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16. Abstract

This report documents the research project "Evaluation of Current Technologies and Development of Novel Techniques for Detection of Obstacles Buried in Snow," performed in response to a California Department of Transportation (Caltrans) Request for Proposals (RFP). The project's goal was the development of a radar system to detect obstacles obscured by deep snow, and to provide range information for guardrails under snowbanks. After the project started, the need for such a system was re-evaluated by Caltrans end users and management, and it was determined that such a system would not currently be cost-beneficial. In response, research work on this project halted after approximately one quarter of work. This report documents the work performed in one quarter, which included the development of complete architecture and high-level system design, as well as preliminary detailed system design. The report also provides further information on the motivation and history of the project.

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Evaluation of Current Technologies and Development of Novel Techniques for Detection of Obstacles Buried in Snow

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ABSTRACT

This report documents the research project "Evaluation of Current Technologies and Development of Novel Techniques for Detection of Obstacles Buried in Snow," performed in response to a California Department of Transportation (Caltrans) Request for Proposals (RFP). The project's goal was the development of a radar system to detect obstacles obscured by deep snow, and to provide range information for guardrails under snowbanks. After the project started, the need for such a system was re-evaluated by Caltrans end users and management, and it was determined that such a system would not currently be cost-beneficial. In response, research work on this project halted after approximately one quarter of work. This report documents the work performed in one quarter, which included the development of complete architecture and high-level system design, as well as preliminary detailed system design. The report also provides further information on the motivation and history of the project.

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DISCLAIMER/DISCLOSURE

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aerospace Engineering at the University of California – Davis, and the Division of Research and Innovation at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

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LIST OF ACRONYMS AND ABBREVIATIONS

A/D	Analog-to-Digital converter
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
CAD	Computer-Aided Design
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
CW	Continuous Wave
D/A	Digital-to-Analog converter
DDS	Direct Digital Synthesis
DHCP	Dynamic Host Configuration Protocol
DHIPP	Digital Highway Inventory Photography Program
DOT	Department of Transportation
DRI	Caltrans Division of Research and Innovation
DSP	Digital Signal Processor
EM	ElectroMagnetic
ESC	Caltrans Equipment Service Center
FM	Frequency Modulation
FM-CW	Frequency-Modulated Continuous-Wave
GHz	GigaHertz
GPR	Ground-Penetrating Radar
HMI	Human Machine Interface
HUD	Head-Up Display
HW/SW	Hardware / Software
IF	Intermediate Frequency
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LFM	Linear Frequency Modulation
LO	Local Oscillator
MHz	MegaHertz
MUSIC	MUltiple SIgnal Classification
NRC	Non-Recurring Costs
OEM	Original Equipment Manufacturer
OLS	Caltrans Office of Land Surveys
PATH	Partners for Advanced Transit and Highways
PDF	Portable Document Format
R&D	Research & Development
RF	Radio Frequency
RFID	Radio Frequency IDentification
RFP	Request for Proposals
SDR	Software-Defined Radar
SPR	Surface-Penetrating Radar
S/W	Software

ACKNOWLEDGMENTS

CHAPTER 1:
INTRODUCTION

Background and Motivation

Under previous research, the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, in conjunction with its research partner, the California Partners for Advanced Transit and Highways (PATH), developed driver assistance and full automation for control of a rotary snow blower. This research included preliminary investigation into methods for detecting obstacles obscured by deep snow, with the goal of alerting the rotary plow operator before obstacles were ingested into the blower mechanism.

Based on these preliminary results, the California Department of Transportation (Caltrans) solicited research and analysis to determine the best method of detecting objects hidden under snow, in advance of snow removal equipment, specifically rotary snow blowers. The goal was to contribute to Caltrans' goal of increased safety for its maintenance workers, as well as increased efficiency for the snow removal operation. Rotary snow blower vehicles often collide with or ingest objects buried in snowpack—these objects range from small rocks and vehicular tire cable chains to large rocks and hidden vehicles. At a minimum, this results in snow blower downtime while the operator attempts to clear the ingested object on the roadside. In more serious cases, damage to stalled public vehicles or severe and costly damage to the rotary mechanism can result from a collision with a large buried object. Additionally, snow blowers typically impact or press on the face of guardrails when clearing roadside snowpack, thus partly or completely destroying the guardrail over the course of a winter maintenance season. The destruction of roadside guardrails entails a large replacement cost, and associated risk to the traveling public.

In response to the Caltrans Request for Proposals (RFP) identifying this problem, the AHMCT Research Center proposed research and development to directly address these problems by developing a state-of-the-art purpose-built radar system which can detect objects buried in roadside snowpack and display this information to the operator as efficiently as possible. The proposed research was to include research, development, field testing, and delivery of two state-of-the-art purpose-built hardware system prototypes: one for detecting buried objects in the path of the snow blower, and one for determining the lateral distance to a guardrail buried in roadside snowpack.

