



Hardware Article

Phone cam array – An open-source, modular photogrammetry system made of Android phones



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ABSTRACT

Photogrammetry is a 3D reconstruction technique using photographs of the target from multiple angles. Taking pictures around a static object with a single camera can yield high-quality models, but if the subject moves between images, 3D reconstruction might fail. One way to mitigate this is to use multiple cameras.

This project aimed to develop a tool for fast and precise wound documentation for clinical forensic medicine.

This paper describes a simple, low-cost modular system, where smartphones of different manufacturers are used as networked cameras. Exposure is initiated at the same time in all the phones with a simple circuit emulating a headset button press.

A proof-of-concept device was built, where four phones (Huawei nova 8i (2 pcs), Samsung Galaxy S7 Edge, Oukitel K4000 Pro) were attached to a curved, 3D-printed, hand-held frame.

The average delay of image capture was 636 ms between the quickest and the slowest phones. When compared to the single-camera approach, the use of different cameras did not reduce the quality of the 3D model. The phone cam array was less susceptible to movement artefacts caused by breathing. Wound assessment was possible based on the 3D models created with this device.

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Specifications table

Hardware name	Phone Cam Array
Subject area	<ul style="list-style-type: none"> • General
Hardware type	<ul style="list-style-type: none"> • Imaging tools
Closest commercial analogue	Custom-built commercial systems made of digital cameras
Open source license	Creative Commons Attribution-ShareAlike 4.0 International License
Cost of hardware	50 USD+ the mobile phones
Source file repository	https://doi.org/10.17632/2nhfs99zcy.1

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Hardware in context

Photogrammetry is a 3D reconstruction technique where photographs of the target from multiple angles are used for the reconstruction of its 3D model. In principle, photogrammetry software analyzes overlapping 2D images of the object, matching common points, and then the relative positions of these points are calculated resulting in the surface of the object. One of the earliest and still common application of photogrammetry is topographic reconstruction based on satellite or aerial imagery [1,2]. One of the main advantages is that it allows the building of high-precision 3D models without the need for special 3D instrumentation. Recent advancements in algorithms and computing power made this method widely accessible.

Medical applications of photogrammetry are not a new concept [3], but it is only recently that this method became widely accessible and more widely adopted. Applications range from archaeology, postural reconstruction [4], documentation of autopsies [5], and teaching forensic medicine [6], just to name a few. When photogrammetric reconstruction of human bones was compared to their Computed Tomography (CT) scans, it was found that photogrammetry is a reliable and accurate alternative [7], which illustrates the potential of this lower-cost technique.

General image quality recorded by smartphone sensors reached high standards the recent years, making photogrammetry even more widely available.

Cullen et al described the possibility of digitizing transtibial sockets [8]. The fit of a prosthesis is crucial for the lower limb amputees' quality of life. The traditional method of creating a fitting interface would require several in-person meetings, but 'scanning' the prosthesis could up the process.

Cranial deformations of infants were recorded with Samsung S7 Edge and compared with the results of manual measurements [9]. To mitigate the effect of hair and to help the reconstruction with recognizable points, the heads were covered with a mesh cap. The differences were between the two models 2 ± 0.9 mm. A similar approach was used to improve the localization of scalp-mounted neuroimaging sensors [10]. The cap containing the sensors was placed on a standard head phantom and was recorded with different smartphones. The median localization error was 0.7 mm.

External ears were remodelled using 30 images taken by an iPhone 8S, with an accuracy of 1.5 ± 0.4 mm compared to a commercial Artec Spider 3D scanner [11]. Facial scanning was performed by Nightingale et al with a very similar setup, using iPhone 8S phones. The results were also compared to Artec Spider scans with an accuracy of 1.3 ± 0.3 mm [12].

Some studies recorded video [9,10] instead of images, but the latter publication shows that the higher resolution footage decreased mean error. In this project still images were acquired because they have higher resolution. Also, too fast movement of the camera while recording video footage can yield blurry frames.

The examples mentioned above illustrate that images from single mobile phones can be a basis of medicine-related photogrammetry. One of the main limitations of photogrammetry of living subjects when using a single camera is that it needs a static target. If the subject moves or its shape changes between images, the reconstruction algorithm will not be able to calculate the relative position of the surface points, leading to an inaccurate or failed 3D reconstruction. It was shown above that small body parts can be scanned with a single camera, but when larger parts are considered, the increased time required for image capture increases the chance of small involuntary movements of the subjects. In certain cases, the breathing movements can interfere with 3D reconstruction.

One potential solution for this problem is to connect several cameras pointing at the target and release them at the same time. One of the main users of this kind of device is the movie and video game industry to scan actors or "assets" [13,14]. The research field has also recognized this technique:

Leipner and colleagues created "3D mug shots" for forensic purposes with a system created by 26 mid-range Canon EOS 80D digital single-lens reflex DSLR cameras, connected by USB to a computer. Cameras were controlled by the software Smart Shooter 3 (Tether Tools), which allowed the researchers to change settings and take images remotely and concurrently [15].

Pesce et al. proposed a simple system using eight entry-level Canon Power Shot A480 cameras [16]. The cameras are organized as pairs, creating stereo-photogrammetry images. This approach created high-quality 3D models using low-cost cameras, but their system needed a calibration process. The test dummy was also scanned with a Minolta Vivid 910 laser scanner, with an overall average deviation of ± 1.1 mm.

VirtoScan is an automated solution for surface documentation of human cadavers by attaching seven mid-range Canon EOS 100D DSLR cameras to a CT scanner and taking photos during the full body CT scanning with a mean surface deviation of 0.36 mm [17].

Richard Garsthagen published an open-source system built from 98 Raspberry Pi cameras in 2014 [18]. The following project successfully networked 40 Raspberry Pi cameras for this purpose [19]. Yang et al described an open-source solution consisting of 50 Raspberry Pi cameras connected to routers [20]. They were able to capture high-quality hand models, which is difficult by using photogrammetry with the mean absolute error of 0.68 ± 0.28 mm compared to a scanned model of an Artec Spider.

These systems above illustrate that several approaches can lead to high-quality 3D models of human subjects. Generally, photogrammetry reproduction requires several images, which can be achieved by multiple, networked cameras. All the above-mentioned systems generated high-quality 3D models of human bodies or body parts, but their direct comparison is difficult because results are often presented in different approaches (e.g., the photogrammetry model was compared to a model created by a commercial 3D scanner, number of created polygons or recognizable facial features were counted,

etc.). The photogrammetry models were usually compared to a 3D model created with an alternative method. One conclusion is that while the image quality of the Raspberry Pi cameras is inferior to the DSLR cameras, their images were suitable for 3D reconstruction.

Raspberry-based solutions are affordable compared to DSLR cameras, but building an array with dozens of cameras can be costly: currently, the lowest price for a Raspberry Pi 4 8 GB board is 116 EUR from an official Hungarian distributor and the additional Raspberry Pi Camera board v3 costs 37 EUR [21]. A current problem is that at the time of the submission of the manuscript, it is difficult to source Raspberry boards due to the chip shortage. Building a Raspberry Pi-based system might require some knowledge in coding or at least scripting, but then the user could tailor the system to their needs. On the other hand, soldering is not needed which might be an advantage.

