A PARAMETERIZED SIMULATION OF DOPPLER LIDAR

by

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A proposal submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Electrical Engineering

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UTAH STATE UNIVERSITY
Logan, Utah

2017

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CHAPTER 1

INTRODUCTION

Recent and upcoming missions for the exploration of solar system bodies require accurate position and velocity data during the descent phase to ensure safe landing at predesignated sites. Because of inertial measurement unit (IMU) drift during travel, the data provided by the IMU may not be reliable. One solution proposed by NASA is the use of a frequency modulated continuous wave (FMCW) Doppler lidar system during the landing phase to provide additional information about attitude, position, and velocity to contribute to a successful landing [1–3]. The optimization and comparison of potential configurations of such a system would be greatly aided by an appropriate simulation tool.

LadarSIM is a robust parametrized simulation tool for time of flight lidar developed at Utah State University's Center for Advanced Imaging Ladar over the past decade and a half [4, 5]. LadarSIM has the flexibility to simulate a wide range of time of flight lidar systems with varying beam and scanner patterns as well as parametrized transmitters and receivers. These simulated systems can be evaluated using scenarios consisting of user specified terrain, targets, and flight paths.

The proposed research has three objectives. First, to add a parameterized simulation of an FMCW lidar transmitter and receiver, second, utilize that simulation to perform a trade-off study to determine the effects of varying laser transmission power, beam divergence, aperture diameter, and FFT size on a Doppler lidar system, and third, to use the simulation to compare traditional and novel scanning patterns in planetary landing scenarios.

The resulting simulation will be useful in the development of Doppler lidar systems with a wide range of transceiver characteristics and nearly arbitrary beam and scanning parameters. The information gained from the trade-off study will provide valuable insight for someone designing or selecting a Doppler lidar system to meet mission requirements. Point clouds from the comparison of scanning patterns will test the potential utility of a

Doppler lidar system for terrain mapping, navigation, and hazard avoidance.

CHAPTER 2
LITERATURE REVIEW

2.1 Frequency Modulated Continuous Waveform Homodyne Detection

A continuous wave radar in which a single microwave oscillator serves as both the transmitter and local oscillator (LO) is, generally speaking, a homodyne radar. Frequency modulated continuous waveform (FMCW) radar systems often leverage a homodyne architecture. In FMCW homodyne radar, the continuous wave signal is modulated to create a linear chirp which is transmitted via antenna toward a target. The return echo signal, which is delayed in time, is mixed with the LO signal. The result is a signal which is comprised of a linearly increasing chirp signal, which is actively filtered out, and the beat frequency which is used for detection [6].

Because microwaves and lasers are both electromagnetic radiation, just in different segments of the electromagnetic spectrum, an FMCW homodyne lidar can be developed by replacing components such as the antenna and the microwave oscillator with equivalent devices for creating, transmitting, receiving, and analyzing a laser signal.

2.2 Simplified Homodyne Detection

Adany et al. describe the operation and performance of a simplified homodyne detection scheme. In this scheme a waveform generator drives an electro-optic modulator which modulates an optical signal from a laser. The resulting signal is split into two parts. One part is amplified and sent to the telescope and the other is used as the local oscillator. The returning signal from the telescope is optically mixed with the local oscillator signal and detected by a balanced photodetector. An FFT is then performed on the detected signal to determine detected range and speed. [7]. This scheme was tested on NASA's Morpheus test vehicle in order to demonstrate its utility as a potential instrument for planetary landing missions. [1–3, 8]. Because of its use by NASA, the simplified homodyne detection scheme has been selected as the basis of the Doppler lidar simulation in LadarSIM.

2.3 Simplified Homodyne Performance

Adany et al. tested their lidar at ground level at ranges of 50 m and 370 m [7]. The NASA instrument has been tested mounted on a helicopter and the morpheus test vehicle to demonstrate its performance. In the helicopter tests, the altitude was varied from approximately 50 m to 1700 m [9, 10]. The Morpheus test vehicle was launched to a 250 m altitude then descended along a 30 degree path to a simulated landing field [8]. These tests provide useful data to compare with simulated results. The results of Adany et al. are particularly interesting because they include a return spectrum from the 370m experiment which will be useful in comparing to simulated spectra. The experiments of Adany et al. fall short in that the targets all had relatively good reflectivity and an approximately 90 degree angle incidence; therefore, there is little to be learned about spectra resulting from non-ideal conditions. The experiments performed by NASA accurately mimic real world circumstances but no data on the resulting spectra is provided and no information on the performance of the system at long ranges.The simulation proposed will therefore provide insight on data which is not readily available, performance information and spectra from non-ideal scenarios. This data will be useful in making decisions about Doppler lidar system characteristics as well as improving detection algorithms for Doppler lidar.

