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System Design for 3D Wound Imaging Using Low-Cost Mobile Devices

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ABSTRACT

The state-of-the art method of wound assessment is a manual, imprecise and time-consuming procedure. Performed by clinicians, it has limited reproducibility and accuracy, large time consumption and high costs. Novel technologies such as laser scanning microscopy, multi-photon microscopy, optical coherence tomography and hyper-spectral imaging, as well as devices relying on the structured light sensors, make accurate wound assessment possible. However, such methods have limitations due to high costs and may lack portability and availability. In this paper, we present a low-cost wound assessment system and architecture for fast and accurate cutaneous wound assessment using inexpensive consumer smartphone devices. Computer vision techniques are applied either on the device or the server to reconstruct wounds in 3D as dense models, which are generated from images taken with a built-in single camera of a smartphone device. The system architecture includes imaging (smartphone), processing (smartphone or PACS) and storage (PACS) devices. It supports tracking over time by alignment of 3D models, color correction using a reference color card placed into the scene and automatic segmentation of wound regions. Using our system, we are able to detect and document quantitative characteristics of chronic wounds, including size, depth, volume, rate of healing, as well as qualitative characteristics as color, presence of necrosis and type of involved tissue.

Keywords: Wound imaging, 3D imaging, 3D registration, dense reconstruction, wound assessment, photographic documentation

1. INTRODUCTION

Human skin is the largest in terms of surface and heaviest in terms of weight organ. Enclosing the body, it serves the protective function preventing various kinds of damage, such as loss of water or harmful influence from outside.[1] Pathological processes beginning internally or externally can cause a breakdown in the integrity of the skin and result in wounds. A wound is the loss of continuity of epithelium, with or without loss of underlying connective tissue (e.g. muscles, bones, nerves)[2] caused by many possible factors, such as trauma, surgery, thermal and chemical burns, vascular compromise (arterial, venous, lymphatic or mixed), or metabolic diseases, including diabetes and calciphylaxis.

When such a skin breakage occurs, a special protective mechanism called healing is initiated. Healing is represented by a sequence of biochemical events, including blood clotting (hemostasis), inflammation, tissue growth (proliferation) and tissue remodeling (maturation).[3] This process is very complex and fragile. Its failure and interruption may lead to chronic, or non-healing, wounds. There are many factors which may impair wound healing. Amongst those are presence of foreign bodies, tissue maceration, ischemia and infection.[4] Occurrence of such a complicated wound can lead to the loss of a limb or even become lethal. That explains the high necessity of professional clinical management of chronic wounds.

Wound management includes diagnosis, treatment, monitoring and documentation. We focus our work on the latter two issues. Accurate wound monitoring and proper documentation are necessary for medical, legal and reimbursement related reasons. We aim at providing a new standard for quantitative and qualitative documentation of chronic wounds utilizing low-cost consumer hardware (i.e., smartphones featuring a single camera) by introducing an automatic method for wound reconstruction in 3D followed by an automatic analysis of the lesion. Our goal is to make the technology inexpensive, connective, and available for broader use.

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2. STATE-OF-THE-ART

Wound evaluation is usually based on rather quantitative observations such as wound size, depth, volume, total time to heal and rate of healing, as well as rather qualitative characteristics such as color, odor, exudate, location, presence or absence of undermining and necrosis, pain and type of tissue involvement.[5] In the clinical settings, the size of a wound is measured by physician who traces the outline of the wound to special transparent sheets.[6] Depth is measured by placing a foam-tipped applicator vertically in the deepest-seeming part of the wound and marking the applicator at the skin level.[7]

Despite their simplicity, such measurements have several drawbacks such as limited reproducibility and accuracy: firstly, due to the irregularity of wound, these methods are very inaccurate; secondly, they require direct contact to the wound, which might be painful for the patient and, without precautions, may lead to the wound being infected. Moreover, this methods are not suited for different kinds of wounds: if a large skin area is affected, a tracing paper might be too small or tracing might be complicated by the presence of skin folds and other body surface irregularities. As for the depth measurement, this method does not allow volumetric measurement of convex-shaped wounds. Furthermore, this methods do not provide rich documentation and do not make it possible to reconcile the qualitative characteristics afterwards.

