Camera-Motion and Mobile Imaging

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ABSTRACT

Due to the demanding size and cost constraints of camera phones, the mobile imaging industry needs to address several key challenges in order to achieve the quality of a digital still camera. Minimizing camera-motion introduced image blur is one of them. Film photographers have long used a rule-of-thumb that a hand held 35mm format film camera should have an exposure in seconds that is not longer than the inverse of the focal length in millimeters. Due to the lack of scientific studies on camera-motion, it is still an open question how to generalize this rule-of-thumb to digital still cameras as well as camera phones. In this paper, we first propose a generalized rule-of-thumb with the original rule-of-thumb as a special case when camera-motion can be approximated by a linear motion at 1.667 °/sec. We then use a gyroscope-based system to measure camera-motion patterns for two camera phones (one held with one hand and the other held in two hands) and one digital still camera. The results show that effective camera-motion function can be approximated very well by a linear function for exposure durations less than 100ms. While the effective camera-motion speed for camera phones (5.95 °/sec and 4.39 °/sec respectively) is significantly higher than that of digital still cameras (2.18 °/sec), it was found that holding a camera phone with two hands while taking pictures does reduce the amount of camera motion. It was also found that camera-motion not only varies significantly across subjects but also across captures for the same subject. Since camera phones have significantly higher motion and longer exposure durations than 35mm format film cameras and most digital still cameras, it is expected that many of the pictures taken by camera phones today will not meet the sharpness criteria used in 35mm film print. The mobile imaging industry is aggressively pursuing a smaller and smaller pixel size in order to meet the digital still camera's performance in terms of total pixels while retaining the small size needed for the mobile industry. This makes it increasingly more important to address the camera-motion challenge associated with smaller pixel size.

Keywords: Camera-motion, mobile imaging, digital photography, image stabilization, hand-jitter.

1. INTRODUCTION

Camera phones have quickly become the most common image capture devices in the world. According to Gartner Dataquest's report [1], 48% of worldwide mobile phones in 2006 have a camera and this number will grow to 81% by 2010. Though the gap is closing, the image quality of camera phones is generally regarded as inferior to that of digital still cameras (DSCs). The key challenge for camera phones to achieve DSC-like image quality comes from the fact that the space available for a camera module in cell phones is quite limited. To meet the market's demand for higher pixel count camera phones, camera phone designers have managed to cram more pixels into that space by shrinking the pixel size. With pixel size reduced, the signal-to-noise ratio (SNR) gets smaller as well [2-5]. To bring the SNR up to an acceptable level requires longer exposure time. This presents a problem for hand-held photography, since a long exposure will result in motion blur that limits the effective spatial resolution of the captured images [6-8].

Camera-motion introduced motion blur is a well known problem in film photography. To minimize its impact, film photographers have long used a rule-of-thumb that a hand held 35mm format SLR camera should have an exposure in seconds that is not longer than the reciprocal of the focal length in millimeters. For example, the exposure duration for a 35mm film camera with a 50mm focus length lens should not exceed 1/50 sec. While this rule-of-thumb proves to be very helpful for 35mm format SLR cameras, it is unclear how it would generalize to digital still cameras as well as camera phones. As our previous study [8] indicates, there are many factors (camera-mass, user's skill level, sensor pixel

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count etc.) that can impact the amount of camera-motion significantly. The original rule-of-thumb fails to take these factors into account which could be attributed to the fact that variation of these factors among 35mm format SLR cameras is much smaller than that among digital still cameras as well as camera phones. First of all, the size of typical digital imaging sensors can vary all the way from 1/3.6 inch to that of 35mm film format while the choice is quite limited for film cameras. Secondly, it is expected that user's skill level can vary very significantly as imaging capture devices become more accessible to the general public. Thirdly, camera weight has dropped significantly as digital photography goes mobile (from over 1000 grams to under 100 grams). Other factors that are new to mobile imaging, such as holding camera in one hand or two hands, can also impact camera-motion in general. In this paper, we first propose a generalized rule-of-thumb for maximum exposure duration that links the 35mm film photography with digital photography in general. Then we use a gyroscope-based system to measure camera-motion of particular interest to the mobile imaging industry.

