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Low-cost, open-source contact angle analyzer using a mobile phone, commercial tripods and 3D printed parts



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ABSTRACT

Measurement of contact angle is important in many areas of science and engineering research. Contact angle analyzers are however not easily accessible due to their expensive cost, which hinders their use in research and also in education. In this study we propose a low-cost contact angle analyzer that can be assembled with 3D printed parts. Mobile phone is used for imaging, and the image is analyzed using an open-source ImageJ plugin. Commercial camera tripods are used as platform that provides movement in many degrees of freedom, which are important in leveling of the substrate and proper imaging of droplets. We utilize the tripods to build imaging modules, sample plate module and volume metering module, each of which perform distinct tasks. Especially, we characterize the usefulness of the volume metering module, which helps users dispense same volume of liquid to reduce human error during measurement. The cost of an analyzer is \$255.10, which is an order of magnitude lower compared to commercial products. With the advancement in open source software and upgrades in the hardware modules, we expect that the proposed contact angle analyzer to have a positive impact in resource limited research labs and educational environments.

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Specifications table

Hardware name	Contact angle analyzer
Subject area	<ul style="list-style-type: none"> Educational Tools and Open Source Alternatives to Existing Infrastructure
Hardware type	<ul style="list-style-type: none"> Measuring physical properties and in-lab sensors
Open Source License	CC BY CN 3.0
Cost of Hardware	\$255.10
Source File Repository	http://dx.doi.org/10.17632/mtj3zzv3z8.1

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Hardware in context

Observation and measurement of wetting properties have been important and widely used in both fundamental science and applied engineering [1,2]. Wettability is usually determined by measuring the contact angle formed between the solid-liquid interface and the tangent line of the liquid-vapor interface (Fig. 1A). The measurement is done by using a camera and analyzing it using a software, which are aspects that sets the cost of the contact angle analyzers in the order of several thousands of dollars. Additionally, in research labs, they are typically operated by technicians because some models are difficult to use. These are some of the reasons that can hinder wide use of the instruments in resource limited research environment or for education purposes, which calls for the need of developing a low-cost, open source analyzer.

There are number of contact angles that can be measured by different set ups and they can be categorized as static and dynamic contact angles, depending on whether motion is impressed on the liquid-solid-air boundary [3]. Static contact angle (θ) is measured with a stationary droplet whose volume remains constant. The contact angle is mostly measured by a technique called sessile drop technique, which is done by placing a liquid droplet on a surface and measuring the contact angle [4]. Surface is considered hydrophobic if static contact angle is greater than 90° , and hydrophilic if the angle is less than 90° [5]. Dynamic contact angles are measured while the droplet, or the liquid-solid-air boundary is moving. Two dynamic contact angles can be measured, which are advancing angle (θ_A) and receding angle (θ_R). To measure the dynamic contact angles, techniques such as tilting method (Fig. 1B) [6,7], needle method [8] (Fig. 1C), and Wilhelmy plate method (Fig. 1D) [9,10] are used to cause a motion of the liquid-solid-air boundary.

Typical commercial contact angle analyzers that are built to measure both the static contact angle and the dynamic contact angle consist of a droplet dispensing module, sample stage, and imaging system (including background light) (Fig. 1E). Such a set up allows users to measure static contact angle by the sessile drop method, and the dynamic contact angle by the needle method. The dispensing module can either be a manual type, which requires users to create a drop by controlling a dial or pushing a plunger; or an automatic type, which uses a mechanical system to create the droplet automatically. The latter is typically more expensive. The measurement of the contact angles involves imaging of the droplet placed on the substrate. The images are then analyzed by using a software that comes with the analyzer. The hardware of the analyzer needs to perform three things: 1) imaging, 2) leveling, and 3) dispensing. Firstly, imaging is done by placing a light source and a camera on each side of the substrate of interest. This can be done by using a camera, or a mobile phone camera [11-13]. The distance between the object and the camera, as well as the height needs to be adjusted in order to focus the image and capture the image while the substrate is horizontal. Secondly, leveling of the substrate requires the tilting of the substrate along at least two-axes in order to make the droplet axis-symmetric. If it is not, then there can be a difference between the static angle measured at two edges of the droplet. Thirdly, dispensing is can be done by either the user or a machine as mentioned before. To transfer the droplet that is hanging at the tip of the needle to the surface of a substrate, the sample platform's height needs to be raised in order to transfer the droplet onto the substrate.

To meet the abovementioned mechanical requirement of the analyzer, we decided to use a camera tripod. The tripods can easily control the height of the mobile phone holder, angle in three axes, both of which are needed for leveling and imaging. A camera tripod does just that. Additionally, with the wide spread of mobile phone users, it is easy to buy tripods that have

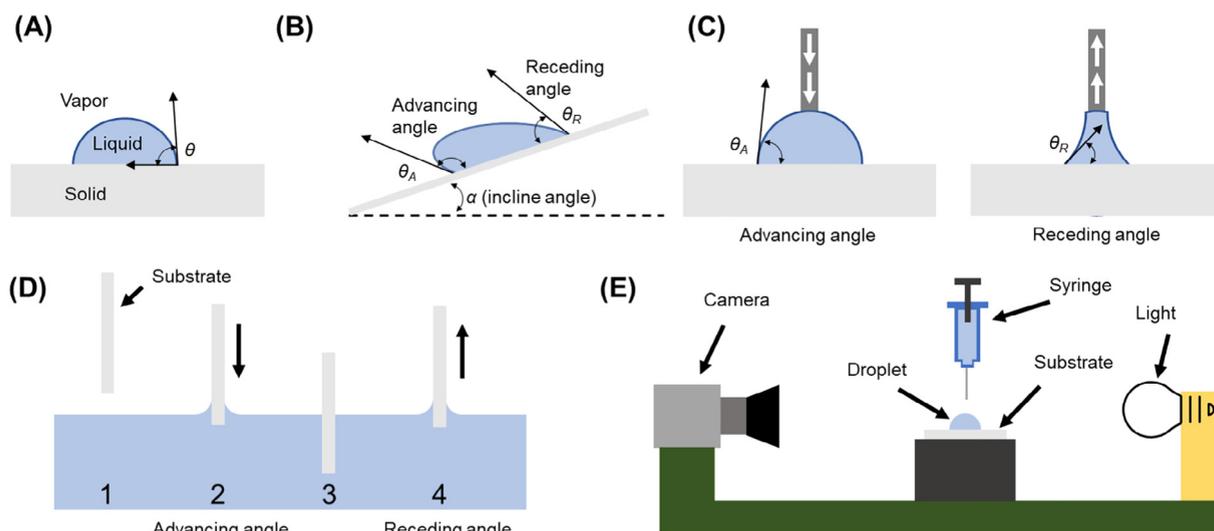


Fig. 1. A) Static contact angle. Schematics of setups of B) Tilting method, C) Needle method, and D) Wilhelmy plate method for the measurement of dynamic contact angle. E) A typical setup of a contact angle analyzer.

mobile phone mounts nowadays. By using 3D printed parts and assembling the tripods, a DIY contact angle analyzer is developed. We assess its precision and compare its measurement result to that of a commercial instrument.

