

Fast and Efficient Detection of Shading of the Objects

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ABSTRACT

The human thermal comfort, which has been a subject of extensive research, is a principal objective of the automotive climate control system. Applying the results of research studies to the practical problems require quantitative information of the thermal environment in the passenger compartment of a vehicle. The exposure to solar radiation is known to alter the thermal environment in the passenger compartment. A photovoltaic-cell based sensor is commonly used in the automotive climate control system to measure the solar radiation exposure of the passenger compartment of a vehicle. The erroneous information from a sensor however can cause thermal discomfort to the occupants. The erroneous measurement can be due to physical or environmental parameters. Shading of a solar sensor due to the opaque vehicle body elements is one such environmental parameter that is known to give incorrect measurement. The fundamental geometric principles of the intersection of a line segment and a plane can be used to determine if sensor is shaded, for given position of the sun with respect to a vehicle and geometry of the passenger compartment. However, realization of these principles using the fixed-point arithmetic is computationally expensive, due to their high memory and execution time requirements. The analytical method that uses relatively simple geometric relations is proposed to obtain the exact same results at significantly lower cost. The proposed method uses a constant azimuth curve to determine the range of elevation for each transparent body element of a vehicle, such as windshield, side glasses, rear glass and sun roof, for which a solar sensor is exposed to the direct-beam solar radiation. A sensor is said to be shaded if the current solar elevation angle is not included in any of the calculated ranges. The corrective action to the erroneous solar intensity while sensor is shaded, is suggested such that its influence on the thermal comfort of occupants is minimum.

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INTRODUCTION

A principal purpose of the automotive climate control system is to provide conditions for the thermal comfort of vehicle occupants. Feedback control theory based automatic climate control systems are common in today's automobiles. Since their introduction, continuous improvement in their design are made only to improve thermal comfort inside the cabin under various vehicle operating conditions. The thermal comfort of human being is found to depend on direct temperature and moisture sensations by the skin, deep body temperatures and the efforts necessary to regulate body temperature such as the clothing and the level of activity [1]. The exposure of vehicle occupants to the solar radiation passing through the vehicle glasses results in heat gain by the human body. Hodder et al. [2] conducted three experiments designed to establish a relationship between the solar radiation and the thermal sensation of the human body with respect to intensity of solar radiation, its spectral content and the transmissivity of vehicle glasses. The results of their experiments show that the 30 minutes of exposure produces a warmer thermal sensation by one scale point on ISO scale for each increment of 200 W/m² of solar radiation intensity. Blazejczyk et al. [3] gave regression relationship of the mean skin temperature and the global solar radiation with a correlation coefficient of 0.743, which was reported to be higher than the correlation coefficient for water vapor pressure (0.67) and air velocity (-0.13). Madsen et al. [4] noted that

the solar radiation exposure of the compartment produces asymmetric thermal load for the climate control system. Under the test conditions therein, temperature at the driver seat was recorded 4-5°C higher than the temperature at the front passenger seat when only the driver seat was exposed to the solar radiation. The heat gain of the occupants due to a continuous exposure to the solar radiation can be significant and must be considered while designing a climate control system to provide conditions for thermal comfort in the passenger compartment for various vehicle operating conditions.

The climate control system uses a photovoltaic-cell based sensor to obtain quantitative information of the direct-beam and diffuse solar radiation [5]. A solar sensor can provide solar intensity along with the angle information (azimuth and elevation) of the sun (or solar radiation) with respect to the vehicle driving direction. However, a combination of fundamental and empirical equations can also be used to obtain the sun angle information [6]. Such equations use the time and location data received from the Global Positioning System (GPS) satellites to calculate solar azimuth and elevation. Furthermore, the empirical models are also available to obtain the clear sky sun intensity [7-8]. However, the results are applicable to the clear sky conditions and are not accurate enough to be used for practical problems under the varying cloudy conditions.

The use of a solar sensor in the automotive climate control systems is therefore essential. However, a sensor can produce erroneous measurement when it is not exposed to the sufficient direct-beam solar radiation. Such an error has adverse impact on the operation of the climate control system if one or more occupants of a vehicle have heat gain due to exposure to the solar radiation. The location of a solar sensor is such that the opaque vehicle body elements such as roof and B-pillar can obstruct the direct exposure of a sensor to the direct-beam solar radiation. Therefore, a corrective action by the climate control system upon shading of a solar sensor is required to avoid the adverse impact on the thermal comfort of the vehicle occupants.

Kakade et al. [9] presented a method to determine shading of a solar sensor for a known position of the sun with respect to the vehicle driving direction and a given geometry of the passenger compartment. The method uses fundamental geometric principles to calculate intersection of a line segment and a planar surface. A solar ray was considered as a line segment with one end of a line taken at the location of a solar sensor and the other end is pointing in the direction of the sun. An arbitrary length of a line such that its intersection with any planar surface of a vehicle can be determined. The planar surfaces were used to represent triangular facets of each vehicle glass - windshield, side screens, rear glass, etc. The number of triangular facets for a glass was determined to closely represent the actual shape of that non-planar vehicle glass. The intersection was then determined between the solar ray and every triangular facet. The Barycentric coordinates of an intersection point were used to determine if an intersection point is on the inside of that triangular facet [10]. This was repeated for all the vehicle glasses to determine if any of the intersection point is found on the inside of a facet and hence a vehicle glass - windshield, any of the side glass, rear glass, etc. If such an intersection point is found, then the solar sensor is determined exposed to a direct-beam solar radiation, otherwise it is shaded by an opaque body element of a vehicle.