The first system would detect buried objects down to the size of cable chains that are in the path of vehicle travel. The second system would detect a buried guardrail at high resolution and speed sufficient to keep the snow blower operating at 2-6 inches from the face of the barrier. Related information would be displayed to the vehicle operator in the most intuitive and non-intrusive fashion. The systems would achieve this by utilizing frequency-modulated continuous-wave (FM-CW) radar techniques and implementing this radar in a novel architecture that lends itself to rapid reconfiguration.

The research methodology to be followed would include:

- Review of the most promising technologies in order to develop a ranking on their applicability to address the stated problem.

- A final best-fit technology would be selected, enhanced, and used to design a system which is compact, low-cost, robust, and reconfigurable while meeting all specification requirements.

The goal is not only to create a platform which facilitates research in software-defined radar (SDR), but to actually develop an SDR system which is field-ready, commercializable, and deployable for the purpose of detecting objects buried in snowpack.

The proposed systems would operate with much higher resolution and speed than existing ground-penetrating radar (GPR) systems, with implementation size being much smaller, and targeted commercialized system cost in the $1-$2k range. Since existing GPR systems, compared to our proposed systems, provide lower resolution, operate at relatively slow speeds, are larger in size, require additional development and integration, and typically cost between $15k and $50k on average, these systems are deemed inappropriate for solving Caltrans' current needs.

Deployment of the proposed systems would result in significant reductions in the frequency of collision with and ingestion of objects by snow blowers. This will have an immediate impact on operation in the form of time savings, repair and replacement costs, and increased public safety. By a preliminary estimate, the annual savings, per vehicle, by implementing the proposed systems could be on the order of $10k, not including the large but currently uncalculated benefits of increased public safety and reduced DOT liability. Therefore the system cost, which could be recovered early in the first season, seems small compared to the benefit that would be achieved by full deployment. The key deliverables of this project include:

- one field-proven prototype generalized collision avoidance buried object SDR and HMI system,

- one field-proven prototype SDR system with human machine interface (HMI) capable of providing lateral distance to a buried guardrail,

- a plan for commercialization and deployment,

- and the system documentation and final report.

After Caltrans issued its RFP based on perceived customer need, and awarded this research contract, the need for such a system was re-evaluated by Caltrans end users and management. At this time, Caltrans determined that such a system would not currently be cost-beneficial. In response, AHMCT halted research work and expenditures on this project after approximately one quarter of work. This report documents the project's progress, including complete architecture and high-level system design, as well as preliminary detailed system design.

CHAPTER 2:
PROBLEM DETAILS AND RADAR BACKGROUND

Rotary snow blowers are a core part of Caltrans' winter maintenance fleet. These vehicles remove snowbanks built up by snowplows, and blow up to four tons per hour of snow off of the shoulders. Operators must contend with the safety and operational hazards of hidden objects covered in snow [5].

When clearing the snowpack, the blower either collides with or ingests everything in its path. Although there are sometimes large buried objects such as abandoned cars or large rocks from land slides, typical buried objects are small rocks, tire carcasses, and tire and cable chains. Clearly ingesting any of these objects is undesirable as it causes damage to the snow blower cutting blades and internal machinery, e.g. the bearings. Additionally, it represents a cost in job and vehicle down-time, operator risk in roadside diagnosis, vehicle repair, and traffic delays. Collision with larger objects such as abandoned vehicles buried in snow represents a risk of property damage and associated liability. On a regular basis, snow blower operators ingest tire cable chains which can quickly wrap around the blower blades and/or bearings, stopping the blower operation. The operator must get out of the cab, diagnose the problem, and make cumbersome roadside repairs. In more severe cases, the vehicle must be removed from service and repaired back at the maintenance yard. Clearly there is a need for a system which can reliably detect these objects and report their location to the operator before collision or intake. This type of system must see through the snowpack and detect both large and small objects of various compositions with high resolution and accuracy. The current project was established to research and develop (R&D) a system which can rapidly and accurately determine the distance between the snow blower and the buried object, and relay this location to the operator in the most intuitive and least burdensome way possible.

Guardrail damage is an additional concern in rotary plow operations, and a variation of the above system can alleviate this problem as well. Considerable damage is caused to the guardrails each time a snow blower operator accidentally or intentionally utilizes the guardrail as a means of guidance during road clearing operations. The blower tends to collapse the face of the guardrail and/or causes the support posts to lean away from vertical. This results in the guardrail becoming ineffective in a collision from an automobile or other vehicle. Additionally, guardrail repair or replacement is expensive in material, labor, and time, as well as the associated delay to road travelers. When clearing snowpack from the roadsides it has been stated by Caltrans that the ideal clearance between the snow blower and the guardrail should be between 2-6 inches at all times [2]. Thus there is a well-defined need for a system which can keep the snow blower at the specified distance from the guardrail without disruption to the rail or surrounding infrastructure. As in the previous case, this system would need to relay this information, ideally utilizing the same human interface, in an intuitive and non-burdensome fashion. A second portion of this research effort involved parallel R&D of a system which can rapidly and accurately determine the distance between the snow blower and the guardrail and relay this distance to the operator in the most intuitive and least burdensome way. Such a sensor will provide a key enabling technology for driver assistance or control when operating near the guardrail. AHMCT intended to use this technology in a separate research project on Winter Maintenance Vehicle Guidance, thus providing synergy and cost savings to Caltrans.

