

A Study of Frequency Properties for Forward Looking Imaging Radar

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Abstract

Autonomous UGVs (unmanned ground vehicles) has been extensively investigated its capabilities for military applications. In order to operate the UGVs on the open fields, they must be able to detect obstacles (eg. holes, stumps, rocks, etc) concealed behind vegetation canopies, as well as to detect surface. Forward looking imaging radar is necessary to autonomous UGVs for collision avoidance and the frequency range of the radar is definitely important to decide radar performance of the vegetation penetration. In this paper, the performance of penetrating radar is analyzed at various frequency range and vegetation biomass using the scattering model such as vector radiative transfer theory.

Keywords : Microwave Scattering, Vector Radiative Transfer, UGV, Forward Looking Radar

1. Introduction

Autonomous navigation system will be focused on core in the Army's FCS (future combat system). Nowadays, Autonomous UGVs has been extensively investigated its capabilities for military applications. The Army Research Laboratory (ARL) has designed and fabricated an impulse-based, ultra-wideband imaging radar for foliage penetration [1]. iRobot PackBot UGV has been studied to navigate autonomously through foliage (such as tall grass) while avoiding obstacles and building a map of the terrain[2]. In order to operate the UGVs on the open fields, they must be able to detect obstacles concealed behind vegetation canopies, as well as to detect surface. Forward looking imaging radar is necessary to autonomous UGVs for collision avoidance and the frequency range of the radar is definitely important to decide radar performance of the vegetation penetration. The imaging radar for UGVs usually employs a physical array of antennas to provide the necessary aperture for sufficient cross-range resolution in the forward-looking geometry. The down-range resolution is a function of the signal bandwidth. Thus, the ultra-wideband (UWB) is required to increase the down-range resolution and the length of the array antenna has to be long enough to reach the high cross-range resolution. Moreover, the length of antenna should be longer to penetrate all vegetation conditions. But the radar system is required small size and low-cost because of the limitation of the platform. We have to decide the optimum frequency band not too low to detect concealed obstacles well. In this paper, the performance of penetrating radar is analyzed at various frequency range and vegetation biomass using the scattering model such as vector radiative transfer theory.

2. Scattering Model

The vector radiative transfer (VRT) theory was applied to study the capability of detection of concealed obstacles inside vegetation canopies at various frequency ranges. The theory has been commonly used in computations of electromagnetic scattering from a vegetation canopy for radar applications [3], [4]. The radar backscattering from two-layered vegetation canopy comprises five main scattering mechanisms such as (1) vegetation scattering (2) ground-vegetation scattering, (3) vegetation-ground scattering (4) ground-vegetation-ground scattering, and (5) ground scattering. Fig. 1 shows a vegetation canopy consisting of a single horizontal vegetation layer over a dielectric ground rough surface.

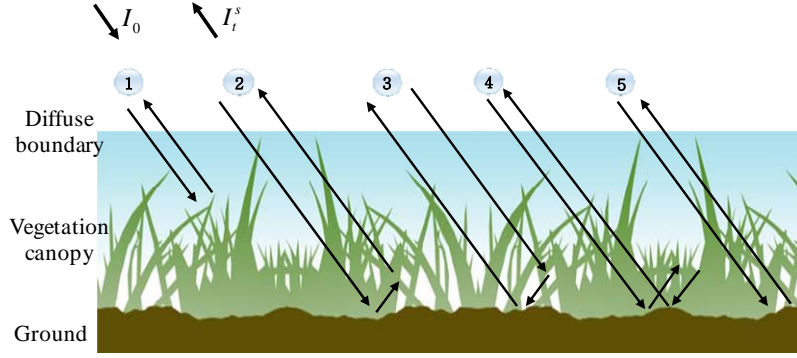


Figure 1: Scattering Mechanisms

The total backscattered intensity $\bar{I}_t^s(\mu_0, \phi_0)$ is related to the intensity I_0 incident upon the canopy through $\bar{T}_c(\mu_0, \phi_0)$ and $\bar{T}_g(\mu_0, \phi_0)$ represent the vegetation canopy and ground transformation matrix, respectively, [3]

$$\bar{I}_t^s(\mu_0, \phi_0) = [\bar{T}_c(\mu_0, \phi_0) + \bar{T}_g(\mu_0, \phi_0)] \bar{I}_0(-\mu_0, \phi_0). \quad (1)$$

where $\mu_0 = \cos\theta_0$, θ_0 and ϕ_0 are the vertical and horizontal incidence angles. The expression for \bar{T}_g is given by

$$\bar{T}_g(\mu_0, \phi_0) = \exp(-\bar{k}_e^+ d / \mu_0) \frac{1}{\cos\theta_0} \bar{M}_{pq} \cdot \exp(-\bar{k}_e^- d / \mu_0) \quad (2)$$