The inspiration for this project came from clinical forensic medicine. In the case of accidents or assaults, the investigation or the legal process might depend on the feature and severity of injuries. However, written descriptions are often not detailed enough. Even single 2D photographs can lack important aspects. A simple way to create imagery for photogrammetry could be helpful in these cases as the forensic medical expert could revise the features of the injury based on the 3D model. Using multiple mobile phones could speed up the image-taking process. Also, their Wi-Fi connectivity could help automatically upload in the background.

Fast wound documentation was the main goal of the project, but several other fields could benefit from this tool, for example, anthropometry, anthropology, veterinary sciences, or plastic surgery. The low cost of the components and the ubiquity of available mobile phones enable small research groups or schools to build this instrument. If the required number of unused Android phones can be obtained, the rest of the components are very affordable compared to other multicamera systems. The fact that cell phones from different manufacturers could greatly help to source for low prices or even for free.

The aim was to build a device incorporating multiple mobile phones of various makers for photogrammetry. The following features were evaluated:

- The shutter lag between the phones.
- If the use of different cameras influences the model quality compared to the single-camera approach.
- The ability to create models of living subjects.
- Compare the wound descriptions based on the 3D models to the original wound descriptions.

Hardware description

In this paper, a simple, but modular 3D-printed frame is described. The phones are attached to a handheld, curved frame, which ensures that all the cameras would focus on the same point. The pieces are joined by heat-set inserts and metric screws. The 3D-printed phone mounts are attached with cable ties.

- A simple modular system of Android phones to capture images concurrently for photogrammetry reconstruction.
- The phones do not need to be the same model or make.
- The phones are attached to a 3D-printed handheld frame.
- The system allows the 3D reconstruction of living, moving subjects.

Fig. 1 shows the basic construction of the Phone Cam Array. The phones are attached to the circular 3D-printed frame with cable ties. Each phone needs a phone mount and a junction box. All the cameras are released with a single button on the control grip, which houses the battery for the system as well. This proof of concept is composed of four phones with a handheld frame (a maximum of six phones could be attached to this frame). Sequential images of body parts or small objects can be taken as depicted in Fig. 2A the recommended path for a whole body 'scan' is shown in Fig. 2B If more phones are available frame sections can be stacked vertically with columns screwed to the optional attachment points, this would provide more angles of the same regions, offering higher resolution (Fig. 2C).

The core of the system is a simple controller module, which connects to the phone with a 3.5 mm jack plug and emulates the press of volume + of a headset, to release the camera shutter. The design is based on the Android Open Source Project (AOSP) accessory specification [23]. The R3 resistor (5000 Ohm) simulates the resistance of the microphone unit, the phone recognizes that a headset is plugged in by this resistance. R1 and R2 (330 Ohm and 22 Ohm) emulate the button press, when they are connected by the PC817 optocoupler (Fig. 3A). When the optocoupler is turned on, an internal LED (light emitting diode) activates an internal phototransistor and closes that circuit. The advantage of using optocouplers over relays is that they are smaller, more reliable and use less energy. D1 diode protects against reverse polarity. R4 (2.2 k Ohm) resistor drops the voltage of the battery for the optocoupler. The units are connected via JST XH 2 connectors. The design of the controller printed circuit board (PCB) is intentionally simple, using only through-hole components, not the smaller SMD ones. With minimal soldering experience, one can assemble them safely. Also, if someone cannot order the PCBs from a manufacturing company, it is possible to etch them at home or build it on a prototyping board. Every phone used in this network needs its own control circuit. The phones are interconnected to each other and the control grip as shown in Fig. 3B.

The ideal frame of the camera array largely depends on the intended application. The structure will differ if one wants to fill a whole room with dozens of cameras or wants to create a portable version containing only four–six phones. It is possible

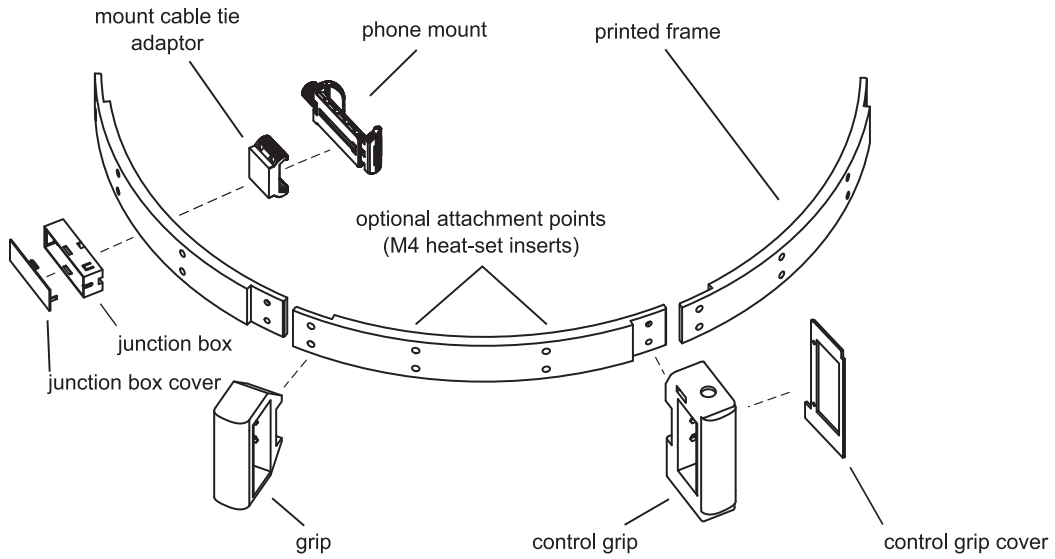


Fig. 1. Schematics of the Phone Cam Array. To avoid clutter, only a single phone mount, mount cable tie adaptor and junction box are pictured. The width of the assembled frame is approximately 61 cm.

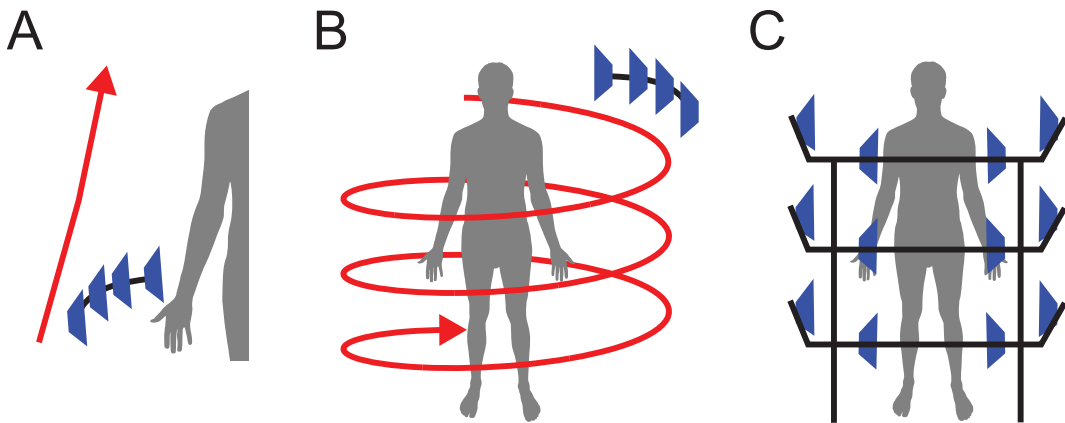


Fig. 2. Proposed uses of Phone Cam Array. To take the images stop briefly and press the expo button at regular intervals. A. To scan a body part, move the array alongside. B. To scan a full body, follow a spiral pattern. C. If multiple cameras (>20) are available, it is possible to build an array of static cameras (human body silhouette [22], public domain).