This work began investigating two systems which detect objects buried in snowpack. One of these detection systems would be placed in front of the blower for detection of various buried objects, while the other system would be placed on the side of the blower and would detect the range to the buried guardrail. These systems would be based on a sensor, processing, and a human interface for displaying the necessary information. Since the primary component in these systems is the sensor, it is important to review the current literature for the competing technologies. In all cases we are talking about detecting objects in snowpack, i.e. the transmission medium is snow. So the question is: "What type of system signal can reliably propagate through this medium and sense the buried object?" The commonality of the transmission medium for both cases implies a common hardware basis for the sensing technology for the two systems, again leading to cost savings for Caltrans.

Research has been conducted at the AHMCT Research Center regarding radar at microwave frequencies for high-accuracy detection of objects buried in snowpack. The current state–of-the-art and applicable problems are well understood by the AHMCT researchers working in the area of surface-penetrating radar (SPR) [3,6,7]. The scope of the current project was to continue research in the area of modulated continuous-wave radar and develop a field-ready, deployable, and commercializable sensor which can be used in a system for detection of general buried objects in snowpack, and as a side-fire radar for detection and ranging of buried guardrails in snowpack. In both cases the system will be required to operate at a sufficiently high frequency to provide the necessary resolution while providing the required range. In the case of guardrail detection, the system will employ a modulation scheme to provide high–resolution, high-speed, close-range detection. In the case of the forward buried object detector, the system will use the same hardware as the side-fire radar, but will be loaded with additional firmware to determine the bearing to the buried object. In general, all hardware will be identical and compact, with low cost targeted by using commercial off–the-shelf (COTS) components common in current wireless devices. The goal is to have a common, low-cost user interface which can display both the distance to the guardrail as well as the range and bearing to buried objects in front of the snow blower. This generalized system can be used in the target applications, and can function as a research testbed for development of more advanced radar modulation schemes and research into the optimal angle-of-arrival of a received signal.

The system would have an immediate impact on existing snow blower operations and guardrail infrastructure. The result of this research would be a field-ready system which can solve the current problems of snow blower buried object detection without any change to the existing infrastructure. The main goal is to develop a generalized system which can be used to detect the distance and bearing to a general buried object as well as the distance to a buried guardrail as a single, highly-integrated, upgradeable, low-cost system. This allows any vehicle which needs to detect objects buried in snowpack to immediately use this system. As a result, snow blower operators will reduce their downtime, virtually eliminate vehicle and infrastructure damage due to collisions, and reduce overall costs. The frequency of costly guardrail repair or replacement will be substantially reduced. Additionally, public safety will be improved through reduction of unintended delays and properly functioning barriers. Clearly this project is essential to the improvement of our transportation system. Without such a system, plow operators will continue to suffer breakage and downtime due to ingestion of buried objects, with associated monetary costs and safety liabilities. Additionally, many miles of roadside guardrail will continue to be damaged, increasing repair costs, and reducing overall public safety.

Existing commercial radar systems are not appropriate for the rotary plow obstacle detection application. As such, there is a need for a field-ready obstacle detection system carefully engineered and developed to Caltrans' special requirements, i.e. purpose-built. Research into advanced radar systems has been conducted by the AHMCT Research Center. Our theoretical analysis, computer simulation, and initial feasibility tests have shown that a cost-effective solution is viable. The ability to detect and avoid these obstacles will provide immediate improvements in Caltrans snow removal operations, with associated benefits in overall operations cost, as well as a reduction in the risks to Caltrans operators and vehicle maintenance personnel.

Anticipated Outcome & Initial Cost Benefit

The objective of this research was the R&D of practical snowbank obstacle detection methods and systems, leading to prototype hardware engineered to meet Caltrans' requirements.

These systems would be composed of fully-developed stand-alone hardware and an operator display interface. Both systems share many common modules, making this parallel development possible and highly cost-effective. The systems would be field-tested as part of the project. The system designs will explicitly incorporate engineering constraints to target rugged, reliable, and effective systems that are low-cost and easily installed and maintained, leading to deployment-ready systems at the end of the project. The systems would be designed to be ready for deployment into Caltrans Winter Maintenance operations. Improvements would include safety and operating efficiency gains by preventing ingestion of buried obstacles, and reduced guardrail maintenance due to improved on-road rotary operations, all resulting in potentially significant cost savings for the Department of Transportation (DOT).

Certainly, a research project of this type could be directly reproduced and sold as a commercial product. However, in a truly commercialized product the system needs to be designed with an eye on cost and manufacturability at every step during the research and development stage. Fortunately, this is an essential component of AHMCT's general research approach and goals. The goal is a radar platform which can be readily reproduced at low cost, for Caltrans benefit and to facilitate AHMCT's internal research of advanced radar modulation schemes and signal processing. Another major phase in the commercialization of any product is making sure the product is fully debugged and meets all system requirements. The project entails a substantial research-grade debug and development phase. As a result of the built-in design for reuse/upgradeability, this system could be modified at any time without requiring hardware redesign. The final commercial products must be fully qualified and would require additional testing and debugging. Although such detailed testing and debugging is out of the scope of this project, it would be facilitated by the nature of the design. Finally, suitable system packaging must be developed and manufactured. In summary, the outcome of this research effort would be a system that is as close as possible to a commercialized product within the context of a research effort.