Hardware description

Overall description of the contact angle analyzer

The contact angle analyzer proposed in this study can be divided into four different modules, each of which is responsible for performing specific functions. They are light box module, sample plate module, volume metering module, and camera holder module. Each of the modules are built using a camera tripod that can provide as many as four degrees of freedom, which is very useful for alignment and camera focusing required for proper imaging and measurement. The tripods also have a universal 1/4"-20 (1/4-inch diameter, 20 threads per inch) screw, which can be used to mount the light, sample plate, volume metering module, and camera holder. Such features of a tripod make it a versatile platforms imaging where distance, angle adjustment and leveling are important.

Light box module

The light box module is a four-sided box that contains a light bulb. One side of the box is transparent to let the light out. This side is made with 2 mm thick acrylic sheet which is covered with a diffuser film in order to provide even lighting.

Sample plate module

For contact angle measurement, it is important to level the surface on which the drop is placed because measuring the contact angle on a tilted surface can result in the difference between each end of the droplet where the contact angle is determined. To make a plane level, at least two axes need to be adjusted and the mechanical structure of the tripod allows one to do that. Additionally, to place a droplet on a substrate, the droplet hanging from a needle needs to be transferred to the substrate by physical contact. This is typically done by raising the sample plate, which can be easily done by the height adjusting feature of the tripod.

Volume metering module

It is easy to see companies selling contact angle analyzers in two different versions: a manual version whose droplet dispensing is done by hand; and automatic type whose droplet dispensing is done automatically by a mechanically controlled system. The proposed design of the open source contact angle analyzer is also a manual device and users need to dispense a droplet on their own. Although it is easy for experienced experimenters to control the volume of the droplet by using a syringe, it may not be the case for some people, and also it can be difficult to repeat the exact volume for multiple measurements. Thus, in our design we implement an O-ring based locking mechanism that can restrict the range of movement of the plunger, which can help create droplets of the same size repeatably.

Camera holder module

The camera holder module is essentially a tripod with a mobile phone holder. One of the functions of the camera holder module is to help adjust the angle and height of the camera during imaging. Another important function is to help focus the droplet by moving the camera close and away from the sample plate module.

Possible applications

- The proposed contact angle analyzer It can be used for surface analysis of materials in various science and engineering research.
- Other important measurement parameters such as surface tension and surface free energy can also be obtained by utilizing downloadable or customized open software or mobile phone applications.
- The low-cost contact angle analyzer can also be built in schools for education purposes, or used in resource-poor countries for alternatives to expensive instruments.

Design files**Design files summary**

Design file name	File type	Open source license	Location of the file
Ball screw_left.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Ball screw_right.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Body leg_single.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Body leg_double.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Camera tripod holder.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Handle.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Handle_supporter.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Light box.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Linear holder_double.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Linear holder_tri.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Linear_left.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Linear_right.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Plunger holder.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Sample plate.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Stick_left.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Stick_right.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Syringe holder.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Syringe stick.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Tripod holder_double.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1
Tripod holder_single.stl	CAD(STL)	CC BY NC 3.0	http://dx.https://doi.org/10.17632/mtj3zzv3z8.1

Bill of materials

Bill of materials

Designator	Component	Number	Cost per unit - currency	Total cost - Currency	Source of materials	Material type
Leveling mount	Leveling legs	6	\$3	\$18	https://www.amazon.com/Furniture-Leveling-Levelers-Adjust-Diameter/dp/B08S7FM7TL/ref=sr_1_170?crid=126C8099VNI5l&keywords=leveling+feet&qid=1639998821&refinements=p_36%3A1253528011&rnid=1243644011&s=hi&sprefix=leveling+%2Caps%2C341&sr=1-170	Metal
Clamp	Camera mount clamp	3	\$15.99	\$23.99	https://www.amazon.com/ChromLives-Super-Clamp-Photography-Umbrellas/dp/B075T3DNRX/ref=sr_1_1_sspa?keywords=crab+clamp&qid=1640003887&sr=8-1-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUFjNlpaQkJTVUFOMzcmZW5jcnlwdGVkSWQ9QTAzNDk2NzAzOUNFOFo5VFI5QkczJmVuY3J5cHRIZEFkSWQ9QTA5NjcwMDEyNlhJRkpJNDNXRUVlJndpZGldE5hbWU9c3BfYXRmJmFjdGlvbj1jbGJja1JlZGlyZWNOJmRvTm90TG9nQ2xpY2s9dHJ1ZQ==	Metal
Camera tripod	Aluminum Video Tripod	4	\$19.99	\$79.96	https://www.amazon.com/Travel-Camera-Lightweight-Aluminum-Olympus/dp/B09DY2652X/ref=sr_1_28?keywords=Tripod&qid=1636357063&refinements=p_36%3A1253503011&rnid=386442011&s=electronics&sr=1-28&th=1	Other
Linear motion (LM) guide	Miniature linear sliding rail	1	\$19.19	\$19.19	https://www.amazon.com/Sinoblu-Stainless-Carriage-Printers-Machine/dp/B098KXR9SN/ref=sr_1_23_sspa?keywords=linear+guide+rail&qid=1639559629&sr=8-23-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUFmQzdCU09GMknQMDImZW5jcnlwdGVkSWQ9QTA2NjM2NDExSjdBUFRCOEswTDNDJmVuY3J5cHRIZEFkSWQ9QTA0OTY0MjcXUUg0MlhXMlVHTVVCJndpZGldE5hbWU9c3BfbXRmJmFjdGlvbj1jbGJja1JlZGlyZWNOJmRvTm90TG9nQ2xpY2s9dHJ1ZQ==	Metal
Acrylic plate	Acrylic sheet	1	\$0.799	\$0.799	https://www.amazon.com/IVARSOYA-Templates-Projects-Protective-Transparent/dp/B08SGBRL7V/ref=sr_1_13?keywords=transparent%2Bacrylic%2Bplate&qid=1636359247&sr=8-13&th=1	Other
Diffuser film	Blank stencil making sheet	1	\$0.666	\$0.666	https://www.amazon.com/Stencil-Making-Sheets-Silhouette-Gyro-Cut/dp/B07LCT5TGD/ref=sr_1_4?keywords=opaque+sheet&qid=1636359918&rnid=2638325011&s=arts-crafts&sr=1-4	Other

