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Determining absolute orientation of a phone by imaging celestial bodies

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Determining absolute orientation of a phone by imaging celestial bodies

ABSTRACT

The absolute orientation of a phone is of importance in a variety of applications, e.g., navigation, augmented reality, photography, etc. Phone sensors, e.g., gyroscope, etc. can determine relative changes in orientation, but absolute orientation is generally poorly known or unknown. Absolute orientation is not factory-set, and if it is set, requires periodic recalibration. This disclosure provides techniques to determine absolute orientation of a phone by imaging celestial bodies, e.g., sun, moon, etc. Once the absolute orientation is determined, phone sensors measure relative changes in orientation and thereby keep track of absolute orientation.

KEYWORDS

- Absolute orientation
- Sensor-image fusion
- Solar position locator
- Lunar position locator

BACKGROUND

The absolute orientation of a phone is the orientation of the phone with reference to certain standard axes. For example, absolute orientation is defined by the following angles:

- **Azimuth:** the angle between the North-South line and the projection of longitudinal axis of the phone onto the horizontal plane.
- **Pitch:** the angle between the longitudinal axis of the phone and the horizontal plane.
- **Roll:** the angle by which a phone is displaced about its longitudinal axis.

The absolute orientation of a phone is important for applications such as navigation, augmented reality, photography, etc. For example, the absolute orientation of the phone can be used to avoid harsh sunlight conditions during photography, to improve sky rendering, and to generally improve lighting composition. In augmented reality applications, the absolute orientation of the phone (or other device) can be used to improve insertion of virtual objects, even under difficult conditions where traditional computer vision methods fail.

Smartphones generally include good instrumentation to determine changes in orientation, but lack an initial reference orientation. For example, initial reference orientation is not set at factory; even if it were set, is lost during a power cycle for the device. Due to the lack of initial reference orientation, the quality of absolute orientation is poor, if known at all.

Currently, absolute orientation is estimated by magnetometer and accelerometer readings; e.g., the magnetometer reports the magnetic North Pole and the accelerometer reports the direction of the vertical. However, magnetometer readings are susceptible to errors due to presence of nearby ferrous materials or local magnetic fields. Heuristics are also used to estimate absolute orientation. For example, in a moving vehicle, accelerometer readings are superposed on a map to determine the direction of heading, and hence the direction of the North Pole. However, such heuristics are slow-converging and frequently inaccurate.

DESCRIPTION

Given latitude, longitude, altitude, and local time, values that can be obtained from a GPS sensor, standard astronomical formulas can be used to predict the position, e.g., azimuth and zenith angles, of celestial bodies. Therefore, a smartphone with a GPS sensor can easily determine a current location of the sun in the sky.

Mathematically, a photograph of an object, e.g., the sun, is a translation of the object from its coordinate system to the coordinate system of the photograph. The translation is represented by a matrix, itself the product of two matrices, an intrinsic matrix and an orientation matrix. The intrinsic matrix is a known matrix dependent on camera parameters. The orientation matrix represents the absolute orientation of the smartphone, e.g., its azimuth, pitch and roll, and is unknown.

Techniques of this disclosure utilize one or more photographs of the sun (or moon or other celestial body) and determine the unknown orientation matrix. The techniques minimize the square difference between the sun's coordinates in the celestial and photograph reference frames, treating the orientation matrix as a variable of optimization. When the square difference is minimized, the absolute orientation of the phone is obtained.