On the contrary to the manual acquisition, novel hardware supports automatic assessment of precise volumetric wound models and is able to handle the drawbacks of manual approaches. Laser scanning microscopy, multi-photon microscopy, optical coherence tomography and hyper-spectral imaging can serve as examples of such systems.[8] Major disadvantages of these methods are the high cost of the hardware and the lack of portability, which might be an issue if a patient is on home-care and transporting to the hospital is not desired.

Recently, a new generation of 3D wound imaging devices has evolved.[9–12] Such systems rely on advances of structured light illumination and 3D imaging. Developers at Fuel 3D Technologies have created a handheld 3D reconstruction device which integrates multiple cameras, light sources, touchscreen and a circuit board enabling fast image processing.[9] ARANZ Medical's approach is composed of a palm-sized sensor featuring fixed focus digital camera equipped with lasers and an LED light source for accurate illumination.[10] The system of Wu et al.[11] makes use of a tablet with an attached structured light 3D-sensor. GPCSL has a 3D wound measurement system running on an Intel RealSence tablet featuring a system of two calibrated cameras.[12] Although such devices are comparably more portable and less expensive, they still require specific equipment and, therefore, their application is limited with respect to self or home monitoring. Furthermore, such devices are provided with proprietary software interfaces and images can be captured and used exclusively with the vendor's software. There is no interconnection with picture archiving and communication systems (PACS), since the devices are not compliant with the digital imaging and communications in medicine (DICOM) standard.

Due to the high prevalence of chronic wounds, there is still a need of inexpensive and portable devices for 3D imaging of skin lesions directly delivering the source images and 3D models into the PACS.

3. MATERIALS AND METHODS

In this section, we propose a system design for wound reconstruction, analysis, and communication with a help of a low-cost consumer-level smartphones featuring just a single RGB camera.

3.1 System architecture

The system architecture is presented on Fig. 1: images are recorded by the patient or an assisting person using the interactive app running on the mobile device. The app guides the user how to do recordings in the correct way. In addition to the image data, inertial measurement unit (IMU) data of the device is also recorded. IMU includes date, time, global positioning system (GPS) coordinates, 3D acceleration and compass directions.

All data is transferred to the operational server, where the processing chain is performed. Inherently to our system design, the operational server might by external (e.g., cloud service) or internal (e.g., the entire computational load is shifted to the smartphone). Disregarding internal vs. external computations, all data is stored on an external data storage that might be proprietary or according to the DICOM standard. The resulting data can be shown to the patient using a proprietary client app and to the clinician by means of the client desktop software as well as PACS interconnection. The clinician, observing quantitative and qualitative outcomes makes a diagnostic decision (that may be coded with DICOM structured reporting) and may provide some comments to the patient. The comments, in turn, become available to the patient by means of the client app.

