruct the DSM of the surveyed terrain topography without distortion, the sampling frequency of the obtained point cloud theoretically should be at least two times higher than the Nyquist frequency of the surveyed terrain [12]. Additionally, the higher the sampling frequency of helicopter-borne LiDAR, the higher the point density of the obtained laser point cloud, and the higher the accuracy of the reconstructed DSM [13]. The ideal working state of airborne LiDAR requires that the airborne platform should be of a consistent flight speed and unchanged attitude angles. However, in reality, due to various disturbances, the airborne platform often generates fluctuation in both the flight trajectory and the attitude angles [14–16]. Researches showed that the attitude fluctuations have more significant impact on the point density than the trajectory fluctuations [17–19]. The attitude fluctuations not only cause the coverage area of point cloud shifting from the left to right along the flight trajectory, but also cause the point density uneven [20]. Some target topography may be failed to scan due to the horizontal shifting of point cloud coverage area, especially narrow terrain mapping objects such as railways, highways and power lines [21]. The decreasing of the point cloud density could also decrease the sampling frequency for the surveyed terrain, deteriorating the accuracy of the reconstructed DSM [22]. Therefore, it has a practical significance to compensate the platform attitude fluctuations for helicopter-borne LiDAR.

The airborne platform for LiDAR can be divided into two categories [23]. One is the own payload cabin of helicopters or other kinds of aircrafts. For this kind of platforms, the attitude fluctuations can be up to $\pm 10^\circ$. The other is various kinds of airborne stabilized platforms, which are mounted on the payload cabin of the aircrafts. However, due to LiDAR, IMU and other payloads such as cameras are all mounted on the airborne stabilized platform, the size, mass and inertia of the airborne stabilized platform should be very large. Therefore, the residual attitude variation of the airborne stabilized platform is still of a significant impact on laser point cloud [24]. Wang [25] analyzed the platform attitude variations of a type of airplane in actual flight, showing that the actual yaw varied within $\pm 2.5^\circ$, the pitch within $\pm 1.5^\circ$ and the roll within $\pm 3.0^\circ$. By research shown in [20], we know that the above size of the attitude fluctuation is still unfavorable for the quality of point cloud products. Therefore, it is very necessary to compensate the platform attitude fluctuations for helicopter-borne LiDAR, no matter what kind of airborne platforms the LiDAR installed on.

In current literature, some references have studied the influence of attitude fluctuations of airborne platform on quality of point clouds and accuracy of DSM from airborne LiDAR [22,26–28]. As for the compensation study of platform attitude fluctuations for airborne LiDAR, 'roll compensation' method has been applied in several airborne LiDAR systems, such as Leica's ALS50-70, Optech's ALTM3100, and ALTM's Pegasus HA500, according to their product specifications [29,30]. But the specific compensation details have not been reported. In reference [31], Li et al. analyzed the influence of attitude errors on airborne down-looking synthetic-aperture imaging LiDAR, proposed and theoretically verified a compensation method for attitude errors. In Ref. [32], we have proposed a real-time compensating method for the platform roll and pitch fluctuations for airborne LiDAR, and the compensation principle of the proposed method was simulated and verified. In this research, we further studied the control strategy design of the compensation prototype, tested the control performance, and quantitatively evaluated the dynamic compensation effectiveness of the prototype for helicopter-borne LiDAR.

2. Fundamentals

2.1. Impact of attitude fluctuations on point cloud

According to airborne LiDAR measurement principle, the conventional three-dimensional (3-D) coordinates of laser points measured by airborne LiDAR in the local mapping coordinate system (denoted as LM system) can be expressed as following [33]:

$$\begin{bmatrix} x_{\mathbf{P}}^{\mathrm{LM}} \\ y_{\mathbf{P}}^{\mathrm{LM}} \\ z_{\mathbf{P}}^{\mathrm{LM}} \end{bmatrix} = \mathbf{R}_{\mathrm{Attitude}} \left(\mathbf{R}_{\mathrm{Mis-angle}} \mathbf{R}_{\mathrm{Scanning}} \begin{bmatrix} 0 \\ 0 \\ S \end{bmatrix} - \begin{bmatrix} x_{\mathrm{Offset}} \\ y_{\mathrm{Offset}} \\ z_{\mathrm{Offset}} \end{bmatrix} \right) + \begin{bmatrix} x_{\mathrm{GPS}}^{\mathrm{LM}} \\ y_{\mathrm{GPS}}^{\mathrm{LM}} \\ z_{\mathrm{GPS}}^{\mathrm{LM}} \end{bmatrix} \quad (1)$$