It is possible to provide a preliminary and rough estimate of commercialization costs—of course, these are speculative, and ultimately these costs are outside of the control of the researchers. Based on the projected parts costs in manufacturing quantities greater than 1000, the costs required to perform system qualification and package development, and associated vendor

profit margin, it is feasible that systems could be commercialized and sold competitively in the $1-2k range. Obviously, lower quantities would result in increased system costs.

There is a direct cost benefit to implementation of these systems, and it is possible to provide a rough estimate. Of course, variations on the assumptions can be made as appropriate given more detailed knowledge, particular of downtime and guardrail costs. Assume a user purchases a buried object radar and a guardrail radar with unified display for total system cost of $5k. Also, assume during an average season an operator would ingest one chain a week with two hours downtime for repairs, as well as ingest two other objects per season that each require four hours repair at the maintenance shop. Additionally, assume the replacement cost of a 25 foot section of guardrail is $800, and that on average snow blowers cause 250 feet of accidental damage per season each. If employees are paid $50/hour then during an average six month season there is a loss of $3k in operator and mechanic labor, and $8k worth of damaged guardrail, plus unknown loss due to public vehicular accidents. This rough analysis excludes the cost of traffic accidents due to snow blowers stopped on the side of the road, related economic impacts due to decreased mobility, and increased injury due to damaged or ineffective shoulder guardrails.

CHAPTER 3:
RADAR SYSTEM DESIGN

Based on a survey of existing technologies, and on the desire of Caltrans maintenance to not have any mechanical methods of object detection or rejection, it was proposed to detect buried objects using electromagnetic technologies. Specifically radar was the proposed method to both detect guardrails adjacent to the vehicle and buried objects in front of the vehicle in question. In this discussion it is assumed that the radar is operating in snowpack and ranging objects also buried in the same snowpack.
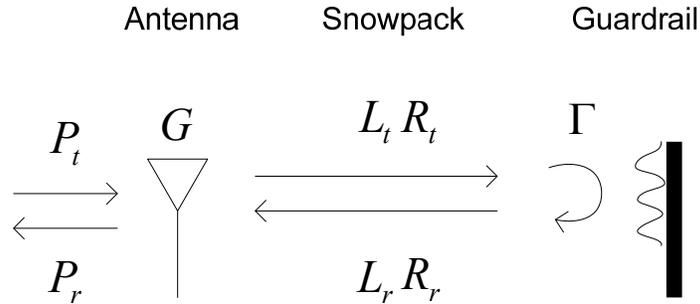
Antenna   Snowpack   Guardrail

$$P_t \quad G \qquad L_t\, R_t \qquad \Gamma$$

$$P_r \qquad\qquad L_r\, R_r$$

Figure 1: Channel path loss model for the guardrail radar

The channel model in Figure 1 represents the radar antenna mounted on the side of the rotary plow facing the guardrail looking through snowpack. The radar would transmit a signal with a power level of P_t, where it would be attenuated and isotropically radiate as it travels through the snowpack. The incident signal on the guardrail would then be reflected back towards the radar, be attenuated and isotropically radiate again, and then be received with a signal power of P_r. This received power can be determined given the well known radar equation [6].

$$P_r = \frac{P_t G_t L_t \Gamma L_r G_r}{4\pi R_t^{\,2}\, 4\pi R_r^{\,2}} \; . \tag{1}$$

where P_r is the power returned to the receiving antenna, P_t is the transmitted power, G_t and G_r are the gains of the transmitting and receiving antennas, L_t and L_r are the path loss coefficients due to attenuation (here, by snowpack), Γ is the reflection coefficient, and R_t and R_r are the distances from the transmitter and receiver to the target.

Equation (1) specifies the signal power return given the transmit power, antenna gain, snowpack loss, range to guardrail, and guardrail reflection coefficient. Because the path loss and range are the same for both the incident and reflected directions (i.e. $R_r = R_t \equiv R$), with $G_r = G_t \equiv G$ and $L_r = L_t \equiv L$, (1) can be rearranged into (2) to determine L_{ch}, the loss of the channel.

$$L_{ch} = \frac{G^2 L^2 \Gamma}{\left(4\pi R^2\right)^2} \; . \tag{2}$$

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$$\Gamma = \frac{\lambda^2 \sigma}{4\pi} \, ,$$

(3)

where λ is the signal wavelength, and σ is defined as

$$\sigma = \frac{4\pi w^2 h^2}{\lambda^2} \, .$$

(4)

The reflection coefficient for a flat-sheet reflector [6] with width w and height h can be determined by substituting (3)-(4) into (2) as

$$L_{ch} = \frac{G^2 L^2 w^2 h^2}{\left(4\pi R^2\right)^2} \, .$$

(5)

Given the attenuation of RF energy of snow as a function of frequency it is determined that a frequency of 1 GHz gives an attenuation of -8 dB/m at 10% moisture content [1]. Although lower frequencies exhibit less attenuation, higher frequencies have smaller wavelengths and thus have smaller RF circuitry. 1 GHz is an acceptable initial frequency for research. Given (5), the approximate dimensions of a typical guardrail section, and the path loss of snow pack, we can determine that our channel attenuation is -100 dB at 3 m. This is a very high attenuation and thus necessitates a very sensitive receiver.