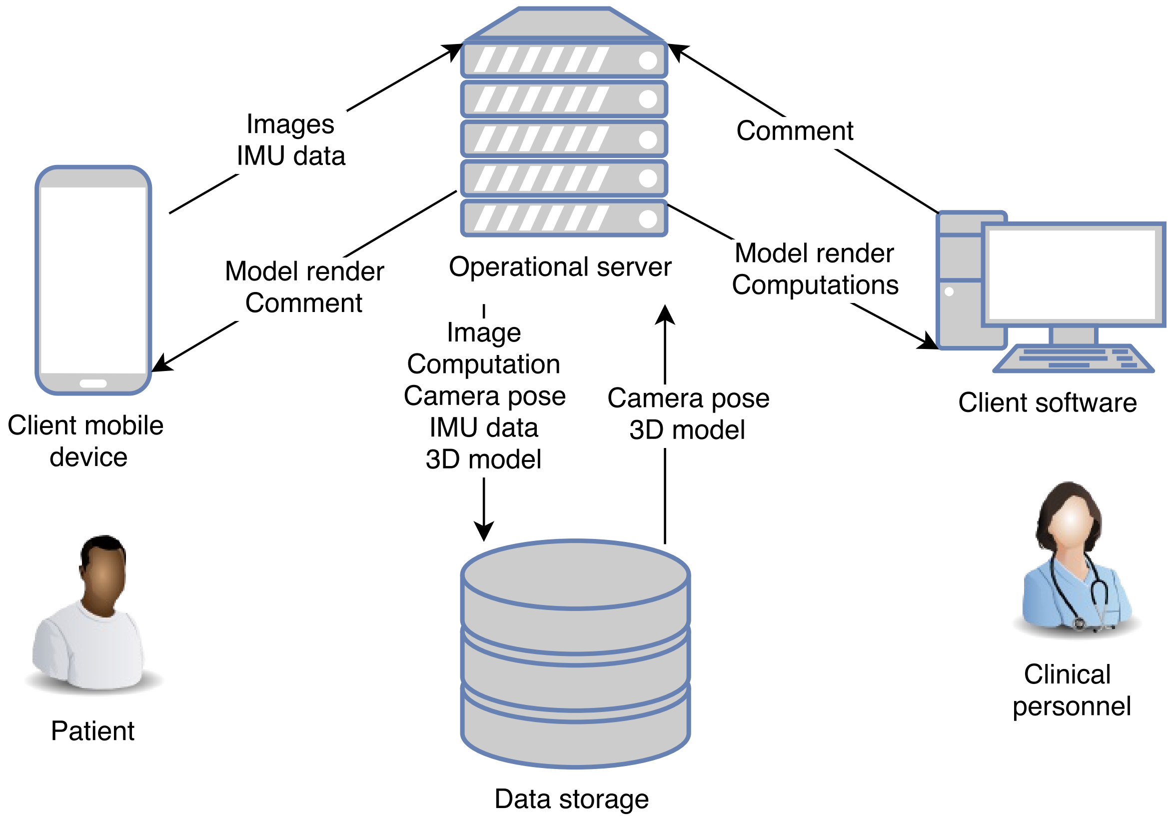

Figure 1. System architecture.

3.2 Processing chain

The general processing chain can be divided into three major tasks: (i) data acquisition, (ii) color correction, and (iii) 3D reconstruction. Additional steps as wound tissue segmentation and wound tracking over time are also possible and can be integrated into the software product or can be performed by third-party systems supporting the original standard. The interaction between these procedures is shown on the Fig. 2: frames and models pools loop processing until the pools are processed entirely.

3.2.1 Data acquisition

Smartphone-integrated cameras (e.g., Samsung Galaxy Tab3, Samsung Electronics GmbH, Germany or iPhone 6, Apple, USA) are used for image recording. In addition, a consumer color reference card (2×3-inches, 24 color plates, CameraTrax, USA) is placed into the scene to enable further color correction. The reference color-checker card is composed of 24 squared color tiles arranged in a custom order and covering the entire RGB color space.[13,14] The images are recorded sequentially with a high frame rate (25–30 fps) so that a large part of each new image overlaps with the previous one.

3.2.2 Color correction

Images recorded by a consumer-level camera are often affected by ambient light conditions and reflections from the environment, which makes the recordings inconsistent even if those were taken with the same device. It is

