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Sensor Fusion for Assured Vision in Space Applications

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Abstract

By using emittance and reflectance radiation models, the effects of angle of observation, polarization, and spectral content are analyzed to characterize the geometrical and physical properties—reflectivity, emissivity, orientation, dielectric properties, and roughness—of a sensed surface. Based on this analysis, the use of microwave, infrared, and optical sensing is investigated to assure the perception of surfaces on a typical lunar outpost. Also, the concept of employing several sensors on a lunar outpost is explored. An approach for efficient hardware implementation of the fused sensor systems is discussed.

Introduction

Human presence on the lunar surface for extended periods of time (for up to 2 years at the beginning of the next millennium) will require extensive supporting capabilities including habitat modules, power generation modules, operational control modules, and life support modules. Emplacement of this evolutionary lunar base will require preliminary robotic missions such as surface exploration or mining for construction purposes. Because of specific illumination conditions in space and mission requirements, achieving these operations—either automated or teleoperated—requires advanced sensing technologies to assure perception of the lunar scene at any time and in any location by a vision system.

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The scene perception and interpretation capabilities of the vision system being designed at the NASA/Johnson Space Center with the collaboration of ITMI, France, will be based on physical models that underlie the reflection and emission radiations phenomena. These physical models take into account the relationship between environmental illumination (which can be active in the presence of radar sensors or passive in the presence of thermal or visible sensors), surface parameters, and perceived data. Physical models will be used jointly with fuzzy logic techniques to perform fusion of the multisensor data and to interpret the physical and geometrical properties of the sensed surfaces. The perception system architecture is represented by the following scheme (fig. 1), which shows sensor selection and fusion modules.

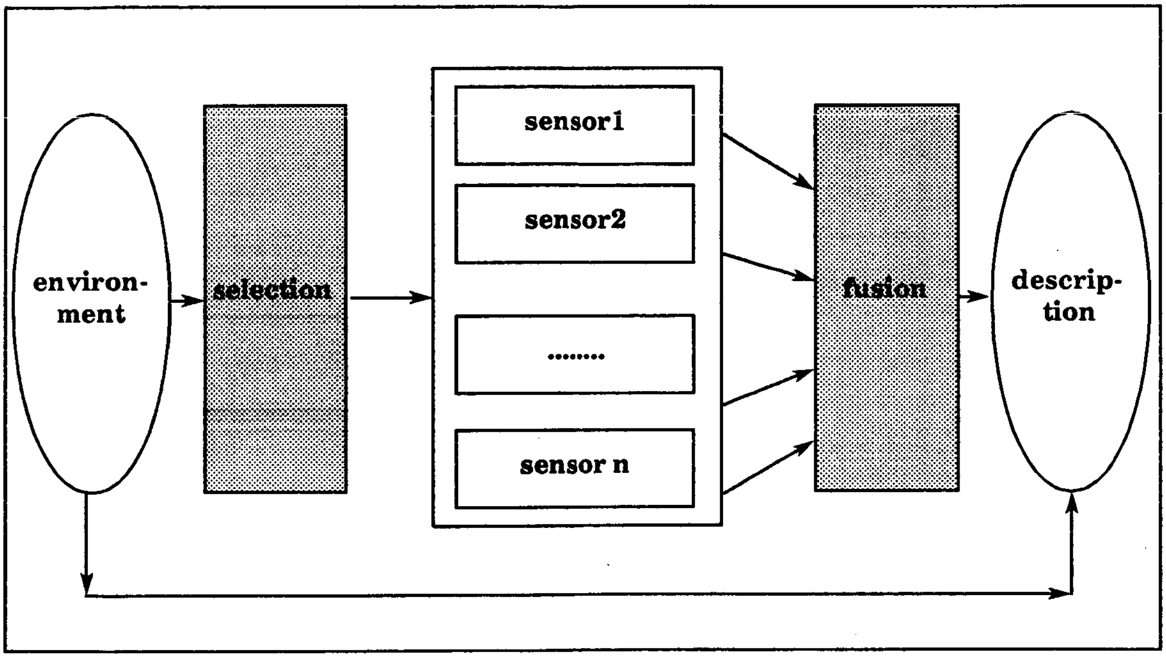

Figure 1. Perception system architecture.