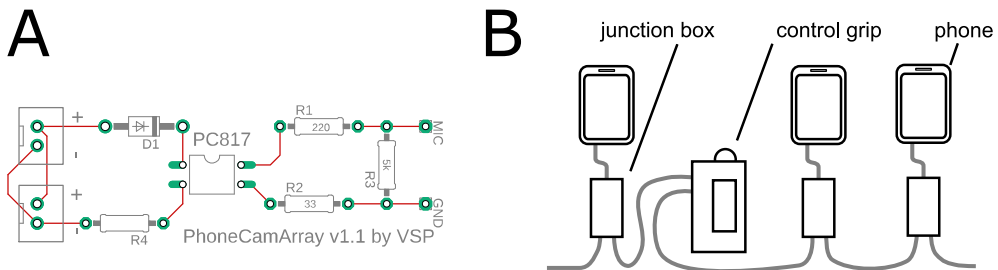


Fig. 3. The controller circuit. **A.** The circuit of the control PCB. **B.** Schematic drawing of the assembled Phone Cam Array.

to attach the phones to an existing object (for example a CT instrument). The frame design described in this paper allows the stacking of units with vertically oriented pillars attached to the frame via the optional attachment points.

*Design files***Design files summary**

Design file name	File type	Open source license
Junction box	STL and STEP	Creative Commons Attribution-4.0 International License
Junction box cover	STL and STEP	Creative Commons Attribution-4.0 International License
Frame	STL and STEP	Creative Commons Attribution-4.0 International License
Grip	STL and STEP	Creative Commons Attribution-4.0 International License
Control grip	STL and STEP	Creative Commons Attribution-4.0 International License
Control grip cover	STL and STEP	Creative Commons Attribution-4.0 International License
Mount - cable tie adapter	STL and STEP	Creative Commons Attribution-4.0 International License
Control PCB	Gerber, Eagle, pdf	Creative Commons Attribution-4.0 International License
JST connector PCB	Gerber, Eagle, pdf	Creative Commons Attribution-4.0 International License

Design file name	Description
Junction box	Holds the control circuit
Junction box cover	Protective cover of the junction box
Frame	3D printed frame section of the camera array
Grip	A simple handle for the frame
Control grip	A handle that houses the release button, battery and JST-XH connectors
Control grip cover	Protective cover of the control grip
Mount - cable tie adapter	Makes it possible to attach the phone mount to the frame with cable ties
Control PCB	The printed circuit, necessary to control the cameras. It goes to the junction box
JST connector PCB	A simple PCB to mount two JST-XH female connectors in the control grip

All the source files can be downloaded from Mendeley Data repository (<https://doi.org/10.17632/2nhfs99zcy.1>).

Bill of materials**Bill of materials summary**

Designator	Component	Number	Total cost USD	Source of materials
Optocoupler	PC817	1*	0.5	aliexpress.com/item/4001128373856.html
R1 resistor	220 Ohm	1*	0.05	aliexpress.com/item/1005001931818502.html
R2 resistor	33 Ohm	1*	0.1	aliexpress.com/item/1005001931818502.html
R3 resistor	5.1 k Ohm	1*	0.05	aliexpress.com/item/1005001931818502.html
R4 resistor	2.2 k Ohm	1*	0.05	aliexpress.com/item/1005001931818502.html
diode	1 N4004	1*	0.025	aliexpress.com/item/1005002872292563.html
JST-XH connector	JST-XH female side entry connector	2*	0.025	aliexpress.com/item/1005004985397880.html
JST-XH cable	Male-male JST-XH 2-pin cable	1*	0.2	aliexpress.com/item/32807634326.html
Control PCB	Control circuit	1*	2	Manufactured on request
JST connector PCB	Connector of the control grip	1	1	Manufactured on request

(continued on next page)

Specifications table (continued)

Designator	Component	Number	Total cost USD	Source of materials
Prototype PCB jack cable	Prototyping PCB	1**	3	
	Male-male 3.5 mm 4-pin audio cable	0.5*	2	delock.com/produkt/83434/merkmale.html
USB hub	USB hub with external power source	1 for 10 phones	25	aliexpress.com/item/4001313106975.html
M4*20 screw	M4*20 mm countersunk screw	4	0.28	mcmaster.com/screws/metric-steel-Phillips-flat-head-screws/
M4*10 screw	M4*10 mm button head screw	2	0.26	mcmaster.com/screws/metric-alloy-steel-button-head-hex-drive-screws/
M4 nut	M4 nut	4	0.12	mcmaster.com/nuts/thread-size~m4/metric-low-strength-steel-hex-nuts/
M4 short heat-set insert	M4 × 4.7 mm brass heat-set insert	4	1	mcmaster.com/94459A150/
M4 long heat-set insert	M4 × 8 mm brass heat-set insert	2 + optional	0.6	mcmaster.com/94459A170/
9 V battery	9 V battery	1	1.7	amazon.com/Amazon-Basics-Performance-All-Purpose-Batteries/dp/B00MH4QM1S
9 V battery connector	9 V battery connector	1	1.5	aliexpress.com/item/1005003686160836.html
push button	push button	1	1.2	aliexpress.com/item/32968186880.html
cable ties	200 × 4.8 mm cable ties	2*	0.06	cable-ties-online.co.uk/shop/cable-ties/length:200mm/width:4-8mm/colour:black/nylon-6-6-cable-ties.html
PLA filament	Filacorn PLA BIO HI	1 kg	21	filanora.eu/filanora-filacorn-pla-bio-hi-filament-175mm-antracit
phone	Android phone	variable	variable	

*: the number of components needed for each phone used.
 **: only needed if the Control PCB or the JST connector PCB is not manufactured.

The use of ready-made male-male JST-XH cables and male-male jack cables increases the reliability of the system compared to crimping and soldering the individual components.

Key components not listed above are the phones themselves. The minimum requirements are:

- Take acceptable images with autofocus.
- Have a functioning: audio jack, Wi-Fi adapter, screen and battery.
- Cracked screen, cosmetic defects or old Android version do not affect the use of the phone in this project.

