DATA SIMULATION OF LADAR SENSOR: FOCUSING ON GEOMETRIC MODELING

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ABSTRACT:

LADAR (LAser Detection And Ranging or Laser Radar) can rapidly generate 3D points by sampling the surfaces of targets using laser pulses, which can be efficiently utilized to reconstruct 3D models of the targets automatically. To make wide use of LADAR, it is necessary to assess the data quality and to develop data processing algorithms. However, the accuracy verification of LADAR system is difficult, because we cannot know the accurate reflected positions of the returned signals at target's surface. Under the consideration of this difficulty, the verification based on LADAR simulation can be a more feasible alternative solution. The purpose of this study is to derive the geometric models of such LADAR sensors and to generate simulated data based on these models. Here, we derived the sensor equation by modeling not only the geometric relationships between the LADAR sub-modules, such as GPS, INS, Laser Scanner but also the systematic errors associated with them. This is an important step to establish mutual geometric and time correspondence among the individual sensors on a multi-sensor system. The geometric correspondence means that each sensor is defined with its position and attitude in a common coordinate system. And the time correspondence means that individual sensor time is synchronized. Based on this equation (the geometric model), we developed a program that generates simulated data with the system parameters of a LADAR sensor, a terrain model, and its trajectories over this model given. The results of this study will be useful for the system design of a LADAR sensor and the algorithmic development for LADAR applications.

1. INTRODUCTION

A LADAR (LAser Detection And Ranging or Laser Radar) sensor can generate 3D points by sampling the surfaces of targets using laser pulses, which can be efficiently utilized to reconstruct 3D models of the targets automatically. This sensor has the advantage of observing a large area for a short time, supporting higher resolution and accuracy on measurements of range, velocity, and angular position than other sensors (for examples, microwave radar, etc.). Since it can measure each sub-area of target's surface with high resolution, it can permit more robust identification and recognition of the targets (Kamerman, 1993). Therefore, LADARs have been increasingly applied to the fields of Defense and Security, for examples, being employed to intelligently guided missiles and manned/unmanned reconnaissance planes. It has been also applied to the fields of Remote Sensing such as precise construction of three-dimensional spatial models of the targets, the creation of DTM (Digital Terrain Model) for the forest area or the rapid change detection of city regions.

Computer simulation has taken important roles in modelling diverse physical systems. Generally it can be effectively applied to the design, performance estimation and analysis of hardware. It is useful for the design of a new system and the improvement of an existing system.

To utilize LADAR sensors effectively in various applications, it should be necessary to assess more accurately their data and to develop data processing algorithms dedicated to specific applications (Lee, 2003). However, the accuracy assessment of LADAR system is relatively difficult because we cannot accurately determine the true position on a target surface at which the returned laser signal is reflected. The verification based on LADAR simulation can be thus a more feasible alternative solution.

The purpose of this study is to derive the geometric models of such LADAR systems and to generate simulated data based on these models. Here, we derived the sensor equation by modeling not only the geometric relationships between the individual sensors of a LADAR system, such as GPS, INS, Laser Scanner but also the systematic errors associated with them. Using the sensor equation based on the geometric model, we developed a program that generates simulated data with the system parameters of a LADAR system, a terrain model, and its trajectories over this model given.

The simulation will be effectively used to validate the accuracy about a variety of sensors and to assess the performance of the data processing algorithms in more economical ways. Furthermore, it will be also used to determine the optimal parameters for a LADAR system being developed.

2. METHODOLOGY

2.1 Geometric Modelling

To simulate LADAR data, we need to derive the sensor model and its corresponding sensor equation. This equation indicates the mathematical representation of the three dimensional coordinates of the position on a target surface where the returned laser signal is reflected. In a multi-sensor system like a

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LADAR system, this equation must be a function of the data acquired by the individual sensors. In order to derive the sensor equation by combining the data acquired by the individual sensors, it is necessary to establish the geometric and time correspondence of all individual sensors. The geometric correspondence means that each sensor should be defined with its position and attitude in a common coordinate system; and the time correspondence means that the time referred to the individual sensors should be synchronized. These correspondences can be established by defining the mutual geometric and time relation to individual sensors.