where \bar{k}_e^+ and \bar{k}_e^- are the 4×4 extinction matrices of the vegetation layer for upward and downward propagation, respectively. \bar{M}_{pq} is the modified Stokes scattering operator given by

$$\bar{M}_{pq} = \sum_{k=1}^K \frac{i2\pi N_k}{k_0} \langle S_{pqk}(\theta_s, \phi_s; \theta_j, \phi_j) \rangle_k \quad p, q = v, h, \quad (3)$$

where the summation over k represents an addition over the component such as leaves and branches within the canopy, N_k is the density per unit volume of each constituent, $\langle \rangle_k$ represents statistical averages over the size and orientation distributions, S_{pqk} is the scattering matrix corresponding to polarization pq for component k . It is necessary to compute the scattering metrics of leaves (lossy dielectric elliptical thin disks), branches (lossy dielectric circular cylinders) and randomly rough surfaces. There are several theoretical models such as PO(physical optics), GO(geometric optics) and GRG(generalized Rayleigh gans) for computation lossy dielectric disks and cylinders. The scattering matrix of leaves for a \hat{q} -polarized incident wave and a \hat{p} -polarized scattered wave is given as

$$S_{pq} = \hat{p}_s \cdot \frac{ik}{2\pi} (\hat{v}_s \hat{v}_s + \hat{h}_s \hat{h}_s) \cdot [\hat{z} \times (\hat{k}_i \times \hat{q}_i)] \Gamma_q m(\hat{k}_s, \hat{k}_i) \quad (4)$$

where $m(\hat{k}_s, \hat{k}_i)$ and Γ_q are the phase interference function and reflection coefficient, respectively[5]. The Rayleigh approximation is applied to compute scattering matrix of branches because this model can be used to the case of a homogenous dielectric cylinder of arbitrary cross section whose transverse dimensions are much smaller than λ_0 [6]. Oh's model[7] was used for computation of surface scattering matrix, because the model not only agrees with experimental observations over a wide range of rough surface conditions but also agrees with the IEM(integral equation method) and GO models over their validity regions. For forward surface scattering the classical theoretical models such as PO, GO and SPM are used, because the Oh's model is not able to be used for the forward scattering.

3. Simulation Results

At first, the sensitivities of the scattering coefficients on input parameters was examined and selected only eight most important input parameters, which are (1) the volumetric moisture content m_v (cm^3/cm^3) and (2) the rms surface height s (cm) of the ground surface, (3) the height h (m)

of the vegetation layer, (4) leaf density $N_l (m^{-3})$, (5) leaf length $L_l (cm)$, (6) leaf width $W_l (cm)$, (7) branch density $N_b (m^{-3})$, (8) branch length $L_b (cm)$. Other input parameters are appropriately induced from the 8 major input parameters. For examples, the orientations of leaves are assumed to be uniform over $0 \leq \theta \leq \pi$, $0 \leq \phi < 2\pi$, and for branches the vertical angles have Gaussian distribution over $0 \leq \theta \leq \pi/2$ and uniform distribution over $0 \leq \phi < 2\pi$. The diameter of a branch is assumed to be 0.013 times the length of the branch. There is a linear relation between the measured volumetric moisture content $Mv(cm^3/cm^3)$ of soil surfaces and the measured gravimetric moisture content $Mg(g/cm^3)$ of leaves for a tall grass field. The gravimetric moisture contents of vegetation particles are derived from the soil moisture content with the linear regression formula ($M_g = 0.81M_v + 0.36$). These formula and multiplication constant of 0.013 are obtained from the experimental observations. Table 1 shows the value of the input parameters of the scattering model. The scattering coefficients are computed by the VRT using these 8 input parameters.

Table 1: Input parameters for various vegetation density

| No. | Classes | Input parameters | Vegetation Density | | | |
|-----|-------------------|--|-----------------------------|------------|------------|-----------|
| | | | Sparse | Normal | Dense | |
| 1 | Ground Surface | Mv (soil moisture content) [cm^3/cm^3] | 0.01 ~ 0.4 | 0.01 ~ 0.4 | 0.01 ~ 0.4 | |
| 2 | | s (rms height) [cm] | 0.1 ~ 5.0 | 0.1 ~ 5.0 | 0.1 ~ 5.0 | |
| 3 | Vegetation Canopy | Vegetation height, h [cm] | 5 ~ 30 | 30 ~ 60 | 60 ~ 150 | |
| 4 | | Leaf | Length, L_l [cm] | 5 ~ 20 | 20 ~ 50 | 50 ~ 100 |
| 5 | | | Width, W_l [cm] | 1 ~ 2 | 1 ~ 5 | 1 ~ 10 |
| 6 | | | Density, N_l [m^{-3}] | 1 ~ 100 | 100 ~ 500 | 500~5000 |
| 7 | | Branch | Length, L_b [cm] | 5 ~ 20 | 20 ~ 50 | 50 ~ 100 |
| 8 | | | Density, N_b [m^{-3}] | 1 ~ 20 | 20 ~ 100 | 100 ~ 500 |