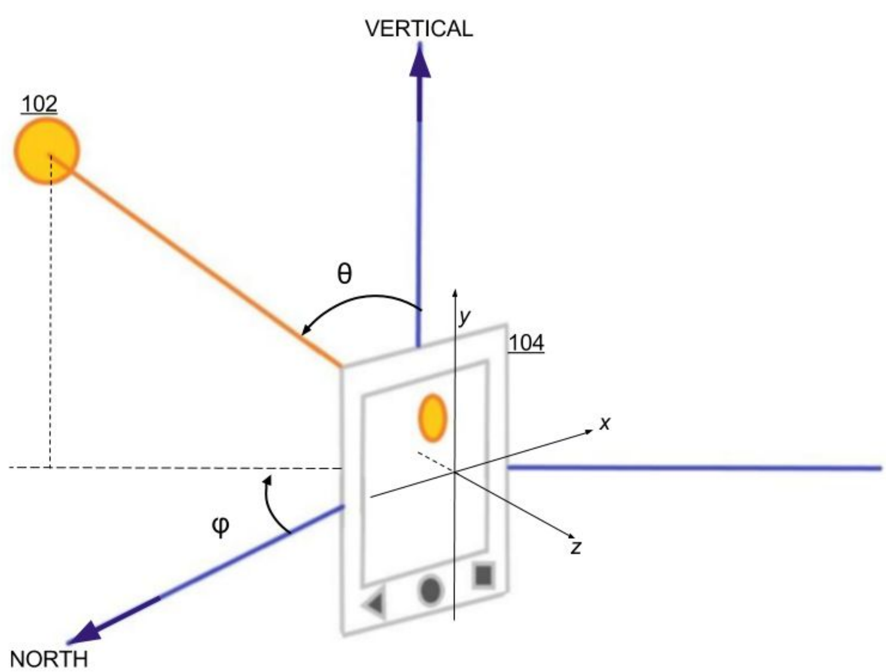

Fig. 1: Imaging the sun

Fig. 1 shows the capture of an image of a celestial body (102), e.g., sun, by a camera, e.g., smartphone (104). The zenith angle, e.g., angular displacement of the celestial body from the local vertical, is denoted θ. The azimuthal angle of the celestial body, e.g., the angle between the North-South axis and the projection of the celestial body on the horizontal plane, is denoted φ. The (θ, φ) frame of reference that locate a celestial body in the sky are known as world coordinates.

The camera frame of reference (e.g., for the smartphone camera) is illustrated by coordinate axes x, y and z, wherein, for example, the y-axis is a longitudinal axis of the smartphone; the x-axis, a transverse axis; and the z-axis, a normal to the plane of the smartphone. The coordinate system of an image taken by the smartphone, also known as camera frame of reference, is the same as the x-y-z frame of reference of the smartphone.

The world coordinates of the sun, e.g., its azimuthal and zenith angle pair (θ, φ), is related to the coordinates of its image in the frame of reference of the camera by the following matrix relationship.

$$\mathbf{s} = \mathbf{KRS}, \tag{1}$$

where

s is a vector comprising the coordinates of the image of the sun in the x-y-z frame of reference of the smartphone;

K is a matrix known as intrinsic matrix, whose entries depend on camera parameters such as focal length, principal point offset, etc.;

R is a matrix representing the absolute orientation of the smartphone, e.g., its azimuth, pitch, and roll; and

S is a vector based on the (θ, φ) coordinates of the sun, e.g., **S=[**$\sin\theta\sin\varphi$, $\sin\theta\cos\varphi$, $\cos\theta$, 1**]**^{T}, where superscript T represents matrix transpose.

Per the formulation of this disclosure, **s**, **K**, and **S** are known quantities. **S** and **s** are reported by sensors of the camera. The unknown is the absolute orientation of the smartphone, represented by **R**. In order to achieve greater accuracy in estimating **R**, the techniques may capture a plurality of images of the sun, as illustrated in Fig. 2.