2. GENERALIZED RULE-OF-THUMB

Mathematically, the original rule-of-thumb for exposure duration T (in seconds) while handholding a 35mm format SLR camera can be expressed as the inverse of the lens focal length f (in millimeters):

$$T \le \frac{1}{f} \tag{1}$$

Naturally, we propose the generalized rule-of-thumb for maximum exposure duration for both film and digital cameras as:

$$F(T) \le \frac{CoC}{f} \times \frac{180}{\pi} \tag{2}$$

where

F(T): effective camera-motion function (measured in spatial degree).

CoC: circle of confusion at imaging focal plane (measured in millimeters).

Equation 2 states that blur circle incurred by camera-motion at exposure time T should not exceed the circle of confusion (CoC) at the imaging focal plane. In general, the CoC depends on both the imaging media size (film size or imaging sensor size) and the final print size [9-10]. While the final print size is usually unknown in advance, a standard print size of 8x10 inch is usually assumed in practice for 35mm format film photography [9]. If we replace the actual focal length f for any non-35mm imaging media with its 35mm equivalent focal length f_{35} in Equation 2, then we can also use the 35mm format CoC_{35}. Historically, CoC_{35} value from 0.024 mm to 0.033 mm has been used in practice for 35mm format film [9]. Kodak [11] also recommended an angular format of CoC as 2 minutes of arc which is equivalent to CoC of 0.0291 mm for a 50 mm lens on 35 mm format. For any non-35mm imaging media format (most digital still cameras as well as camera phones), we can substitute its 35mm equivalent focal length f_{35} and CoC_{35} (0.0291 mm in this case) into Equation 2:

$$F(T) \le \frac{CoC_{35}}{f_{35}} \times \frac{180}{\pi} = \frac{0.0291}{f_{35}} \times \frac{180}{\pi} = \frac{1.667}{f_{35}} \tag{3}$$

If the effective camera-motion function F(T) follows a linear motion model with effective speed of k (°/sec):

$$F(T) = k \times T \tag{4}$$

Then Equation 3 can be simplified as:

$$T \leq \frac{1.667}{k \times f_{35}} \tag{5}$$

The original rule-of-thumb for 35mm film camera (Equation 1) is a special case of Equation 5 when

$$k = 1.667 \ ^{\circ}/\sec \tag{6}$$

The key question now is how well camera-motion can be approximated by a linear motion model, especially for short exposure durations (less than 100ms for example). In our previous study [8], we showed that camera-motion can be better described by a 2D random-walk model for exposure duration longer than 1/8 second. For exposure duration less than 1/8 second, we indicated that camera-motion is closer to a linear motion model though the method used in that study (taking pictures of a point light source) didn't provide accurate enough measurement to verify this. Thus, we employed a more accurate method to measure camera-motion in this study to check how well a linear motion model can model camera-motion. In addition, we would also like to investigate how the effective camera-motion speed k varies with factors such as camera-mass, user-to-user, capture-to-capture and holding camera with one hand or two hands.

3. EXPERIMENTAL SETUP

Three cameras were used in this study: a flip camera phone, a slider camera phone and a digital still camera (Table 1). Both camera phones have similar mass while the digital still camera is lighter than a typical 35mm film SLR camera. The flip camera phone has its capture button in the center of the keypad while the slider camera phone has its capture button on it side. For comparison, subjects were asked to hold the flip camera phone with one hand while taking pictures and hold the slider camera phone with two hands while taking pictures. The digital still camera was held with two hands for all subjects. A dual-axis gyroscope sensor from Invensense, Inc. [12] was attached close to the lens in order to record both yaw and pitch movement of the cameras. Camera-motion data along with a time stamp when the shutter button was pressed were recorded at 50 samples/second by a USB DAQ board. Seven non-paid subjects (six males and one female, ages from 30 to 45 years old, all Motorola Employees) participated in this experiment (including three of the authors). Though all of them have used camera phones and digital still cameras prior to the experiment, most of them are considered "casual" photographers. For each camera, subjects were asked to take 25 pictures while holding it naturally with camera's viewfinder on. For each capture, at least two seconds of camera-motion data (yaw and pitch) were recorded starting from the time capture button was pressed.

