NoShake: Content Stabilization for Shaking Screens of Mobile Devices

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Abstract—**Consumer electronics and mobile devices intended for pervasive applications are often subject to shaking that makes their screen difficult to read. To address this usability challenge, we present NoShake, a system for screen content stabilization. NoShake utilizes a single accelerometer, now present in numerous consumer electronics and mobile devices. The core of NoShake is a physics inspired model that dynamically compensates for the device shaking by shifting the screen content opposite the direction of the shake. The model is efficient, parametric, and can be fine tuned based on shaking pattern detection. We implement a prototype of NoShake on an Apple iPhone and conduct user studies in a number of scenarios, which highlight the strengths as well as limitations of NoShake in coping with shaking devices.**

Keywords-component; accelerometer; stabilization; screen

I. INTRODUCTION

Consumer electronics and mobile devices are often operated in shaky environments, for example reading emails on a bus, or looking at a screen mounted on a shaking structure (e.g. a GPS screen mounted on the car dashboard). In both of these scenarios the frequent and often random movement of the device makes it difficult to read the screen. This leads to an important impediment for mobile devices to be used in a truly pervasive manner.

In this work we present an accelerometer-based solution to this problem, called *NoShake*. NoShake counters the effect of shaking by dynamically shifting screen content. No-Shake leverages the low-cost accelerometer found in an increasing number of consumer electronics and mobile devices to accurately detect shaking; it then continuously shifts the screen content in the opposite direction of the shaking in real time.

There are several challenges to the efficacy of NoShake. First, an accelerometer only provides the device acceleration, not the displacement. Double integrating the acceleration to calculate displacement is impractical because the noise in accelerometer readings rapidly becomes egregious. Gravity exacerbates this problem, especially when the device is tilted, as it is difficult to separate the effect of gravity on accelerometer readings from that of external force. Second, and most importantly, shaking can be introduced by a variety of sources and therefore can have diverse and often random patterns. This makes it difficult to estimate the appropriate amplitude and direction to shift the screen content in order to counter the effects of shaking. Third,

there are only limited resources for detecting the shaking, computing the appropriate shift, and rendering the screen content in real time.

To address these challenges, we base NoShake on a simple yet effective physics inspired model. The screen content is modeled as a mass suspended in each direction by a critically-dampened spring and damper. The springs allow the mass to remain relatively steady during shaking, while the dampers prevent oscillation of the mass. The model is parametric and can be fine tuned by the user.

Using a prototype of NoShake implemented on an Apple iPhone, we conducted a user study with 10 participants in order to evaluate the detrimental impact of a shaking screen and the efficacy of NoShake. Each participant used No-Shake in four different scenarios and then provided us with their subjective opinion. Our user studies highlight the practical value of NoShake and its ability to significantly reduce random screen shaking in three of our four test scenarios. While our prototype is based on a mobile phone, it can also benefit other portable and vehicle-mounted electronics.

While there has been considerable research on reducing unwanted shaking in video and image capturing, to the best of our knowledge, our work is the first publicly reported mobile device based implementation and user study of suppressing the effects of screen shaking.

The rest of the paper is organized as follows: To begin, we provide background information for NoShake and discuss related work in Section II. We then present technical details of the physics-inspired model in Section III and continue by describing an iPhone based prototype implementation in Section IV. We provide results from a user study of No-Shake in Section V, and finish with discussions and conclusions in Section VI and VII.

II. BACKGROUND AND RELATED WORK

A. Impact Of Shaking Screens

The negative impact of screen shaking on usability is clear; half of the participants in our user study reported that they encounter situations where the shaking screen of a portable electronic device, such as on a bus and during jogging, annoys them.

It is important to note that not all shaking is the same. Imagine there is a straight line connecting the eye and the ob-

ject it is focused on, or *sight line*. The human eye has a relatively large depth of field, at least ±0.3 Diopters at a pupil diameter of 3 mm [7]. This is equal to more than 5cm at a viewing distance of 30cm. Therefore, small displacements of an object along the sight line do not require refocusing, and their usability impact is small. As a result, *No-Shake does not compensate for shaking perpendicular to the plane of the screen.* If the object moves in the plane perpendicular to the sight line, the eye needs several hundred milliseconds to start tracking it, known as *smooth pursuit* [12]. Thus, people are more annoyed by random and high frequency shaking than low frequency and predictable shaking. As a result, *we target NoShake at reducing high frequency and random shaking in the same plane as the screen.* Furthermore, while the device could also be subject to rotational shaking, in the scenarios we focused on, rotational shaking is negligible compared to other shaking. Regardless, it is impossible to detect rotational shaking with a single 3-axis accelerometer; it would need a gyroscope or a second accelerometer. Notably, the same principals and physical model could also be applied to rotational shaking on the sight line axis, while for the same reasons mentioned above, the impact of rotational shaking on axes perpendicular to the sight line would be small.