Phone holders There are several 3D printable phone holder designs available, that could be suitable for this application. For this prototype to attach the phones to the frame the 'Modular Mounting System' was chosen by Ryan Huang (<https://www.myminifactory.com/object/3d-print-modular-mounting-system-34864> Share alike – Attribute – Remix – Non-commercial license). For each phone, the following parts should be printed:

- Mount Phone Clamp A
- Mount Phone Clamp B
- Knob for Phone
- Mount cable-tie adapter

The following BOM contains the necessary hardware for a single phone holder.

Designator	Component	Number	Total cost USD	Source of materials
M5*70 screw	M5*70 mm hex head screw	1	0.8	mcmaster.com/screws/18-8-stainless-steel-hex-head-screws-10/
M5 nut	M5 nut	1	0.03	mcmaster.com/nuts/thread-size~m4/metric-low-strengt-h-steel-hex-nuts/
PLA filament	Filacorn PLA BIO HI filament	40 g	1	filanora.eu/filanora-filacorn-pla-bio-hi-filament-175m-m-antracit

Software used to design and create this project:

- Fusion 360 (Autodesk) for the design of the case and grips. Free for hobbyist use or with an educational license.
- EAGLE (Autodesk) to design the PCB. Free for hobbyist use or with an educational license.
- Cura slicer (Ultimaker) to slice the 3D models for printing.

Tools and materials used for assembly:

- An FDM (Fused Deposit Modelling) 3D printer with a build plate minimum of 220*220 mm
- Soldering iron and solder
- Multimeter
- Side cutter pliers
- Screwdrivers
- Wire stripper
- Glue (cyanoacrylate or E5000)
- Hot glue gun
- Electrical tape
- Optional: thread locker solution (e.g.: Loctite Threadlocker Blue 242 (Henkel))

To create the 3D models the following software were tested:

- Meshroom (AliceVision) – free, open source.
- 3DF Zephyr Free (3Dflow) – commercial, the free version can process a maximum of 50 images.
- ReCap Photo (AutoDesk) – paid, commercial. A free educational license is available, with a limit of a maximum of 100 images. The educational license should be renewed annually by uploading a valid student ID or an official document stating that the user is a member of an educational institution.

All three tested software were able to process images from different phones, they are suitable for generating 3D models from images of Phone Cam Array. Meshroom is widely used in academia, it is open source and offers a huge array of settings to fine-tune the results but has a steep learning curve. Meshroom and 3DF Zephyr require a capable computer with a CUDA-enabled nVidia GPU, while ReCap Photo handles most of the processing on the server side. The 3D models shown in this paper were generated by ReCap Photo.

Build instructions

Preparing the phones

Ideally, one can assign decommissioned Android phones permanently to this task. It is recommended to create a separate Google or Huawei account for the phone cam array and use all the phones with that single account.

We advise performing the following steps on each phone. It is rather a guideline than a detailed description because the exact settings can differ between manufacturers, software versions and languages.

1. Perform a factory reset.
2. Restart the phone and sign in with the newly created credentials.
3. Connect to the Wi-Fi network.
4. Disable the lock screen.
5. Disable the unnecessary applications (almost everything).
6. Turn off Bluetooth, and location to conserve battery.

7. Update the operating system and all the remaining applications.
8. Go to settings and set the screen timeout to the longest possible interval.
9. Download the free Auto Start Manager app (creator: 'The Tree Team') from Google Play (<https://play.google.com/store/apps/details?id=com.phongphan.auto.start.manager>), then set up the application so that it starts the camera directly after booting the cellphone. (other applications with the same feature can be also used)
10. In the Play Store disable auto update of applications.
11. Start the camera application and check if the press of the volume button releases the trigger. If it has not taken an image, enable the option to "take a photo by pressing the volume button" option.
12. Additional settings of the camera app: enable HDR (High Dynamic Range) mode and autofocus. Turn off the LED flash.

One of the best features of using mobile phones is their ability to automatically back up the photographs to a central repository. On Android phones, the simplest method is using the Google Photos backup option. On Huawei phones, running Harmony OS, Huawei Mobile Cloud offers the same feature. The OneDrive app (Microsoft) also allows the backup function. If someone is running their Network Attached Storage (NAS), then the manufacturer of the NAS often provides applications, such as DS photo (Synology), Qphoto (QNAP) or ZyXEL photo (Zyxel). It is also possible to set up an FTP server for this purpose. In the case of concern of cloud services, one can set up a local Wi-Fi network without internet access to connect the phones and a local server/NAS.

Preparing the shutter cables

1. Cut the male–male 3.5 mm aux cables to half (Fig. 4A).
2. Strip the outer insulation layer.
3. Twist the outer shielding metal wires. (Other cables might lack this shielding layer of metal wires. In that case, it should contain four individually insulated inner cables.)
4. Check which wire corresponds to the microphone (innermost pad on the male jack plug) and the ground (next to the innermost pad of the plug) (Fig. 4B). It can be performed with the continuity testing function of a multimeter.
5. Cut off the wires corresponding to the left and right sides. Strip the end of the mic line.

Making the circuit boards

The Gerber files attached to the manuscript contain all the necessary information for PCB manufacturers (e.g. JLCPCB, PCBWay, just to name a few) to create boards. To order the boards, after registration only the Gerber files should be uploaded. Leave additional settings on default.

Because of the simple layout, it is possible to etch the boards at home, using the 'control PCB – DIY.svg' or 'PCB-DIY.pdf' file (uploaded to the Mendeley repository). The paths are enlarged to facilitate DIY etching.

It is even possible to create the circuit board using prototype PCB boards. Building several boards this way is time-consuming and the holder box ought to be resized, these versions should be functional as well (Fig. 5).

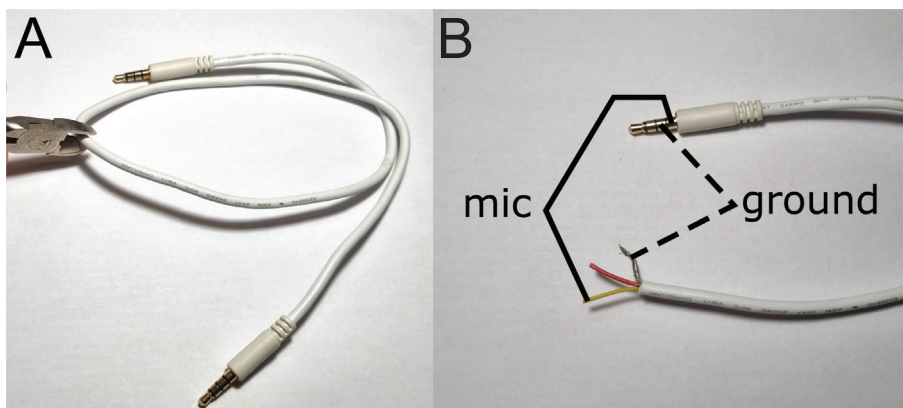


Fig. 4. Preparing the shutter cable. **A.** Cutting the male–male aux cable to half. **B.** Shielding outer metal mesh is twisted. The lines corresponding to MIC and GND are identified with the continuity testing function of a multimeter.