This paper first presents the reflectance and emittance models on which sensor selection and sensor fusion are based. These models allow us to understand the effect of surface parameters on the response of multiple sensing devices. The constitutive key parameters are roughness, the dielectric constant, orientation, temperature, and emissivity of the surface. These surface parameters are needed for scene perception and interpretation in the context of planetary operations. The second part of the paper, which is based on reflectance and emittance model analysis, presents the effect of these key parameters on sensor responses for different sensors. The third part of the paper deals with a method being developed to assure the perception and interpretation of the scene for space operations.

Physics of perception

In the remote sensing field, perception models have been used extensively to characterize surfaces for Earth observation purposes [1],[2],[3],[4]. The models presented here are issued from this domain. The following sections will present a survey on the most commonly used theoretical models for scattering and emission mechanisms.

Scattering models

Energy reflected off a surface and received by a remote sensing device is related to a scattering coefficient, σ_{pq}, that is dependent on surface physical properties. The subscript *pq* indicates that the received field is *p*-polarized and the transmitted field is *q*-polarized. The most common values for *p* and *q* are horizontal and vertical polarizations. To obtain a numerical solution of the scattering coefficients, σ_{pq}, several models have been developed that depend on the frequency range of illumination and on surface geometry. By making assumptions on the scattering mechanisms, it is then possible to get relatively simple numerical solutions for the scattered coefficients.

According to the Kirchoff approximation, a scattered field can be estimated using the Fresnel reflection coefficients R_v and R_h for vertical and horizontal polarizations. As shown in the following expressions [5], these coefficients depend on the electrical properties of the surface and on the incident angle:

$$R_h = [\mu \cos\theta - (\mu\varepsilon - \sin^2\theta)^{1/2}] / [\mu \cos\theta + (\mu\varepsilon - \sin^2\theta)^{1/2}]$$

$$R_v = [\varepsilon \cos\theta - (\mu\varepsilon - \sin^2\theta)^{1/2}] / [\varepsilon \cos\theta + (\mu\varepsilon - \sin^2\theta)^{1/2}]$$

Using the Kirchoff approximations, numerical simplification leads to the scattered coefficients estimation first derived by Beckmann-Spizzichino [7].

$$\sigma_{pq} = \sigma_{1pq} + \sigma_{2pq} + \sigma_{3pq}$$

σ_{1pq} is the specular reflection term, and σ_{2pq} and σ_{3pq} are due to the surface roughness and slope effects, respectively. Figure 2 presents a typical backscattering response as a function of the incidence angle θ using different values of the standard deviation of the surface heights σ (representing the surface roughness).