(continued on next page)

Bill of materials (continued)

Designator	Component	Number	Cost per unit - currency	Total cost - Currency	Source of materials	Material type
Power cord	Lamp control cord	1	\$4.53	\$4.53	https://ko.aliexpress.com/item/1005002612589903.html?spm=a2g0o.productlist.0.0.b6024c00Jx0jn7&algo_pvid=d3ea5d81-7c43-4c22-8af8-8d4174b72467&algo_exp_id=d3ea5d81-7c43-4c22-8af8-8d4174b72467-8&pdp_ext_f=%7B%22sku_id%22%3A%2212000021409051066%22%7D	Electronic
Ball screw	SFU1204	1	\$17.99	\$17.99	https://ko.aliexpress.com/item/1005003318520603.html?spm=a2g0o.productlist.0.0.f14d65ef7RQPbx&algo_pvid=0c8dc232-bf78-4400-9033-cb8d0affcba3&aem_p4p_detail=20211108204916387632712892800040557877&algo_exp_id=0c8dc232-bf78-4400-9033-cb8d0affcba3-0&pdp_ext_f=%7B%22sku_id%22%3A%2212000025816469976%22%7D	Metal
Light source	LED bulb	1	\$0.9	\$0.9	https://ko.aliexpress.com/item/4001109254737.html?spm=a2g0o.productlist.0.0.211411c85PnE1p&algo_pvid=82cb762b-a574-4db2-96bd-3842fc0999ee&aem_p4p_detail=202111082058581262142917805000043751978&algo_exp_id=82cb762b-a574-4db2-96bd-3842fc0999ee-1&pdp_ext_f=%7B%22sku_id%22%3A%2210000014436240250%22%7D	Electronic
Glass syringe	Hamilton syringe	1	\$56.15	\$56.15	https://www.sigmaaldrich.com/AI/en/product/sial/20701	Glass
Macro lens	10 × Macro lens	1	\$18.81	\$18.81	https://www.coupang.com/vp/products/5393064890?vendorItemId=75336337654&sourceType=MyCoupang_my_orders_list_product_title&isAddedCart=	Glass, Metal

∞ Total cost of build a single contact angle analyzer: \$255.10.

Build instructions

Base assembly

Download and 3D print Linear_left.stl, Linear_right.stl, Stick_left.stl, Stick_right.stl, Ball screw_left.stl, Ball screw_right.stl, Camera tripod holder.stl, Body leg_single.stl, Body leg_double.stl, Linear holder_double.stl, and Linear holder_tri.stl. Each of Linear_left.stl, Linear_right.stl parts have square holes into which square tips of Stick_left.stl and Stick_right.stl parts can be placed (Fig. 2A right). Ball screw_left.stl and Ball screw_right.stl parts have a round hole for mounting the ball screw (Fig. 2A left). After placing leveling mounts to the Body leg_single.stl and Body leg_double.stl parts, they are attached using glue (Fig. 2B). Insert the ball screw nut into the hole in the middle of the Camera tripod holder part, then fix it using a screw (Fig. 2C). Connect the Stick_left part to the Linear_left part. Connect the Stick_right part to the Linear_right part. Connect each of the joined linear parts to each other to assemble a Linear rail (Fig. 2D). Repeat and make two linear rails total. Combine the groove on the Ball screw_left part with the groove on the Ball screw_right part. Mount the ball screw by penetrating through the round hole of the Ball screw_left and Ball screw_right (Fig. 2E). Connect the Body leg_single part and the end of the Ball screw_left part using glue and connect the Body leg_double part between the ball screw assembly and the two Linear rails and at the end of the linear part using a screw (Fig. 2F). Install the linear holders (Linear holder_double and Linear holder_tri) so that the two Linear rails are fastened (Fig. 2G). Install the LM guide in the long groove at the bottom of the assembled ball screw parts to finish assembling Ball screw rail module (Fig. 2H).

Handle assembly

Download Handle.stl and Handle_supporter.stl files and print them using a 3D printer. After attaching the Handle_supporter part to the Handle part, wedge an O-ring (ID: 4.4 mm, CS: 2 mm) into the hole of the Handle_supporter in a manner that allows the O-ring to seat in the grooves of the rods of Handle (Fig. 3A). After attaching another O-ring (ID: 14 mm, CS: 2.5 mm) to the end of the protruding ball screw so that it can help tight fitting of the assembled Handle (Fig. 3B).