B. Related Work

Extensive efforts have been made to counteract shaking in video and image capturing. Many cameras employ accelerometers and gyroscopes to detect shake and compensate for it by shifting a lens element [8, 18] or the image sensor [14]. Many video recorders reduce the impact of camera shaking in software by dynamically shifting captured frames based on image analysis. Furthermore, some digital cameras employ sensors to select the best sensitivity and shutter speed [9], or moment [10] to capture the image after the user presses the button. There has also been extensive research on removing the effects of camera shake in captured images [6, 11, 15]. While these works focus on reducing the impact of shaking on video and image capturing, our work focuses on stabilizing mobile display output relative to the eyes of human users in order to improve screen readability.

Dynamically shifting the screen content to reduce the effects of shaking has been studied by Behringer [4, 5], who employs a physics-inspired model similar to what is used in NoShake. However, his work solely addresses vertical shaking, as it focuses on displays mounted in vehicles. Furthermore, he does not provide a user study or any analysis of his model's efficacy. Two US patents [1, 21] also present the idea of using accelerometers for display image stabilization. However, they do not provide an implementation, analysis, or user evaluation. To the best of our knowledge, our work represents the first working mobile device based implementation and user study to address content stabilization. Additionally we provide analysis and optimization of our compensation model according to its physical characteristics and human cognition.
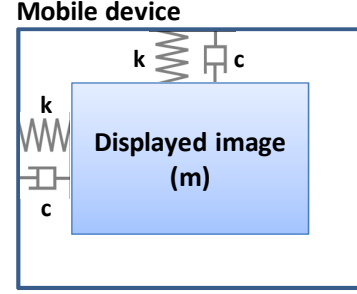
Mobile device

Figure 1: Spring-mass-damper physical model for No-Shake screen stabilization

There have been extensive studies on the effects of context on mobile device usability, including human reading performance while walking in simulated or realistic conditions [2, 3, 13, 17]. These studies show that user performance degrades considerably under contexts involving shaking screens, thus highlighting the practical value of NoShake. Only Kane et al. present a solution to this challenge, by dynamically increasing text size to counter the effects of shaking [13].

III. NOSHAKE: SCREEN CONTENT STABILIZATION

A. Physical Model for NoShake

We base NoShake on a simple yet effective physics-inspired model, shown in Figure 1. The model represents the screen as a mass suspended in the mobile device with a spring and viscous damper independently in each direction. Since we will be able to remove the impact of gravity in this physical model, we begin by analyzing the model without considering it.

The mass-spring-damper model is particularly well suited for reducing display shaking since the spring allows the mass to move in the opposite direction of shake, therefore reducing the effects of shaking, especially that of higher frequency. The dampers are necessary to prevent oscillation of the mass, since oscillation would lengthen the time of perceived screen shaking, and hence would be counterproductive. The dampers can be tuned to achieve critical damping, which causes the mass to converge to the steady state point as fast as possible without oscillation.

Furthermore, we show that the mass-spring-damper system only requires acceleration to compensate for shaking, solving one of our main challenges.

B. Model Analysis and Optimization

This system can be analyzed in each direction independently, as shown in Figure 2, using the differential equation:

$$m(\ddot{x} + \ddot{y}) + c\dot{y} + ky = 0 \qquad (1)$$

$$m\ddot{y} + c\dot{y} + ky = -m\ddot{x} \qquad (2)$$

where k is the spring rate, c is the damping coefficient, y is the displacement of the mass relative to the device (the
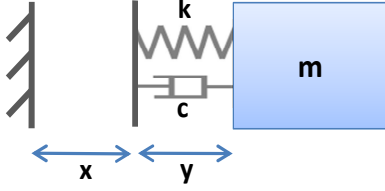
Figure 2: Physical equivalent model in one dimension

offset of the screen content), and x is the displacement of the device due to shaking. As made apparent by the second equation, it is possible to use the acceleration of the device, $\ddot{x}$, to calculate the displacement, y. Thus, utilizing real-time data from an accelerometer in a mobile device, we can accurately model the physical spring-mass-damper system.