Traditional radar is based on time of flight of a transmitted pulse. Since electromagnetic signals travel at the speed of light (3 x 10^8 m/s), the time between transmit and receive pulses at 1 m range would be 3.3 ns. This requires very fast and expensive hardware for a short-range radar. Therefore phase-based continuous wave (CW) radar, which measures the phase difference between the transmit and receive signals, is better for the current application. Linear frequency-modulated (FM) continuous wave (FM-CW) radar varies transmit frequency linearly so that the received signal is offset in frequency proportional to the range of the object. The transmit and receive signals are then multiplied, resulting in a tone representing the difference between the two signal frequencies, and hence the object range. The modulation signal waveform is saw-tooth and the frequency is chosen as to meet maximum range requirements while simultaneously keeping the frequency high enough to provide necessary resolution. Each object or reflection provides an additional delay and hence a different resulting tone representing range. This allows for the simultaneous detection of multiple objects. A general system level model of the radar system is shown in Figure 2. A more detailed block diagram of the radar system is shown in Figure 3.
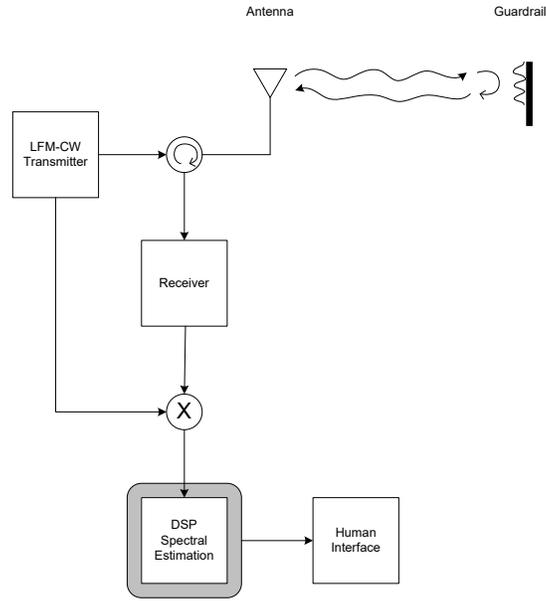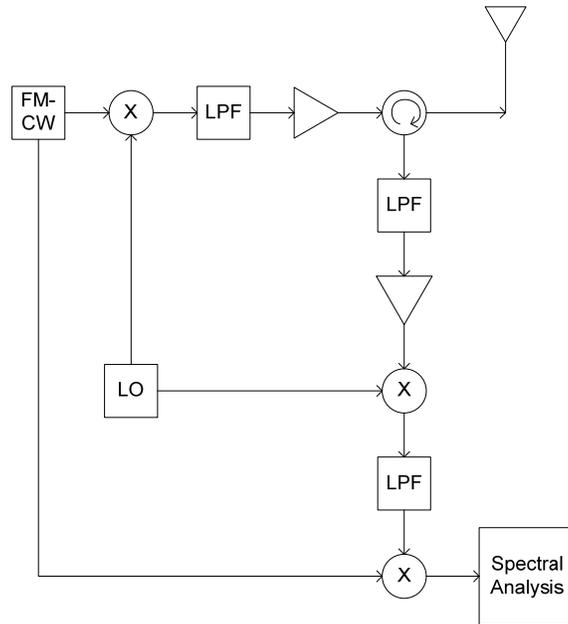
Figure 2: Radar system block diagram

Figure 3: Detailed radar system block diagram

Based on the principle of FM-CW radar [4] with the processing done at intermediate frequency (IF), the following equations (6)-(11) show that IF processing holds. The resultant signal in equation (11) will be a tone with frequency proportional to the object range.

The FM-CW baseband signal is represented as

$$x(t)_{tx\_if} = A\cos(\Delta\omega m(t)).$$

(6)

The baseband signal is then up-converted to RF and filtered and transmitted:

$$x(t)_{tx\_rf} = A' \cos(\omega_c t + \phi_A + \Delta\omega m(t)t) .$$
(7)

The RF phase-delayed received signal is filtered:

$$x(t)_{rx\_rf} = B' \cos(\omega_c t + \phi_B + \Delta\omega m(t - \tau)t) .$$
(8)

The RF received signal is down-converted and filtered:

$$x(t)_{rx\_if} = B \cos(\Delta\omega m(t - \tau)) .$$
(9)

A mixer output which is filtered can be represented as a multiplication of two signals:

$$x_c(t) = x_a(t) \cdot x_b(t) .$$
(10)

The output of the mixing of the original FM-CW baseband signal (6), and the received phase delayed FM-CW signal (9) is

$$x_c(t) = \cos(\phi_A - \phi_B) + \Delta\omega(m(t) - m(t - \tau)) t .$$
(11)

What is important is the second quantity in (11). This represents a single tone proportional to the distance between the radar and the reflective object.