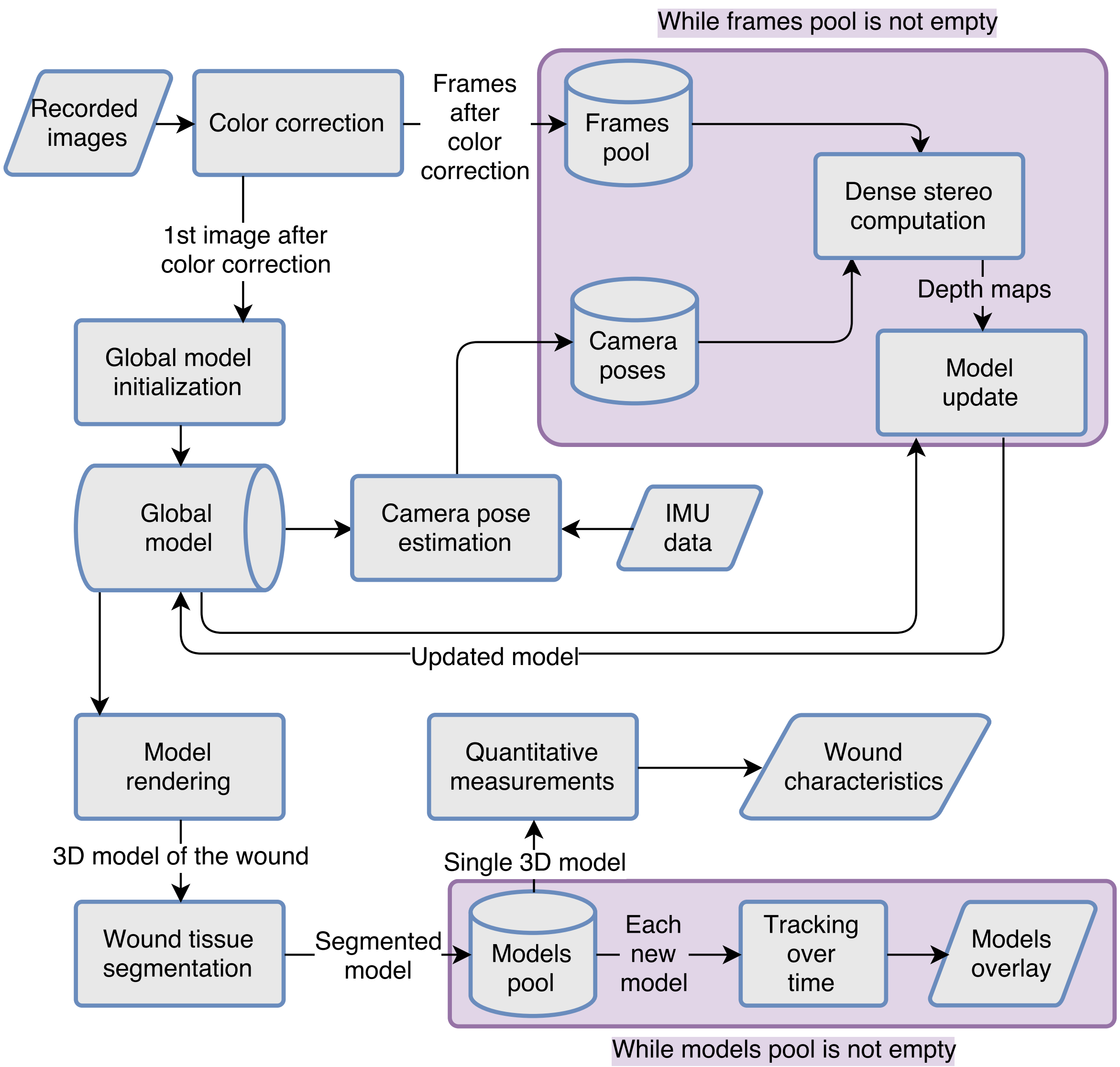

Figure 2. Processing chain.

important to apply color correction to make quantitative analysis of a wound possible. We apply color calibration on original 2D images prior to 3D reconstruction. For color correction, we extend our automatic method[13] that makes use of a reference color card with 24 plates covering the entire red-green-blue (RGB) color space: (1) the color card is located in the image using a mean-shift belief propagation algorithm for deformed lattice detection in real-world images,[15] (2) the 24 color regions are located within the card, and (3) the color of each tile is measured and transferred into a least squares fit to the reference values in the RGB color space. The resulting color transformation is applied to the image.[14]

3.2.3 3D reconstruction

The main task of 3D reconstruction is generation of dense geometric models of high quality. Models of high quality are those which depict the real world objects at closest, preserving fine details, being able to maintain occlusions and redundancy, and being free of gaps and noise. Fully automatic methods, which return precise and 100% realistic representation when using a single RGB camera only, do not exist yet. However, some methods have been proposed that are accurate enough to be used for reconstruction of small scenes and objects, and, therefore, can be used for 3D wound imaging.[16–21] Due to the advances of graphical processing unit (GPU) in modern smartphones, which allows parallel computations, most of these methods were designed to run purely on a mobile phone without a need of an additional computational server.

In general, there are two fundamentally different approaches to the reconstruction using a single camera. The first one relies on the sparse reconstruction of an object in a form of a point cloud by means of structure from motion (SfM), followed by a mesh generation applied to the point cloud.[22,23] It requires complex computations, which cannot run in real-time. Contrarily, real-time or near real-time performance is mandatory for immediate user feedback. Furthermore, due to the lack of texture in some regions, the corresponding parts of the model might be missing, which leads to a semi-dense reconstruction. Only selected points are assembled in sparse geometric models, while in a dense model depth map is created for every pixel. As a human wound is a continuous object, we consider dense reconstruction more suitable for our task. The second approach leads to dense model creation. It is based on generation of depth maps from images on the input level followed by depth fusion and do not require sparse point cloud generation.[18,20] It supports parallel implementation and can be performed fast even on smartphones without the need of additional cloud-based processing.