where $\mathbf{R}_{\mathrm{Scanning}}$ is the rotation matrix related to the instantaneous scanning angle of LiDAR; $\mathbf{R}_{\mathrm{Mis-angle}}$ is the rotation matrix related to the bore-sight misalignment angles between the laser scanner frame and the IMU frame; $\mathbf{R}_{\mathrm{Attitude}}$ is the rotation matrix related to the attitude angles of airborne platform, i.e., roll of ω, pitch of ϕ and yaw of κ; $(x_{\mathrm{Offset}}, y_{\mathrm{Offset}}, z_{\mathrm{Offset}})$ are the 3-D lever arm offsets between the GPS antenna phase centre and the optical centre of LiDAR; $(x_{\mathrm{GPS}}^{\mathrm{LM}}, y_{\mathrm{GPS}}^{\mathrm{LM}}, z_{\mathrm{GPS}}^{\mathrm{LM}})$ are the 3-D coordinates of the GPS antenna phase centre in the LM system.

Eq. (1) shows that attitude angles (ω, ϕ, κ) of airborne platform will influence the 3-D coordinates of laser points through $\mathbf{R}_{\mathrm{Attitude}}$, wherein, the measurement errors of (ω, ϕ, κ) may affect the positioning accuracy of the obtained laser points, and the fluctuations of angles (ω, ϕ, κ) will affect the coverage area and distribution density of the point cloud.

In ideal helicopter-borne LiDAR working procedure, the ideal roll (ω) and pitch (ϕ) angles are both zero, and the ideal yaw (κ) is a constant value denoted as κ_0, then in this case, the obtained laser points are referred to as the ideal laser points, and the 3-D coordinates can be calculated by Eq. (1) and denoted as $(x_{\mathrm{P(I)}}^{\mathrm{LM}}, y_{\mathrm{P(I)}}^{\mathrm{LM}}, z_{\mathrm{P(I)}}^{\mathrm{LM}})$. However, in actual flying state, the roll, pitch and yaw are hard to be constant and would be time-changing, and their deviations as compared to the ideal state are denoted as $\Delta\omega_{\mathrm{D}}$, $\Delta\phi_{\mathrm{D}}$ and $\Delta\kappa_{\mathrm{D}}$, respectively. Then the obtained laser points are referred to the actual laser points, and the 3-D coordinates are denoted as $(x_{\mathrm{P(A)}}^{\mathrm{LM}}, y_{\mathrm{P(A)}}^{\mathrm{LM}}, z_{\mathrm{P(A)}}^{\mathrm{LM}})$. Hence, we can calculate the spatial positioning deviations of the actual laser points caused by the impact of the attitude variations of airborne platform, as following:

$$\begin{bmatrix} \Delta x_{\mathrm{P(A)}} \\ \Delta y_{\mathrm{P(A)}} \\ \Delta z_{\mathrm{P(A)}} \end{bmatrix} = \begin{bmatrix} x_{\mathrm{P(A)}}^{\mathrm{LM}} \\ y_{\mathrm{P(A)}}^{\mathrm{LM}} \\ z_{\mathrm{P(A)}}^{\mathrm{LM}} \end{bmatrix} - \begin{bmatrix} x_{\mathrm{P(I)}}^{\mathrm{LM}} \\ y_{\mathrm{P(I)}}^{\mathrm{LM}} \\ z_{\mathrm{P(I)}}^{\mathrm{LM}} \end{bmatrix} \quad (2)$$

The RMS statistics of the 3-D coordinate deviations from Eq. (2) can reflect the impact of attitude variations on the whole point cloud, as following:

$$\begin{bmatrix} \mathrm{RMS}_{\mathrm{x(A)}} \\ \mathrm{RMS}_{\mathrm{y(A)}} \\ \mathrm{RMS}_{\mathrm{z(A)}} \end{bmatrix} = \begin{bmatrix} \sqrt{\sum_{i=1}^{n} [\Delta x_{\mathrm{P(A)}}(i)]^2/n} \\ \sqrt{\sum_{i=1}^{n} [\Delta y_{\mathrm{P(A)}}(i)]^2/n} \\ \sqrt{\sum_{i=1}^{n} [\Delta z_{\mathrm{P(A)}}(i)]^2/n} \end{bmatrix} \quad (3)$$

where i and n refer to the serial number and total number of laser points in the actual point cloud, respectively. By Eq. (3), we can analyse the coverage area and density changing of the actual point cloud under the effect of the attitude variation of airborne platform.

In Ref. [20], a numerical simulation about the impact of attitude variations on the coverage area and distribution density of point cloud has been completed. The simulation results showed that, the attitude variations of airborne platform can make the distribution region shift horizontally and the point density of point cloud uneven, especially the roll and pitch fluctuations, while the impact of yaw fluctuation is much smaller. Therefore, taking appropriate compensation method is very necessary for helicopter-borne LiDAR to reduce the impact of roll and pitch variations.

2.2. Proposal for attitude compensation

A proposal to compensate the platform attitude fluctuations for the