IEEE Access
The journal for rapid open access publishing

Received July 22, 2014, accepted August 9, 2014, date of publication August 18, 2014, date of current version August 27, 2014.

Digital Object Identifier 10.1109/ACCESS.2014.2348943

Algorithms for Smartphone and Tablet Image Analysis for Healthcare Applications

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This work was supported by the Natural Sciences and Engineering Research Council of Canada under Grant 448147-2013.

ABSTRACT Smartphones and tablets are finding their way into healthcare delivery to the extent that mobile health (mHealth) has become an identifiable field within eHealth. In prior work, a mobile app to document chronic wounds and wound care, specifically pressure ulcers (bedsores) was developed for Android smartphones and tablets. One feature of the mobile app allowed users to take images of the wound using the smartphone or tablet's integrated camera. In a user trial with nurses at a personal care home, this feature emerged as a key benefit of the mobile app. This paper developed image analysis algorithms that facilitate noncontact measurements of irregularly shaped images (e.g., wounds), where the image is taken with a sole smartphone or tablet camera. The image analysis relies on the sensors integrated in the smartphone or tablet with no auxiliary or add-on instrumentation on the device. Three approaches to image analysis were developed and evaluated: 1) computing depth using autofocus data; 2) a custom sensor fusion of inertial sensors and feature tracking in a video stream; and 3) a custom pinch/zoom approach. The pinch/zoom approach demonstrated the strongest potential and thus developed into a fully functional prototype complete with a measurement mechanism. While image analysis is a very well developed field, this paper contributes to image analysis applications and implementation in mHealth, specifically for wound care.

INDEX TERMS Algorithms, image analysis, smartphones, wound care.

I. INTRODUCTION AND OBJECTIVE

Smartphones and tablets are finding their way into healthcare delivery to the extent that mobile health, or mHealth, has become an identifiable field in eHealth. mHealth refers to the practice of medicine and public health supported by mobile devices, with an extensive range of applications ranging from apps that allow users to track their own diet and fitness, to devices and associated apps that allow for health condition monitoring and recording on a smartphone (e.g. blood sugar), to the use of mobile devices by nurses, physicians, and allied health professionals in direct healthcare delivery and medical record maintenance.

In prior work, a mobile app to document chronic wounds and wound care, specifically pressure ulcers (bedsores) was developed for Android smartphones and tablets. This mobile app allowed users to take images of the wound using the smartphone or tablet's integrated camera. In a user trial with nurses at a personal care home, this feature emerged as a key benefit of the mobile app [1].

Following on this finding, the current work had the objective to develop image analysis algorithms that facilitate non-contact measurements of irregularly-shaped images taken with a sole smartphone or tablet camera, using only the sensors integrated in the smartphone or tablet with no auxiliary or add-on instrumentation on the device, and where the measurements have less than 10% error, for images taken from distances of up to 30 centimeters.

II. BACKGROUND

A. WOUND CARE MOBILE APP DESIGN AND USER TRIAL

Pressure ulcers, also known as bedsores or decubitus ulcers, are a common but preventable condition seen most often in elderly persons and people with limited mobility. Pressure ulcer incidence rates vary widely from healthcare facility to facility, but the Canadian Association of Wound Care reports that one in four people in any healthcare facility have a pressure ulcer at any given time [2], [3]. Pressure ulcers are a disabling condition with numerous impacts on patient health and quality of life. Since they are often a secondary condition that develops upon admission to hospital, pressure ulcers can lengthen hospital stay, delay the recovery of the patient, and exacerbate mobility limitations and social isolation [4].

Pressure ulcers are also associated with increased mortality rates from underlying conditions [5]–[9], and the financial impact of treating pressure ulcers is substantial [10].

In addition to common interventions to prevent and treat pressure ulcers, including support surfaces, regular repositioning of the patient, optimizing nutrition, and skin care [11], risk assessment and regular standardized documentation are critical steps [12]. Faced with high incidence of non-compliance to protocol and inconsistency of documentation [13], [14], attention is increasingly focused on electronic information systems as one part of an overall strategy of pressure ulcer prevention and treatment. This is a natural outgrowth of eHealth and mHealth initiatives whose intended outcomes are promoting patient safety, improving patient outcomes, enhancing financial and other efficiencies, and facilitating communication between multiple partners [10].

Prior work resulted in a mobile app for wound care designed to replicate the paper-based charting currently used in the province's largest regional health authority. The wound care app allows nurses to enter a new patient record, view an existing patient record, enter and assess new wounds on patients, and re-assess existing wounds on patients using the Pressure Ulcer Scale for Healing (PUSH tool) [15], Braden Scale [16] and the Bates-Jensen tool [17]. In addition to replicating the paper-based charting used in the WRHA, the app was designed for several intended benefits relative to paper-based charting of wounds and wound care:

- Telehealth: the potential to share data over cellular and Wi-Fi networks within and across facilities, for expert consultation and data sharing among multiple caregivers, whether they are located in close proximity or separated by hundreds of miles. This reduces the need to transport patients for specialized consultation, avoiding considerable patient physical and emotional stress, time, and expense.
- Data Organization & Interpretation: the wound care app generates alerts for the caregiver upon login, notifying the caregiver to wounds that are in need of re-assessment and wounds that have been deteriorating from one assessment to the next. The app further generates wound histories in graphical and text-based formats, including wound image.

By design, a benefit of the wound care software app is its potential as a stand-alone electronic medical record (EMR) and its positioning for integration into a facility-wide or region-wide EMR system. Privacy of personal health information and medical records is a significant priority, and being IP centric, all public internet security protocols would be integrated.