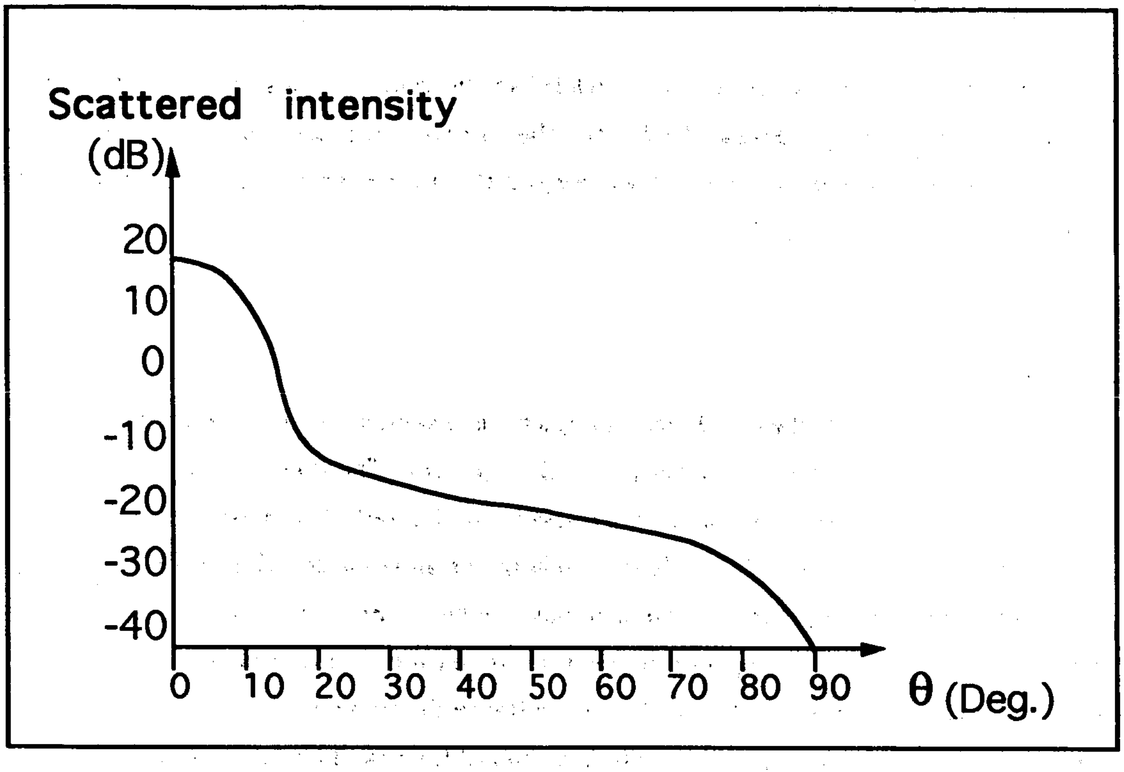

Figure 2. Typical backscattering for a composite surface model.

Emission models

Emission models are the governing models for passive sensors such as infrared sensors and radiometers (passive microwave sensing). The spectral brightness B_f (in W.m^{-2}.sr^{-1}.Hz^{-1}) perceived by a thermal sensor is related to the physical temperature T of the surface and to the surface emissivity coefficient $e(\theta_r, p)$ as formulated by the following equation using Planck's radiation law:

$$B_f(\theta_r, p) = e(\theta_r, p)\,2hf^3c^{-2}(\exp^{hf/kT} - 1)^{-1}$$

where h, f, c, and k are, respectively, Planck's constant, the frequency, the velocity of light, and the Boltzmann constant; $e(\theta_r, p)$ is the emissivity perceived from the observation angle θ_r with respect to the surface normal; and p is the polarization of the perceived radiation.

To simplify an analysis of emitted radiations, the theoretical models are divided into two categories: (1) high-frequency models and (2) low-frequency models. These models are presented in the following paragraphs.

The low-frequency model allows us to simplify the exponential term of Planck's radiation law when $hf/kT << 1$, which is also equivalent to $\lambda T > 0.77$ with λ in meters and T in Kelvin.

The Rayleigh-Jeans, or low-frequency approximation, of Planck's radiation law is

$$B_f(\theta_r, p) = 2k/\lambda^2 e(\theta_r, p)T$$

From this equation it appears that, in the microwave region, radiation emitted by the surface linearly depends on surface temperature. Therefore, considering the radiations emitted by the surface only, a radiometer provides a brightness temperature measurement T_b that depends on the surface parameters. T_b is defined as

$$T_b(\theta_r, p) = e(\theta_r, p)T$$

In the case of thermal equilibrium, emissivity is defined as [6]

$$e(\theta_r, p) = 1 - r(\theta_r, p)$$

where $r(\theta_r, p)$ is the reflectivity of the surface when illuminated with an incident angle θ_r with respect to the surface normal.

At high frequencies, Planck's radiation law is reduced to a simpler model when $hf/kT >> 1$, which is also equivalent to $\lambda T < 0.77$ with λ in meters and T in Kelvin. Using a high-frequency approximation, Planck's law is reduced to

$$B_f(\theta_r, p) = e(\theta_r, p) 2hf^3 c^{-2} \exp^{-hf/kT}$$

At high frequencies, the emissivity is adequately modelized by a Lambertian law for any surface type. Using the previous formulation, the perceived intensity at the sensor is then

$$E = (1 - \sigma_0/4)\,2hf^3c^{-2}\int exp^{-hf/kT}\,df$$

The emitted intensity is therefore a function of physical temperature and dielectric constant of the surface (through σ_0) but is independent on the observation angle.

An example of temperature brightness given by a thermal sensor is shown as a function of the surface temperature in the following figure (fig. 3).