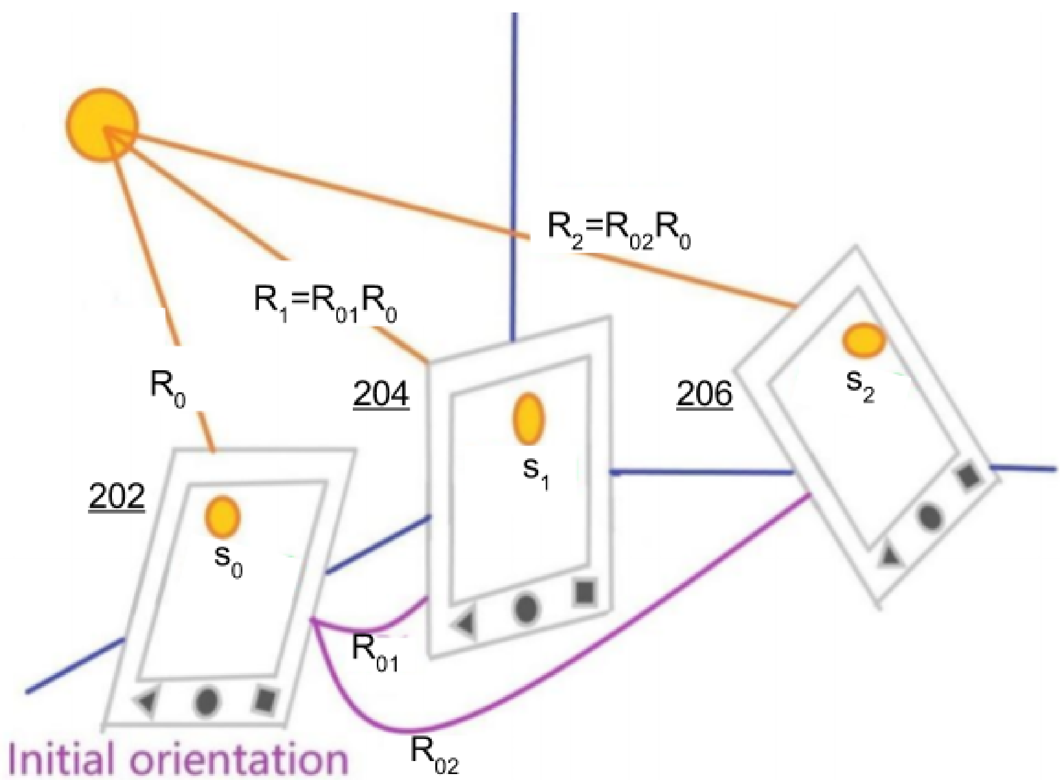

Fig. 2: Taking multiple images of the sun in order to achieve improved accuracy in estimation of the smartphone's orientation

As illustrated in Fig. 2, a smartphone captures an image the sun while at an initial orientation (202), followed by images captured while at additional orientations 204 and 206.

The *i*th orientation is characterized by an absolute orientation matrix $\mathbf{R}_i$ and a corresponding sun-image position $\mathbf{s}_i$ on the smartphone screen. For example, initial orientation 202 is characterized by an orientation matrix $\mathbf{R}_0$ and a sun-image position $\mathbf{s}_0$; orientation 204 is characterized by an orientation matrix $\mathbf{R}_1$ and a sun-image position $\mathbf{s}_1$; orientation 206 is characterized by an orientation matrix $\mathbf{R}_2$ and a sun-image position $\mathbf{s}_2$; and so on.

Any two absolute orientations $\mathbf{R}_i$ and $\mathbf{R}_j$ are related by relative orientation-change matrix $\mathbf{R}_{ij}$. For example, $\mathbf{R}_1=\mathbf{R}_{01}\mathbf{R}_0$; $\mathbf{R}_2=\mathbf{R}_{02}\mathbf{R}_0$; etc. Note that the relative orientation-change matrices $\mathbf{R}_{ij}$ are known, since the gyroscope on the smartphone can measure relative changes in orientation. The absolute orientations $\mathbf{R}_i$ are unknown, and are determined by techniques herein. If any one absolute orientation, e.g., $\mathbf{R}_0$, is determined, then the other absolute orientations are determined as well, since they are inter-related by known relative orientation-change matrices.

Equation (1) that relates the sun-image position on the screen to the sun position in the sky applies to each of the orientations $\mathbf{R}_i$. Thus,

$$\mathbf{s_0} = \mathbf{KR_0S},$$

$$\mathbf{s_1} = \mathbf{KR_1S} = \mathbf{KR_{01}R_0S},$$

$$\mathbf{s_2} = \mathbf{KR_2S} = \mathbf{KR_{02}R_0S}, \text{ etc.}$$

In order to obtain multiple images of the sun, the user points the smartphone to the sun such that its image appears on the screen, and slightly moves or rotates the smartphone. As the camera captures images at a particular frame rate, e.g., at 30 frames-per-second, the whole process of obtaining multiple sun images can be completed quickly, possibly within one second.

An example application is to mount the smartphone on the windscreen of a car. Once the sun is spotted, the absolute orientation of the smartphone can be determined using techniques of this disclosure. Once the sun images are obtained, processing can be done without having to point the camera at the sun or having the sun in the field of view. Unlike navigation applications, GPS accuracy need not be high. For example, even if the GPS reading is erroneous by a mile, the sun location in the sky does not change much. Because the sun is very far away, relative orientation measurement as reported by the gyroscope is sufficient, and accelerometer readings are not required.