However, the above method is found math-intensive and computationally expensive for a fixed-point embedded hardware. It requires extensive memory - Random Access Memory (RAM) and Read-Only Memory (ROM) and execution time. An opportunity for an algorithm that uses relatively simple geometric relations is therefore existed.

The proposed algorithm uses relatively simple geometric principle of intersection of a curve and a line segment. The solar azimuth angle, obtained from either a solar sensor or the GPS data is used to define a *constant azimuth curve*. A boundary or an edge of a vehicle glass is used to define a line segment. Four such line segments are used to represent a side glass and six line segments are used to represent a windshield. At a point of intersection, the magnitude of a constant azimuth curve defined by its radius r , solar azimuth Φ , and solar elevation θ in the spherical coordinate system is equal to the magnitude of a line defined by x, y, z coordinates of its endpoints in the Cartesian coordinate system and a parameter t that defines relative weighting of an intersection point with respect to the endpoints. On equating the magnitudes, we get three simultaneous equations with a radius of the curve r , solar elevation of an intersection point θ , and parameter t as unknowns. Therefore, we have a system of three simultaneous equations with three unknowns and is solved for a solar

elevation of an intersection point θ and a parameter t . An intersection point is considered valid if a corresponding parameter t has a value between 0 and 1. As described in detail later, only one intersection point of total six, for a windshield and two intersection points of total four, for each side screen are found to have t between 0 and 1. Such intersection points are termed valid intersection points. The valid windshield intersection point gives a lower limit on the solar elevation, beyond which a solar sensor is always exposed to the direct-beam solar radiation passing through a windshield. And, the valid side screen intersection points give a range of solar elevation for which a solar sensor is exposed to the direct-beam solar radiation passing through that side screen. Similarly, two valid intersection points can be obtained for a rear screen and a sunroof. A solar sensor is then determined shaded if the current solar elevation obtained from either a sensor or the GPS data is less than the windshield solar elevation limit and outside of the elevation range obtained for each of the other glasses.

Further improvement in memory utilization and controller throughput is obtained by the following.

1. The vehicle symmetry between the left and right sides of a solar sensor reduces the calculations to half. Solar sensor is assumed to be on the centerline of a vehicle.
2. The ranges of azimuth and elevation are obtained for each vehicle glass by using the azimuth and elevation of six points for windshield and four points for each of the other glasses. The calculation of the intersection points for a glass is performed only if the sensor measured or the GPS data calculated azimuth and elevation are in the range of azimuth and elevation calculated for that glass.
3. The solar elevation is calculated for only the valid intersection points. An intersection point that is beyond the endpoints of a glass boundary is discarded.

VEHICLE COORDINATE GEOMETRY

The location of a solar sensor in a vehicle is taken as the origin of the Cartesian coordinate system and the Spherical coordinate system. The coordinate data (x, y and z) for the glasses of a vehicle are defined with respect to the origin (or solar sensor). The x -axis of a Cartesian coordinate system is defined along the driving direction of a vehicle. The resulting Cartesian coordinate system is shown in [Figure 1](#).

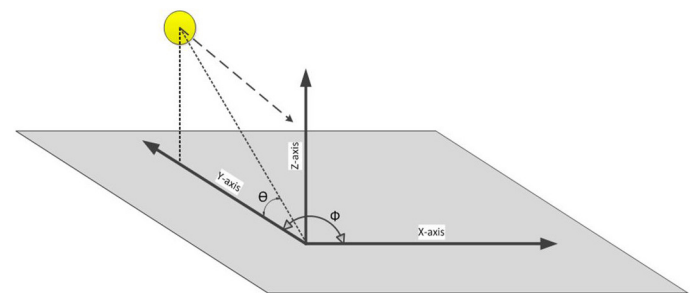


Figure 1. The Cartesian coordinate system with the location of a solar sensor taken as the origin and x -axis defined along the vehicle driving direction. Also given are the definitions of solar elevation θ and solar azimuth Φ .

As described earlier, symmetry of a vehicle about its centerline is used. Therefore, the calculations are performed for only one side (left or right) of a vehicle. Fig. 2 shows points on the edges of windshield half and a side glass. These points define the endpoints of the four line segments that represent the planar surfaces for a windshield half and a side glass. The two additional symmetric points can be used for a windshield, however vehicle symmetry makes them redundant.