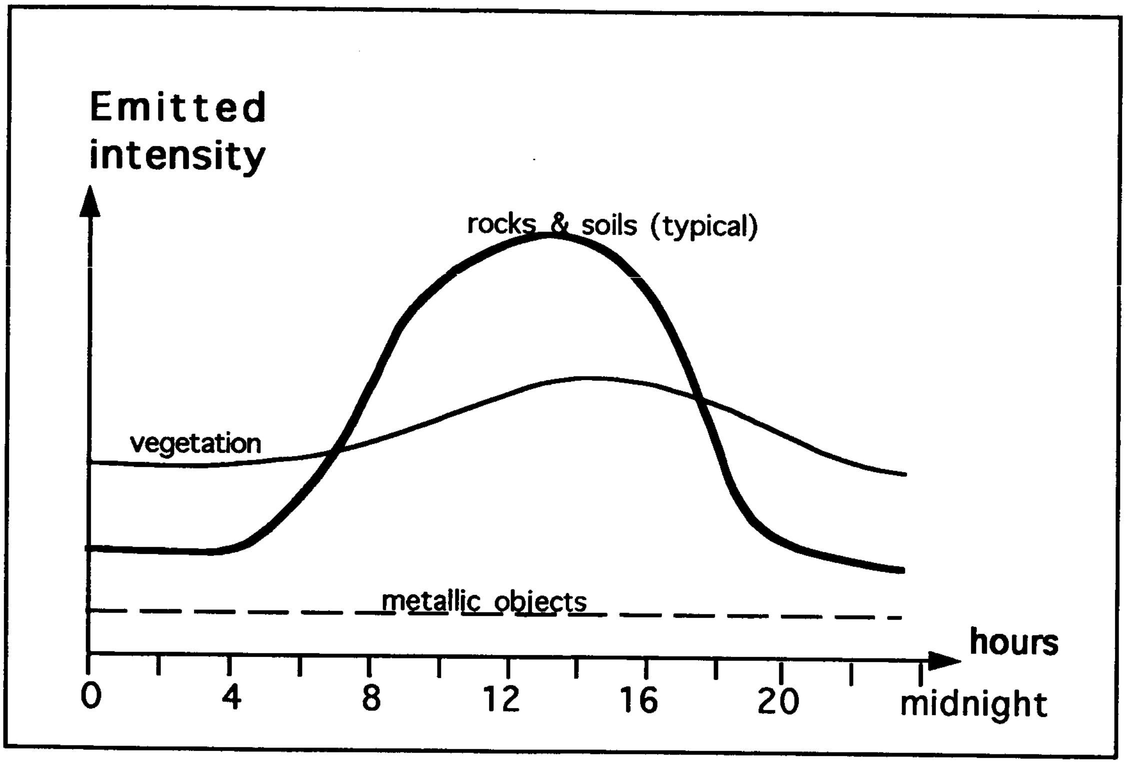

Figure 3. Radiant temperature for typical materials.

Key parameters

From theoretical modeling of scattering and emission, it appears that sensor responses are mostly dependent on surface parameters—roughness and dielectric constant—on viewing parameters—incidence and observation angles—and on sensor characteristics—frequency and polarization. The purpose of this section is to understand to what extent these parameters are affecting sensor response. This parametric analysis should then lead to the selection of a sensing configuration (sensor, sensor mode, and frequency range) that is the most sensitive to a required parameter.

By presenting experimental data as a function of incidence angle, the surface parameters, the sensor frequency, and the polarization effects are illustrated in the following paragraphs.

Roughness

The most affecting parameter is the surface roughness parameter. Roughness affects both the intensity and shape of the reflection and emission pattern. The higher the roughness, the more diffuse the scattering. Therefore, if there is a way to distinguish between a specular return and a diffuse return (which will be discussed later), surface roughness can be estimated. The perception of a surface as either smooth or rough then allows us to select the appropriate scattering and emission model with which to recover other surface parameters.

From theoretical analysis and experimental observations, the effects of surface roughness on sensor responses can be summarized as follows:

- A planar surface is smooth when
  - $k\sigma < 0.2$, where σ is the standard deviation of surface heights.
  - with active sensors, the cross-polarized return is negligible compared to direct polarization for near normal observation angles; at grazing angles, they have the same order of magnitude.
  - with active sensors, the direct polarization may be either very high or very low depending on the observation and incidence angles.
  - with passive sensors, the relative difference between perpendicular returns is high at high observation angles and very low at near normal angles.

- A planar surface is rough when
  - $k\sigma > 1.0$
  - with active sensors, the cross- and direct-polarized returns present approximately the same intensity level for any observation angle.
  - with passive sensors, the relative difference between perpendicular returns is low for all observation angles.

- An intermediate roughness surface presents intermediate behaviors for emitted and scattered intensities when
  - the surface behaves like a smooth surface at near normal angles and like a rough surface at higher angles.

- the surface presents two roughness scales. The small-scale roughness is predominant at high angles, and the large-scale roughness (or locally smooth surface of the Kirchoff theory) predominates near normal angles (< 30 deg).

Dielectric constant

The dielectric constant is a clue parameter for scene interpretation since it allows us to distinguish objects on the basis of their surface material and composition.

The dielectric constant is the second most influential surface parameter after surface roughness. This constant affects sensor response through the Fresnel reflection coefficient R. Since the Fresnel coefficient influences both reflection and emission, the dielectric constant will affect both passive and active sensing devices.