The behavior of this system depends on the damping ratio:

$$\zeta = \frac{c}{2\sqrt{km}} \qquad (3)$$

When $\zeta < 1$, the system is under-damped and will oscillate at its resonance frequency. Because we intend to suppress oscillation, $\zeta < 1$ is unacceptable. When $\zeta > 1$, the system is over-damped; an over-damped system will not oscillate but takes longer to stabilize than a critically damped system where $\zeta = 1$. Therefore, we design our system to obtain the critical damping ratio ($\zeta = 1$) for optimum response. For the sake of simplicity, without losing generality, we assume the unit mass ($m = 1$)[1]. In this case, we have

$$\begin{cases} \zeta = \frac{c}{2\sqrt{km}} \\ \zeta = 1 \\ m = 1 \end{cases} \Rightarrow \quad c = 2\sqrt{k} \qquad (4)$$

The critically-damped system equation becomes:

$$\ddot{y} + 2\sqrt{k}\dot{y} + ky = -A(t) \qquad (5)$$

Where $A(t)$ is the acceleration of the device at time t (replacing $\ddot{x}$). To calculate the response of this system, $Y(t)$, we can simply convolve the input, $A(t)$, and the impulse response of the system, $H(t)$:

$$Y(t) = H(t) * -A(t) \qquad (6)$$

NoShake compensates screen displacement by shifting the screen content proportional to $Y(t)$.

$H(t)$, the impulse response of the spring-mass-damper system, can be calculated from the system equation as:

$$H(t) = te^{-t\sqrt{k}} \qquad (7)$$

Note that $H(t)$ diminishes quickly as t increases.

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[1] If the system mass is an arbitrary m instead of 1, we can scale k and c by m and achieve the same response of the original unit-mass system.

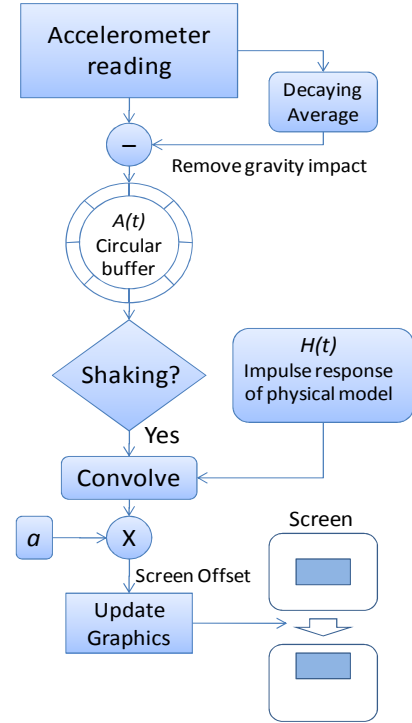
Figure 3: NoShake system implementation overview

C. Tuning of System Parameters

According to the model described above, there is only one tunable parameter for the critically-damped mass-spring-damper system, k. A larger k is analogous to firmer springs and appropriately matched dampers. NoShake compensates by shifting the screen content proportional to the output of the above system, by $\alpha \cdot Y(t)$ pixels. The choice of α and k depends on the nature and extent of the device shake and how much free border space exists around the screen content. In our current implementation, users can adjust α and k manually.

D. Acceleration Estimation

The physics inspired model described above only requires the acceleration of the device as input. Many mobile devices, including the iPhone, already have accelerometers, which are a natural choice to supply the acceleration information efficiently. However, the accelerometer reports the combined effect of gravity and device shake. It is necessary to remove the impact of gravity from the accelerometer readings and only consider acceleration engendered by shaking.

IV. IMPLEMENTATION

We implemented a prototype of NoShake on the Apple iPhone mobile platform. We chose the iPhone because of its large, high quality display, and its embedded low-noise, tri-axis accelerometer, which NoShake samples at 50 Hz. Figure 3 illustrates the implementation.

A. Gravity Compensation

To compensate for the effect of gravity, NoShake uses a simple high-pass filter. NoShake computes the gravity as the decaying average of previous raw accelerometer readings, and deducts it from the current raw reading to obtain the true acceleration of the device. This enables NoShake to quickly adapt to changes in gravity on any of the axes; for example when the device is tilted it takes less than a second to compensate.

B. Circular Buffer

After gravity is removed from the raw acceleration reading, the result is stored in a circular buffer for later use. The length of the circular buffer is chosen to be four seconds because $H(t)$, the impulse response of the spring-mass-damper system from Equation (7), quickly approaches zero as t increases and therefore a history as short as four seconds can yield a very good approximation. It is important to note that the longer the circular buffer, the higher the computational cost for the convolution stage is, as explained below.