Table 1: Camera information

Camera format	Flip camera phone	Slider camera phone	Digital still camera
Mass(grams)	~100	~105	~400
Holding mode	Single hand	Two hands	Two hands

4. RESULTS

4.1 Data analysis

For each capture at exposure duration T, we first extract the long and short axis vectors of the corresponding camera-motion data using the principal component analysis method [13]. A rectangle with edges along the long and short axis is then constructed so that it just contains all data points (Figure 1). We then define the effective camera-motion function at exposure duration T, F(T), as the length of the rectangle's longer edge. With this definition, the effective camera-motion function F(T) for linear motion at constant speed k would be k*T instead of k*T/$\sqrt{12}$ (standard deviation for uniform distribution, see reference [14]) if we choose the standard deviation along the long axis as used in our previous study [8]. The new definition fits better with linear camera-motion data than the old definition.

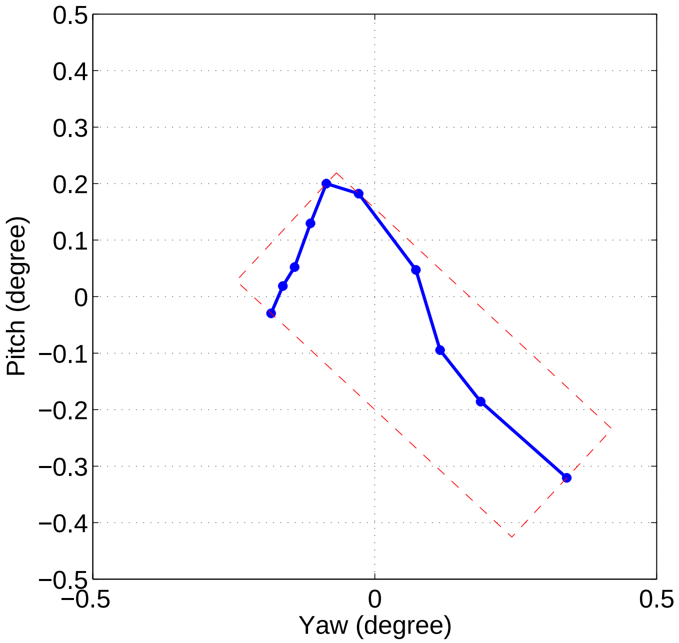

Figure 1. This example illustrates how to extract the effective camera-motion function at exposure duration T. The camera's position data from time 0 to T were recorded as blue dots. The long and short axis vector of these data points were extracted using the principal component analysis method. A rectangle (red dashed line) with edges along the long and short axis was then constructed to just contain all data points. The effective camera-motion function F(T) at exposure duration T is defined as the length of the rectangle's long edge.

4.2 Linear camera-motion model

To check how well a linear motion model (Equation 4) can approximate the effective camera-motion function, we first average the effective camera-motion function F(T) across all subjects and captures. Then we define the error function at time T_N (where k_N is the estimated linear camera-motion speed at T_N that minimizes the error function):

$$error(T_N) = \frac{1}{N}\sum_{i=1}^{N}\left[\frac{F(T_i) - k_N \times T_i}{F(T_i)}\right]^2 \qquad (7)$$

Figure 2 plots the effective camera-motion function (averaged across all seven subjects and captures) from time 0 to 300 ms for the three cameras and Figure 3 plots the fitting error using the best linear motion model (Equation 7) as a function of time for the three cameras. As the fitting error grows with exposure time, it provides further evidence that the effective camera-motion function F(T) is closer to a linear motion model for shorter exposure duration (less than 100ms for example). For longer exposure duration (longer than 100ms for example), the results are consistent with the 2D random-walk model suggested in our previous study [8]. Since exposure duration longer than 100ms is rarely used in practice, we will use the estimated camera-motion speed at 100ms for following analysis.

