Speed measurement of spherical objects using an off-the-shelf digital camera

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Abstract. Motion blur is a result of finite acquisition time of practical cameras and the relative motion between the camera and moving objects. We present a method for speed measurement of spherical objects using motion blurred images captured by a digital camera. The object is assumed under a straight line uniform-velocity motion, and the speed is calculated according to the imaging geometry and blur extent estimates. We have established a link between the motion blur information of a 2-D image and the speed information of a moving object. Experimental results are presented for the real-scene images. © 2008 SPIE and IS&T. [DOI: 10.1117/1.2952845]

1 Introduction

In recent years, because of advances in the development of various aircraft, baseball exercise, and electronic devices, people are becoming more interested in determining the speed of flying objects, the pitching speed of sports players, and the speed of motor vehicles detected by law enforcement agencies. Currently, most speed measurements of moving objects are achieved by microwave radar or laser devices.

In this work, we present an approach for speed measurements of spherical objects based on the images taken by a hand-held digital camera. The basic idea of our approach is as follows. Due to the relative motion between the camera and the moving object during the finite exposure time of the camera, motion blur will appear on the dynamic regions of the image. For any fixed shutter speed, the moving distance of the object is proportional to the amount of motion blur caused by the imaging process. Thus, if the direction and extent of the motion blur can be identified, it is possible to recover the physical displacement of the moving object using the intrinsic and extrinsic parameters of the camera.

Since the projection of a sphere-like object on the image plane is circular, more accurate motion extent of the object can be obtained by applying a circle fitting algorithm on a sequence of deblurred images created with the initial blur extent estimation. Last, the uniform velocity of the straight line object motion can be calculated by means of displacement divided by the camera exposure time. To demonstrate the idea of the proposed method, several assumptions are made for the experiments, namely, (1) the object is moving in front of a homogeneous background scene, (2) the object motion is linear during the image acquisition process, and (3) the camera parameters (CCD pixel size and shutter speed) provided by the manufacturer are accurate.

2 Object Speed Measurement

As shown in Fig. 1, suppose that the center of a spherical object with diameter \(d\) is located at \(P=(x, y, z)\) in the camera coordinate system and the corresponding image point is \(P'=(\hat{x}, \hat{y})\). Then the depth of the object can be derived as

\[
z = \frac{d \cos(\alpha + \theta)}{2 \sin \alpha},
\]

where \(\theta\) is the angle between the optical axis and the ray passing through the left edge point of the object, and \(\alpha\) is half of the angles between the rays passing through the edges of the object. Moreover, \(x\) and \(y\) are given by

\[
x = \frac{\hat{x} z}{f} \quad \text{and} \quad y = \frac{\hat{y} z}{f},
\]

from perspective projection, where \(f\) is the focal length of the camera. If \(\hat{x}_l\) and \(\hat{x}_r\) represent the left and right edge points of the object in the image, respectively, then \(\theta\) and \(\alpha\) are given by

\[
\tan \theta = \frac{\hat{x}_l}{f},
\]

and

\[
\tan(\theta + 2\alpha) = \frac{\hat{x}_r}{f}.
\]

Thus, the 3-D coordinates of an object can be identified from the captured image if its actual size is available.

Suppose that the initial and end positions of the object are \(P\) and \(P'\) for a single image capture, as illustrated in Fig. 2. The speed \(v\) is then given by
\[
v = \frac{d}{T} = \frac{\|P' - P\|}{T},\tag{5}
\]

where \( T \) is the shutter speed. Thus, if the motion blur is identified and denoted as a displacement vector \( \mathbf{u} \), and the center of the object in the deblurred image is denoted as \( P \), then the corresponding image points of \( P \) and \( P' \) are given by \( p = p + u \), respectively. Suppose that the identified motion direction is an angle \( \beta \) with respect to the image scanlines and blur extent is \( K \) pixels along the motion direction. We then have \( \mathbf{u} = (Ks_x \cos \beta, Ks_y \sin \beta) \), where \( s_x \) is the CCD pixel size of the camera.