The system implementation of the RF front-end which implements equations (7)-(9) is shown in Figure 4.
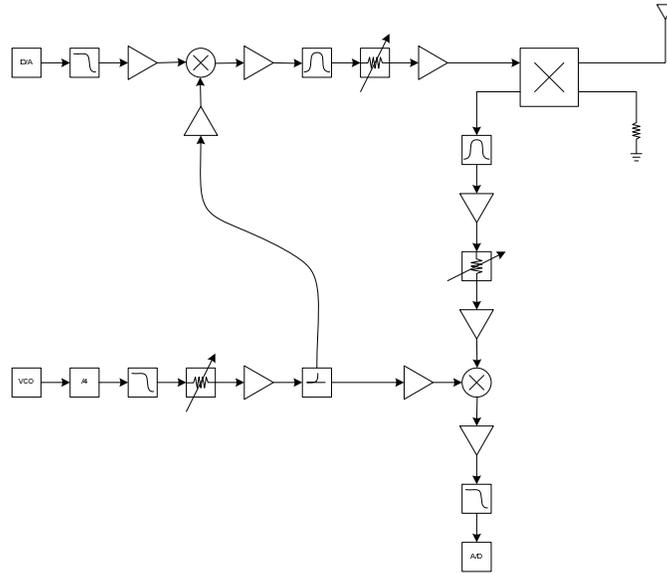

Figure 4: Radar system front-end block diagram

The FM-CW baseband signal is created using direct digital synthesis (DDS) and input to the front-end in Figure 4 through the D/A. The signal is lowpass filtered, amplified, and then up-converted to 1 GHz, filtered and then amplified to +20 dBm (100 mW) before being transmitted out the antenna. Once transmitted through the wide-beam low-cost planar antenna, the reflected

signal is received, filtered, amplified, and then down-converted. The received IF signal is filtered, then sampled by the A/D, and then fed to the DSP unit. This RF front-end can operate over a wide dynamic range, as is required when the radar is to operate both in snowpack and free air. In the free-air case the radar would transmit +20 dBm and the majority of that power could be reflected back, depending on the distance to the guardrail, and overload the receiver front-end. To address this concern, there are variable attenuators at both the transmit and receive chains of the front-end that would be dynamically adjusted depending on the receive power level. Since the remainder of this radar system is implemented digitally, the architecture is general enough to allow for the exploration of several signal types. Also by shifting the majority of the signal processing to the DSP, the front-end cost is kept to a minimum. At the time of the noted project cancelation, the entire RF front-end as depicted in Figure 4 was designed and simulated with the Local Oscillator (LO), and some amplifier prototypes were fabricated. All of the blocks in Figure 4 were designed with commercial off-the-shelf (COTS) RF components, except for the filters, power dividers, and couplers. These were implemented using discrete components and microstrip. The ultra-compressed rat-race 3 dB hybrid coupler is shown in Figure 5.
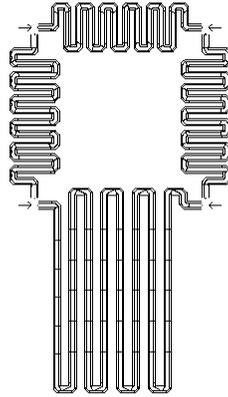

Figure 5: Ultra-compressed rat-race 3-dB coupler

All signal processing blocks in Figure 6, such as the linear frequency-modulation (LFM) signal, lowpass filter, calibration/control, mixer, and spectral estimation, are implemented on a DSP. This allows for design exploration without having to redesign/implement the radar frontend. The LFM creates the FM-CW baseband signal that is input into the front-end D/A. The received IF signal is A/D-converted and sampled, the DSP then lowpass filters the signal, and the power level is calculated for control of the front-end attenuators. This filtered signal is then digitally multiplied with the LFM baseband signal, followed by spectral estimation of the resultant frequencies. Each spectral peak represents a ranged object. The lowest frequency is the closest object. Of course, the actual input will not be pure tones, but several wide tones in the frequency spectrum. Well-known spectral estimation techniques such as MUSIC (MUltiple SIgnal Classification) are implemented in the DSP to estimate the center frequency of the spectral components from the noisy input signal [8].
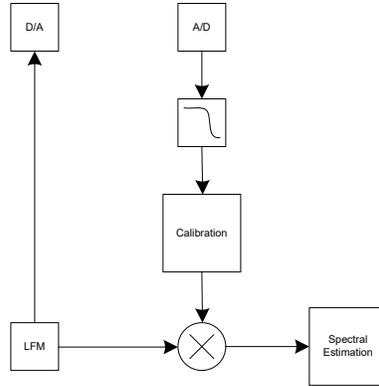
Figure 6: Radar system back-end

In general there will be one strong signal representing the guardrail. There could be objects ranged beyond the guardrail which will show up in the spectrum at higher frequencies since they are further away. The goal is to determine with high accuracy what is the closest object represented by the frequency spectra independent of the signal strength.