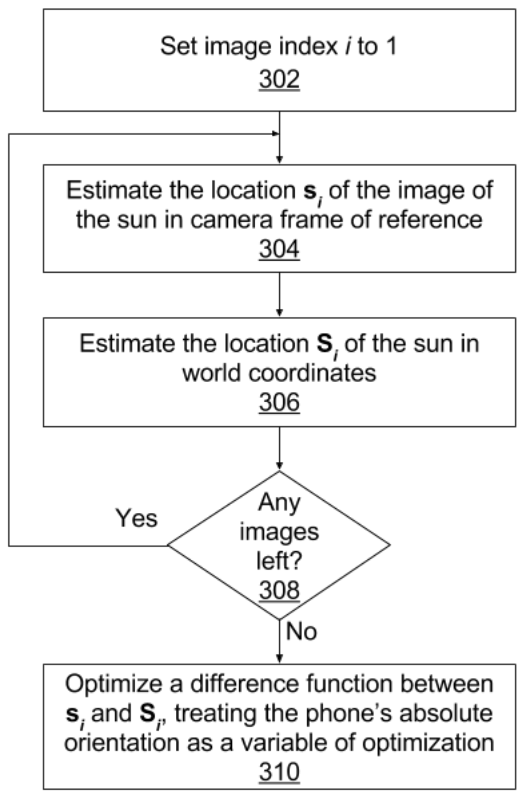

Fig. 3: Determining absolute orientation of a smartphone

Fig. 3 illustrates processing steps involved in determining absolute orientation of a smartphone. A total of *N* images of a celestial body, e.g., the sun, are captured. The *i*th image is taken at an (unknown) absolute orientation $\mathbf{R}_i$. The *i*th and *j*th absolute orientations are related through a relative orientation $\mathbf{R}_{ij}$ that is known based on gyroscopic signal. An image index i is set (302) to the first image.

The location $\mathbf{s}_i$ of the image of the sun is determined (304) in the camera frame of reference. The world coordinates $\mathbf{S}_i$ of the sun are estimated (306), using the GPS readings (lat-long, altitude, time) of the smartphone and standard astronomical formulas. When the N images are processed (308), a difference function between the N pairs of ($\mathbf{s}_i$, $\mathbf{S}_i$) is optimized (310), treating the phone's absolute orientation as a variable of optimization. The absolute orientation of the phone is obtained as the result of the optimization.

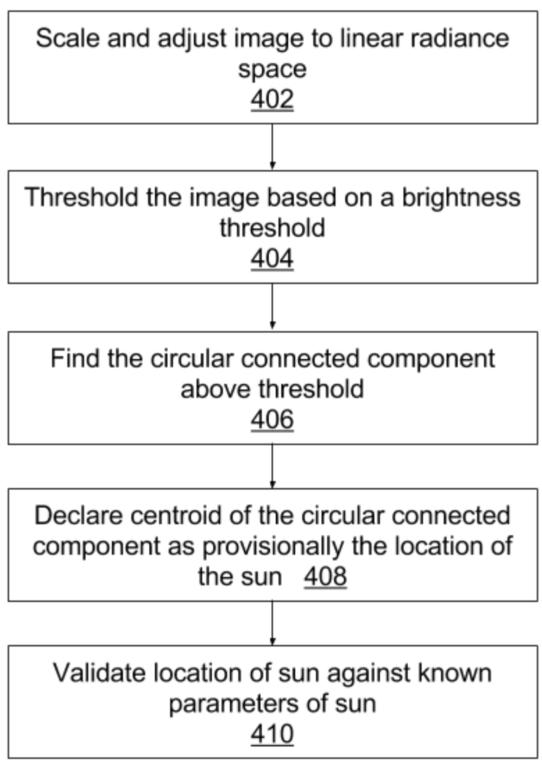

Fig. 4: Determining the location of the sun in the camera coordinate system

Estimation of the location of the image of the sun in the camera coordinate system

The estimation of the location of the image of the sun (304) in camera coordinates is illustrated in greater detail in Fig. 4. An image containing the sun is scaled and adjusted to a linear radiance scale (402). The image is thresholded based on brightness threshold, thereby converting the image to a black-and-white image (404). The threshold is based on parameters of the camera and of the sun. For example, the sun has an absolute brightness for a specific camera under a specific exposure, which fact is used to establish by a one-time calibration procedure the brightness threshold.