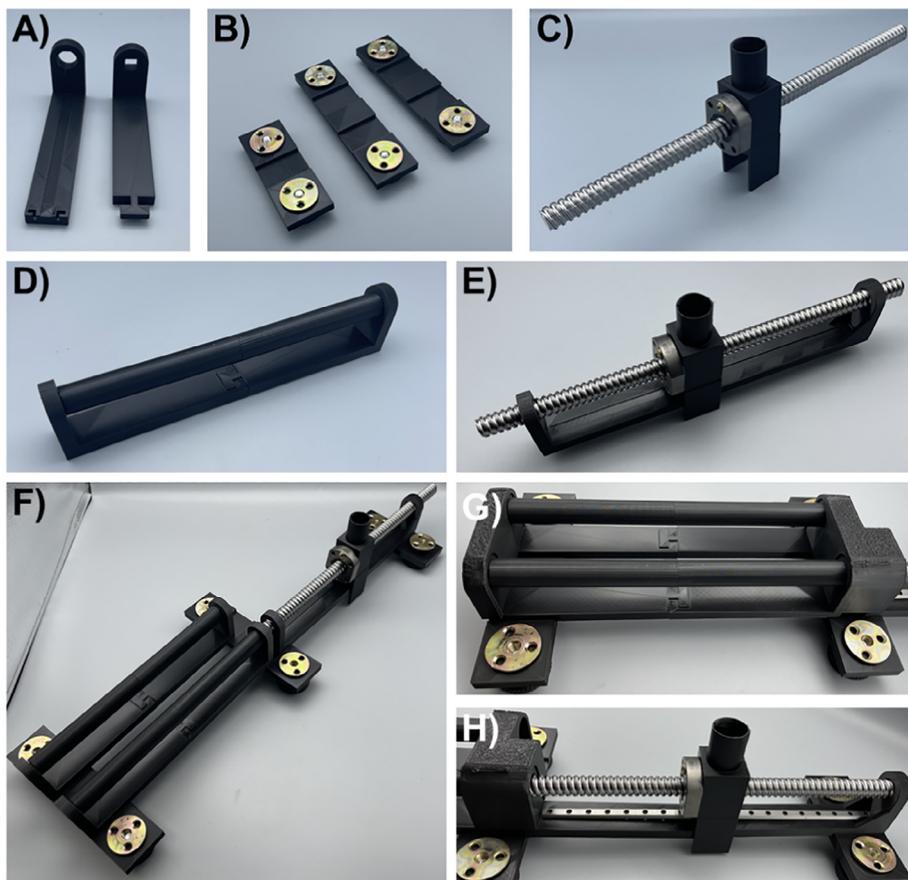


Fig. 2. A) Screw_left has a circular hole, Linear_left has square hole. B) leveling mounts are attached to Body leg_single and Body leg_double by using glue. C) Camera tripod holder is assembled with ball screw using bolt. D) Assembly of Linear rail, which consists of Linear_left, Linear_right, Stick_left and Stick_right. E) Combination of Ball screw_left and Ball screw_right with ball screw installed in the middle. F) Assembly of the Linear rail and Ball screw rail module. G) Photo showing the Linear holder_double and Linear holder_tri on the Linear rail. H) Mounting the LM guide to finish assembling the Ball screw rail module.

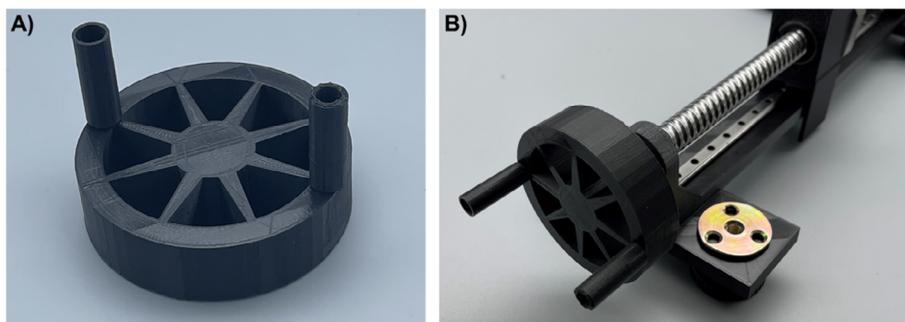


Fig. 3. A) Photo of the Handle with Handle_supporter with Handle_supporter placed on top (O-rings not shown). B) Picture showing the assembled handle attached to the end of the ball screw by tight fitting.

Light box module assembly

Detach the three legs and the leg joints of the camera tripod using a saw or cutter, then cut the rod of the tripod to a length between 10 and 15 cm, depending on the user's preference (Fig. 4A). Download the Light box.stl file and print it using a 3D printer. Cut 2 mm thick transparent acrylic (78 mm × 75 mm) using a laser cutter (Fig. 4B). Attach the diffuser film to the cut acrylic plate (Fig. 4C). When attaching the diffuser film, apply it by pushing it from one end using a ruler or a plastic plate scraper to prevent air bubbles from forming. Install the acrylic plate into the groove on the front of the light box (Fig. 4D). Install the bulb socket with the bulb in the round groove inside the light box with the power cord slid into the slit (Fig. 4E). Screw the 1/4 in. bolt of the tripod into the thread of the Light box, which is designed at the bottom of the box.

Sample plate module assembly

After downloading the Sample plate.stl file, print it using a 3D printer. The printed plate has a flat side (Fig. 5A) and a thread for screw attachment (Fig. 5B). The flat surface is where the substrate will be placed, and plate is coupled with the 1/4 in. bolt located at the top of a trimmed camera tripod (Fig. 5C), which was trimmed in the same manner as described in *Light source assembly* section.

Volume metering module assembly

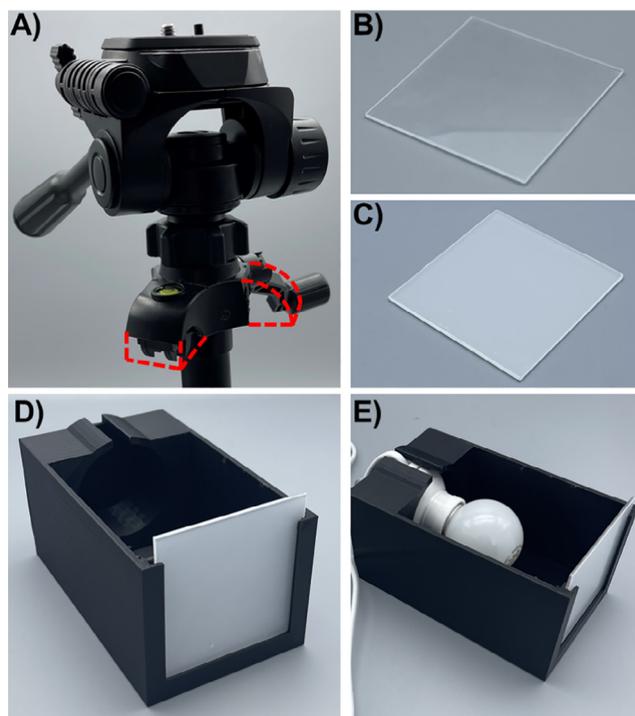


Fig. 4. A) Picture of the neck of the camera tripod showing the remaining parts after detaching the legs and cutting the joints (red dashed line). B) Acrylic plate cut with laser cutter. C) Acrylic plate after attaching a diffuser film. D) Diffuser is assembled with the Light box. E) Light bulb and bulb socket are fitted into the light box. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