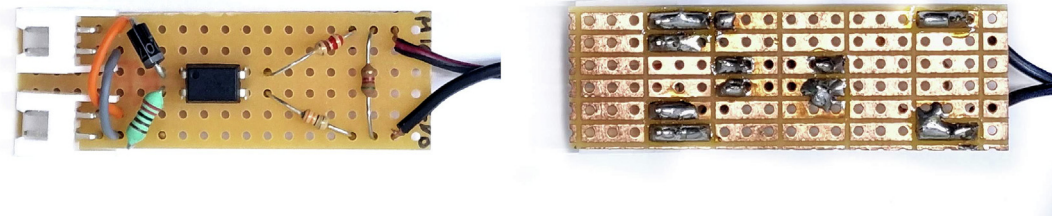


Fig. 5. A control circuit built of prototyping PCB.

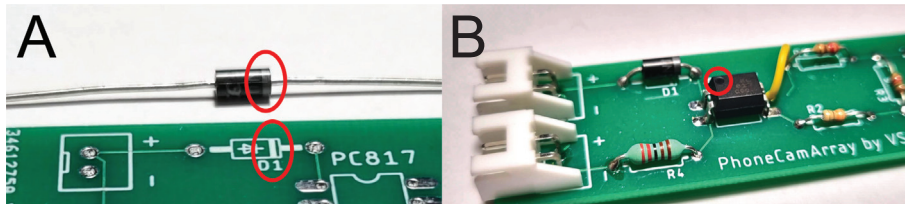


Fig. 6. A. Orientation of the diode. B. The circular indent on the corner of the optocoupler must point towards the connectors.

Assembly of the control circuit

Soldering the components should pose no major challenge to users with minimal experience.

1. The resistors have no polarity, they can be soldered in both directions.
2. The grey line found on the diode should line up with the marking on the PCB (Fig. 6A)
3. One corner of the optocoupler is labelled with a small circular indent. It must point towards the connectors (Fig. 6B).
4. Solder in the jack cable. Even if the MIC and GND are labelled on the PCB, their orientation is not crucial, they are interchangeable.
5. When the assembly is completed, it is recommended to test each board individually.
6. The finished board can be inserted into the protective box. The JST connectors should be pushed through their designated cut-out, and then the other end of the board should be pushed down (Fig. 7). It should click in place.

Print settings

All the 3D-printed parts were designed with Fused Deposition Modelling (FDM) printing in mind. None of the 3D printed components of this project should be a challenging print. Rafts, brims or supports are not needed. Polylactic acid (PLA), which is the most common material in FDM printing, is suitable, but polyethylene terephthalate glycol (PETG), acrylonitrile styrene acrylate (ASA) or acrylonitrile butadiene styrene (ABS) can be considered as well.

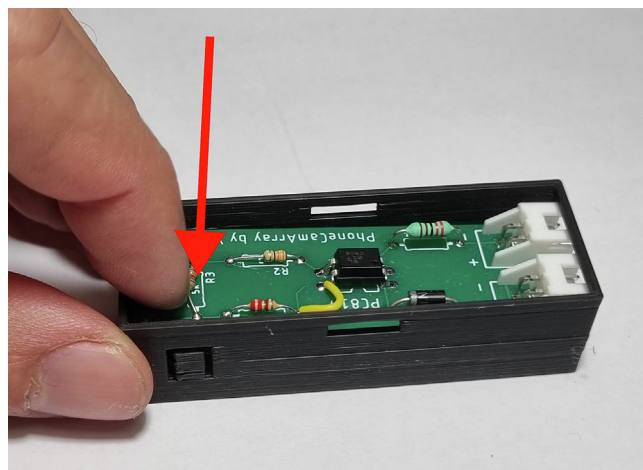


Fig. 7. Insert the PCB into the protective box. The clips should hold it in place.

The exact printing parameters can differ between filaments and printers, the following tools and settings were used:
 Printer: Artillery Genius (Shenzhen Yuntuchuangzhi Technology Co., Ltd).
 Filament: Filanora PLA BIO HI (filanora.eu).
 Hot end temperature: 220 °C.
 Build plate temperature: 60 °C.
 Nozzle diameter: 0.6 mm.
 Line width: 0.8 mm.
 Wall count: 4.
 Infill 10 %.
 Bridging mode enabled.
 Recommended printing orientations can be seen in Fig. 8.

Heat-set inserts

Heat-set inserts are versatile and affordable tools to create strong separable connections. They offer stronger, more durable connections, than 3D-printed plastic threads. Also using a heat-set insert make it possible to remove and insert the screw without comprising structural integrity. In this design, brass inserts are used to connect the 3D-printed frame modules and hold the cover of the control grip. A short description of the installation of the heat-set insert can be seen in Fig. 9. It might be necessary to remove bulging plastic after the installation with a utility knife.

If someone has no access to the threaded inserts and only wants to use three sections of the frame with two grips, the inserts might be not needed as the M4 nuts embedded in the grips would be able to hold together the frame parts. In this case, the use of a thread locker solution is highly recommended to prevent the screws from becoming loose. The control grip cover could be fixed with electrical tape.