A user trial of a prototype wound care app for Android-based smartphones and tablets was implemented in 2013 in Winnipeg, Canada. The site of the user trial was a 380-bed facility that caters to adults with rehabilitation, palliative and long term care needs in hospital and personal care home units, as well as outpatient and community programs. The app was used by eight nurses over a period of several months, in which they augmented their regular nursing duties with wound assessments enters on the app. Full details on the user trial implementation are available in [1].

From the user trial, wound images (photographs) strongly emerged as the key value and benefit of the wound care app, with benefits for the caregiver, the patient and their family, and for the physician and allied health professionals. Nurses indicated that they appreciated taking pictures of the wound and showing the photograph to the patient. They noted that being able to show a wound photograph to the patient was particularly useful when the wound was in a location that the patient would otherwise not be able to see, such as the buttocks, back of the legs or under the foot. Several participants noted that patients and their families appreciated seeing the wound and in doing so, gained a new appreciation of the instructions they had been given regarding hygiene and dressings in caring for their wound. Nurses reported that in day-to-day practice, it can take up to 20 minutes to treat and re-dress a wound, and then a physician or allied health professional may enter the room and ask to view the wound. In the user trial, nurses reported that physicians found the wound image sufficient for their purposes and did not require the wound to be undressed for visual inspection. Further, participants reported that the wound image was useful in augmenting a verbal description of the wound in a group consult away from the patient's room. By using wound images with physicians, wound care consultants, and other consulting partners, the number of dressing changes of a wound can be reduced, and this in turn promotes wound healing.

Wound photography has already been recognized for its value in the care of other types of chronic wounds [18], [19], including the evaluation of pressure ulcers via videoconferencing in which the observations reasonably approximated those obtained via an in-person assessment [20]. In one study, an EMR system specific to chronic wound treatment has shown promise to simplify the evaluation and treatment of chronic wounds, although a standard protocol for wound images was vital to the value of the system [10]. Our work derives significant value from the naturalistic use the smartphone for photographs, meaning that there is no need for any auxiliary or peripheral devices on the smartphone or tablet when taking photographs, and there are no particular set-up restrictions with the patient (e.g. positioning devices, lightboxes, etc.).

B. IMAGE ANALYSIS FROM PHOTOGRAPHY

While smartphone and tablet cameras are ubiquitously used for recreational photo capture and sharing, the built-in cameras are optimized for small size and are not generally recommended for applications that require high accuracy, precision, and resolution. Following on the findings of the user trial that highlighted the value of the wound images, the current work focused on the development of image analysis algorithms that facilitate non-contact measurements of irregularly-shaped images taken with a sole smartphone or tablet camera, using only the sensors integrated in the smartphone or tablet with no auxiliary or add-on instrumentation on the device, and where the measurements have less than 10% error, for images taken from distances of up to 30 centimeters. The work has applicability beyond the wound care application and into other healthcare problems and other sectors ranging from defense to manufacturing.

Several mobile apps for Android and iOS are available for measurement applications, including Smart Measure and Planimeter for Android [21], and Easy Measure, Point & Measure, and SpectaRuler for iOS [22]. In general, these apps measure range (distance to) and height of an object within the camera's field of vision, with some apps reporting angles and object radii as well. Typical applications require mid-range object dimensions in the image (generally 0.5 m to 20m), with accuracy and precision generally reported at several centimeters. Some of these apps require a reference or calibration object to be in the frame, although preferably a reference or calibration object would not be required.

While our specification called for no auxiliary / add-on devices to be required, the options for image characterization are expanded when add-on devices are considered. Ultrasound, infrared, and laser-based methods may all be used for the determination of range / distance with the addition of an auxiliary device to the smartphone; however ultrasound and infrared ranging may be more suitable for the measurement of shorter distances.

Ultrasonic-transducer rangers [23] are relatively small and inexpensive, and have the ability to measure objects at shorter distances (1cm – 6m), however they are temperamental in their use with accuracy and repeatability as common issues. They are sensitive to plane/position angle, and the topological characteristics (shape, texture) of objects to be measured have a significant effect on the sensor's capability to measure effectively. These sensors can be affixed to a smartphone with relative ease, and require a power source and communications, which may be provided by the port/interface on the smartphone itself.

Infrared distance measuring [24] using a light emitting diode (LED) transmitter and receiver pairing may also be used to accurately measure shorter distance (4cm – 30cm). While these devices may offer higher measurement resolving based on the technique used to measure range/distance, there are also subject to deployment issues; however, these devices may be considered a viable alternative to ultrasound for use in many applications.

Laser rangers comparatively can be bulky and are relatively expensive. They have the capacity to measure longer distances very accurately (10cm – 20m), but shorter measurement (<5cm – 10cm) is not as practical, due primarily to sensitivity of the technology and methods employed to calculate distance based on reflected laser light.

Outside of the smartphone / tablet domain, there are both hardware- and software- based 'depth of field' cameras available in the market place today which hold promise for future integration into smartphones and tablets. They offer relatively high image quality, and unprecedented viewing perspectives. Lytro^{TM} offers a hardware camera [25] that is readily available for purchase today, and Toshiba^{TM} has reportedly one under development, but is not yet commercially available [26]. Google^{TM} , Qualcomm^{TM}, and Nokia^{TM} are also working on camera technology to improve depth of field for smartphone adoption. Google's Project Tango could lead to system development kits (SDKs) that will allow app developers to deal with depth information – leading to improved quality smartphone imaging quality, with re-focus, perception and 3D mapping capabilities [27].