A circular region of connected pixels is determined that is above brightness threshold (406). The area of the circular region is above a certain area-threshold in order to avoid small but bright false detections. The centroid of the circular, connected region is declared provisionally as the center of the image of the sun in camera coordinates (408). The location of the sun as determined is validated against known properties of the sun (410). For example, given camera focal length, the sun has a known radius. The radius of the circular region declared as the sun’s image should match the sun’s known radius. As another example, the sun’s brightness, when normalized by ISO number and exposure, is the highest of all objects. In this manner, other bright sources of light can be ruled out as sun by virtue of their size, brightness, etc., and false detections avoided.

(a) (b)

Fig. 5: An example of detecting the location of the sun's image. (a) image as captured by camera (b) image after thresholding

Fig. 5 illustrates an example of detecting the location of the sun's image in the camera coordinate system, per techniques of this disclosure. Fig. 5(a) is the image as captured by the camera. The red dot indicates the location of the sun, as determined by techniques of this disclosure. Fig. 5(b) is a thresholded version of Fig. 5(a). A small, bright artifact appears below the sun in Fig. 5(b); the techniques successfully reject the artifact as a false detection.

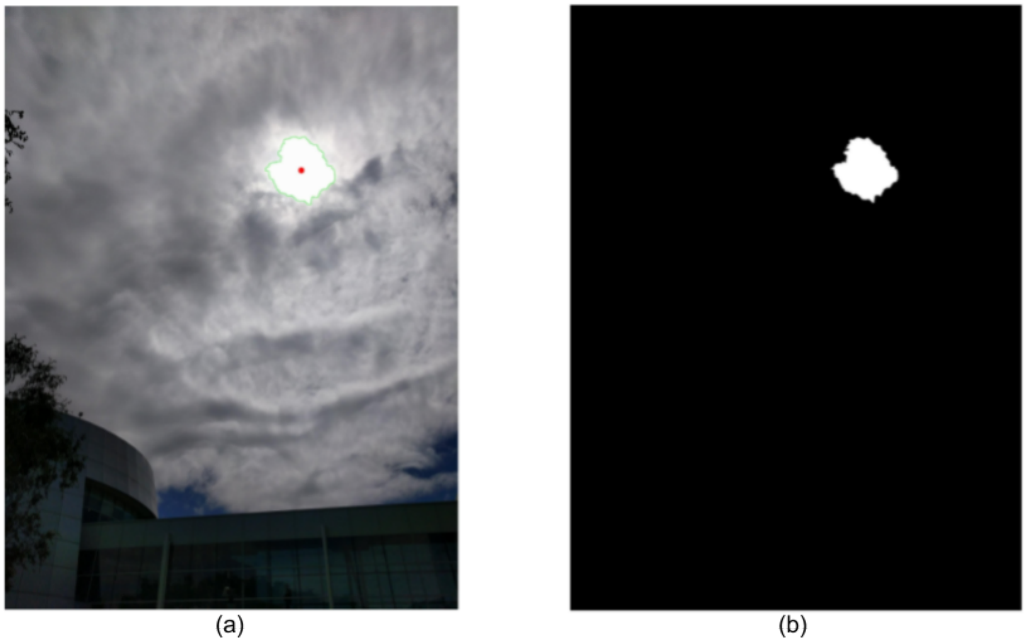

Fig. 6: Detecting the location of the sun's image. (a) image as captured by camera (b) image after thresholding

Fig. 6 is another example of detecting the location of the sun's image in the camera coordinate system, per techniques of this disclosure. Fig. 6(a) is the image as captured by the camera. The red dot indicates the location of the sun, as determined by techniques of this disclosure. Fig. 6(b) is a thresholded version of Fig. 6(a). Due to the sun being hidden behind clouds, its shape appears irregular, but its location is detected correctly. In a similar manner, the techniques of this disclosure are robust to noise arising from blurriness (e.g., due to shaking hands during image capture), unclear sky, dirt smudge on lens, micro-particles in the atmosphere, an occluded sun (due to clouds, sun set/rise), etc.

