Long-Range Imaging Radar for Autonomous Navigation

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of the requirements for the degree of
Doctor of Philosophy

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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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<tbody>
<tr>
<td>2-D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3-D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ACFR</td>
<td>Australian Centre for Field Robotics</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>AFC</td>
<td>Automatic Frequency Control</td>
</tr>
<tr>
<td>AGV</td>
<td>Autonomous Ground Vehicle</td>
</tr>
<tr>
<td>ALG</td>
<td>Automatic Landing Guidance</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>AR</td>
<td>Autoregressive</td>
</tr>
<tr>
<td>ARMA</td>
<td>Autoregressive Moving Average</td>
</tr>
<tr>
<td>BAW</td>
<td>Bulk Acoustic Wave</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>CFAR</td>
<td>Constant False Alarm Rate</td>
</tr>
<tr>
<td>CMU</td>
<td>Carnegie Mellon University</td>
</tr>
<tr>
<td>CRT</td>
<td>Cathode Ray Tube</td>
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<tr>
<td>CW</td>
<td>Continuous Wave</td>
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<tr>
<td>DAC</td>
<td>Digital to Analog Converter</td>
</tr>
<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dBi</td>
<td>Decibel relative to isotropic</td>
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<tr>
<td>dBm</td>
<td>Decibel relative to one milli watt</td>
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<tr>
<td>DBS</td>
<td>Doppler Beam Sharpening</td>
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<td>dBW</td>
<td>Decibel relative to one watt</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DDS</td>
<td>Direct Digital Synthesis</td>
</tr>
<tr>
<td>DERA</td>
<td>Defence Evaluation and Research Agency</td>
</tr>
<tr>
<td>EIK</td>
<td>Extended Interaction Klystron</td>
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<tr>
<td>EM</td>
<td>Electro Magnetic</td>
</tr>
<tr>
<td>EMI</td>
<td>Electro Magnetic Interference</td>
</tr>
<tr>
<td>ENR</td>
<td>Excess Noise Ratio</td>
</tr>
<tr>
<td>EPROM</td>
<td>Erasable Programmable Read Only Memory</td>
</tr>
<tr>
<td>FET</td>
<td>Field Effect Transistor</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulation</td>
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<tr>
<td>FMCW</td>
<td>Frequency Modulated Continuous Wave</td>
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<tr>
<td>FMICW</td>
<td>Frequency Modulated Interrupted Continuous Wave</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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</tr>
<tr>
<td>HUD</td>
<td>Head Up Display</td>
</tr>
<tr>
<td>HUT</td>
<td>Helsinki University of Technology</td>
</tr>
<tr>
<td>I-Q</td>
<td>In-Phase Quadrature</td>
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<tr>
<td>ICC</td>
<td>Intelligent Cruise Control</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>IHS</td>
<td>Intensity Hue Saturation</td>
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<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
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<tr>
<td>IMPATT</td>
<td>Impact Avalanche Transit Time</td>
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<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
</tr>
<tr>
<td>INS</td>
<td>Inertial Navigation System</td>
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<tr>
<td>ILO</td>
<td>Injection Locked Oscillator</td>
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<tr>
<td>IPA</td>
<td>Integrated Phased Array</td>
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<tr>
<td>IR</td>
<td>Infra Red</td>
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<tr>
<td>LO</td>
<td>Local Oscillator</td>
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<tr>
<td>LIDAR</td>
<td>Light Detection and Ranging</td>
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<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>LWC</td>
<td>Liquid Water Content</td>
</tr>
<tr>
<td>MOPA</td>
<td>Master Oscillator Power Amplifier</td>
</tr>
<tr>
<td>MUSIC</td>
<td>Multiple Signal Classification</td>
</tr>
<tr>
<td>mW</td>
<td>Milliwatt</td>
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<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>NF</td>
<td>Noise Figure or Noise Factor</td>
</tr>
<tr>
<td>PCM</td>
<td>Pulse Coded Modulation</td>
</tr>
<tr>
<td>$P_d$</td>
<td>Probability of Detection</td>
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<tr>
<td>PDF</td>
<td>Probability Density Function</td>
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<tr>
<td>$P_a$</td>
<td>Probability of False Alarm</td>
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<tr>
<td>PILO</td>
<td>Pulsed Injection Locked Oscillator</td>
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<tr>
<td>PIN</td>
<td>Positive Intrinsic Negative</td>
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<tr>
<td>PLL</td>
<td>Phase-Locked Loop</td>
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<tr>
<td>PPI</td>
<td>Plan Position Indicator</td>
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<tr>
<td>RCS</td>
<td>Radar Cross Section</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>Rx</td>
<td>Receive(r)</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SAW</td>
<td>Surface Acoustic Wave</td>
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<tr>
<td>SCR</td>
<td>Signal to Clutter Ratio</td>
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<tr>
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<td>Successive Detection Log Amplifier</td>
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<td>SVTD</td>
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<tr>
<td>TUM</td>
<td>Technische Universität München</td>
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<td>Tx</td>
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<td>Acronym</td>
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<td>----------------------------------</td>
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<tr>
<td>UAV</td>
<td>Unmanned Airborne Vehicle</td>
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<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
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<tr>
<td>VCO</td>
<td>Voltage Controlled Oscillator</td>
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<tr>
<td>YIG</td>
<td>Yttrium Iron Garnet</td>
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