The Lytro^{TM} depth of field camera is the first camera of its kind that has the capacity to capture and process the entire light field as opposed to a singular 2D image. By capturing the entire light field, a photographer can refocus, change perspective, and add different enhancement filters for improved image visualization. In this manner, no autofocus mechanism is required to capture the contents of an image. Furthermore, the camera incorporates ''perspective shift'', which lets one change perspective by simply panning among an image on a display, working on the light field on a captured photo. This gives one an unprecedented view and detail when compared to images captured with conventional cameras.

Another hardware-based depth of field camera, which holds much promise for direct integration into smartphones, is a Cube-shaped camera made by Toshiba^{TM}. It works on much of the same principles to that of the Lytro^{TM} camera, but has a much smaller form factor (roughly 1cm per side), a dense array of lenses, and thus, should be capable of direct integration into a smartphone. At this time, the camera has not yet been commercialized, but it is an ideal candidate for advancing the photographic quality of smartphones.

One of the more notable software-based depth of field cameras available today has been developed by Nokia^{TM} and is called ''Refocus Lens.'' The app comes preinstalled on several Nokia^{TM} smart phone models available today, and is available for installation on select legacy Nokia^{TM} phones. It promises infinite depth of field control based on what they call ''clever algorithms'' [28]; it also offers a post-capture refocus technology for changing focus in an arbitrary image, while adding color enhancement. As the camera's algorithm relies solely on digital zoom, magnified images reveal a significant reduction in resolution – as expected for a method based entirely on software. Our approach, specifically, the *Size from Focus* algorithm described in section III takes one auto-focused picture, whereas the Nokia^{TM} ''Refocus Lens'' takes a series of pictures at different focus settings and then merges them together.

Finally, it is expected that smartphones with integrated dual-lens cameras are also poised for mass market entry in the foreseeable future. Currently, they are relatively novel in smartphones but are inherently capable of offering enhanced, accurate and high precision imaging, particularly for subsequent analysis and characterization. Over the years, stereoscopic cameras have been used in a wide range of applications including those in the manufacturing sectors, primarily for object pick-and-place, and machine vision. There are several benefits to incorporating this kind of camera technology, with respect to both image quality and characterization of objects residing in the field of view, and manufactures are striving toward main-stream adoption. Two handset and camera manufactures, HTC™, and Corephotonics™, respectively, have taken the lead in this initiative and are poised to enter the market with such dual-lens camera capability (e.g., HTC – M8) [29].

Corephotonics™ uses two stereoscopic cameras with lenses at two different focal lengths (one wide angle, and the other at 3× zoom). In this manner one can switch lenses to magnify more distant subjects/objects without resorting to a purely software-based digital zoom. The result is a high quality image without loss of pixel resolution. The benefits to such a design are three-fold: i) smooth zooms – employing a combination of digital and lens-switching; ii) improved low-light performance, noise reduction, and clearer image – algorithms work in real-time to match pixels from paired lenses, and scene analysis is performed to identify a most representative pixel assignment; and iii), significant and enhanced depth analysis – improved depth of field, quicker auto-focus, and augmented reality [30].

The combination of these three benefits make smartphones with a dual-lens cameras ideal for contact-free wound care capture, including measurement and analysis/classification, without the requirement for reference aids or artifact to measure actual wound-size (area). The enhanced image quality is also important for the representative capture of wound-characteristics (such as depth, color, and texture). The methods employed for the accurate and precise wound measurement (length, width, area, depth) result primarily from the improved depth of field capability, utilizing imaging algorithms to combine the images from two different sources (i.e., binocular vision, from two adjacent focal length cameras). In this case, two juxtaposed cameras view the object (e.g., wound) from two different perspectives (i.e., angles), whereby disparity or parallax can be used to measure, with very high accuracy (mm to cm) the actual position and distance of each pixel in the pair of images by comparing the disparity-effect of each corresponding pixel in the said images. Hence, the actual distance from smartphone to object can be measured to within a very degree of accuracy, and the area of an object can also be determined knowing the size of the imaging element and other smartphone characteristics. From an object analysis perspective, these enhanced images also support multiple post-capture refocus, and provide several color- and light- enhancements, useful for improving wound photography for real-time or subsequent assessment. Furthermore, a care provider may use the captured image set to actually peer inside the cavity of more serious wounds (perceive 3D) to assess severity, and to plan a course of action, commensurate with an appropriate intervention and hence treatment.

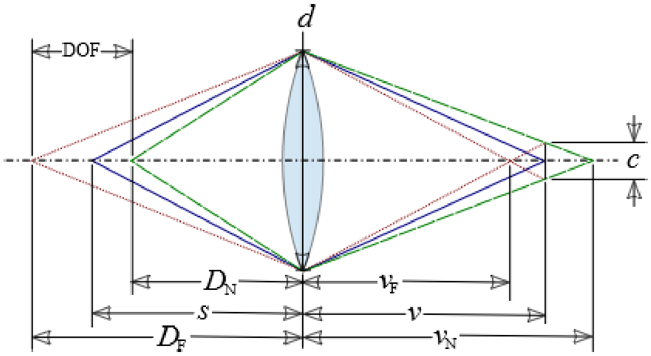


FIGURE 1. **Focus lines detail [32].**

III. IMAGE ANALYSIS

This work developed image analysis algorithms that facilitate non-contact measurements of irregularly-shaped images (e.g. wounds), where the image is taken with a sole smartphone or tablet camera and the image analysis relies on the sensors integrated in the smartphone or tablet with no auxiliary or peripheral devices, and no auxiliary set-up devices (e.g. lightboxes or patient positioning templates). While image analysis is certainly a very well developed field, this work derives novelty and contribution from image analysis application to and implementation in mHealth, specifically for wound care.