A sensor equation for a general LADAR system without considering any errors associated with the system is derived as

$$P_W = R_{GW} R_{NG} (R_{LN} R_{0L} u_z r + t_{NL_N} + t_{GN_N}) + t_{WG_W}, \quad (1)$$

where each variable is explained in Table 1. Here, 0, L, N, G and W are used as a subscript indicating of its corresponding coordinate system, such as the initial LS coordinate system, the LS coordinate system, the INS coordinate system, the GPS coordinate system, the WGS84 coordinate system, respectively. These coordinate systems are shown in Figure 1. In addition, R and t indicates the rotation matrix and the translation vector, respectively. They are introduced to establish a geometric relationship between two coordinate systems.

Variables	definition and description
p_w	The true values of laser pulse's reflected point based on the WGS84 coordinate system
u_z	The unit vector (0,0,1) along the z-axis based on the initial LADAR coordinate system
r	The range from the starting point of the transmitting laser pulse to its reflected point on the target surface
R_{0L}	The rotation matrix used for the transformation from the initial LADAR coordinate system to the LADAR coordinate system
R_{LN}	The rotation matrix used for the transformation from the LADAR coordinate system to the INS coordinate system
R_{NG}	The rotation matrix used for the transformation from the INS coordinate system to the GPS coordinate system
R_{GW}	The rotation matrix used for the transformation from the GPS coordinate system to the WGS84 coordinate system
t_{NL_N}	The translation vector connected from the origin of the INS coordinate system to the origin of the LADAR coordinate system represented in the INS coordinate system
t_{GN_N}	The translation vector connected from the origin of the GPS coordinate system to the origin of the INS coordinate system represented in the GPS coordinate system
t_{WG_W}	The translation vector connected from the origin of the WGS84 coordinate system to the origin of the GPS coordinate system represented in the WGS84 coordinate system

Table 1. The definition and description of the variables embedded in the sensor equation

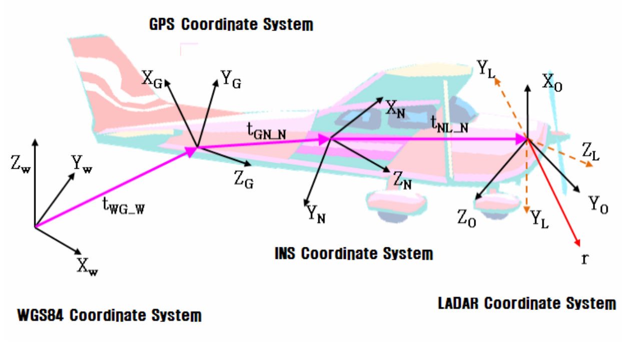

Figure 1. The coordinate system referred to each sensor

The sensor equation presented Eq. (1) does not consider any errors and hence produces the true point at which a laser pulse is reflected. However, every measurement acquired by a sensor must include some systematic and random errors. Thus we identified the error sources and derive their parametric models.

The errors associated with LADAR measurements are largely categorized into two groups, that is, the individual sensor errors and the sensor integration errors. The first group includes the systematic errors associated with the individual sensor, for examples, INS drift errors, GPS bias errors, the LS range error and other errors. The second one is caused from the integration of different sensors in terms of their geometry and time. For examples, thee individual sensors (GPS, IMU, LS) are mounted at different positions at a platform. Hence, the primitive data acquired by each sensor are represented with respect to the coordinates system fixed to each sensor. To combine these data, one should transform them into a common coordinate system. Here, the transformation parameters composed of the translation vector and rotational matrix can include some systematic errors. In addition, the different acquisition frequency of the individual sensors and the deviation from the time referred to the individual sensors can cause some errors. More details on the error sources and their parameterization are presented by Schenk (2001) and Lee (2005).

From the parameterization of the main ones among these various error sources, we can derive the sensor equation with errors as

$$\begin{aligned} P_W^* &= R_{GW} \Delta R_{NG} R_{NG} (\Delta R_{LN} R_{LN} \Delta R_{0L} R_{0L} u_z (r + \Delta r) \ldots \\ &+ t_{NL_N} + \Delta t_{NL_N} + t_{GN_N} + \Delta t_{GN_N}) + t_{WG_W} + \Delta t_{WG_W} + \Delta t_{TB}, \end{aligned} \quad (2)$$

where p_w^* indicates the observed values of the true laser pulse's reflected point p_w, which includes all the systematic errors. The variables representing the systematic errors starts with the notation of Δ. For example, Δr means the range bias added to the true range r.

2.2 Data Simulation

The essential information required for simulation are the flight paths, the attitude of the platform, and the three dimensional geometric models of the terrain or targets such as a DSM.