Optimizing the difference function

An example of a difference function at 310 between the N pairs of ($\mathbf{s}_i$, $\mathbf{S}_i$) is E_1 below:

$$E_1 = \sum_{j=1}^{N} \| \mathbf{s}_j - \mathbf{K}\mathbf{R}_{0j}\mathbf{R}_0 \mathrm{S}_j \|^2.$$

Here the variable of optimization is the initial absolute orientation $\mathbf{R}_0$. Thus the initial absolute orientation is given by

$$\mathbf{R}_0 = \underset{\mathbf{R_0}}{\operatorname{argmin}}\, E_1. \tag{2}$$

As noted before, the jth subsequent orientations is given by $\mathbf{R}_j = \mathbf{R}_{0j}\mathbf{R}_0$, with $\mathbf{R}_{0j}$ known from gyroscopic signal.

Another example of a difference function at 310 to optimize for $\mathbf{R}_0$ is E_2, defined below:

$$E_2 = \sum_{j=1}^{N} \| \mathbf{s}_j - \mathbf{K}\mathbf{R}_j \mathrm{S}_j \|^2 + \sum_{i=1}^{N} \sum_{j=1}^{N} \| \mathbf{R}_j - \mathbf{R}_{ij}\mathbf{R}_i \|^2, \tag{3}$$

with optimization performed simultaneously over the N absolute orientation matrices $\mathbf{R}_j$. Thus the N absolute orientations, each treated as a variable of optimization, are given by

$$\mathbf{R}_j = \underset{\mathbf{R}_1, \mathbf{R}_2, \dots, \mathbf{R}_N}{\operatorname{argmin}}\, E_2, \text{ for } j = 1, 2, \dots, N.$$

The second term of (3) enforces the constraint that relative rotations be close to the one provided by the gyroscope. Minimization of E_1 or of E_2 is done via numerical optimization techniques.

The special case of N=1

If the number of images taken of the celestial body, e.g., sun, is just one, then the problem of optimizing E_1 or E_2 is under-determined. Sometimes under-determination can occur even if N>1, but if the different positions used to capture images of the sun do not result in substantially different locations of the sun on the smartphone screen. In this case, an alternate approach to finding the phone's absolute orientation is as follows.

The absolute orientation matrix **R** is split into its component azimuth, pitch and roll matrices, so that (1) is rewritten as

$$\mathbf{s} = \mathbf{KRS} = \mathbf{K}\,\mathbf{R}_{\mathbf{roll}}\mathbf{R}_{\mathbf{pitch}}\mathbf{R}_{\mathbf{azimuth}}\,\mathbf{S}. \tag{4}$$

The roll matrix is generally well-estimated by on-board sensors, and is hence considered known. Transposing known quantities to the left-hand side, (4) is rewritten as

$$\mathbf{R}_{\mathbf{roll}}^{-1}\mathbf{K}^{-1}\mathbf{s} = \mathbf{R}_{\mathbf{pitch}}\mathbf{R}_{\mathbf{azimuth}}\,\mathbf{S}. \tag{5}$$

The form of the pitch and the azimuth matrices are known in terms of their respective angles. For example, if α and β are respectively the azimuth and pitch angles, then $\mathbf{R}_{\mathbf{azimuth}}$ and $\mathbf{R}_{\mathbf{pitch}}$ are given by

$$\mathbf{R}_{\mathbf{azimuth}} = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}; \qquad \mathbf{R}_{\mathbf{pitch}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{pmatrix}. \tag{6}$$

Substituting (6) in (5), a matrix equation is obtained in two unknown variables, α and β, which is solved by standard equation-solving techniques, e.g., Newton's method.

CONCLUSION

Techniques of this disclosure determine absolute orientation of a smartphone (or other camera device) by fusing sensor data with images of celestial bodies. Per techniques of this disclosure, a celestial body, e.g., sun or moon, can be tracked more accurately than possible by only sensor (e.g., GPS, accelerometer, etc.) readings. Some applications of the described techniques include sun-flare detection, improved sky-rendering and improved lighting composition in photographs, improved navigation, accurate positioning of virtual objects in augmented reality, etc.