Control grip

1. Press fit the M4 nuts and insert the M4 heat-set inserts. (Fig. 10.)

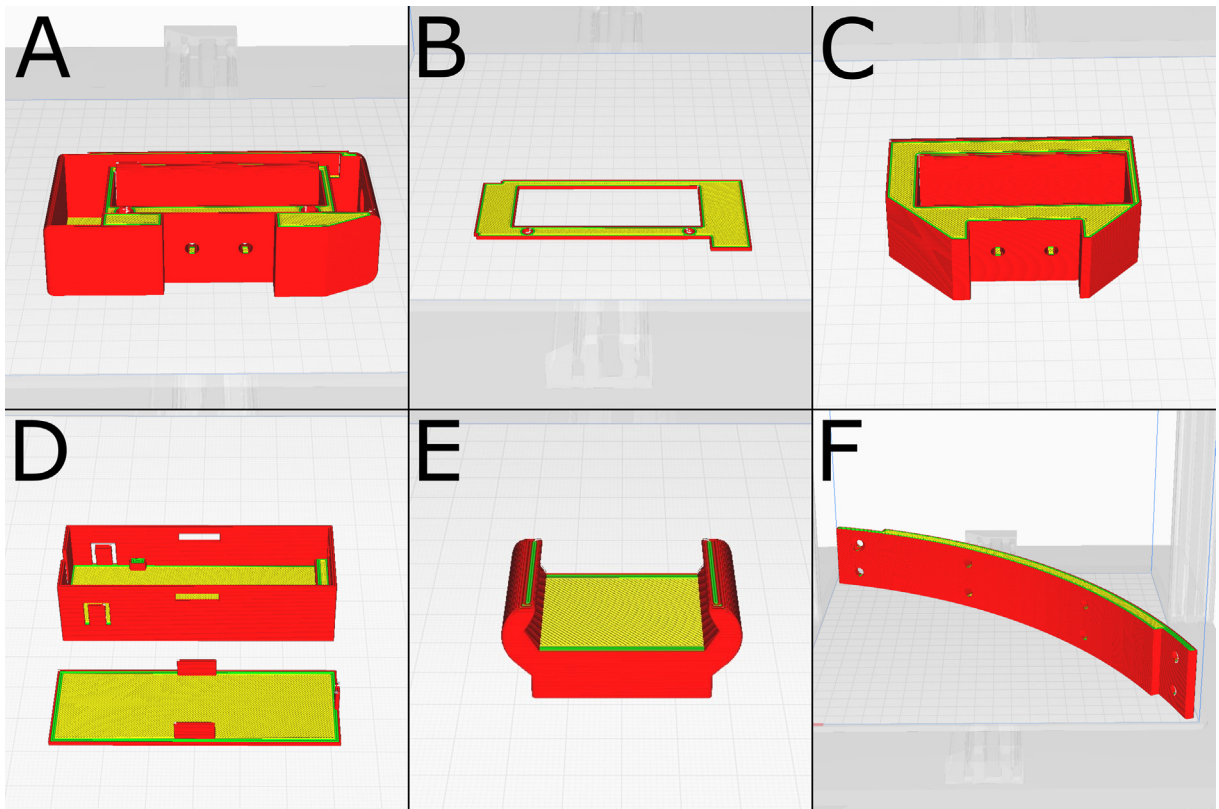


Fig. 8. Recommended printing orientations. **A.** Control grip **B.** Control grip cover **C.** Grip **D.** Junction box and Junction box cover **E.** Mount cable tie adapter **F.** Frame.

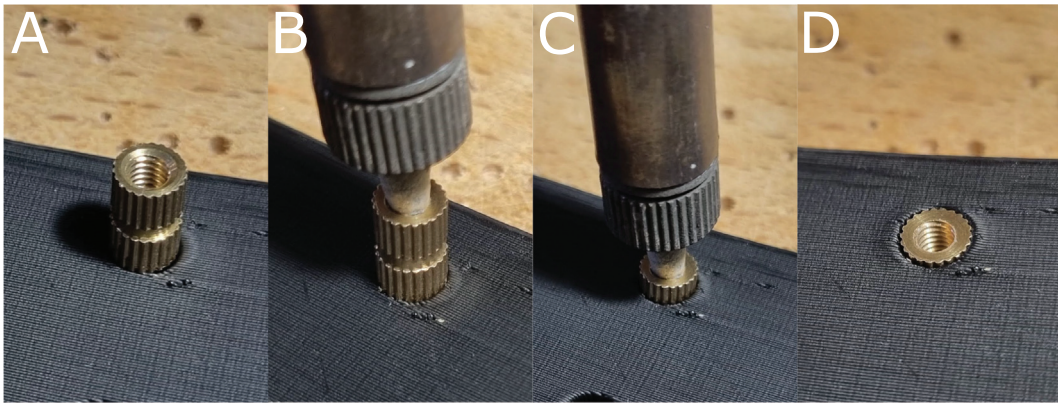


Fig. 9. Installation of the heat-set inserts. **A.** Place the right-sized insert over the hole. **B.** Heat the insert with the tip of a soldering iron. **C.** Gently push the insert downwards with the soldering iron. Keep it perpendicular to the surface. **D.** The set insert.

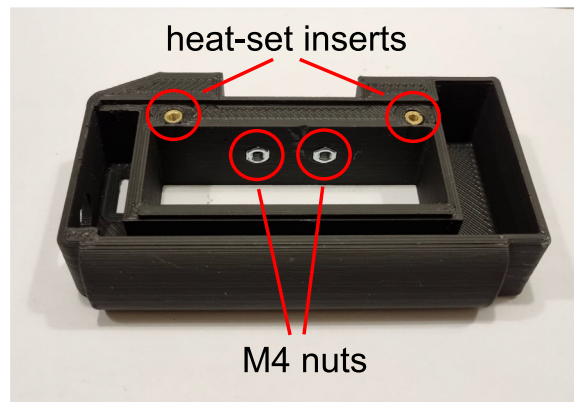


Fig. 10. The position of heat-set inserts and M4 nuts of the control grip.

2. The circuit of the control grip follows a very simple design, the JST-XH connectors are connected to the battery with the switch inserted (Fig. 11A). The assembled version is shown in Fig. 11B.
3. Solder the two JST-XH female connectors to the JST connector PCB or a prototype PCB.
4. Solder the cables to the switch, then screw it to the control grip.
5. Connect the shutter release button with the 9 V battery terminal and the JST connector panel by soldering. Fix the JST connector panel with hot glue to its position (Fig. 12A)
6. Screw on the cover of the control grip with M4 screws. (Fig. 12B)

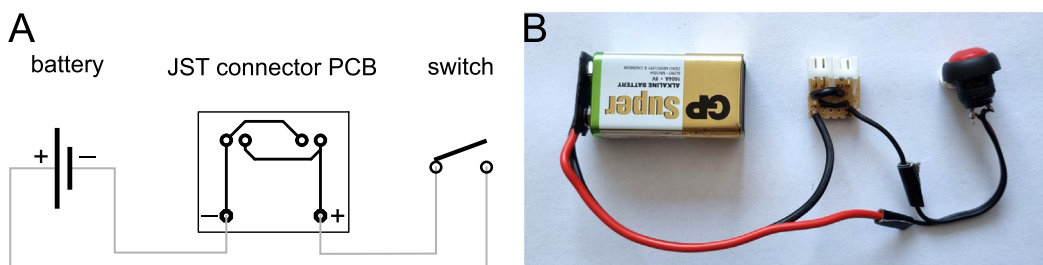


Fig. 11. Simple schematic of the control grip circuit (A.) with the assembled components (B.) Please note that it is recommended to solder the wires to the switch first, then screw it into the grip body.

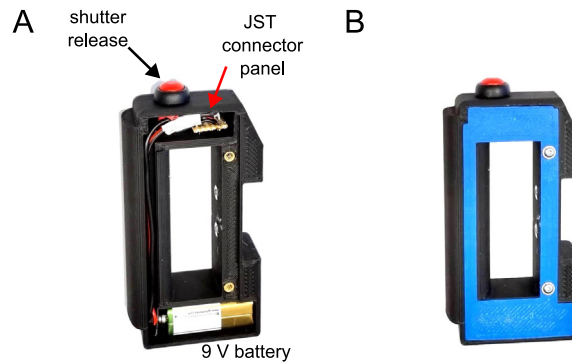


Fig. 12. **A.** The internals of the control grip. **B.** The cover is installed on the control grip.

Assembly of the frame

1. Insert the necessary heat-set inserts into the printed frame parts (Fig. 13)
2. Assemble two frame parts and the grip or control grip with the M4*20 mm countersunk screws (Fig. 14).
3. Fasten the phone mount and the junction box to the frame with two cable ties (Fig. 15).