Three approaches to image analysis were evaluated and compared: computing depth using autofocus data (herein denoted size-from-focus), a custom sensor fusion of inertial sensors and feature tracking in a video stream, and a custom pinch/zoom approach. These three approaches all were developed to some degree of functionality, with the pinch/zoom approach demonstrating the strongest potential and thus developed into a fully functional prototype complete with a measurement mechanism. Two additional concepts were explored but not evaluated. These included light field processing, as well as correlating subject distance with the compensation achieved by the camera's auto-exposure algorithm; however, the Android framework did not provide access to this data. Finally, a user interface was developed to allow the user to make and view measurements on the image on the device.

A. SIZE FROM FOCUS

1) BACKGROUND

This approach was explored to find distance to an object and did not include analysis of the size or dimensions of the object in the image. This approach is based on a common computer vision technique called Depth from Focus (DFF). DFF is commonly used in the field of monocular depth perception. It reverses an old method for focusing cameras. Before autofocus became ubiquitous, and even before focus aids such as a focusing screen, camera lenses would be focused by finding the distance to the subject and adjusting the lens properties such that its focal distance and focal length would match the actual distance to the image subject and the actual distance to the image plane (film or CMOS sensor) (Fig. 1). The image

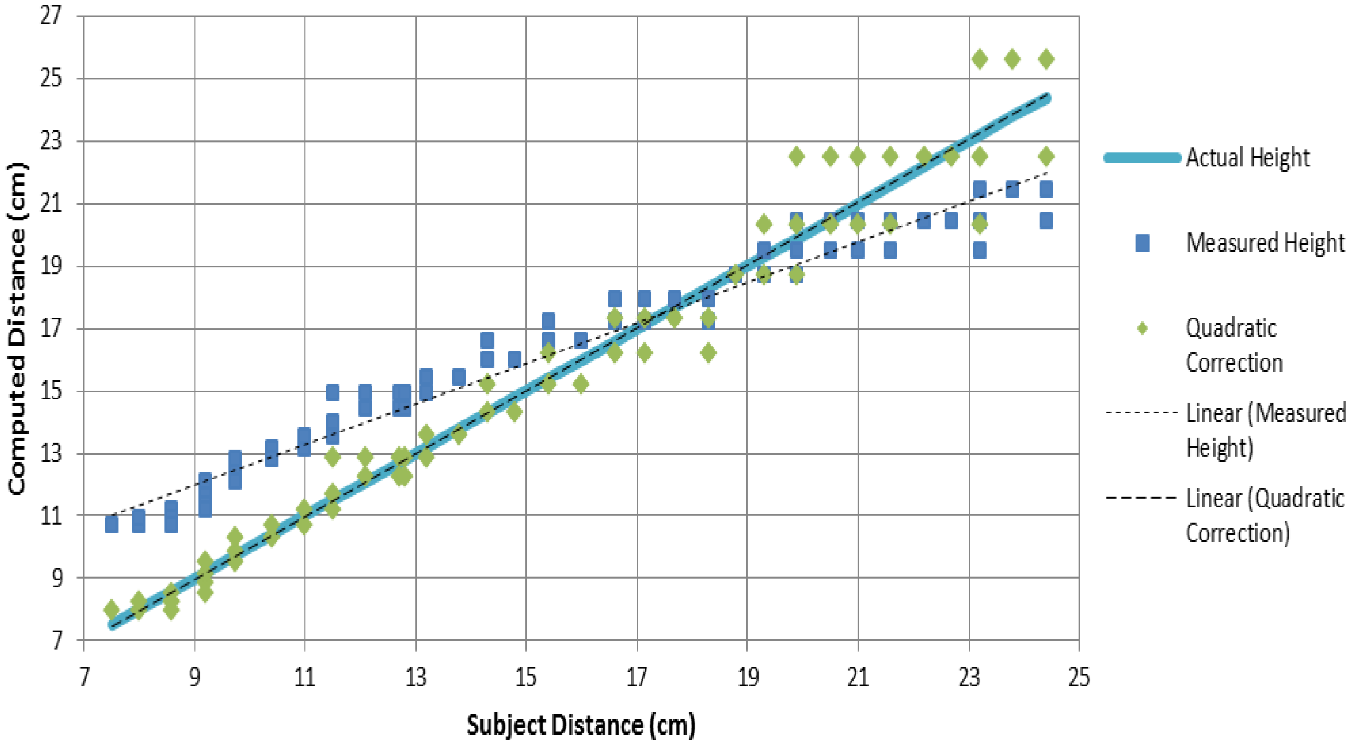


FIGURE 2. **Correcting the perceived distance of a Nexus 4 camera.**

plane is represented as being a distance *v* from the center of the lens. The quantity *c* represents the acceptable level of blur (usually the size of a pixel since the sensor cannot resolve anything finer than that), and the subscripts *F* and *N* represent the far and near ranges of the Depth of Field (DoF), respectively [31]. Autofocus adjusts the lens position and shape using motors, and uses image processing techniques to find the best parameters for a particular shot.

DFF assumes the presence of some auto-focus system. Once the image has been focused, we can look at the lens properties to calculate how far away the subject is. This approach is limited by the DoF of the camera. The DoF is the range of depths for which subjects will appear in focus (Fig. 1). For smartphones, the DoF is fairly wide since the lenses have relatively small sensors and apertures. As a result, it is difficult to get a depth measurement that is better than a ballpark estimate. Furthermore, the farther away the subject is, the wider the DoF becomes and the more the accuracy suffers.