Fig. 2 shows the computation results. Surface scattering/vegetation scattering means the direct ground scattering (5) over the vegetation scattering which are the (1), (2), (3) and (4) shown in Fig. 1. To build a map of the terrain and detect the hidden obstacles inside the vegetation canopy, the surface scattering must be stronger than the vegetation scattering. The lower frequency signal can penetrate the vegetation canopy well as expected. That means the surface scattering is dominant at lower frequency. These results indicate that the higher frequency radar is very effective at penetrating sparse vegetation, but less effective at penetrating dense vegetation. Therefore forward looking imaging radar for autonomous UGVs should be used the lower frequency band to see through all vegetation conditions.

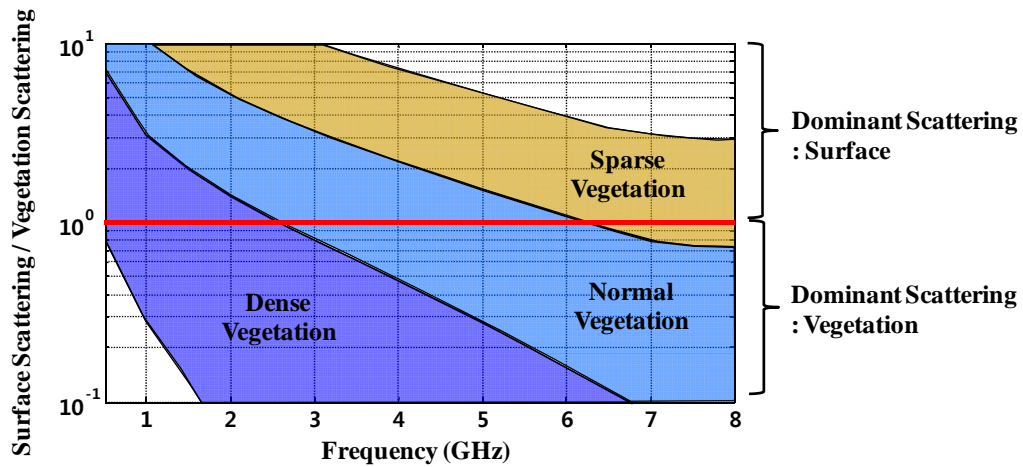


Figure 2: Surface scattering/Vegetation scattering at various frequency range

The imaging radar for UGVs usually employs a physical array of antennas to provide the necessary aperture for sufficient cross-range resolution in the forward-looking geometry. The down-

range resolution is a function of the signal bandwidth ($\Delta r = \frac{c}{2B}$) where c is the speed of light and B is the bandwidth of the radar signal. Thus, the ultra-wideband (UWB) is required to increase the down-range resolution and the length of the array antenna has to be long enough to reach the high cross-range resolution. Moreover, the length of antenna ($L \approx \lambda/2$) should be longer to penetrate all vegetation conditions. But the radar system is required small size and low-cost because of the limitation of the platform. We have to decide the optimum frequency band not too low to detect concealed obstacles well. We propose the frequency channel selective radar system for various vegetation conditions. The frequency range of the radar is suggested from 2GHz to 5GHz for small size and low-cost. If the UGVs operate on the sparse or normal vegetation density condition, the frequency channel can be selected ch 2, 3 and 4. If the UGVs operate on the dense condition, the frequency channel can be selected 1 as below. Our next study will be to verify and compare with the experiments and simulation results.

Table 2: Available frequency ranges for various vegetation density

| Ch. | Center Frequency | Frequency Range | Bandwidth | Available Density |
|-----|------------------|-----------------|-----------|-------------------|
| 1 | 2.5 GHz | 2.0 ~ 3.0 GHz | 1 GHz | Normal or Dense |
| 2 | 3.0 GHz | 2.0 ~ 4.0 GHz | 2 GHz | Normal |
| 3 | 3.5 GHz | 2.5 ~ 4.5 GHz | 2 GHz | Normal |
| 4 | 4.0 GHz | 3.0 ~ 5.0 GHz | 2 GHz | Sparse or Normal |

4. Conclusions

For autonomous UGVs, we propose the frequency channel selective radar system to detect the hidden obstacles behind the various vegetation conditions. The frequency range of the radar is suggested from 2GHz to 5GHz for small size and low-cost. If the UGVs operate on the sparse or normal vegetation density condition, the frequency channel can be selected ch 2(2 ~ 4GHz), 3(2.5~4.5GHz) and 4(3~5GHz). If the UGVs operate on the dense condition, the frequency channel can be selected 1(2~3GHz). Our next study will be to verify and compare with the experiments and simulation results.

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