Setting up the camera array

1. Connect all the phones to their control boxes via the 3.5 mm audio jack cables.
2. Connect the control grip to the closest two junction boxes with the JST-XH cables.
3. Then connect the next junction boxes to the previous ones, until all of them are interconnected (Fig. 2B.). Both the control grip and the junction boxes have two JST-XH connectors, they are identical.
4. Secure the connecting cables with electrical tape (Fig. 16).

Operation instructions

1. Turn on all the phones.
2. Wait until all the devices are started up and loaded the camera application.
3. Press the shutter button once.
4. Verify that all the phones have taken an image.
5. Ask the subject not to move while taking the images, if necessary.
6. If the frame is handheld, hold it steady while capturing the images.

The phones can be charged individually or preferably by a permanently plugged into an externally powered USB hub.

The number of needed images can depend on several factors (e.g. size and complexity of the subjects, distance of the cameras, focal length of the lenses, etc.). Usually, at least 20 photographs are needed for the reconstruction of a body part or injury, but a full body reconstruction might require 70 to 100 images. It is advised to determine the number of necessary photographs in each use case.

Even lighting and sharp, in-focus images are the two most important keys to successful photogrammetry. A detailed description of this topic is explained in the Supplementary material of the following publication by Tóth et al [6]. Another good resource for photogrammetry workflow a guideline for the Unity their visual engine [13].

Photogrammetric reconstruction of 3D models can be performed with specific software applications. The exact steps necessary for 3D reconstruction vary greatly between applications, it cannot be attempted to give a detailed description of each.

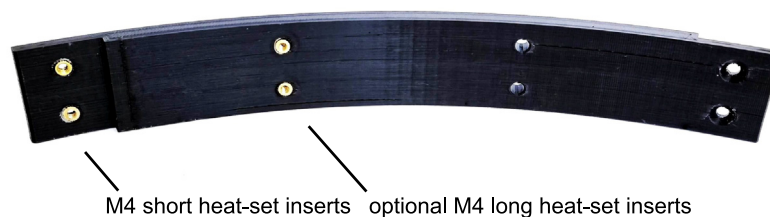


Fig. 13. Position of the heat-set inserts of the frame. The optional attachment points can be used for vertical expansion.



Fig. 14. Assemble two frame parts and one of the grips with two M4*20 mm screws.

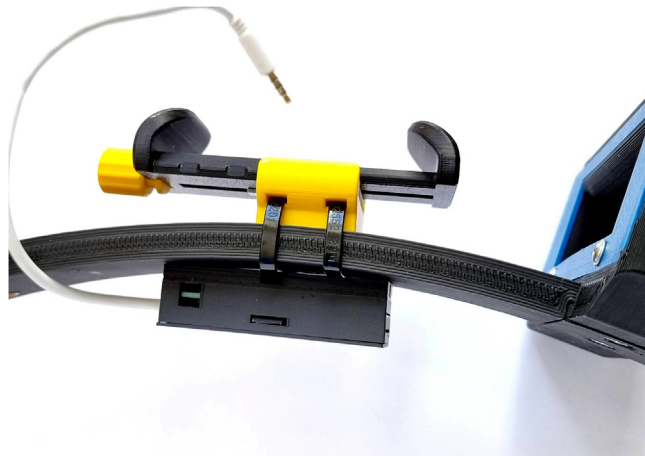


Fig. 15. Fasten a phone mount and a junction to the frame with two cable ties.

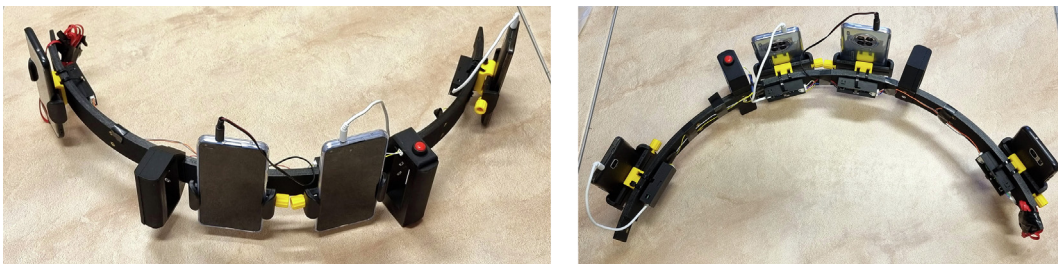


Fig. 16. The fully assembled 3D printed frame with the phones attached.

In this project, all the processing was performed with Autodesk ReCap Photo. A detailed step-by-step description of the process can be found in the second Supplementary file of the paper by Tóth et al [6].

Validation and characterization

The phones used in this proof-of-concept project are listed in [Table 1](#). The Huawei phones are current mid-range models, the Samsung is an old flagship, while the Oukitel is an old, entry-level one.

Table 1

Phones used in this pilot project. * The resolution of the sensor is 64 megapixels, but in normal camera mode, it is subsampled to 16-megapixel images. ** The equivalent focal length is roughly the same as the other two phones.

Manufacturer	Model	Released	Camera		
			Resolution (megapixel)	Aperture	Focal length (35 mm equivalent)
Huawei	nova 8i	2021 July	64 (16*)	f/1.9	~27 mm
Samsung	S7 Edge	2016 March	12 MP	f/1.7	~26 mm
Oukitel	K4000 Pro	2015 August	8 MP	f/2	n.a.**



Fig. 17. Testing the release lag between the cameras. The frame is an early prototype, the circuits are as described in the paper.

To measure the time delay of the different cameras, pictures were taken of an iPad screen running the stopwatch (Fig. 17).

A constant trend was that the Samsung took the images first, it was followed by the Huawei and the Oukitel was the slowest. At the initial measurements, its average delay compared to the Samsung was almost 1 s (966 ms). The simple tweak of turning on the continuous autofocus mode of the Oukitel decreased the delay significantly to 636 ms (Table 2). The average difference between the two Huawei phones was 160 ms (SD: 107 ms). Yang and colleagues measured the delay lag between identical Raspberry Pi cameras by synchronizing the clocks of the boards, then used the timestamp of the images they were able to decrease the lag to 80 ms [20].

Validation of multi-camera array by scanning living subject, comparison to single camera setup

It was previously proven that images taken by a single cell phone are sufficient for photogrammetry reconstruction [9–12]. The aim of this validation experiment was to test if using images of different cameras has a negative effect on the quality of the 3D model.

To test the system, markers (short rulers) were placed in varying orientations on the arm and torso of a healthy, living volunteer, who was asked to sit still and breathe quietly. Twenty pictures with the Phone Cam Array (four phones listed above). The frame was held perpendicular to the arm and moved alongside the arm as shown in Fig. 2A. The movement was stopped five times to take the images. Also, twenty pictures were taken with a single phone (Samsung Galaxy S7 Edge) from the same positions. The multicamera array needed significantly less time (11 s) than the single camera (34 s).