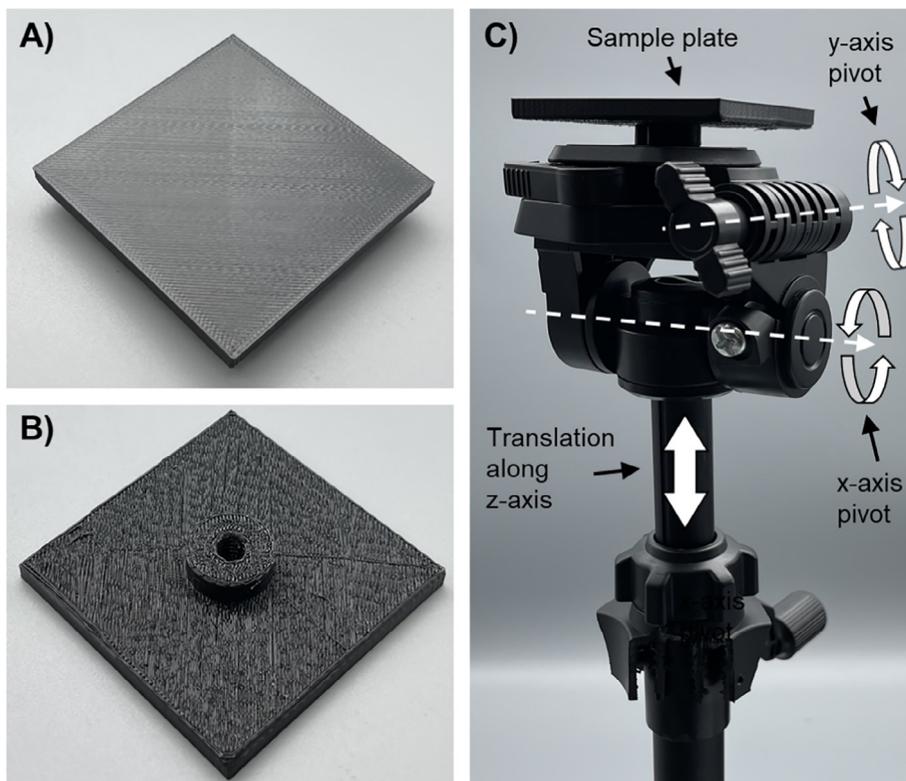


Fig. 5. A) Top view of the Sample plate, and B) bottom side of the Sample plate with screw threads. C) Photo of sample plate attached to the tripod whose height and angle can be adjusted for leveling of the sample plate.

Download the Plunger holder.stl, Syringe stick.stl and Syringe holder.stl files, print them using a 3D printer (Fig. 6A). Attach an O-ring (ID: 3 mm, CS: 1.5 mm) to the rod of the Plunger holder and push it in (Fig. 6B). The O-ring restricts the movement of the plunger and helps dispense targeted volume of liquid set by the user. The rod of the Plunger holder part enters the circular hole located on the top of the printed Syringe holder part (Fig. 6C). Attach another O-ring to the bottom of the rod of the Plunger holder. Attach the Syringe holder to the groove on the top of the Syringe stick (Fig. 6D). Attach the Syringe stick to the 1/4-inch bolt located on the top of the tripod (Fig. 6E). The slot at the bottom of the Syringe stick allows sliding and rotation of volume metering module, which helps users with the positioning of the tip of the needle, which should be above the substrate that needs to be tested. Once the position is set, the bolt can be tightened to fix the position.

Tripod holder assembly

Download Tripod holder_single.stl and Tripod holder_double.stl files, and print them using a 3D printer (Fig. 7A). Slide the clamp into the gap at the bottom of the 3D printed Tripod holders (Fig. 7B). Place the Tripod holder (both single and double) on the Linear rail by sliding the plastic rod into the upside-down U-shaped groove of the Tripod holder and also in a manner that allows the clamps to grasp the plastic rod. The Tripod holder_single is placed on a rod whose axis is along the axis of the ball screw, and the Tripod holder_double is attached to both rods (Fig. 7C). After placing the both Tripod holders in the correct position, tighten the clamp and fix their positions by tightening the clamps' handles.

Camera holder module

Detach the legs and trim another camera tripod as described in Light source assembly. Attach a mobile phone holder (included with the purchased camera tripod) to the 1/4-inch located at the top of a camera tripod (Fig. 8A). Fig. 8B shows the rotational and translational movements that can be used for focusing and angle adjustment. Stick the trimmed rod of the tripod to the tripod holder that is connected to the ball screw as shown in the bottom of Fig. 8B.

Final assembly

Stick the rod of the Light box module to the hole located at the top of the Tripod holder_single. Stick the rods of the sample plate module and the volume metering module into the holes of the Tripod holder_double as shown in Fig. 9.

Operation instructions

Setting the dispense volume and loading the syringe

- 1) Adjust the leveling mount at the bottom of the contact angle analyzer to make it level.
- 2) Place the solid sample whose surface contact angle is to be measured on the sample plate. Correct the angle of the sample plate so that the surface of the solid sample is leveled.

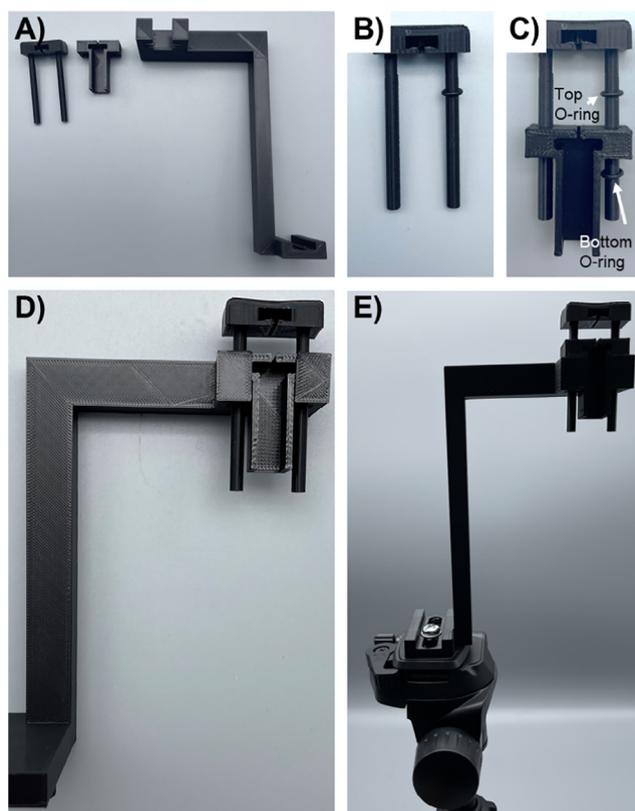


Fig. 6. A) Printed Plunger holder, Syringe stick, Syringe holder. B) O-ring installed to restrain the movement and to control the dispensed volume. C) Plunger holder assembled with Syringe holder. D) The assembled volume metering module. E) Volume metering module fixed to the tripod by using a bolt.