2) SYSTEM DESIGN/IMPLEMENTATION

Despite these known limitations, the approach was pursued because the Android framework implemented it already. A simple prototype application was built that would capture an autofocused image and ask the Android software to compute the subject distance. The distance would then be displayed. The app allowed the user to enable or disable the flash. It was found that the system performed better with the flash enabled because it threw textured parts of the image into higher relief and resulted in a quicker and more accurate autofocus.

3) TESTING

The prototype was easy to use and easy to program, but a great deal of per-device calibration was required in order to get usable results. In order to improve the results, a transfer characteristic was found by taking several images at varying distances. An offset was found that could be corrected using a simple quadratic correction. (Fig. 2). This led to improved results, but the app was still susceptible to errors of up to 5cm when used on a different smartphone (even of the same model). This appears to be due in large part to the high DoF of the camera on the development smartphone (LG Nexus 4).

B. INERTIAL SENSOR/FEATURE TRACKING SENSOR FUSION

1) BACKGROUND

Sensor fusion is a fairly common design principle. The idea is that inputs from several different types of sensors can be combined to produce a measurement of a quantity that is more accurate than any of the single sensors by themselves. Combining sensors in this way allows the strengths of a given sensor to compensate for the deficiencies of another sensor. An excellent example of sensor fusion is in Inertial Measurement Units (IMUs). These devices usually combine the inputs of magnetometers, accelerometers and gyroscopes to produce relatively stable and drift-free measurements of device orientation, linear acceleration and angular velocity [33].

This approach sought to combine data from the smartphone's integrated IMU with feature tracking information from the camera to detect size information about the images within the scene being recorded. Of the three approaches outlined in this work, this approach was the most computationally intense. Integrating accelerometers is not a reliable method to get position information because they are subject to drift that becomes amplified by the double-integration operation [33].

2) SYSTEM DESIGN/IMPLEMENTATION

The problem of accelerometer drift was approached by forcing the user to move the smartphone device in a periodic manner in the Z-axis, i.e. towards the subject and away from it. Subsequently, the motion curve could be compared with the changing size of the image subject using the following algorithm:

1) Integrate acceleration data and compute the average acceleration over a single period. This value is used to determine the accelerometer offset. It is subtracted from all successive integrations to remove the acceleration offset.
2) Integrate again to obtain the offset-free position function.
3) Compute the true area A (in cm^2) of the image object using the following equation:

$$A = \frac{k\,(z_2 - z_1)^2\,(A_{p1}A_{p2})}{f^2\left(\sqrt{A_{p1}} - \sqrt{A_{p2}}\right)^2}$$

where k is the width of a single pixel on the physical imaging sensor, $z_2 - z_1$ is the distance interval moved, f is the focal length of the lens (in millimeters), and A_{p1} and

$$k = \frac{Sensor\ Width\ (millimeters)}{Sensor\ width\ \ (pixels)}$$

A_{p2} are two consecutive area measurements in pixels.

This algorithm was tested using various images of red blobs on a white background. This type of image is trivial to segment. By simplifying the problem of image segmentation, the measurement algorithm could be tested independently of an algorithm for detecting arbitrary wounds in arbitrary images.

A simple Android app was developed that recorded linear acceleration and recorded the area of the red blob as perceived in each frame of video, and the algorithm was prototyped in MATLAB for greater flexibility. The data samples are considered as a set rather than incrementally. This means that the algorithm is not real-time; several seconds of sampling are needed. The algorithm was found to be highly sensitive to noise in the area measurement. In order to ensure good data was passed to the algorithm, noisy data were discarded based upon the following criteria in the order shown:

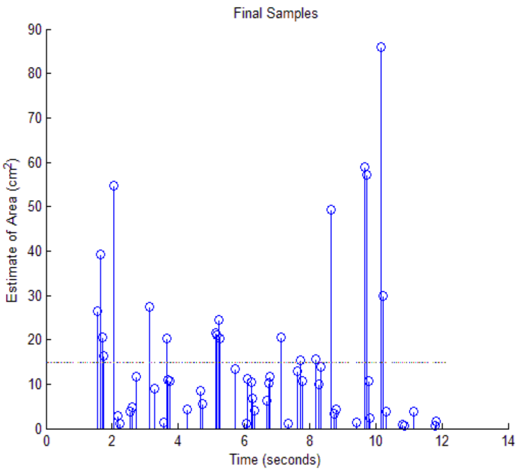


FIGURE 3. **Samples used to compute area (dotted line is true area).**

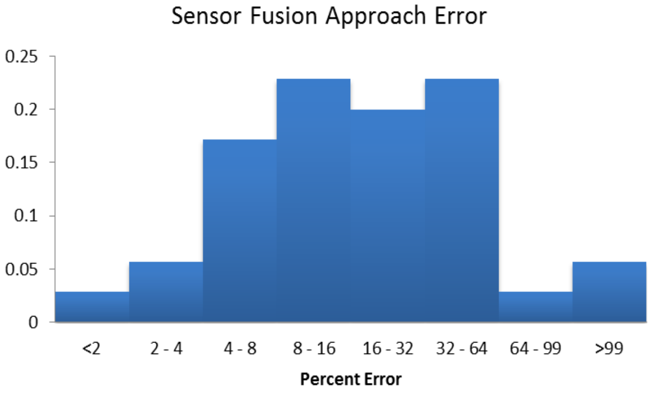


FIGURE 4. **Histogram of Sensor Fusion Error.**

1) Since the motion $z(t)$ is periodic, we discard data samples where $A_{p2} - A_{p1}$ is close to 0 because those samples are likely to cause spikes in the estimate of A.
2) Discard data samples that are surrounded by removed samples, because they are also likely affected by noise.
3) Discard spikes in A. A spike is defined as a sample that is over 3x larger than its neighbours.
4) Discard outliers in A. An outlier is defined as being less than 1/20th the median and greater than 20× the median of the samples in A.