The 3D models from both image sets were created with ReCap Photo (Fig. 18A and B). To quantify the dimensional accuracy of the models, known dimensions (10 mm segments on the rulers) were measured virtually within ReCap Photo. Thirty segments were measured on both models by a volunteer, who did not know which model was created with the multicamera

Table 2

Delay of exposure compared to the fastest camera (Samsung S7 edge). The mean of five measurements. All units are milliseconds.

	Oukitel K4000 Pro	Huawei nova 8i (A)	Huawei nova 8i (B)
Delay (ms)	636	362	522
SD (ms)	45	46	109

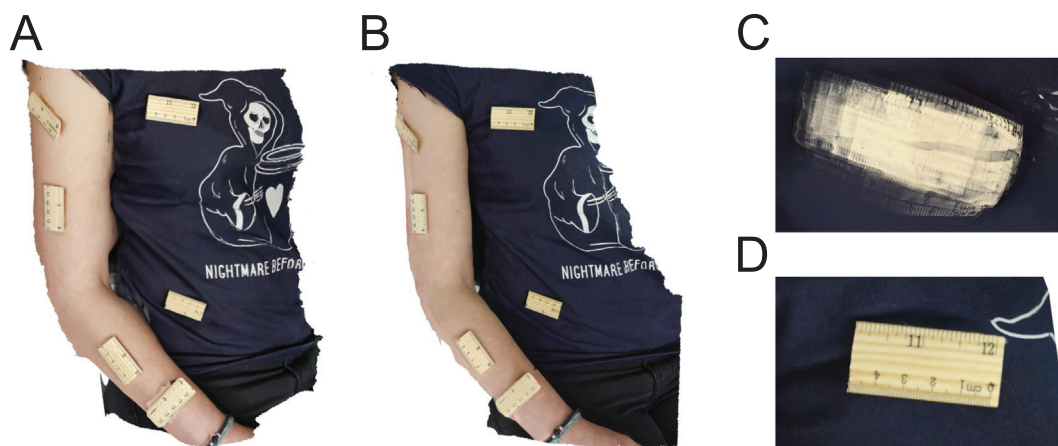


Fig. 18. Comparison of models created with a single phone (A.) and four phones (B.) of a living volunteer. The phone and the phone cam array were handheld. The subject was asked to breathe lightly during taking images for A. and B. models. When the subject breathed normally, the movement of the chest caused an artefact when a single camera was used (C.), while the one taken with the camera array did not suffer from this (D.).

array. Statistical analyses were performed with GraphPad Quickcalcs (Dotmatic). The means of the two models (Table 3) did not differ significantly (t -test, $p = 0.29$).

One of the main advantages of multicamera systems is that image capture takes a shorter time, decreasing the chance of motion artefacts appearing. To assess the artefacts caused by breathing movements, another set of images was taken, with the same setting as described above, but the subject was asked to breathe normally. Normal breathing movements of the chest caused artefacts when a single camera was used (Fig. 18C), while the one taken with the camera array did not suffer from this (Fig. 18D).

Wound scanning

In this study, the main aim was to create a multicamera system for wound and injury documentation. To illustrate this, the handheld camera array was used to take several images of two cadavers with external injuries as a proof of concept. The images (32 photos in the case of the leg and 40 photographs in the case of the arm) were taken as shown in Fig. 2A.

Fig. 19 illustrates, that this system was able to capture images for high-quality 3D model reconstruction. Two forensic medical experts were asked to describe the injuries based on the cadavers, then later based on the 3D models. The experts gave the same descriptions and reached the same conclusion regarding the mechanisms of injury.

Limitations

- Photogrammetry is scaleless. An object of known size (for example a ruler or tag) must be included in the pictures, which will serve as a calibrator after the model reconstruction.
- Probably a similar system could be built of iPhones, but the control box of this system is using Android or Harmony OS-specific signals.
- The average latency between the different phones was 636 ms. It could be improved by using the same type of phone (in the case of two Huawei nova 8i models, it was 160 ms), but it might be still not enough to capture very fast movements.
- If a full cage array is built, the devices might block available light. It could be countered by attaching LED strips to the vertical rods of the frame.
- Manufacturers omit the 3.5 mm jack from current-generation phones. USB C to 3.5 mm jack adapters might be used, but compatibility issues can emerge, as manufacturers might implement the adapters differently.

Table 3

Comparison of the model created by the multicamera array with the model created with a single camera.

	Time needed to capture 20 images (seconds)	Mean of the measurements (mm)	SD (mm)	Maximum deviation from 10 mm (mm)
Phone Cam Array	11"	10.032	0.073	0.172
Single camera	34"	10.007	0.104	0.238

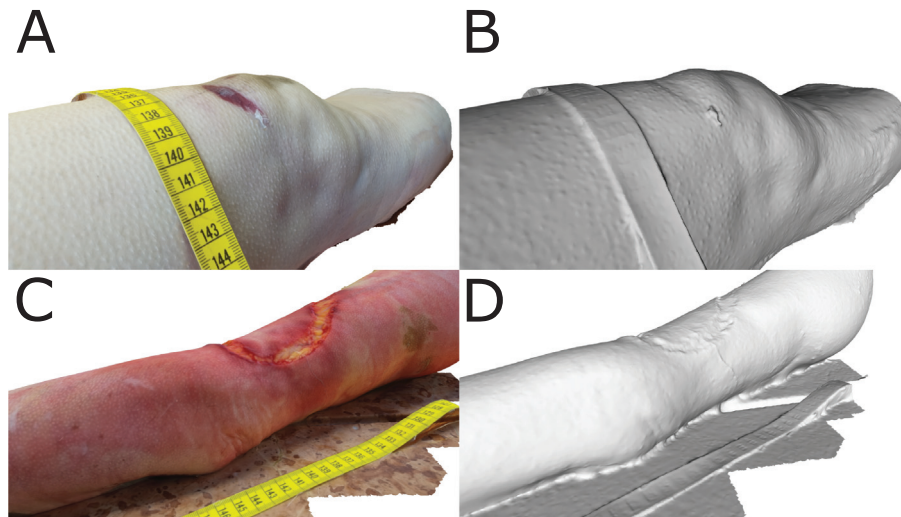


Fig. 19. Three-dimensional reconstruction of wounds of limbs. **A.** Abrasion above the kneecap with texture. **B.** The same model without textures. The small epidermal tag is reconstructed correctly. **C.** Continuity disruption affecting the full thickness of the skin with slightly irregular edges caused by extreme heat trauma. **D.** The same model without textures.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The work was supported by the Huawei SEEDs Excellence Scholarship, the Application Work was created with the support of Huawei Technologies Hungary Kft. The sponsors did not interfere with the project. There is no suggestion in the manuscript that Huawei phones should be used for this camera array.

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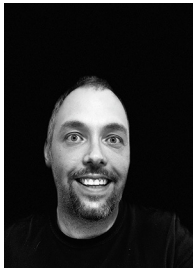
Ethical approval

The photogrammetric reconstruction of human bodies was approved by the Regional Research Ethic Committee, Pécs (8836 – PTE 2021).

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