Photometric Stereo Imaging (PSI)

Target of Investigation

Photometric stereo imaging is employed to detect surface cracks and surface textures of pavements.

Description

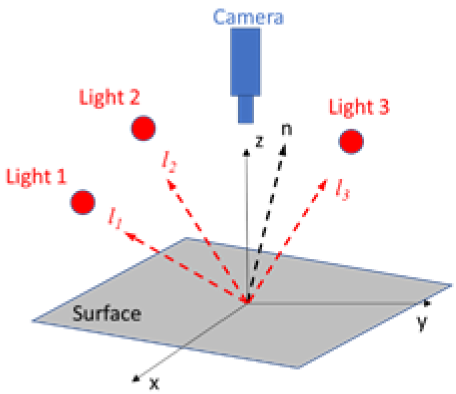
Unlike stereography, which uses two cameras, photometric stereo imaging uses a single camera and multiple light sources at fixed locations to determine local surface orientation (figure 1). The amount of light reflected by a surface is dependent on the orientation of the surface in relation to the light source and observer.[1] By having light sources at different angles, photometric stereo imaging produces images based on variations in shading of individual pixels. It also enables determination of surface orientation.

Figure 1. Photo. Vehicle-mounted photometric stereo imaging system.[2]

This photo shows photometric stereo imaging being performed on concrete pavement. The photometric stereo imaging system is installed at the rear of a vehicle. Red light-emitting diodes set at different angles to the pavement surface are illuminating the pavement.

Physical Principle

As shown in figure 2, the surface normal at a local point is n. If the surface is diffusive, the surface albedo (k) is defined as the ratio of the reflection to the incident light.[3] Three illumination rays from different light sources are of unit vector intensity and in different planes.[4,5] The direction vectors are noted as l_1, l_2, and l_3. Sources illuminate individually, and the light intensities observed by the camera are i_1, i_2, and i_3 corresponding to l_1, l_2, and l_3, respectively. The relationships between the observed intensities and the sources can be expressed by the equation in figure 3.



Source: FHWA.

Figure 2. Illustration. Principle of photometric stereo imaging.

> *This illustration is a schematic of the principle of photometric stereo. The x-axis points to the lower left, the y-axis points to the right, and the z-axis points upward. A surface is in the x–y plane. A camera is facing downward on the z-axis. Three circles represent three light sources, and arrows to the light sources from the x-y-z origin indicate their directions. A dashed arrow from the origin to the upper right indicates the direction of the surface normal.*

$$(i_1, i_2, i_3) = k(l_1, l_2, l_3)n$$

Figure 3. Equation. Observed intensities, light source directions, and surface normal.

> *Open parenthesis i subscript 1, i subscript 2, i subscript 3 close parenthesis equals k times open parenthesis l subscript 1, l subscript 2, l subscript 3 close parenthesis times n.*

k is an assumed known value for pavement surface materials (asphalt or concrete). The observed intensities and directions of light sources can be obtained from the test. n can be solved for using the equation in figure 3. Figure 4 shows the matrix form of the equation in figure 3, and n can be solved for using the equation in figure 5. When there are more than three light sources, n can be solved for by making the least-squares errors in the equations, and the solution can be expressed in the matrix form shown in figure 6.[6] This model can also be extended to surfaces with nonuniform albedos.[7]

$$I = k(Ln)$$

Figure 4. Equation. Matrix form of observed intensities, light source directions, and surface normal.

> *I equals k times open parenthesis L times n close parenthesis.*

- Where:
  - I = vector of the observed intensities.
  - L = known 3-by-3 matrix of the normalized light directions.

$$L^{-1}I = kn$$

Figure 5. Equation. Solving surface direction n when there are three light sources.

L superscript negative 1 times I equals k times n.

Where L^{-1} is the inverse of L.

$$(L^T L)^{-1} L^T I = kn$$

Figure 6. Equation. Solving surface direction n when there are more than three light sources.

Open parenthesis L superscript T times L close parenthesis to the negative 1 times L superscript T times I equals k times n.

Where L^T is transposed L.