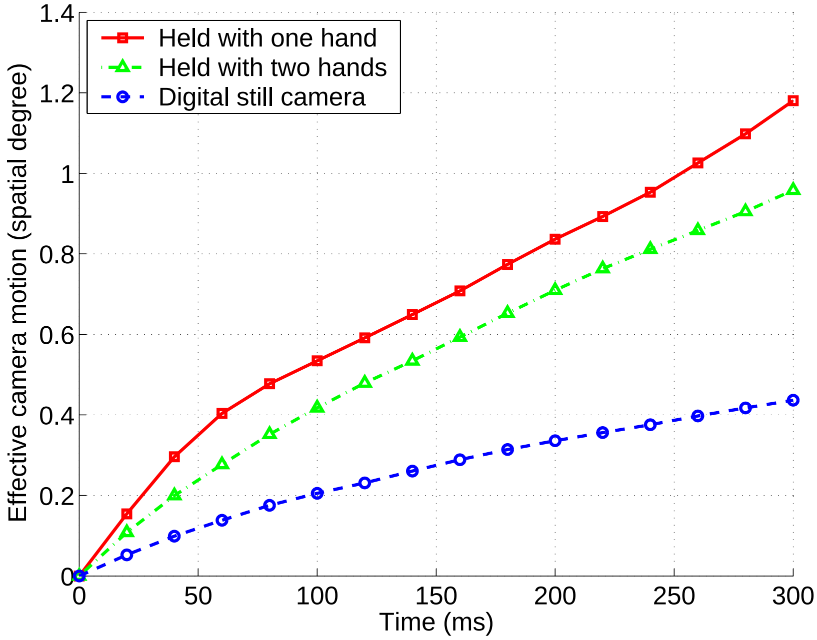

Figure 2. Effective camera-motion function F(T) at different exposure duration (averaged across subjects and captures) for the three cameras.

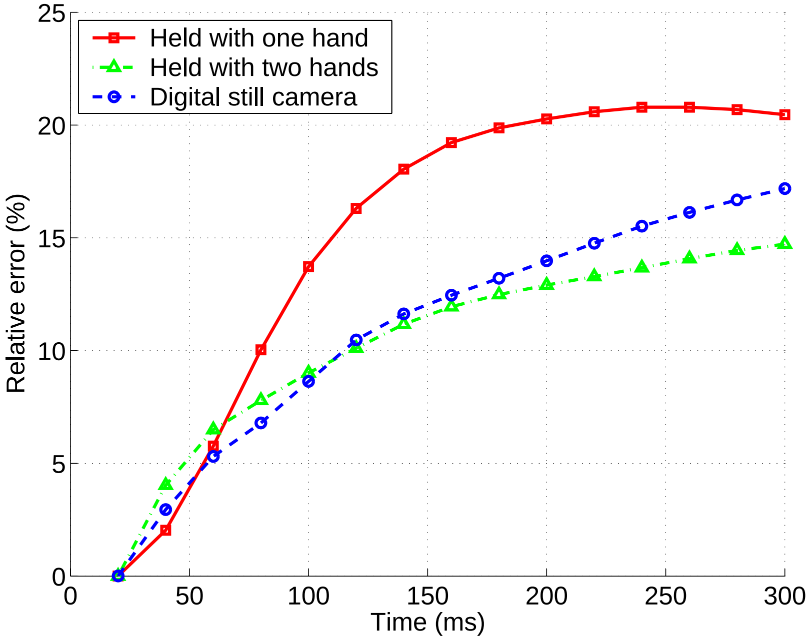

Figure 3. Fitting error using a linear motion model (Equation 7) as a function of exposure duration for the three cameras.

4.3 Camera-to-camera variation

Table 2 lists the estimated linear camera-motion speed and the standard deviation across subjects for the three cameras at exposure duration of 100 ms. For the digital still camera, the estimated camera-motion speed of 2.18 °/sec is slightly higher than the expected value of 1.667 °/sec derived from the original rule-of-thumb (Equation 7). This difference could be attributed to two factors. First, the mass of the digital still camera used in this study is less than most 35mm film SLR cameras. Second, most subjects in this study are "casual" photographers and the original rule-of-thumb is recommended for film photographers with "steady hands". Nevertheless, this further validates the proposed generalized rule-of-thumb for maximum exposure duration for both film and digital still cameras.