C. Shaking Detection

NoShake updates graphics only when shaking is detected. This keeps the image completely still for non-shaky environments, which we determined to be an important usability feature in our initial user evaluations. To determine whether there is shaking, NoShake analyzes the samples from the past 1.8 seconds by aggregating the absolute values of acceleration along each axis and comparing the sum to an empirically determined threshold.

D. Screen Offset Calculation

If shaking is detected, NoShake convolves the recorded acceleration readings, $A(t)$, by the impulse response of the spring-mass-damper system, $H(t)$, to calculate $Y(t)$, according to Equation (6). NoShake then shifts the content in the screen frame buffer proportionally to $Y(t)$ from the center of the screen. The impulse response, $H(t)$, is computed beforehand and is updated whenever the user changes the settings of NoShake.

E. Emperical Parameters

There are several empirically determined parameters in our implementation: k in the spring-mass-damper model, the threshold for shaking determination, and the scale (a in Figure 3). While we set their default values based our experience, these parameters are made customizable so that users can adjust to best fit their specific usage scenarios, as mentioned in Section III.C. Our implementation allows the user to adjust their values by tapping different sections of the iPhone's touchscreen.

F. Performance

The iPhone-based prototype uses on average 30% of the 620 MHz ARM processor during active use. Yet only 1-3% of this is associated with reading the accelerometer, calculating the screen offset, and applying the compensation

Figure 4: iPhone-based prototype with texts displayed for the user study. Only the first paragraph on the screen is stabilized by NoShake

algorithm; the rest is consumed by rendering the shifted graphics as well as system overhead. The high overhead of updating graphics is due to our lack of access to the graphics processing unit; we have to update the entire frame buffer. We believe the offset calculated can be applied much more efficiently if it is handled by the graphic processor directly.

V.   USER STUDY

A. Methodology and Participants

In order to evaluate the effectiveness and user-friendliness of NoShake, we conducted a user study with 10 participants aged between 18 and 29. Three of them were females. After asking them whether they could recall any situations where the shaking screen of a device annoyed them, we showed them the prototype of NoShake. To enable participants to more easily evaluate NoShake, the prototype allowed users to dynamically turn on and off NoShake stabilization, as well as juxtapose stationary and stabilized text, as shown in Figure 4. We let each participant explore the operation and functionality of NoShake.

Our preliminary testing had showed that *our eyes naturally tend to track the entire device in order to maintain focus.* This habit is detrimental while using NoShake, as the text does not move with the device anymore. Therefore, during this phase, we advised our participants to focus on the text, rather than track the shaking phone. As we will see later, failure to do so indeed renders NoShake less attractive.

We then asked the participants to read a paragraph of text with and without NoShake in four specific test cases, each taking approximately 10 minutes:

1. Reading the screen while holding the iPhone and walking at a normal pace
2. Reading the screen held by a second person while walking alongside each other at a normal pace;
3. Reading the screen while sitting in the passenger seat of a car travelling at approximately 30mph on a local city street; and
4. Reading the screen as the iPhone is mounted on the dashboard of a car under circumstances similar to 3.

The tunability of NoShake necessitated finding appropriate parameters for these situations before conducting the user

study. We found these empirically, as different types of shaking responded better to different parameters. In some instances we tuned NoShake during the test based on user feedback.

During each test case we collected the participants' subjective opinions regarding the efficacy and usability of No-Shake. We asked them to compare NoShake stabilized vs. stationary text and recorded their answers based on a quantitative scale between 1 and 5 (1 = significantly worse, 3 = same, 5 = significantly better).

B. Findings

The average objective scores for each test scenario and for the two groups of participants are presented in Table 1. Half of our ten participants reported that they encounter situations where the shaking screen of a portable electronic device annoyed them. These participants had generally positive attitudes regarding NoShake in all test cases. The other half, who did not report using electronic devices in such situations, tended to have neutral feelings regarding NoShake. The typical negative reasons users gave included difficulty to focus on the stabilized text (as they naturally focused on the shaking phone) and reduced contrast of the stabilized text, which was caused by the relatively long response time of the iPhone LCD screen. A more responsive LCD will improve the text contrast, and we believe more usage will help users adapt to focus on the stabilized content.

We have found that not only do different types of shaking affect the optimal parameters of NoShake, but each user appears to have their own personal preferences regarding the parameters.

