Long-Range Imaging Radar for Autonomous Navigation

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the University or any other institute of higher learning, except where due acknowledgement has been made in the text.

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Abstract

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This thesis describes the theoretical and practical implementation of a long-range high-resolution millimetre wave imaging radar system to aid with the navigation and guidance of both airborne and ground-based autonomous vehicles. To achieve true autonomy, a vehicle must be able to sense its environment, comprehensively, over a broad range of scales. Objects in the immediate vicinity of the vehicle must be classified at high resolution to ensure that the vehicle can traverse the terrain. At slightly longer ranges, individual features such as trees and low branches must be resolved to allow for short-range path planning. At long range, general terrain characteristics must be known so that the vehicle can plan around difficult or impassable obstructions. Finally, at the largest scale, the vehicle must be aware of the direction to its objective.

In the past, short-range sensors based on radar and laser technology have been capable of producing high-resolution maps in the immediate vicinity of the vehicle extending out to a few hundred metres at most. For path planning, and navigation applications where a vehicle must traverse many kilometres of unstructured terrain, a sensor capable of imaging out to at least 3km is required to permit mid and long-range motion planning. This thesis addresses this need by describing the development a high-resolution interrupted frequency modulated continuous wave (FMICW) radar operating at 94GHz.

The contributions of this thesis include a comprehensive analysis of both FMCW and FMICW processes leading to an effective implementation of a radar prototype which is capable of producing high-resolution reflectivity images of the ground at low grazing angles. A number of techniques are described that use these images and some *a priori* knowledge of the area, for both feature and image based navigation. It is shown that sub-pixel registration accuracies can be achieved to achieve navigation accuracies from a single image that are superior to those available from GPS.

For a ground vehicle to traverse unknown terrain effectively, it must select an appropriate path from as long a range as possible. This thesis describes a technique to use the reflectivity maps generated by the radar to plan a path up to 3km long over rough terrain. It makes the assumption that any change in the reflectivity characteristics of the terrain being traversed should be avoided if possible, and so, uses a modified form of the gradient-descent algorithm to plan a path to achieve this.

The millimetre wave radar described here will improve the performance of autonomous vehicles by extending the range of their high-resolution sensing capability by an order of magnitude to 3km. This will in turn enable significantly enhanced capability and wider future application for these systems.

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Contents

List of Figures

List of Tables

List of Acronyms

2-D	Two Dimensional
3-D	Three Dimensional
AC	Alternating Current
ACFR	Australian Centre for Field Robotics
ADC	Analog to Digital Converter
AFC	Automatic Frequency Control
AGV	Autonomous Ground Vehicle
ALG	Automatic Landing Guidance
AM	Amplitude Modulation
AR	Autoregressive
ARMA	Autoregressive Moving Average
BAW	Bulk Acoustic Wave
BPSK	Binary Phase Shift Keying
CFAR	Constant False Alarm Rate
CMU	Carnegie Mellon University
CRT	Cathode Ray Tube
CW	Continuous Wave
DAC	Digital to Analog Converter
DARPA	Defense Advanced Research Projects Agency
dB	Decibel
dBi	Decibel relative to isotropic
dBm	Decibel relative to one milliwatt
DBS	Doppler Beam Sharpening
dBW	Decibel relative to one watt
DC	Direct Current
DDS	Direct Digital Synthesis
DERA	Defence Evaluation and Research Agency
EIK	Extended Interaction Klystron
EM	Electro Magnetic
EMI	Electro Magnetic Interference
ENR	Excess Noise Ratio
EPROM	Erasable Programmable Read Only Memory
FET	Field Effect Transistor
FFT	Fast Fourier Transform
FM	Frequency Modulation
FMCW	Frequency Modulated Continuous Wave
FMICW	Frequency Modulated Interrupted Continuous Wave
GPS	Global Positioning System

HUD	Head Up Display
HUT	Helsinki University of Technology
I-Q	In-Phase Quadrature
ICC	Intelligent Cruise Control
IF	Intermediate Frequency
IHS	Intensity Hue Saturation
ILS	Instrument Landing System
IMPATT	Impact Avalanche Transit Time
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
ILO	Injection Locked Oscillator
IPA	Integrated Phased Array
IR	Infra Red
LO	Local Oscillator
LIDAR	Light Detection and Ranging
LNA	Low Noise Amplifier
LWC	Liquid Water Content
MOPA	Master Oscillator Power Amplifier
MUSIC	Multiple Signal Classification
mW	Milliwatt
MW	Megawatt
NF	Noise Figure or Noise Factor
PCM	Pulse Coded Modulation
P_d	Probability of Detection
PDF	Probability Density Function
P_{fa}	Probability of False Alarm
PILO	Pulsed Injection Locked Oscillator
PIN	Positive Intrinsic Negative
PLL	Phase-Locked Loop
PPI	Plan Position Indicator
RCS	Radar Cross Section
RF	Radio Frequency
RMS	Root Mean Square
Rx	Receive(r)
SAR	Synthetic Aperture Radar
SAW	Surface Acoustic Wave
SCR	Signal to Clutter Ratio
SDLA	Successive Detection Log Amplifier
SNR	Signal to Noise Ratio
SVTD	Synthetic Vision Technology Demonstrator
TUM	Technische Universität München
Tx	Transmit(ter)

UAV	Unmanned Airborne Vehicle
UHF	Ultra High Frequency
VCO	Voltage Controlled Oscillator
YIG	Yttrium Iron Garnet