The effective camera-motion speed for both camera phones (5.95 °/sec for holding with one hand and 4.39 °/sec for two-hand) is significantly higher than that of the digital still camera (2.18 °/sec). This is mainly due to the fact that both camera phones are about ¼ of the mass of the digital still camera. It is interesting to note that holding with two hands while taking pictures does help reducing camera-motion in general though both camera phones have similar mass.

Table 2: Estimated camera-motion speed (for exposure duration of 100 ms) and the standard deviation across subjects

Cameras	Single-hand-held	Two-hand-held	Digital still camera
Mass (grams)	~100	~105	~400
Camera-motion speed k (°/sec)	5.95	4.39	2.18
Standard deviation across subject (°/sec)	2.70	1.33	1.40
Max/Min	3.40	2.67	4.76

4.4 Subject-to-subject variation

Figure 4 shows the estimated linear camera-motion speed and the standard deviation across captures for each individual subjects for the three cameras at exposure duration of 100 ms. The variation of camera-motion speed is significant across subjects. Worst performing subject moves camera at least 2 or more times more than best performing subject across all three cameras (Max/Min ratio in Table 2). While holding camera with two hands does help four subjects reducing camera-motion, its impact is less pronounced for three other subjects.

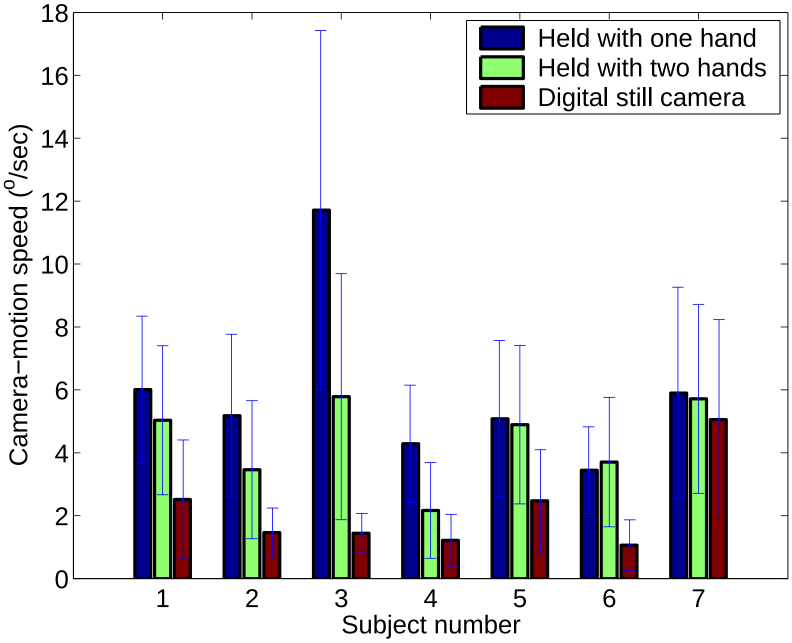

Figure 4. Estimated linear camera-motion speed and standard deviations across captures for all seven subjects.

4.5 Capture-to-capture variation

Table 3 lists the estimated linear camera-motion speed and standard deviation across captures for the same subject (#1) and Figure 5 draws the camera motion pattern for the 25 captures for the same subject. Similar to the significant variation across subjects, we also see significant capture-to-capture variation for the same subject. This implies that the same person can sometimes hold the camera much steadier than other times (comparing motion pattern from capture in [row 1, column 1] with that from capture [row 2, column 2]) and similar results can be found with six other subjects. Further investigation of this capture-to-capture variation (especially for trials when camera-motion is minimized) will be able to shield some light on how to reduce camera-motion even further.