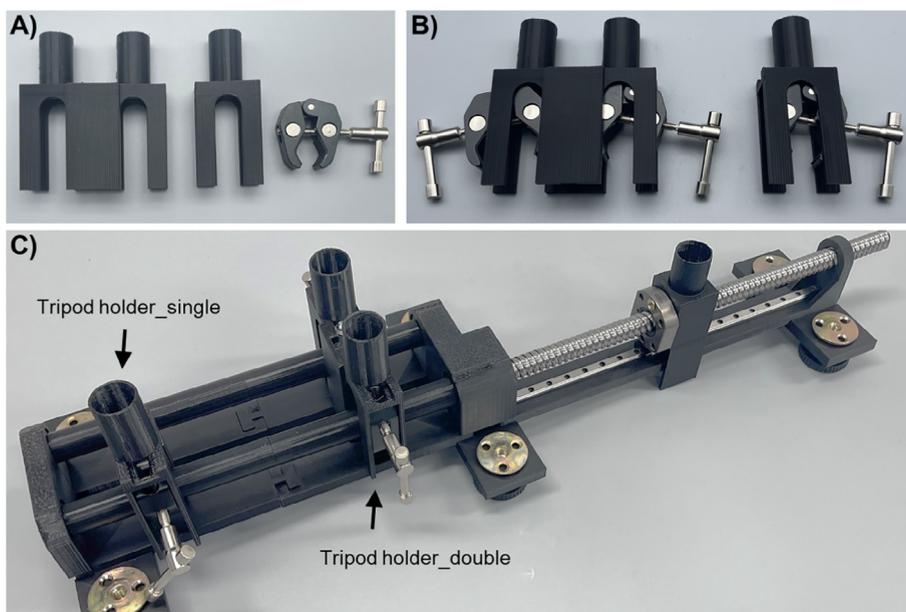


Fig. 7. A) A photo of Tripod holder_double (left) and Tripod holder_single (middle) and clamp (right). B) Photo of Tripod holder parts with the clamps placed inside. C) Tripod holder parts attached to Linear rails.

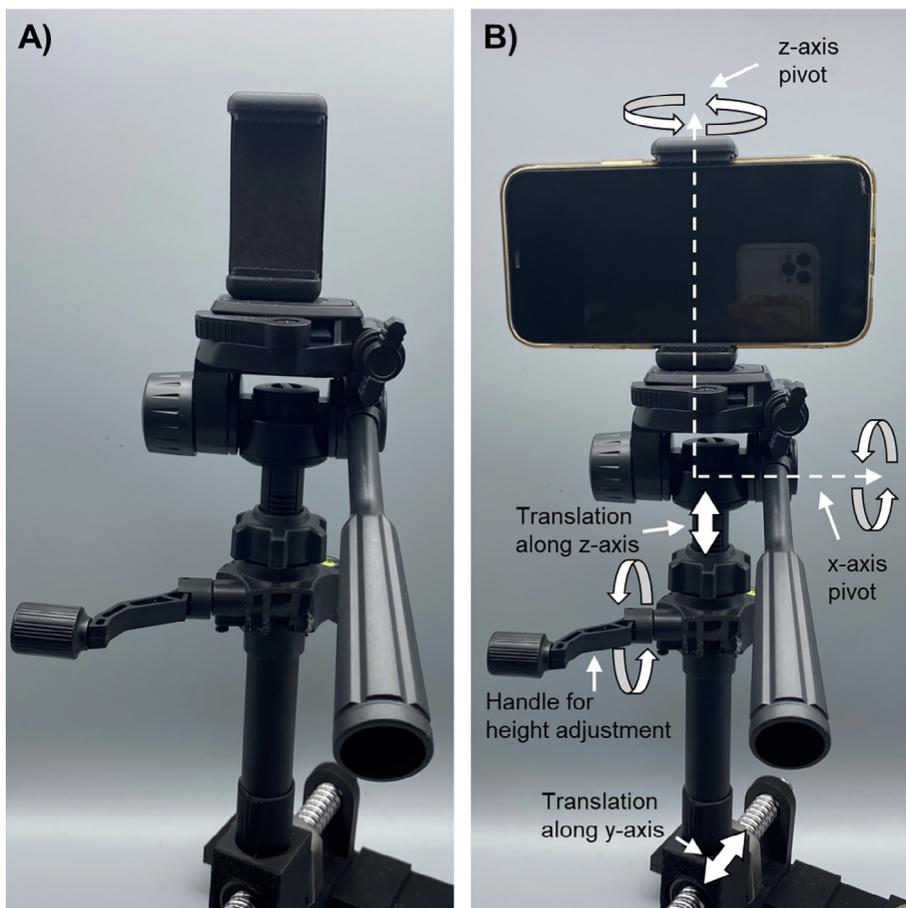


Fig. 8. A) Mobile phone holder attached to a tripod. B) A photo of the camera holder module holding a Mobile phone. White arrows indicate the rotational and translational movements that can be used for imaging.

- 3) Place the needle in front of the glass syringe. When installing the needle, lock it tightly to prevent leakage (we used a 24G needle in this study).
- 4) Fill the 50 μL glass syringe with water, then assemble the syringe with the volume metering module. Set the plunger's position at an arbitrary value (we started used 20 μL in this study), this is the maximum volume of water that the syringe will hold.
- 5) Adjust the position of the bottom O-ring to set the maximum volume of the water. The O-ring should sit right below the bottom hole of the Syringe holder.
- 6) Push the plunger down so that the syringe dispenses the target volume and hold the position.
- 7) Adjust the position of the top O-ring to set the dispense volume. With two O-rings in their place, the syringe can now only draw and dispense a fixed volume of water.
- 8) Dip the syringe needle tip into water and pull the plunger up to a point where bottom O-ring allows.

Imaging and measurement

- 1) Attach a macro lens to the mobile phone camera lens.
- 2) After placing the mobile phone on the mobile phone holder, open the camera application.
- 3) Place the substrate on the Sample plate.
- 4) Focus the camera to the substrate. If the camera's software cannot focus, use the ball screw to move the camera back and forth to focus.
- 5) Adjust the angle and the height of the Sample plate to make the substrate's surface horizontal when viewed by the phone.
- 6) Push the syringe plunger to dispense the set amount of liquid (down to a point where top O-ring allow) and let it hang at the tip of the needle. Be careful not to drop the droplet.



Fig. 9. Photo of the assembled contact angle analyzer showing the light box module, sample plate module, volume metering module and camera holder module (from left to right).

- 7) Rotate the handle of the sample plate module to raise the sample plate until the solid sample and the droplet hanging from the needle tip come into contact with each other.
- 8) Adjust the height so that the sample plate is located in the middle of the LED diffuser.
- 9) Adjust the angle and the height of the camera using the tripod to align the substrate in line of sight.
- 10) After imaging the drop with the mobile phone camera, transfer the image data to the PC.
- 11) Calculate the contact angle using “Drop analysis” plugin of ImageJ software as shown in Fig. 10.