The simulation of each laser point can be performed using the sensor equations in Eq. (1) and (2). The sensor equation without any error in Eq. (1) can be rearranged to

$$P_W = R_{GW} R_{NG} R_{LN} R_{0L} u_z r + R_{GW} R_{NG} t_{GL_N} + t_{WG_W}, \quad (3)$$

where t_{GL_N} is defined as $(t_{NL_N} + t_{GN_N})$, indicating the translation vector between the GPS coordinate system and the LS coordinate system. This equations is further summarized as

$$P_W = u_L r + P_L, \quad (4)$$

where u_L is defined as $R_{GW} R_{NG} R_{LN} R_{0L} u_z$, indicating the unit vector along the direction of a transmitting laser pulse represented in the WGS84 coordinate system; P_L is defined as $R_{GW} R_{NG} t_{GL_N} + t_{WG_W}$, indicating the starting point of the pulse represented in the WGS84 coordinate system.

Based on Eq. (4), the simulation of each laser point can be performed using the following procedures.

1. The position of the platform at a particular time is computed using its flight path and velocity and then used to determine the starting position of a transmitted laser pulse (P_L).

2. With the assumption on the attitude of the vehicle, the direction of the transmitted laser pulse (u_L) is calculated by setting the scanning angle at the time.

3. Starting from the laser pulse starting point, a virtual line is generated with its direction. The intersecting points of this line with the given 3D models are found using a "ray-tracing" algorithm. Among these points, only the first visible point from the sensor is selected as the true point (P_W), where the laser pulse is reflected. Using this point with P_L computed in step 1, the true range (r) is computed.

4. Based on the sensor equation with the errors in Eq. (2) and the true range computed in step 3, the noisy point (P_W^*) is then computed.

Using the flight path given, the true value of sensor platform position (actually, the origin of the GPS coordinate system) at a particular time (t) is derived as

$$t_{WG_W} = P_s + V(t - t_s) \quad (5)$$

where t_s is the time of the platform at the position at P_s and V is the vector of the platform velocity. Here, the flight path information are given with two points, that is, the starting point (P_s) and the ending point (P_e). It is assumed that the platform travels only in a straight line between these two points at the speed of v. In this case, the velocity (V) is expressed as

$$V = \frac{P_e - P_s}{\|P_e - P_s\|} v \cdot \quad (6)$$

We suppose that the description of the ground surface is given by a two dimensional surface function, as represented in Eq. (7). In this case, the surface function is expressed as a DEM or 3-dimensional point clouds.

$$z = f(x, y) \quad (7)$$

The simulation determines the three dimensional coordinates of the reflected point, when a laser pulse is transmitted from the origin point (P_L) to the direction of the u_L reflects from the surface $z = f(x, y)$. This point is determined by a ray-tracing algorithm to find the intersection point between the straight line starting from P_L to the direction of u_R and the surface expressed as $z = f(x, y)$.

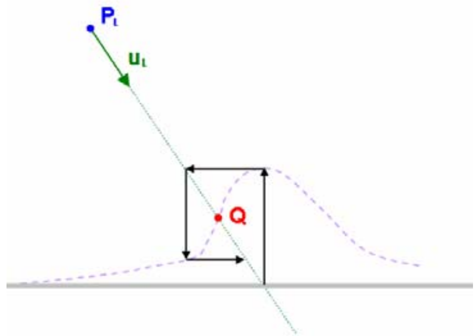

Figure 2. The basic concept of ray-tracing algorithm

The basic concept of this ray-tracing algorithm is illustrated in Figure 2, being summarized as

1. Search the minimum z value of DEM.

2. Establish a virtual horizontal plane with the elevation of this value.

3. Determine the intersection point between this horizontal plane the straight line.

4. Using the horizontal coordinates of this point, compute its corresponding elevation on the DEM.

5. Repeat step 2-4 until there is no change in the elevation value.

These iterative processes finally derive the intersection point (Q) between the straight line and the surface. Using this point, the true range can be computed. By substituting this value for r and other specified bias values for ΔR_{NG}, ΔR_{LN}, ΔR_{0L}, Δr, Δt_{NL_N}, Δt_{GN_N}, Δt_{WG_W}, and Δt_{TB} in Eq. (2), we can determine the observed coordinates of the laser reflected point, P_W^*.

3. EXPERIMENTAL RESULTS

To demonstrate our approach, we generate the simulated LADAR data from the real DEM using the proposed method.