Table 3: Estimated linear camera-motion speed and capture-to-capture standard deviation for subject # 1

Cameras	Single-hand-held	Two-hand-held	Digital still camera
Camera-motion speed k (°/sec)	6.01	5.03	2.52
Standard deviation (°/sec)	2.33	2.37	1.89

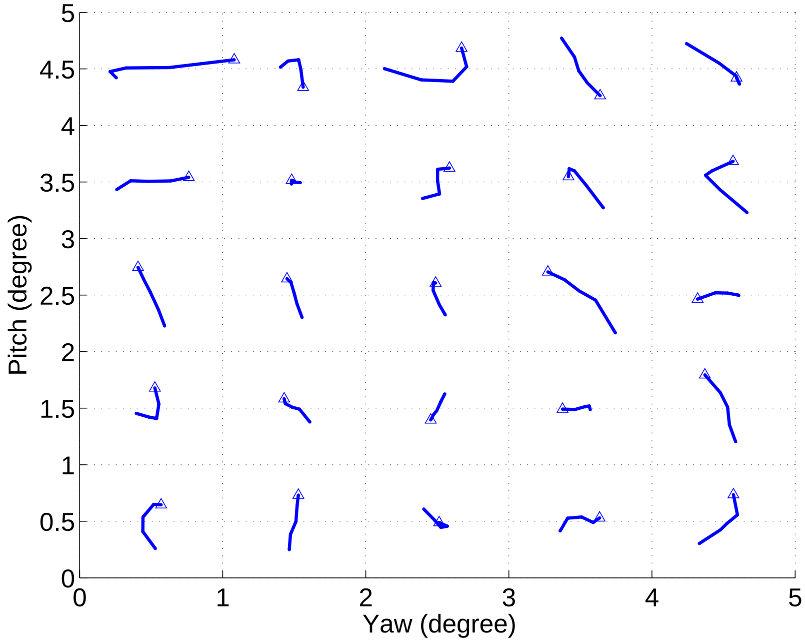

Figure 5. Camera motion pattern (5 rows by 5 columns) for the 25 captures for the subject #1 while holding the camera phone with two hands. The variation across captures is quite significant.

5. DISCUSSION AND SUMMARY

We have shown that effective camera-motion function can be approximated very well by a linear motion function for exposure duration less than 100ms and it deviates away from a linear function as exposure duration increases. Since exposure duration longer than 100ms is rarely used in practice, it is adequate to use Equation 5 as the generalized rule-of-thumb to decide the maximum exposure duration for camera phones as well as digital still cameras.

For a typical thin camera phone (around 100 grams) with 35mm format equivalent focal length of f_{35} mm, the maximum exposure duration for an average user to take pictures while holding camera phone in one hand (effective camera-motion speed of 5.95 °/sec, Table 2) would be:

$$T \leq \frac{1.667}{5.95 \times f_{35}} = \frac{1}{3.57 \times f_{35}} \quad (8)$$

For an average user to take pictures while holding camera in two hands (effective camera-motion speed of 4.39 °/sec, Table 2), the maximum exposure duration would be:

$$T \leq \frac{1.667}{4.39 \times f_{35}} = \frac{1}{2.63 \times f_{35}} \quad (9)$$

For a 35mm format equivalent focal length of 40mm, the maximum exposure durations for single-hand-held and two-hand-held camera phones are 7.0 ms and 9.5 ms respectively. Compared with the original rule-of-thumb for 35mm format SLR cameras, camera phones need much shorter maximum exposure duration to avoid motion blur for the same 35mm equivalent focal length (or the same field of view). In current practice, most camera phones allow maximum exposure duration up to 100ms (10 frames/sec). This would suggest that many pictures taken by camera phones are blurring as measured by 35mm film print's sharpness criteria. However, noise will increase significantly for most indoor scenes if shorter maximum exposure duration is chosen. As the mobile imaging industry is aggressively pursuing a smaller and smaller pixel size in order to meet the digital still camera's performance in terms of total pixels while retaining the small size needed for the mobile industry. This makes it increasingly more important to address the camera-motion challenge associated with smaller pixel size.

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