NoShake proved to be the least successful in reading while holding the iPhone and walking. We attribute this to two factors: First, the user is expecting the bumps and thus their eyes automatically compensate for the motion. Second, the device and the user's eyes are shaking but are relatively stable with respect to each other (same phase and magnitude). NoShake cannot help in such conditions, since *NoShake can only detect the movement of the device and not the user.* Therefore, in this situation, a truly stable text would appear to be bouncing up and down from the user's perspective, since their eyes are bouncing up and down. This scenario typically arises with predictable, large amplitude low frequency shaking, as in walking and jogging. However, it is possible to detect such scenarios through frequency domain analysis of the shaking or detecting the user's activity through the accelerometer readings [16, 19, 20]. NoShake can then either temporarily switch off compensation or only compensate higher frequency and/or non-periodic shaking, which are unlikely to have the same phase at the eyes and the device.

NoShake proved to be effective in reading the screen held by a second person while walking together. This can be attributed to the participant's motion not having the same frequency, phase, and amplitude of the second person.

Table 1: Average objective scores for NoShake in each test case (3 = same as stationary)

Test case	Participants with prior experience of shaking screen	Participants without prior experience of shaking screen
1: Walking	3	2.4
2: Shared walking	4.2	2.6
3: Handheld-automobile	4.6	3.4
4: Mounted-automobile	3.8	3.2

Therefore, the participant is unable to predict the motion of the device.

NoShake proved to be most effective in the vehicular test cases, especially when the participant was holding the device. Participants reported that NoShake helped them keep track of their reading position within the text. This ability to track reading position within text is one of the most important advantage users found while using NoShake, particularly in the vehicular tests; one user noted: "It was basically impossible for me to track the stationary text, but it was easy to track the stabilized text. Even if it wasn't always legible it helped me not lose my position while reading. This would be great while reading a full paragraph in a book." Another participant gave a similar comment: "If we go over a big bump I can't read the stationary text at all, and I lose my place [in the text] completely. The stabilized text is easier to read and I don't lose my place." In one instance a user said they would have given up reading the stationary text, but found the stabilized text relatively easy to read.

VI. DISCUSSION

As mentioned in Section III.C, α and k provide two knobs for adjusting NoShake. In our current implementation, users can manually adjust α and k. However, our preliminary user studies suggest that they can be adaptively adjusted automatically, to reduce the compensation if the peak compensation is reaching the borders of the screen and increasing it if the peak compensation does not approach the borders. k can also be tuned according to the frequency of the shake; lower frequencies require a lower k (a less rigid spring).

NoShake operates by shifting the displayed image to counteract shake. Therefore, any design implementing NoShake must have a border around the main content proportional to the amplitude of the shake NoShake compensates for (Figure 5). Assuming the width of this border is w, and the length of the display is l, the border will take up $\frac{l^2-(l-2w)^2}{l^2}$ of the screen space. Assuming $w \ll l$, this is approximately equal to $\frac{4w}{l}$. Therefore, with the same border width, No-Shake consumes a smaller fraction of screen space on larger screens.
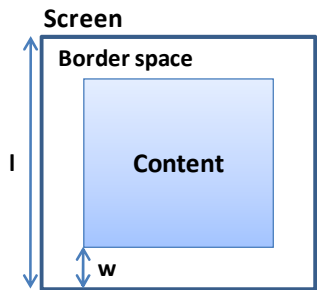
Screen

Border space

Content

I

w

Figure 5: A border for NoShake consumes approximately $\frac{4w}{l}$ of the screen area

Our preliminary user studies indicate that a high contrast border may help the user focus on the stabilized text instead of the shaking device. On the other hand, if it were possible to achieve the same user focus with training rather than a high contrast border, the border space could be used to display useful or infrequently read items such as the scroll bar, status bar, title bar, battery indicator, etc. This would require further studies; the display space usage of NoShake must be weighed against the effects of shaking on readability, as well as the display space usage of other solutions that address the challenge of shaking (e.g. increasing text size [13]).

VII. CONCLUSIONS

We present NoShake to compensate for the rapid and random motions of mobile screens that are observed under many daily usage scenarios, in particular for interactive pervasive applications intended to serve users everywhere. NoShake detects the motion of mobile devices and shifts the screen content in a way that reduces annoying shaking. Our initial user studies confirm that NoShake can considerably improve the user's experience with mobile screens in the presence of shaking. NoShake may have an even greater impact for users who are unable to hold a device steady, such as the elderly or those with the Parkinson's disease.

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