In our system, we adapt the method of Ondrúška et al.,[20] where dense tracking is performed in each recorded frame: camera positions are estimated using a dense feature-free monocular camera tracking method and optionally corrected using the information from the built-in IMU, as it has been proposed by Ondrúška et al.[20] Based on the overlap between images, key-frames are selected and rectified according to the camera position of incoming frame and dense stereo matching is performed using stereo block matching. The acquired depth maps are integrated into a volumetric model using a method resembling the KinectFusion algorithm.[24] Since wound imaging does not require immediate reconstructions after each fused frame, our method can be simplified by omitting the 'live' component.

3.3 Wound analysis

The obtained 3D models allow comprehensive analysis and measurements using segmentation, registration, and tracking.

3.3.1 Segmentation

For the sake of simplicity, the reconstructed 3D wounds are segmented so far based on color information only. Red, green, and blue (RGB) values are mapped into the hue, saturation, value (HSV) domain, where hue ranges for the different tissue types are determined. Note that due to the color calibration, global thresholds can be defined over all the images without the need of image-specific adaptions. However, more precise but complex algorithms might be introduced in future. For example, some adaptation to different healthy skin tones might be beneficial.

The following regions are then revealed: healthy tissue, granulation, slough, and necrosis. By nature of the 3D representations, size and depths measures are obtained automatically for each of the tissue regions.

3.3.2 Quantitative measurement

3D reconstruction allows automatic measurement of such characteristics like wound perimeter, area, depth and volume of wounds. Wound *perimeter* is computed after segmentation as the length of the outer contour separating healthy skin and wound tissues. A 2D plane is then fitted into this contour and the *area* is calculated as the number of pixels in the plane within the contour projection area on this plane. The value in pixels is translated into real-world measurement units (cm^2) using the known scaling factor either derived through camera calibration, which is not desired as the end users of the system might find it confusing, or derived for the reference card, which is an artificial object of well-known geometry. Wound *depth* is estimated as the length of the longest perpendicular from the fitted plane to the wound. The *volume* of the meshed model is estimated through calculation of the signed volume of a tetrahedron.[25]

3.3.3 Registration and tracking

For tracking of wound development, the regions belonging to the same lesion in 3D models acquired over time are registered to each other using generalized ICP (GICP),[26] which is an extension of ICP[27] using point-to-plane metrics instead of the point-to-point metrics. To apply GICP, the dense models are converted into point clouds and correspondences between points of two models are estimated. The error is minimized along the surface normal according to a probabilistic model. The difference between two consecutively captured 3D models is visualized by overlaying the aligned reconstructions. Quantitative measures are computed after segmenting the registered sequence of 3D data.

3.4 Communication

As depicted in Fig. 1, source images, IMU data, computations, camera poses and 3D models are persistently stored in an external device. So far, the storage is connected by a proprietary interface, but integration into a DICOM compliant PACS is straightforward.

4. FUTURE WORK

The presented concept will be implemented and evaluated with a respect to performance and usability. To measure performance, several artificial wound models featuring different size, depth and structure will be designed using modelling software (Blender*), printed using a 3D printer and painted in order to imitate different wound tissues. The models will be measured by several evaluators using manual state-of-the-art method. In addition, the volume will be assessed through filling the models with water and measuring it's volume afterwards. Afterwards the automatic assessment with the proposed software will be performed. Measurement error will be calculated as the average standard error of the mean between measurements performed by each evaluator for each model.

The user study shall be able to reveal potential issues of the system usability for both groups of potential users (patients and clinicians). All test users will be offered to complete a questionnaire designed to assess their satisfaction by the product.

5. CONCLUSION

We present a conceptual design of a system using inexpensive consumer level hardware for 3D wound reconstruction. We have adopted a novel approach to 3D reconstruction using mobile devices equipped with just a single RGB camera into the medical domain. Accompanied with color correction, tissue segmentation, and tracking over time, the proposed system design is capable to provide objective and quantitative measurements of wounds. Furthermore, it supports PACS integration and DICOM communications by architecture's nature.

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