As seen in the scattering models, the intensity of reflected radiations for a planar surface is a product of a roughness term (which depends on viewing and incident angles) and a reflection coefficient. Therefore, for a given roughness and observation angle, the increase of dielectric constant will increase the sensor return.

Because the dielectric constant of material is a measure of its permittivity to incident radiations, the dielectric constant is a function of incident frequency. At low frequencies (microwaves are typical of low frequencies), the dielectric constant is highly related to the water content or moisture of materials. It provides, therefore, a useful clue for object or surface identification and is also useful when assuring the safety of mobile rovers in wet areas. In low-frequency domains, the dielectric constant of material varies from about 2 for dry soil to about 84 for water.

At high frequencies, the dielectric constant is related to material density. For most soils and materials, the dielectric constant ranges from 2 to 8 at high frequencies. In high-frequency domains, the dielectric constant is almost frequency-independent and much less sensitive to moisture.

To summarize, the effects of the dielectric constant on reflection and emission are as follows:

- For all frequencies, an increase of dielectric constant increases reflected intensities while it decreases the emitted intensities.

- The effect of dielectric constant is more sensitive at microwave frequencies than it is at visible frequencies because of its wider variation at low frequencies.

- The effect of dielectric constant is different for horizontally or vertically polarized radiations. For smooth surfaces, the reflection coefficient is higher for horizontal polarization than it is for vertical polarization. This effect is inverted, however, for emitted radiation because of the complementary behavior of emissivity and reflectivity.

Frequency

Because of the interrelationship between parameters, frequency effects present some redundancies with the effects discussed previously—and especially with the roughness effect. According to the Rayleigh criterion, as frequency increases, the surface appears rougher. In the event of a specular return, the sensor response should decrease as the surface appears rougher. In the event of a diffuse return, the sensor response is more likely to increase because of an increase of the diffuse reflection component.

A side effect of the frequency variation relates to the dielectric constant, since the dielectric constant is frequency-dependent at microwave frequencies. A frequency increase will generally produce a decrease in dielectric constant. The resulting sensor response will behave according to the dielectric effects discussed earlier. However, the dielectric constant is influencing the sensor response to a lesser extent compared when to the influence felt by the roughness effect.

Frequency effects can be summarized as follows:

- A frequency increase generally increases the diffuse reflection component and decreases the specular component due to the apparent increase in surface roughness.

- A frequency increase will also correspond to a significantly lower decrease in reflected radiations due to the dielectric constant decrease.

- High frequencies are sensitive to small-scale roughness, and low frequencies are sensitive to large-scale roughness.

- Low frequencies are more sensitive to dielectric constant and moisture variations than are high frequencies.

Polarization

Surface properties affect the polarization state of an incident wave, whether the wave was initially polarized or not. The Sun illumination is not polarized, but waves emitted by active sensors may have a controlled polarization state and might be used for surface analysis. From the sensing side, both passive and active sensors can detect the specific polarization state of received radiation. The polarization or depolarization analysis of reflected and emitted radiations is based on either active or passive sensors. This analysis can provide useful information about surface parameters.

An unpolarized or polarized illumination is reflected off a surface with a polarization or depolarization state that depends on the surface roughness scale. This, therefore, can provide a way of distinguishing diffuse and specular reflection components.

As might be expected from the Fresnel reflection coefficients, upon specular reflection, the horizontally reflected component is significantly larger than the vertically reflected component for an initially unpolarized radiation. These effects are reversed for emitted radiations, where the vertical polarization is higher than the horizontal polarization for smooth surfaces.

The behavior of initially polarized incident radiations (in the case of active sensing only) differs. Depolarization is very low for a smooth to slightly smooth surface. At near normal incident angles, however, the direct horizontal polarization HH (horizontal incident polarization and horizontal received polarization) is similar to the direct vertical polarization VV. This behavior changes at higher incident angles, where the HH polarization is higher than the VV polarization. For all incidence angles, however, the cross-polarization HV or VH (horizontally emitted polarization and vertically received polarization, and vice versa) is still much less significant than is the direct polarization.

For rough surfaces (vegetated surfaces, for example), there is little difference between polarizations because depolarization is high for any incident polarization state. Therefore, both direct and cross polarizations have similar returns and are almost angle-independent. However, the VV return is slightly higher than the HH return. The return magnitudes are also lower than those of specular reflection. Emitted radiations follow the same rule—they are unpolarized in the event of rough surfaces.