3) TESTING

Fig. 3 shows a set of distance estimates after noisy data has been discarded. Even though most of the samples were too noisy to keep, the ones that remain are sufficient to calculate the area of the image or figure. Fig. 4 is a histogram that illustrates the error associated with measurements taken with this algorithm (n=35), using a base-2 exponential scale. This figure illustrates that while almost 50% of the area measurements fell within 16% of the actual value of the area, and 70% of the area measurements were within 30% of the actual value of the area, it also tended to produce measurements that were far out of range. Therefore this approach does not meet the accuracy requirement.

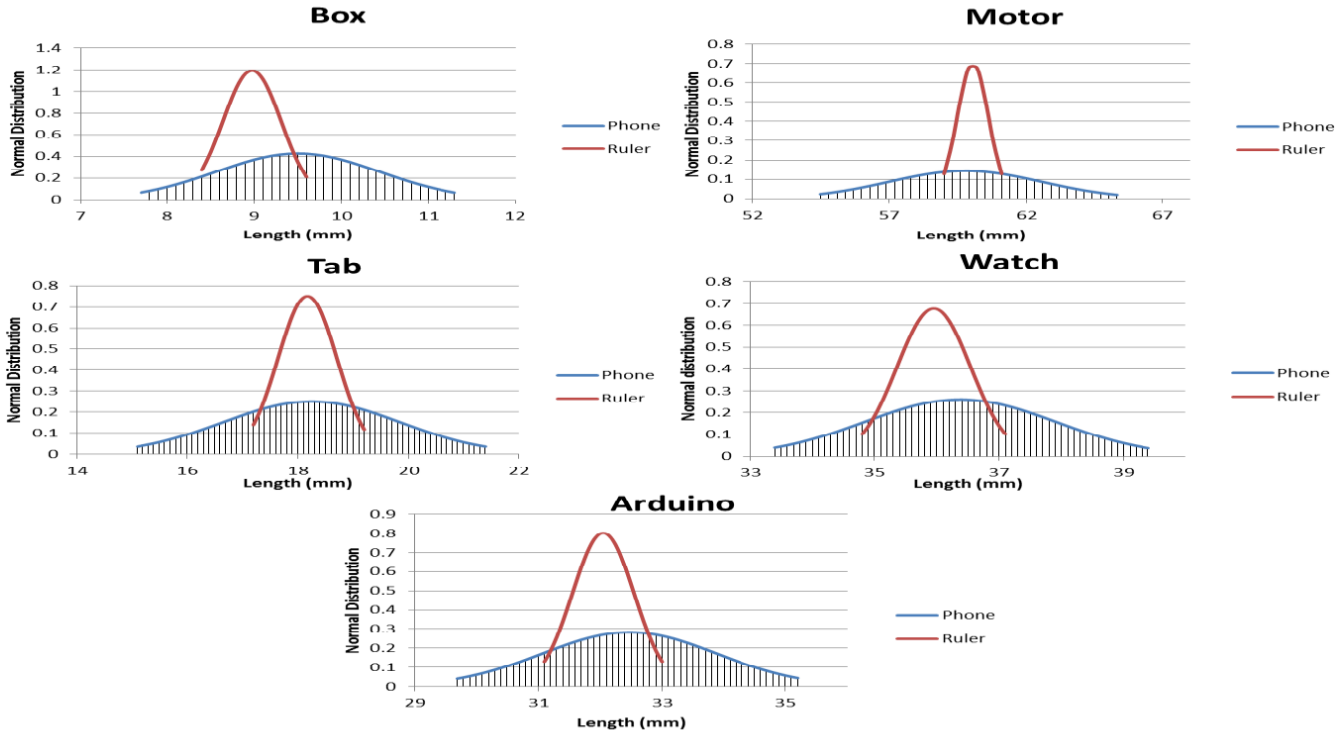


FIGURE 5. Data gathered from pre-testing for several different types of shapes. Graphs show 95% confidence intervals.

C. Pinch/Zoom

1) BACKGROUND AND TECHNICAL PROBLEM

The third approach examined is based on an idea that is similar to other apps that are available in the marketplace. These apps allow the user to measure objects in an image by detecting a reference object of known size and then scaling the world coordinates based on that known object [34]. Like other approaches, it is assumed that all objects in the image lie in the same plane, in particular, a plane that is parallel with the camera's image sensor. This is a valid assumption for most pressure ulcers as they usually occur on the flatter parts of the body (such as the sacral/coccyx region or buttocks), however if the ulcer is too large it may extend out of the assumed plane.

The chief shortcoming of the existing apps is that the user must have the reference object on hand. Although the reference object may be as simple as a computer printout as used by [34], or a common object such as a credit card, the user is still required to have that particular printout or card on hand. In the case of the wound care environment, a suitable object would also need to be chosen and applied with consideration for infection control. A preferable approach and in keeping with the objective would be to calculate size without the assistance of a reference object.