Now, if we consider a special case in which the object is moving in a direction parallel to the image plane and horizontal scan lines, then the displacement can be obtained from similar triangles. Thus, Eq. (5) can be simplified as

\[
v = \frac{zKs_x}{Wf},\tag{6}
\]

where \( K \) is the blur extent in pixels and \( s_x \) is the CCD pixel size of the camera. In this case, the position of the object in the image is not required for speed measurement. Similarly, the distance \( z \) can be derived as

\[
z = \frac{fd}{Ws_x},\tag{7}
\]

where \( d \) and \( W \) are the diameters of the object measured physically and observed in the image, respectively. From Eqs. (6) and (7), the speed \( v \) can be written as

\[
v = \frac{Kd}{Wf},\tag{8}
\]

without the knowledge of the focal length and CCD pixel size of the camera.

For a more general case in which the object is approaching or leaving the camera at a certain angle, the motion direction \( \phi \) is estimated using two image captures. Suppose that the 3-D coordinates of the objects are \((x_1, y_1, z_1)\) and \((x_2, y_2, z_2)\) from the two images. The angle is then given by

\[
\phi = \tan^{-1}\left(\frac{z_2 - z_1}{x_2 - x_1}\right).\tag{9}
\]

It should be noted that the estimation of the angle \( \phi \) can be thought of as a calibration stage and should be done prior to speed calculation. At this stage, the shutter speed of the camera should be set as fast as possible to avoid motion blur. Consequently, the 3-D point \( P' \) is given by

\[
x' = \frac{z'\hat{x}'}{f},
\]
\[
y' = \frac{z'\hat{y}'}{f},
\]
\[
z' = \frac{f(z - x \tan \phi)}{f - \hat{x} \tan \phi},\tag{10}
\]

where \( f \) is the focal length of the camera.

3 Motion Estimation

It is clear that the motion direction of a moving object (appearing in the image) is the same as the direction of motion blur. Thus, the intensity of high-frequency components along this direction is decreased. As a result, the derivative of the image in the motion direction should suppress more of the image intensity compared to other directions. To identify the motion direction relative to the horizontal image scan lines, either spatial or frequency domain approaches can be used.\(^1\) However, most of those methods consider the case in which the whole image is blurred, which is different from the motion blur caused by an object moving in front of a static background.

To solve this problem, a gradient-based method is applied only on the subimage (containing the target object) to estimate the motion direction.\(^2\)\(^3\) The subimage can be ei-
A model for image blur is given by a 1-D case. In this case, a commonly used spatially invariant motion identification model for image blur is given by

\[ g(x) = h(x) \ast f(x), \]

where \( h(x) \) is a linear point speed function (PSF), and \( f(x) \) and \( g(x) \) are the original and observed images, respectively. Furthermore, the 1-D PSF for the uniform linear motion can be modeled as

\[ h(x) = \begin{cases} \frac{1}{R}, & |x| \leq R/2 \\ 0, & \text{otherwise,} \end{cases} \]

where \( R \) is the extent of motion blur. That is, a step edge becomes a ramp edge with a width of \( R \) due to the uniform linear motion of the scene.

It is well known that the response of a sharp edge to an edge detector is a thin curve, whereas the response of a blurred edge to the same edge detector is spread over a wider region. This suggests that the result of edge detection can be used as an initial estimate of the motion blur extent. To obtain the blur extent along the horizontal direction, a Sobel edge detector is first applied on the subimage to find the left and right blur regions. Ideally, there will be two edges with the same width that correspond to the left and right partially motion blurred regions for each image scan line. Thus, the blur extent of a moving object can be obtained by finding the mode of the edge widths in the edge image. However, as shown in Fig. 3, the blur extents along the image scan lines are not all identical due to the circular shape of the spherical object. A good estimate can be given by taking the average of the edge widths that are larger than 75% of the largest edge width.