2.4 Spectrum Analysis Methods

A key step in the detection of FMCW lidar or radar is obtaining the frequency spectrum of the returned signal. This is typically done with an FFT. Resolution of range and speed is inextricably tied to the resolution in frequency domain. Hence, obtaining many samples of the returned signal and performing a large FFT on that signal allows for good resolution. While it is necessary that the FFT be large, only a relatively small number of the bins will contain peaks of the return signal. In order to reduce computational complexity and potentially increase performance, alternative methods can be used to obtain the return spectrum. Al-Qudsi et al. demonstrate how a Zoom FFT (ZFFT) can be used to significantly decrease the computational complexity fo FMCW radar. The ZFFT works by determining what portion of the total signal is of interest then filtering the signal to isolate the signal of interest so that a smaller FFT can be performed [11]. A second approach is the Chirp Z-transform. In short, the Chirp Z-transform differs from the FFT in that the spacing of frequency bins does not need to be uniform. Using the Chirp Z-transform frequency bins can be placed densely where high resolution is required and sparsely where it is not, potentially resulting in better resolution on important details with less computational complexity [12, 13].

2.5 Probability of Dropout and False Alarm

Two very important metrics in evaluating the performance of a Doppler lidar system are probability of detection and false alarm rate. Probability of detection describes the probability that a detection will not be missed and the probability of false alarm describes the probability that something will be detected which is not part of the true return signal. Both of these phenomena are cause by noise in the signal either pulling a returned signal below the detection threshold or simply noise peaking above the detection threshold. In order to simulate this behavior, it is necessary to simulate the noise in the bins of the FFT. Mark A. Richards provides an in-depth derivation of this [14]. Wang et al. also examine the effects of noise on an FMCW radar's performance along with picket fence effect and derive the detection probability and false alarm probability as well as propose an improved threshold detection method [13].

CHAPTER 3
RESEARCH AND DESIGN METHODS

3.1 Simulation Development

LadarSIM is a robust and realistic simulation tool which accurately simulates the real world behavior of a lidar system [4, 5]. LadarSIM works by first performing a geometric simulation on the scenario. During this stage of the simulation, user specified beam scanning patters, platform flight paths, and terrain are used to obtain the true measurements of range that a perfect lidar system would produce. The next stage of simulation, called the radiometry simulation, takes these true measurements and simulates the effects of transmission, environmental and target interactions, receiver processes, and detection. Using the results of this simulation, a point cloud is created which represents the data the simulated lidar would receive in the scenario.

In order to add a simulation of FMCW Doppler lidar to LadarSIM, both stages of this simulation process must be updated to different degrees. The geometry simulation only needs to be modified to include the true velocity measurements in addition to range. On the other hand, there is little overlap between the process of simulating time of flight lidar and Doppler lidar. It is therefore expected that the bulk of the time in updating LadarSIM will be spent creating the simulation of the Doppler transceiver.

3.2 Trade-off Study

The goal of this part of the proposed research is to ascertain and demonstrate the effects of particular parameters on the performance of a Doppler lidar system using the simulation to be developed. The parameters to be studied are laser transmission power, beam divergence, aperture diameter, and FFT size. These parameters have been selected because of their potential effect on the overall performance, cost, power consumption, weight, and computational power of a system. The results of this research will simplify the task of designing or selecting a Doppler lidar system by providing information about where to best allocate resources to achieve performance requirements. The updated LadarSIM software will be used to simulated Doppler lidar systems with varying transmission power, beam divergence, aperture diameter, and FFT size. The performance of these systems will be evaluated in a variety of scenarios by calculating and recording the probabilities of detection and false alarm.

3.3 Scanning Pattern Experiments

NASA's current Doppler lidar instrument, which was tested on the Morpheus test platform uses a fixed telescope that sends beams in 3 directions [1–3, 8]. The resulting scan pattern is useful because it provides 3 points per scan which can be used to obtain attitude and velocity vectors relative to the terrain during landing. This is useful but has disadvantages. Three is the minimum number of points necessary to obtain attitude and velocity vectors. This means that if one point is dropped for any reason it will not be possible to obtain those vectors. The angles between these points are also fixed. There has been some interest on the part of NASA to investigate alternative telescope solutions which would allow for flexible scanning patterns potentially fixing these and other problems with the current system [15]. It is possible that novel scanning patterns could provide better performance in obtaining attitude and velocity data during landing and potentially be used in terrain mapping or hazard avoidance.

Using the updated LadarSIM software, the three point scanning pattern used by NASA as well as other novel scanning patterns will be simulated and compared to research how scanning patterns can improve the reliability of navigational data and explore what roles Doppler lidar systems may potentially fill in future missions.

CHAPTER 4

CONCLUSION

Doppler lidar can contribute useful data in determining altitude, speed, and position of a space craft during the landing phase of a mission. Under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) project, NASA has been developing Doppler lidar systems to provide this data [2]. It is clear that Doppler lidar will play a role in forthcoming space exploration missions. The process of optimizing, improving performance, and developing novel scanning patterns will be greatly aided by the availability of a simulation tool specific to Doppler lidar. Such a tool will be developed and added to the LadarSIM software package.

Using the Doppler lidar simulation a trade-off study will be performed to determine the effects of laser transmission power, beam divergence, aperture diameter, and FFT size on the performance of a Doppler lidar system. The results of this research will simplify the task of designing or selecting a Doppler lidar system by providing information about where to best allocate resources to achieve performance requirements.

Traditional and novel scanning patterns will be simulated and compared. This could provide information on how a particular scanning pattern might improve the reliability of data for a Doppler lidar. By simulating novel scanning patterns, this research will explore the potential utility of Doppler lidar in terrain mapping and hazard avoidance for a planetary landing mission.

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