An optional use of the CW-FM radar is to determine if objects are directly in the path of the rotary plow and reject objects that are not. Two of the preceding RF front-ends with spectral estimation, could be used to determine object range and heading with simple geometry. The two font ends would be packaged in separate enclosures and placed on the front of the rotary plow below the snow line. Both front ends would be controlled by a single backend that would operate the radar units in a cyclical fashion. There are two cases of frontal object detection. The first case is that of a single object possibly in the path of the rotary plow as seen in Figure 7. The first radar R_1 would be enabled and make a range estimate, and then the second radar R_2 would be enabled and make a range estimate.
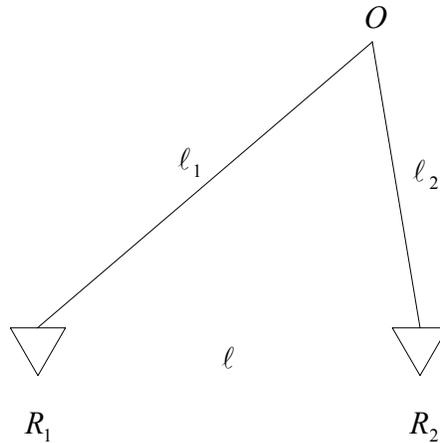

Figure 7: Single object location estimation

Knowing these ranges and the distance between the two radar front-ends, we can unambiguously determine the object location. If equation (12) holds then the object is between

R_1 and R_2 and thus in the path of the rotary plow. If equation (12) is false, then the object should be ignored, as it is not in the plow path.

$$\sqrt{\ell^2 + \min(\ell_1, \ell_2)^2} \geq \max(\ell_1, \ell_2)$$

(12)

The second case with multiple objects is show below in Figure 8. Each radar is to operate in the normal fashion and make two range estimates for the two unknown object locations. For example, R_1 would estimate the distance l_1 from R_1 to O_1, and the distance l_2 from R_1 to O_2 and back to R_1. Similarly for R_2 distances l_3 and l_4.
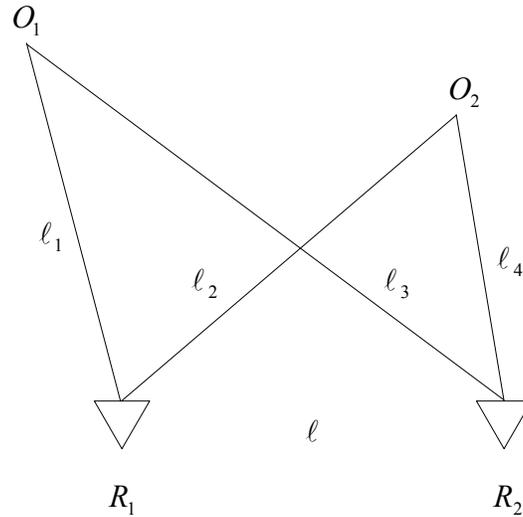

Figure 8: Multiple object location estimation

However, keep in mind that each radar doesn't have any knowledge of what the other radar is doing. If we stopped here we would have ambiguity in our solution since we don't know whether to use pair l_1 and l_3 or l_1 and l_4 to determine the location of O_1, and similarly for pairs for O_2 location. Although we can determine the location of two correct objects we will also determine the location of two ghost objects. The dilemma is that we will not know which are the two correct object locations.

The key to resolving this ambiguity problem is to operate the radars in a second mode. In the second mode the signal would be transmitted by one radar, reflect off of an object and then be received by the other radar. So a measurement would be made from R_2 to O_1 and then to R_1, also from R_2 to O_2 and then to R_1.

Equations (13)–(16) represent the range estimates made at R_1, and equations (17)-(18) represent the range estimates made at R_2.

$$E_1 = R_1 O_1 R_1$$

(13)

$$E_2 = R_1 O_2 R_1$$

(14)

$$E_3 = R_2 O_1 R_1 \tag{15}$$

$$E_4 = R_2 O_2 R_2 \tag{16}$$

$$E_5 = R_2 O_1' R_2 \tag{17}$$

$$E_6 = R_2 O_2' R_2 \tag{18}$$

We also know that estimates E_1, E_2, E_5, and E_6 are mode one estimates, and E_3 and E_4 are mode two estimates. What we don't know is if O_1, O_1', and O_1'' are the same object. Similarly for O_2 terms.