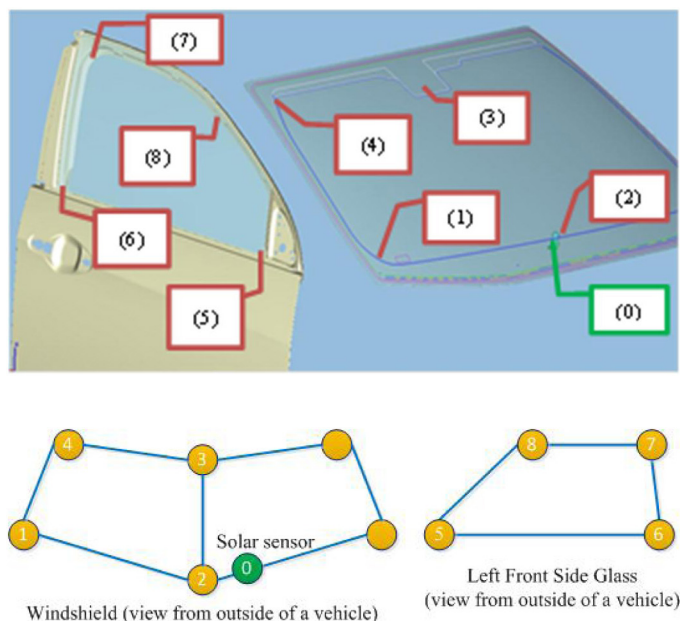


Figure 2. Coordinate geometry of windshield and front side glass of a vehicle with solar sensor taken as the origin. Also shown are the planar surfaces for a windshield and a front side glass.

The applicability of the proposed method to determine shading or an exposure of a solar sensor to the direct-beam solar radiation is demonstrated for a vehicle windshield and a front side glass however, it can be generically extended to include the other vehicle glasses, such as a rear side glass, rear glass and sunroof. Table 1 gives an example coordinate data for the points of Figure 2 for two vehicles, a mid-size sedan and a compact Sport Utility Vehicle (SUV).

Table 1. Coordinate data in millimeter (mm) for the eight points that define two planar surfaces, one for a windshield half and the other for a front side glass.

Coordinate Point	Mid-size Sedan			Compact SUV		
	x	y	z	x	y	z
1 – Windscreen, Lower Left	-10	720	-33	85	673	6
2 – Windscreen, Lower Center	155	0	-53	227	0	13
3 – Windscreen, Upper Center	-619	0	392	-428	0	352
4 – Windscreen, Upper Left	-675	590	367	-492	565	328
5 – Side Screen, Lower Front	-440	743	-32	-151	798	-52
6 – Side Screen, Lower Rear	-1192	753	5	-1031	808	-4
7 – Side Screen, Upper Rear	-1236	600	340	-1074	654	348
8 – Side Screen, Upper Front	-866	600	310	-716	664	318

AZIMUTH AND ELEVATION APPLICABILITY TEST

The calculation of a range of elevation angle for exposure of a solar sensor is performed only if the *applicability test* is passed for a given vehicle glass. For this, the vehicle coordinate data (such as given in Table 1) is converted from the Cartesian coordinate system to the spherical coordinate system. Figure 3 shows a point P defined by (P_x, P_y, P_z) in the Cartesian coordinate system and (r, θ, Φ) in the spherical coordinate system. The conversion uses the following relations.

$$\tan \theta = \frac{P_z}{P_x} \quad (1a)$$

$$\tan \phi = \frac{P_y}{P_x} \quad (1b)$$

These equations, (1a) and (1b), are used to obtain azimuth and elevation of eight coordinate points defined for the two planar surfaces in Table 1. The azimuth and elevation so obtained with respect to the origin - a solar sensor are illustrated in schematic of Figure 4.

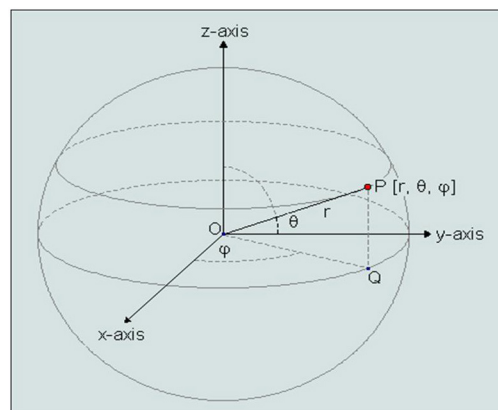


Figure 3. Point P defined by P_x, P_y, P_z in the Cartesian coordinate system and r, θ, Φ in the spherical coordinate system.

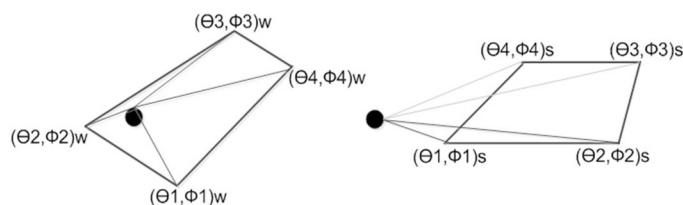


Figure 4. Azimuth and elevation of the coordinate points of planar surfaces of a windshield half and a front side glass.

The range of azimuth and elevation for each vehicle glass is obtained by simply finding the minimum and maximum values of azimuth and elevation of the coordinate points defined for that glass. For a side glass, we obtain

$$\theta_{min,s} = \min(\theta_1, \theta_2, \theta_3, \theta_4)_s \quad (2a)$$