Since the intensity variations inside the object region affect the blur extent estimation, they should be suppressed while searching for the best estimate. The steps of the algorithm for robust estimation of motion length is thus given as follows:

1. Calculate the summation of the edge widths for each row, and find the mode of the summations (the most frequent edge width) for the whole image. Set the number of iterations.
2. Set \( \text{Edge}_\text{width} \) as half of the edge width corresponding to the mode derived in step 1.
3. Compare the summation of the edge widths for each row with \( 2 \cdot \text{Edge}_\text{width} \). Record the summations that are larger than 75% of \( 2 \cdot \text{Edge}_\text{width} \).
4. Find the mode of the preceding summations for the whole image, and replace \( \text{Edge}_\text{width} \) with half of the corresponding summation.
5. Go back to step 2 and repeat until \( \text{Edge}_\text{width} \) converges or a predefined number of iterations is reached.

Due to noise, nonuniform intensity of the background, and other artifacts in real images, the blur extent estimates obtained in the preceding section usually contain several pixels of error. To make the estimation more robust, a circle fitting algorithm is employed to identify the object and estimate the blur extent more accurately. First, a sequence of motion deblurred images is created by Wiener filter or blind deconvolution using the estimated blur parameters. The number of deblurred images to be created depends on the size of the object appearing in the image and the initial blur extent estimation. In the implementation, typically nine deblurred images (each image with one pixel difference of motion deblurring) are generated for circle fitting. For example, if the estimated blur length is \( K \) pixels, then the images are deblurred with \( K-4 \) to \( K+4 \) pixels.

After a sequence of deblurred images is created, a circle detection algorithm is used to obtain the image with the most circle-like object. Figure 4 shows five motion de-

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**Table 1** Softball speed measurement results (in km/h).

<table>
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<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
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</table>
blurred images and the circle fitting results. In the experiments, the difference between the initial blur extent estimation and the result after an additional circle fitting procedure is less than 3 pixels in most cases. This further ensures that nine deblurred images are sufficient for the identification of blur extent used for circle fitting.

4 Experimental Results

The proposed speed measurement algorithms for spherical objects have been tested on real images from outdoor scenes with softball pitching. For the first set of experiments, the camera is placed approximately perpendicular to the motion direction of the softball. The image resolution is set as $1024 \times 768$, and the distance between the camera and the imaged softball position is about 7 m. Equation (8) is used for speed measurements with camera shutter speed $T = 1/320$-s and softball diameter $d = 97.45$ mm. For the images shown in Figs. 3 and 4, the blur extent and the size of the softball are identified as 26 and 72 pixels, respectively. Thus, the speed is found to be 40.54 km/h.

For the second set of experiments, the camera is installed such that the image plane is approximately 30 deg off the moving direction of the softball. The same camera parameters are adopted, except that the shutter speed is first set as $1/800$ s for motion direction estimation. To make the motion direction estimation more robust, the angle $\phi$ is given by line fitting on the $xz$-plane projections of the 3-D coordinates obtained from five different images. The angle $\phi$ is found as 32.5 deg in the experiment. For each speed measurement, Eqs. (1)–(10) are used to compute the speed of the softball with the CCD pixel size of 4.4 $\mu$m. Some results (16 out of 25 pitches) for both cases are shown in Table 1. B1 and B2 represent the first and second sets of the experiments, respectively.

5 Conclusion

Most commonly used methods for object speed measurement adopt radar- or laser-based devices. They are active devices and are usually more expensive compared to a passive camera system. In this paper, we have presented an automatic speed measurement method of spherical objects using a digital camera. Blur parameters of the motion blurred image are estimated and then used to calculate the speed of the object according to a pinhole camera model. Since our approach is an image-based method, it can be implemented with low-cost, off-the-shelf digital cameras. Furthermore, the camera settings (such as shutter speed, image resolution, and focal length) can be easily adjusted to improve the accuracy of the system. In contrast to the commercially available speed measurement devices, our approach has virtually no limitation on the speed test range.

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References

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