3.1 Parameter Setting

To generate the simulated LADAR data, we need to set up the parameters such as the sensor parameters, the flight path of the platform, and the systematic errors associated with the sensors.

The system parameters used for the simulation are presented in Table 2. The pulse rate is the number of laser pulses transmitted per second, and the scan rate is the number of scans per second. The number of laser pulse per one scan is then derived from the scan rate and the pulse rate, which is 600 times. The scan angle indicates the scan range. In this case, the 20 degree of scan angle means that the system scans -10 ~ 10˚ range with respect to the vertical line at the center.

Parameter Name	Unit	Value
Pulse Rate	㎑	30
Scan Rate	㎐	50
Scan Angle	deg	20

Table 2. The systematic parameter of the LADAR system

The Flight Path of the Platform: The flight path in the simulation is assumed as a strip starting from (-150, 550, 1500) to (150, -550, 1500) with the flight speed of 30 m/s.

The systematic errors associated with the sensors assumed in this simulation are described in Table 3. These parameter values are carefully determined by considering the error range of a typical airborne LADAR system. The other parameters not specified in Table 3 among the error parameters incorporated into Eq. (2) are negligible comparing to the specified ones and thus assumed to be zero.

Bias	Symbol	Unit	Value
GPS bias, x	Δt_{WG_W}	m	2
GPS bias, y		m	1
GPS bias, z		m	0
INS bias, omega	ΔR_{NG}	deg	0.1
INS bias, phi		deg	0.2
INS bias, kappa		deg	0
Range bias	Δr	m	0.0

Table 3. The systematic errors associated with a LADAR system

3.2 Input DEM

The input DEM (Digital Elevation Model) used for the simulation is shown in Figure3. This DEM has a variety of terrain slopes. Its grid spacing is 10m. It covers an area of 1.2 km by 2.0 km. This area is enough to include the flight path above.

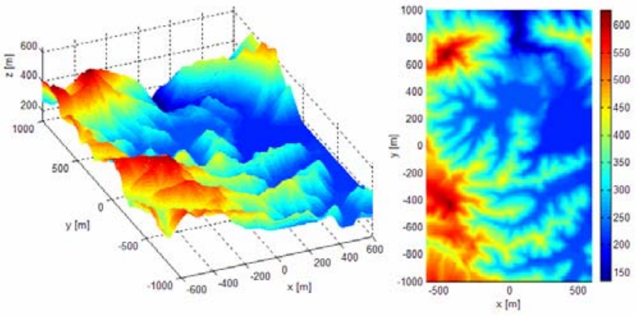

Figure 3. The input DEM used for simulation

3.3 Simulation Results

The simulation methods have been programmed with the C++ language and run on a standard Pentium desktop computer. The simulator generates about 1,140,600 points for the running time of 38.02 seconds. The ground coverage area of the simulated LADAR data is shown in Figure 4. The central bold solid line of the ground coverage indicates the flight path. The point density of the simulated LADAR data is 0.664 points/m^2; its point spacing is 1.774 m; the range of its x-coordinate value is -344.759 ~ 361.978 m; the range of its y-coordinate value is -609.839 ~ 604.533 m.

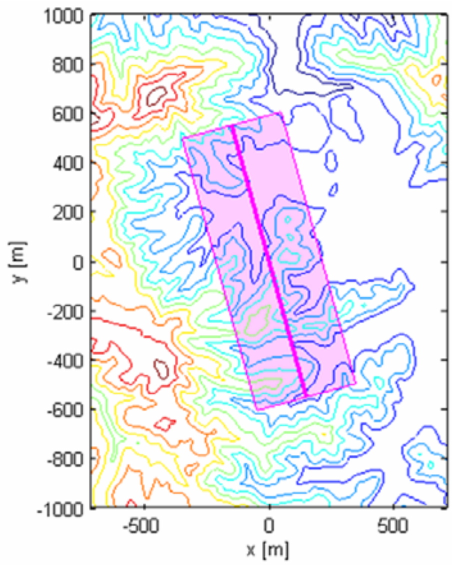

Figure 4. The flight path and the coverage of simulated data

Figure 5 shows the simulated LADAR points on the input DEM; and Figure 6 shows only the simulated LADAR points.

As one of the verification processes, the elevation differences between the simulated LADAR points and the input DEM are computed. Their distributions are shown in Figure 7. The above histogram shows the error distribution of the simulated data without any systematic error. As expected, the elevation differences are relatively small since it does not consider any error. These small errors are mainly caused from not the systematic errors but the interpolation of the input DEM. However, as shown in the below one, the simulated data with systematic errors naturally include more errors.