2) SYSTEM DESIGN/IMPLEMENTATION

One novel approach is to use the smartphone itself as a reference object. The user captures an image of a subject using the built-in camera, and then scales the image such that the subject's on-screen dimensions would match the subject's real-world dimensions. This method requires the user to have an accurate sense of scaling on the smartphone screen. A simple test was devised to determine how accurately people would complete this task. 30 participants were given a smartphone and asked to take a photograph of a number of different shapes on a piece of paper (See appendix for the sample page). For each shape, they re-scaled the image on the smartphone screen so that the on-screen shape was the same size as the shape on the paper. Accuracy was calculated by measuring both the shape on the paper and the shape on the smartphone screen. Both values were recorded and it was found that the 95% confidence interval for the screen measurements averaged 6.6 mm across all the different shapes, while the 95% confidence interval for measurements taken directly on the sheet of paper averaged about 2 mm across all the shapes. Fig. 5 shows the confidence intervals for several different shapes. A prototype app was developed that made use of this principle. The scaling information entered by the user was stored in memory so that users could make on-screen measurements.

3) TESTING

The prototype app was tested using the same methodology with an expanded range of objects. Users were asked to take a photograph of a variety of images of different sizes and shapes on a piece of paper, to re-scale the smartphone image to match the real size of the object on the paper, and then measure the object on the paper and on the smartphone screen. Fig. 6 summarizes the results in much the same way as Fig. 5.

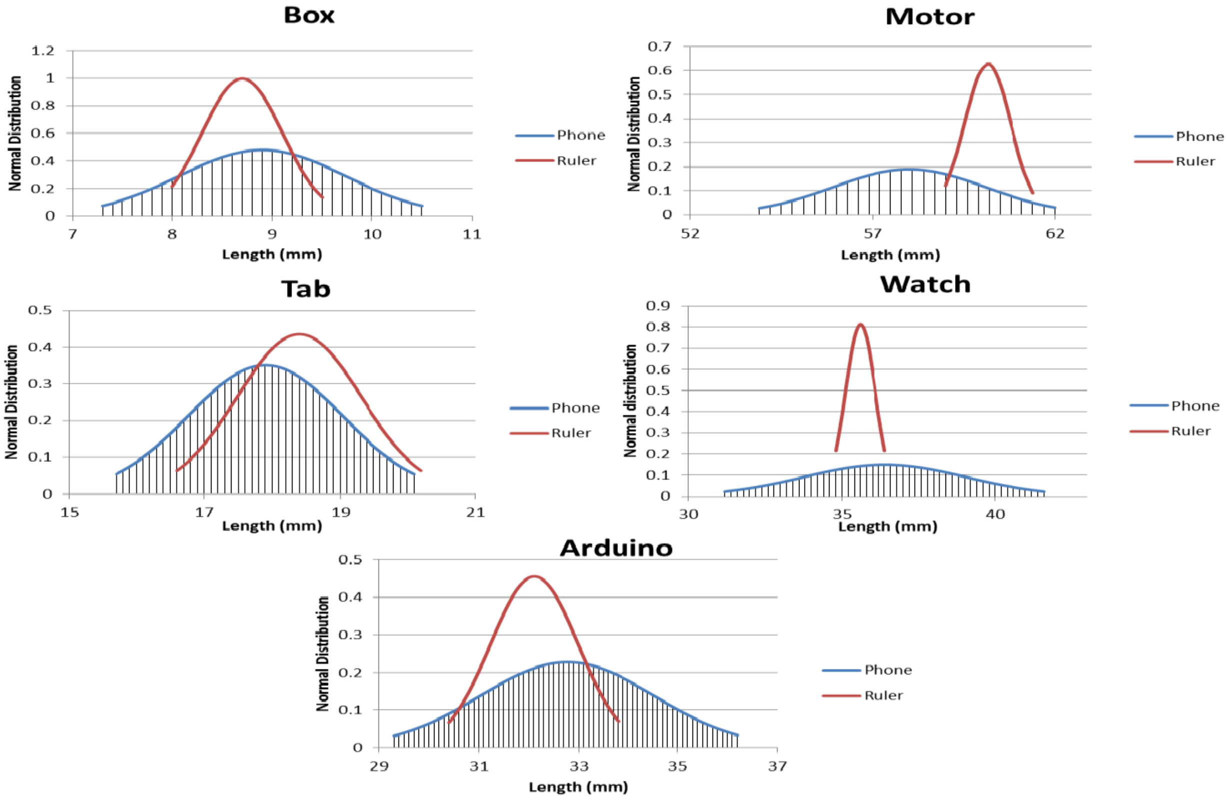


FIGURE 6. **Measurements taken with App Graphs show 95% confidence intervals.**

The data from the prototype largely reflect the data from the initial trial, and in both cases are within the 10% error margin set out as a target.

4) MEASUREMENT ACTIVITY

An Android Activity was built that could take an image that had scale information associated with it and allow the user to draw lines over the image. By dividing the length of this line by the scale factor associated with the image, the length of that line as if it had been drawn in the plane of the image subject could be calculated. This requires accurate knowledge of the smartphone display's dimensions, which can be easily obtained by means of a calibration mechanism. This was implemented in the form of another Activity that displays ruler tick marks, and allows the user to re-scale them to match a physical ruler held up to the screen. This only needs to be done once when the app is first installed.