Operation tips

When loading the syringe with water, be careful not to trap bubbles inside the syringe or in the dead volume formed between the syringe and needle. This can be prevented by partially loading the syringe with water, flipping it upside-down so that the needle is directed upward, and flicking the syringe with a finger to let the bubbles rise up. Then, users can push the plunger while the needle is directed upward, until a small amount of water dispenses. The remaining volume of the syringe can be loaded with water afterwards, during which there will be no air bubbles inside the syringe.

Validation and characterization

To characterize the contact angle analyzer’s performance, static contact angles and dynamic contact angles of various substrates were measured using the sessile drop method. Various models of mobile phones were used for imaging and the analysis was performed using ImageJ software and calculation was performed using Microsoft Excel software.

Drop volume control

As mentioned previously, for repeatable manual dispensing of target volume, we developed a volume metering module. The locations of the O-rings determine the volume of dispensed droplet by constraining the range of movement of the syringe plunger (Fig. 11A). To assess the usefulness of the volume metering module, we dispensed the target volume three times on a same glass slide (Fig. 11B) and measured the contact angles using LB-ADSA (axisymmetric drop shape analysis) method of the ImageJ plugin. This method is based on the fitting of the Young-Laplace equation to the outline of the droplet [14,15]. As shown in Table 1, the largest standard deviation (STDEV) is 0.74° , and the coefficient of variation (CV) value for all tested target volumes (2–5 μL) are between 0.01 and 0.03. This indicates the acceptable repeatability and precision of the target

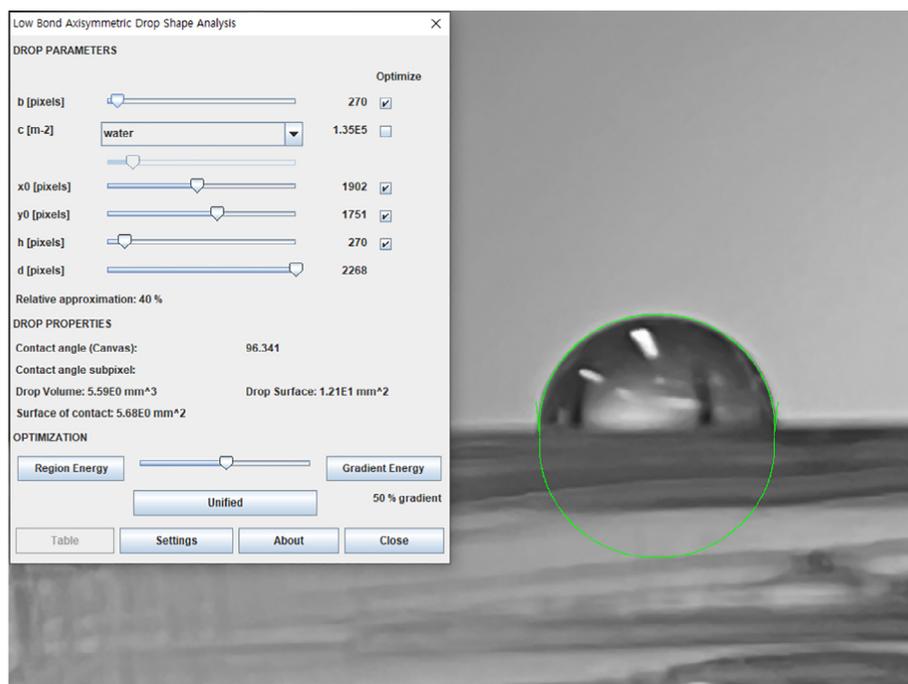


Fig. 10. User interface of Drop analysis plugin. The green line is fitted onto the outline of the droplet image by the user to determine the contact angle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

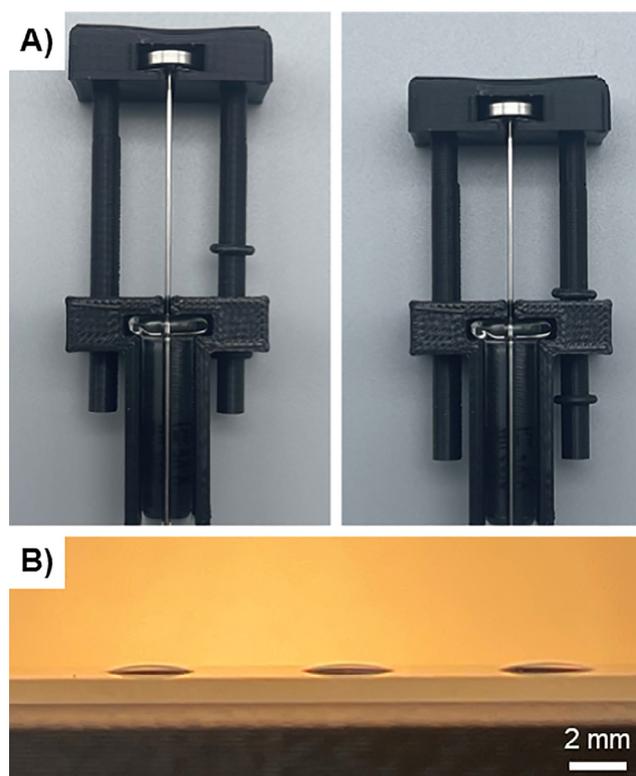
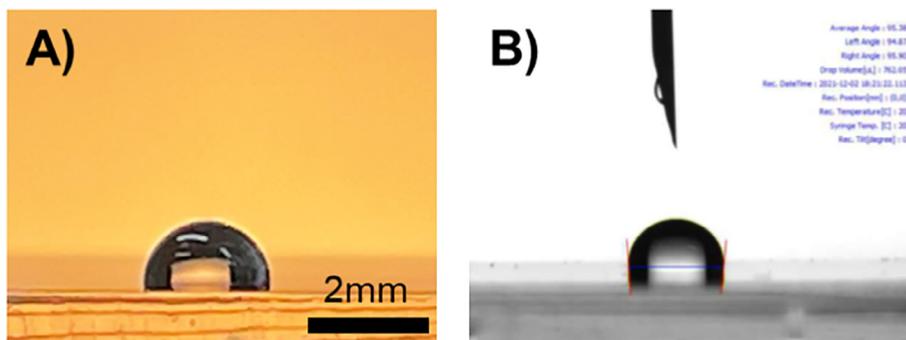


Fig. 11. A) Photos showing the plunger before dispensing (left) and after dispensing the target volume (right) (3 μ L). B) 3 μ L of DI water dispensed three-times on glass slide.