Data Acquisition

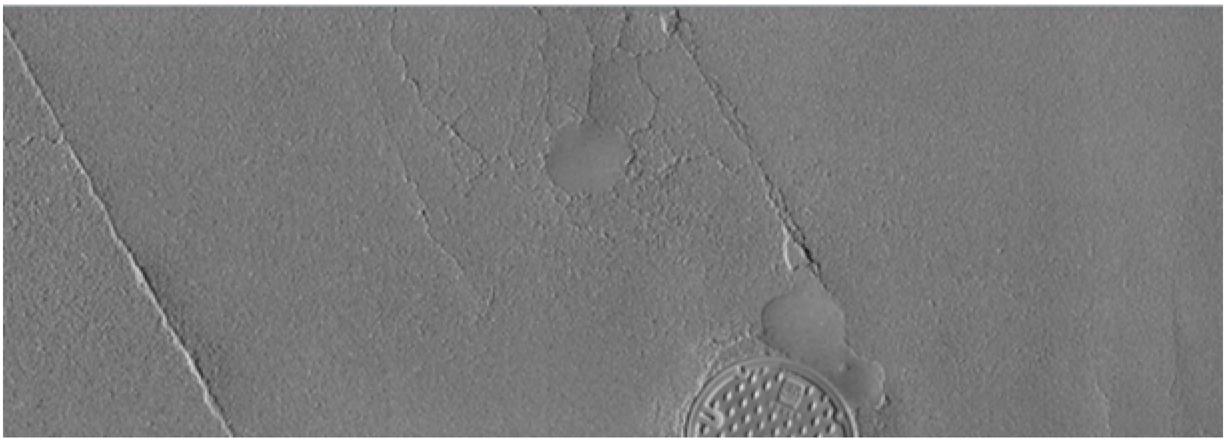
The photometric stereo imaging system is usually integrated with a moving vehicle. Continuous imaging can be taken at highway speeds (100 km/hr [60 mph]), during which the photometric stereo imaging system will illuminate each light source in sequence at very high speeds.(8) A picture of the same area of the pavement surface is taken each time a light source is turned on. For example, a system with four light sources from different illumination angles will produce four images in sequence. The images will be captured by the charged coupled device of the camera and stored in the system's computer for postprocessing.

Data Processing

Image processing is usually done by software, and the surface normalization is provided by the software as an image.

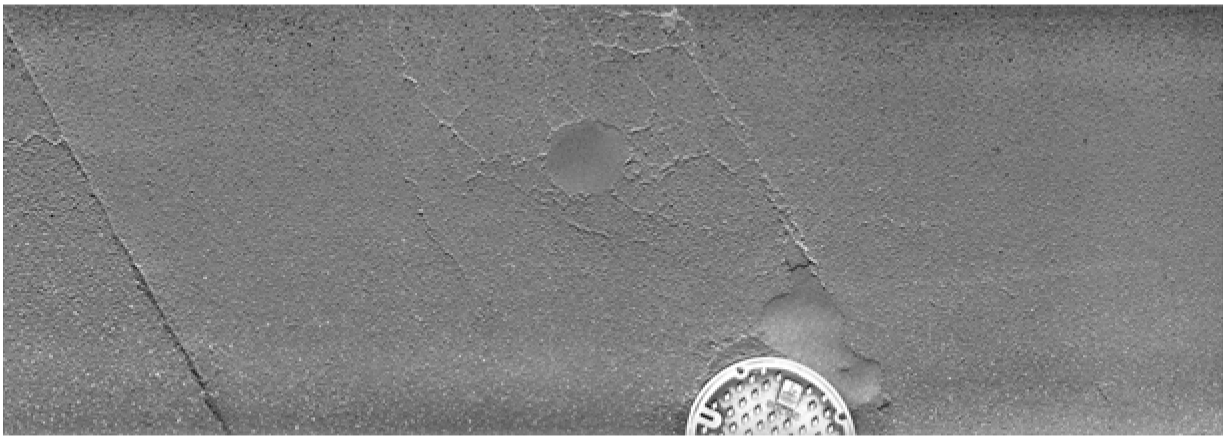
Data Interpretation

Cracks and different textures that cannot be seen in conventionally illuminated imagery can be seen directly in gradient maps generated from photometric stereo imaging (figure 7). Cracks are shown as lines and curves, and different textures are shown as grains of different sizes for different illumination combinations.



A. Forward-angle light source.

This image is of a pavement surface when light was applied at a forward angle. A few cracks appear as bright and dark lines. The manhole *cover located at the bottom of the photo is dim.*



© 2018 Earth Radar Pty Ltd.B. Transverse-angle light source.

Figure 7. Gradient maps. Cracks on the same pavement surface with different light sources.[(2)]

This image is of the pavement surface when light was applied at a transverse angle. A few cracks appear as bright and dark lines. The manhole cover located at the bottom of the figure is bright.

Advantages

Advantages of photometric stereo imaging include the following:

- Noncontact method.
- High accuracy in detecting surface cracks.
- Imaging at highway speeds.

Limitations

A limitation of photometric stereo imaging is the following:

- Cannot detect cracking when the surface is wet or covered by dirt or debris.

References

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