Additionally, some UI enhancements were implemented including:

- Automatic re-scaling of UI elements for different screen densities: This allows this the activity to display well on any display from the low-resolution Nexus 1 up to the high-resolution Nexus 4.
- Saving measurements as overlays: This feature stores the measurement paths as image files so that they may be overlaid on the image and reviewed at a later time. The .png image file format was used so that future revisions might use arbitrary shapes rather than just lines.
- Zooming image on measurement screen: This allows the user to zoom in closely on a small part of the image so that more accurate measurements might be made.

IV. CONCLUSION

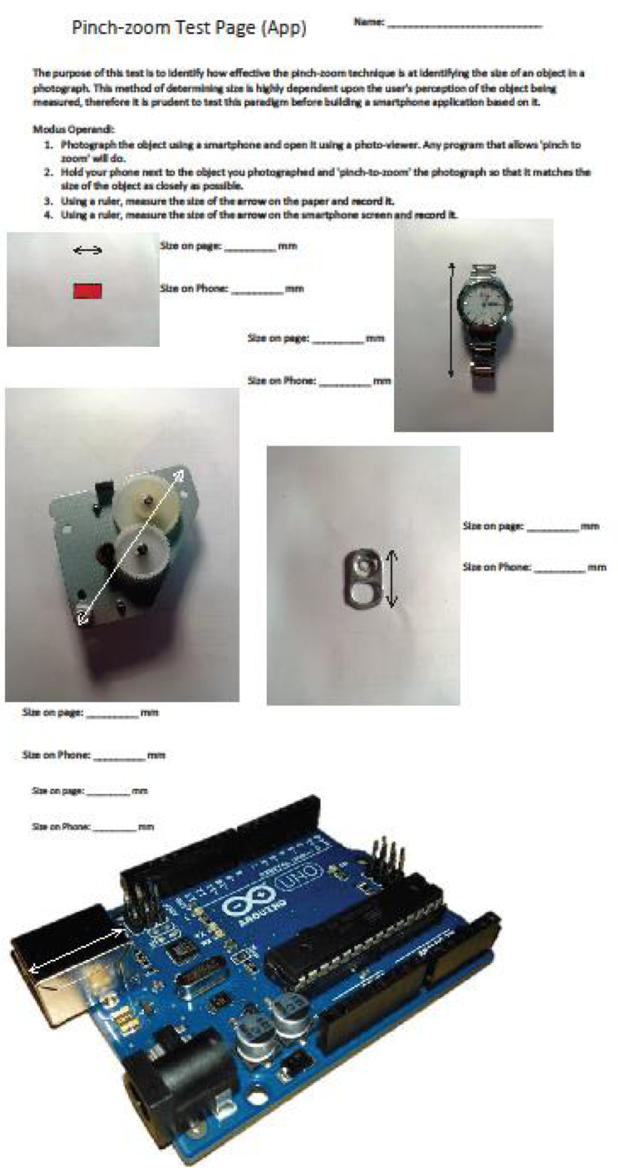
The pinch-zoom app is the most developed approach in this work and has demonstrated the best accuracy of the approaches examined. The sensor fusion approach has a great deal of potential but would need further characterization. In order to be used within the context of wound care, it would need to be paired with a robust segmentation algorithm. This can be done using color recognition, but would likely require either an expert system or an auxiliary device to correctly distinguish between skin and wound tissue. The size-from-focus approach has a great deal of future potential if applied to a light field camera. These devices can create photographs with very shallow depth of field, therefore it might be possible to compute focal distance to a high accuracy. It could even be used to determine how deep a wound is. Toshiba reportedly plans to produce a smartphone camera that can generate light-field photographs. Such a device would be worth using to pursue this option further [35].

One final approach that was examined but not fully developed was lighting the flash and then measuring its intensity. It was noted that compensation of the Auto Exposure algorithm is correlated with subject distance, but due to the nature of the android API, these values are not attainable without greater familiarity with the system. This approach warrants further examination.

Future work will also focus on an analysis on correction for uneven background surfaces and other three-dimensionality of the image. In the realm of wound care, analysis for chromaticity and its correlation to wound conditions will be developed. Both wound color and texture are important indicators of wound type and its relative severity. Three main colors have been identified for critical wound tissue assessment: i) black, ii) yellow, and iii) red, corresponding to necrotic, fibrinous, and granulation tissue, respectively, and future work will focus on adding this capability to the app.

APPENDIX

TEST DOCUMENT USED FOR PINCH/ZOOM VALIDATION



Pinch-zoom Test Page (App)

Name: ____________________

The purpose of this test is to identify how effective the pinch-zoom technique is at identifying the size of an object in a photograph. This method of determining size is highly dependent upon the user's perception of the object being measured, therefore it is prudent to test this paradigm before building a smartphone application based on it.

Modus Operandi:

1. Photograph the object using a smartphone and open it using a photo-viewer. Any program that allows 'pinch to zoom' will do.
2. Hold your phone next to the object you photographed and 'pinch-to-zoom' the photograph so that it matches the size of the object as closely as possible.
3. Using a ruler, measure the size of the arrow on the paper and record it.
4. Using a ruler, measure the size of the arrow on the smartphone screen and record it.

Size on page: ________ mm

Size on Phone: ________ mm

Size on page: ________ mm

Size on Phone: ________ mm

Size on page: ________ mm

Size on Phone: ________ mm

Size on page: ________ mm

Size on Phone: ________ mm

Size on page: ________ mm

Size on Phone: ________ mm

ACKNOWLEDGMENT

The authors acknowledge the collaboration of Dr. Raja Krishnamoorthy and Dr. Moe Barakat of InfoMagnetics Technologies Inc., and the collaboration of Dr. R. D. McLeod of the University of Manitoba.

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