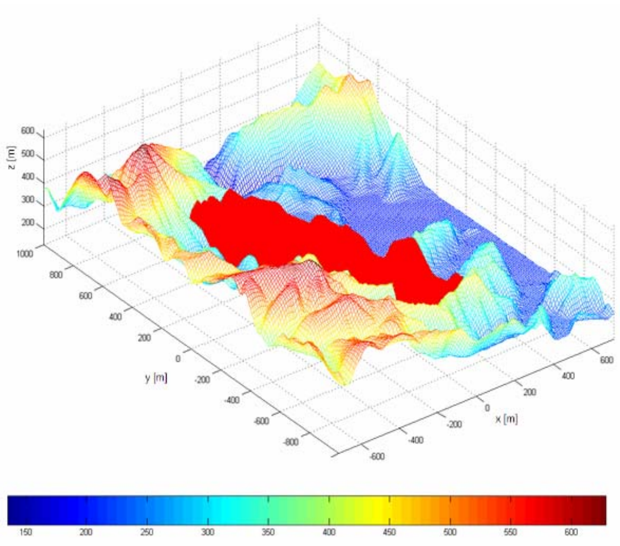

Figure 5. The simulated LADAR data on the input DEM

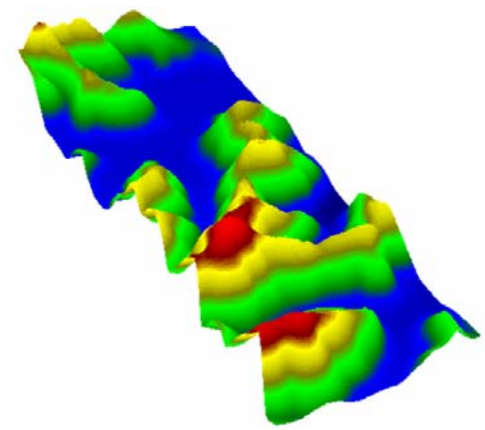

Figure 6. The simulated LADAR data

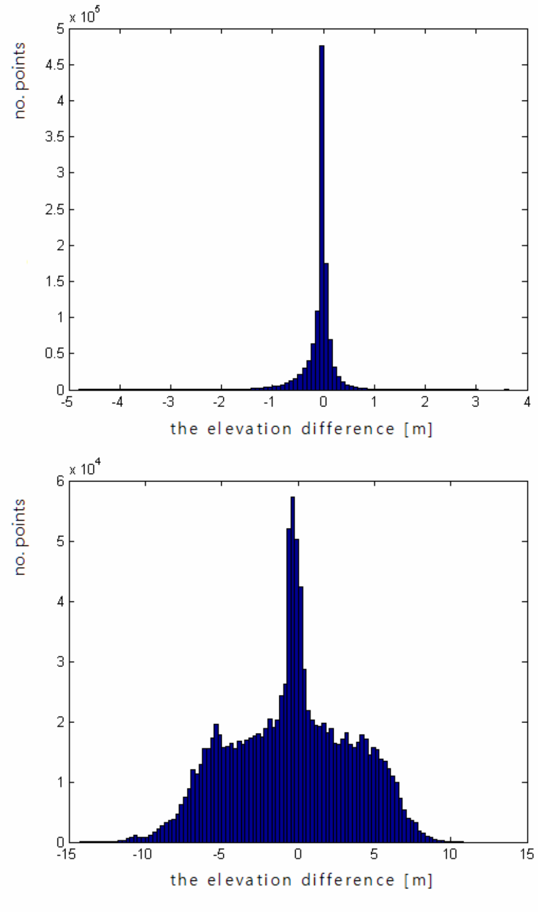

Figure 7. The histogram of the elevation differences between the simulated LADAR points and the input DEM

4. CONCLUSIONS

In this study, we derive the LADAR sensor equation and present a simulation method based on this equation using a ray-tracing algorithms. Using this method, we have successfully generated simulated LADAR data based on an input DEM and the specified system parameters.

The simulated data acquired by the simulator developed by this study will be effectively contributed to developing the data processing algorithms for diverse LADAR applications as the developments require various test data to assess the performance of the algorithms being developed. Furthermore, since the simulation will enable to determine the data quality to be acquired more economically and rapidly before the actual flight, it will be usefully applied to optimizing the system parameters during the development of a LADAR system.

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