In the event of active polarized sensing, direct- and cross-polarized returns present cases of particularly interest. For smooth surfaces, an incident linearly polarized illumination is not depolarized at high incidence angles. A different effect is observed for rough surfaces, where linearly polarized illuminations are depolarized upon reflection. Thus, depolarization is related to surface roughness.

The effects of polarization are summarized as follows:

- The specular reflection of an unpolarized illumination is horizontally polarized (except for near nadir angles where there is no significant depolarization). Horizontal polarization is higher than vertical polarization (the effect is reversed for emitted radiations).

- For a smooth surface, an incident polarized radiation will be poorly depolarized, whatever its initial polarization, so that the incidence of cross-polarization is very low compared to that of direct polarization.

- For smooth surfaces, horizontal direct polarization is similar to vertical direct polarization at near normal angles but is higher at high angles (> 30 deg from normal).

- The depolarization of incident linear polarized radiations becomes higher as roughness increases.

- For diffuse reflections, the incident wave—whether polarization or not—is highly depolarized so that direct- and cross-polarized returns have similar magnitudes. The same holds true for emitted radiations from rough surfaces.

- For diffuse reflections, the scattering pattern is almost angle-independent.

- For diffuse reflections, the VV polarization is slightly higher than the HH polarization.

- The relative difference between direct horizontal and vertical polarizations is related to surface roughness and the dielectric constant of the surface for both passive and active sensors.

Adaptive multisensing strategy

The envisaged approach for the perception system design, which is based on mission requirements and environmental conditions analysis, is to develop an adaptive multisensing strategy that will be determined according to illumination conditions. We focused our investigations and analyses on the following issues: What sensors and corresponding sensing modalities will lead to the best estimation of the needed surface parameters for any environmental conditions? And, how do we use the theoretical models to get information about surface parameters?

Our attempt to solve these problems led to a two-step approach. (1) Select the best appropriated set of sensors with respect to illumination conditions, sensor capabilities and complementations, and needed and known parameters. And, (2) fuse the received data to get the needed parameters. The following paragraphs describe the concepts and methods being developed for these two steps.

The selection of a multisensing configuration can be simply simulated by a table where the possible multisensing strategies are stored. Selection table columns contain a list of surface parameters—roughness, dielectric constant, range, orientation, and temperature. The table rows contain the different available sensors—active and passive microwave sensors, infrared sensors, visible sensors, a laser range finder, and laser radar. For each needed parameter, multiple sensing strategies—i.e., multiple subsets of sensor configurations—are possible. The final configuration is selected according to environmental conditions. For example, a microwave strategy would preferably be selected during a lunar night since the low frequency of emitted radiations would not be perceived using infrared sensors because of the lower temperatures of the lunar surface during the lunar night.

Once the sensing configuration is selected, the perceived data have to be fused to extract the needed parameters. We are developing fuzzy logic techniques to achieve this multisensor fusion. Compared to classical fusion techniques, fuzzy logic fusion has the following advantages [8]:

- Fuzzy logic is well suited for complementary and dependent data fusion by means of fuzzy combination rules.

- Since remote sensing models are approximate modelings of the electromagnetic scattering phenomena, surface properties cannot be determined with a high degree of accuracy. Fuzzy logic techniques allow us to process uncertain, incomplete, and ambiguous [9] measurements using simple implementation methods.

- The fuzzy description of a planetary surface is convenient for rover navigation applications since the rover does not need a highly precise description of surfaces for navigational purposes.

- Fuzzy logic also allows new information to be deduced from sensed data.

Conclusion

The objective of the conceptual perception system, which has been described, is to overcome difficulties related to the space environment illumination. A vision system should be able to perceive the planetary environment for any location and any time on the surface and to provide a description of the scene in terms of surface roughness, material identification, and surface orientation. Multifrequency and multimode sensing devices are used to achieve this analysis. The capabilities of sensors —ranging from visible to infrared and microwaves—are exploited because of complementary capabilities in terms of environmental operativeness (e.g., dust, rain, fog, night, etc.) and in terms of their sensitivity to the required surface parameters (roughness, dielectric constant, and orientation).

So far, perception problems related to space environmental conditions have been identified, an approach for overcoming these problems has been analyzed and selected, the theoretical basis for approach implementation has been settled, surface parameters and their relative influence on sensor returns have been identified and modelized for each sensor, and sensing strategies for surface parameter perception have been identified. The next steps that will lead to the development of an assured vision system are to implement and test the rules for sensor selection and sensor fusion—rules that will lead to the recovering of surface parameters.

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