Since we have known estimates for E_i ($i = 1$-6) we can algorithmically search and determine the relationships between mode one estimates and mode two estimates to remove the ambiguity. We are looking for what pairs of estimates from mode one equal the estimates from mode two. After the search, we find that equations (19)-(20) hold.

$$E_3 = \frac{E_5}{2} + \frac{E_1}{2} \tag{19}$$

$$E_4 = \frac{E_6}{2} + \frac{E_2}{2} \tag{20}$$

So now we know that estimates E_1 and E_5 are a pair and E_2 and E_6 are a pair. We can now use E_1 and E_5 to find the location of one object and E_2 and E_6 to determine the location of the other object. If either equation (21) or (22) holds then there is an object in the path of the rotary plow. Otherwise, there is no object in the path.

$$\sqrt{\ell^2 + \frac{\min(E_1, E_5)^2}{4}} \geq \frac{\max(E_1, E_5)}{2} \tag{21}$$

$$\sqrt{\ell^2 + \frac{\min(E_2, E_6)^2}{4}} \geq \frac{\max(E_2, E_6)}{2} \tag{22}$$

Even though a two-object case was shown, it can fundamentally be extended and applied to an N object case, as follows:

1. Estimate ranges of objects from each radar in mode one.

2. Estimate ranges of objects from a single radar in mode two.

3. Search for pairs of object ranges that equate to the range of objects in mode two. A pair is made up of a single mode-one range estimate from each radar.

4. Use the identified pair and equation (12) to determine the object location with respect to the rotary plow.
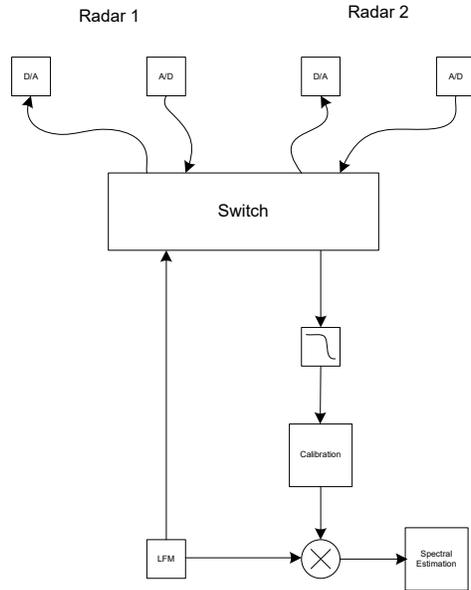
Figure 9: Dual-mode radar system back-end

The block diagram in Figure 9 represents the functionality that is necessary to operate the pair of radars in mode one and mode two. It is important to note that all of this functionality is implemented in the DSP. The top two switch states in Figure 10 represent mode one of the radars. Either of the bottom two switch states can be used to operate the radars in mode two since they result in identical range estimates.
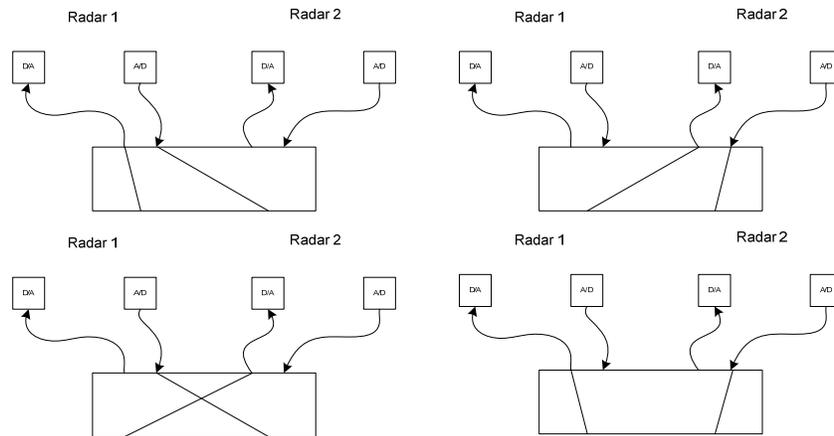

Figure 10: Dual-mode radar system back-end switch cases

This chapter presented a design for an LFM-CW RADAR. The system is low-cost, compact and requires absolutely no additions to the existing infrastructure to implement. The system has very good range and resolution. This system would directly solve two of the major problems associated with rotary plow operation. This design would also provide a platform for further research into spectral estimation and modulation techniques. However, the project was cancelled before a physical prototype could be built.

CHAPTER 4:
CONCLUSIONS

Based on the originally perceived business need and the subsequent Caltrans RFP, this research effort moved quickly to a viable complete architecture and high-level system design, as well as preliminary detailed system design for a snow-penetrating radar system capable of detecting objects hidden under snow, in advance of snow removal equipment, specifically rotary snow blowers. The system design would have been followed up with detailed prototype development, laboratory and field testing, leading to eventual deployment of the system.

The platform would have facilitated further research in software-defined radar (SDR), spectral estimation, and modulation techniques.

Finally, the system, by design and development, would have been field-ready, commercializable, and deployable for the purpose of detecting objects buried in snowpack, all at low-cost relative to existing technologies and systems. The functionality provided by the system would have been higher than available systems.

After the project started, the need for such a system was re-evaluated by Caltrans end users and management, and it was determined that such a system would not currently be cost-beneficial. In response, research work on this project halted after approximately one quarter of work.

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