Table 1

Measured contact angles, calculated mean, standard deviation and coefficient of variation of DI water loaded on glass slide with different dispensing volume.

	1st trial (degree)	2nd trial (degree)	3rd trial (degree)	Mean (degree)	Standard deviation	Coefficient of variation
2 μ L	24.47	24.22	24.20	24.30	0.15	0.01
3 μ L	23.92	23.12	23.12	23.39	0.46	0.02
4 μ L	24.73	23.43	24.70	24.28	0.74	0.03
5 μ L	23.76	24.01	23.47	23.75	0.27	0.01

**Fig. 12.** Droplet on top of PDMS. A) A photo of a droplet taken using the proposed analyzer. B) A photo of a droplet taken using Phoenix 300.

volume dispensing. Additionally, the average value of the contact angle of water on glass is about 24° , which is within the range of measured values in previous publications [16] Fig. 12.

Comparison of static contact angle measurement using open source contact angle analyzer and commercial instrument

In order to compare how much the static contact angle measurement result differs from that of a commercial instrument, we sent a sample of polydimethylsiloxane (PDMS) to a nearby analysis center (Kyungsoong University Instrumental Analysis Center, Busan, Korea). The commercial model used for comparison is Phoenix 300 (SEO, South Korea). The measurements were made in triplicate, which resulted in $100.82 \pm 0.82^\circ$ using the proposed analyzer and $97.12 \pm 2.56^\circ$ using the commercial instrument. Aside from the possible contamination of the substrate, it is important to note that contact angle can be determined to be different between measurers and between measurements made using different software even when measuring the same substrate [17,18]. The measurement result shown in this study and observations reported in previously published studies suggest that it is important to standardize the contact angle measurement procedure, and intrasession repeatability appears to be an ongoing issue that needs to be solved. For reproducible measurement techniques, users may refer to a reference [4].

Static contact angle measurement using various mobile phones

Images were taken using various mobile phones to observe the differences in contact angle measurement images depending on the Mobile phone. We used Android mobile phone Galaxy S22 Ultra (released in 2022), Galaxy note 5 (released in 2015), Apple mobile phone iPhone 12 Pro Max (released in 2020), and iPhone 8 plus (released in 2017). The static contact angle of 5 μ L DI water drop was measured on glass and PDMS. Mobile phone holder can be used to hold all mobile phone models used in the experiment. All mobile phone cameras took pictures at 3.5 times magnification. The images of each sample were taken 3 times using each mobile phone model. Analysis of variance(ANOVA) test result was performed with p value < 0.05 being considered as having statistically significant difference, and the results suggest that there is no statistically significant difference in measured contact angle of water on glass (p value = 0.053) as well as water on PDMS (p value = 0.063) using different mobile phones. This result suggests that using different mobile phones does not cause significant variation in the measured static contact angle value. It is interesting to note that the size of the image sensor is related to the quality of the droplet image. In the case of the image taken using Galaxy Note 5, the oldest of the four phones used in the study and has 1/2.6 in. image sensor, the drop boundary was not as sharp as that taken using newer mobile phones with larger image sensors such as Galaxy S22 Ultra (1/3.52 in.), iPhone 12 pro max (1/3.4 in.), iPhone 8 Plus (1/3 in.). As a result of low resolution of the picture taken by using older mobile phone, the standard deviation can increase slightly as shown in Fig. 13 error bar. However, the average contact angle values do not deviate significantly between groups. Tables S1 and S2 show the measured contact angle, standard deviation, and coefficient of variation for each mobile phone model.

Static contact angle measurement with varying droplet volume

To observe the effect of droplet volume used during the static contact angle measurement, contact angle was measured by increasing DI water in 10 μ L increments in the range of 10 between 60 μ L. Glass and PDMS were used as substrates, and

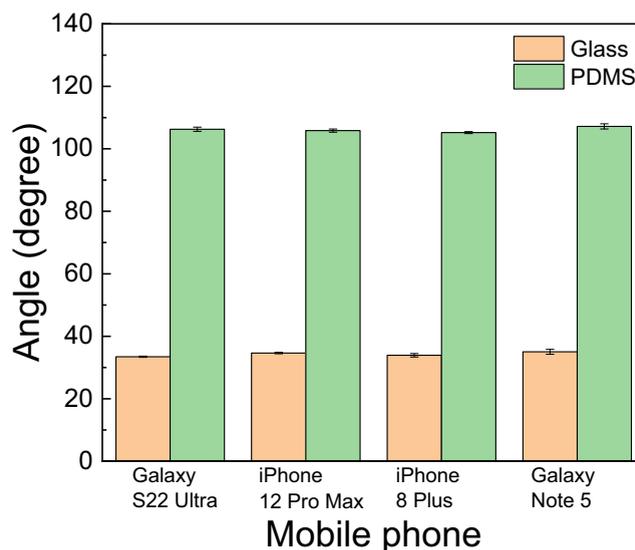


Fig. 13. Contact angle of water on glass and PDMS measured using different mobile phone models.

all experiments were repeated three times using water droplets of different volumes. Drop images were taken using iPhone 12 Pro Max and analyzed using ImageJ program. ANOVA test result (p value = 0.063) in the PDMS sample suggests that there was no statistically significant difference in measured contact angle. Glass on the other hand has significantly smaller contact angle when measuring 60 μ L while the measurement made using 10 to 50 μ L shows no significant difference (p value = 0.524). Table S3 shows the average contact angle, standard deviation, and coefficient of variation of water according to volume in glass and PDMS. This result suggests that using droplet volume up to 50 μ L can result in consistent measurement when measuring the static contact angle of water on glass or PDMS. When using different liquid and solid surfaces, users may refer to a study by Noordmans et al, who suggests using smaller sized droplets for smaller contact angle (below 40°) and larger droplets for larger contact angle (above 90°) [19].

Contact angle measurement of various liquid

In many food labs, the contact angle of beverages like soft drinks and milk are often measured. To assess whether the proposed contact angle analyzer can measure their contact angles, Lipton Iced Tea (Unilever, UK), Lemon-flavored Gatorade (Pepsi, USA) and milk (Seoul milk, South Korea) were used as samples. Measurements were made using the open source analyzer proposed in this paper and also using a commercial instrument named Phoenix-MT(T) (Seo, South Korea), and the results were compared. To measure the contact angles of soft drinks and milk, Dropsnake method was used instead of the LB-ADSA method because the latter requires users to input the surface tension and density of the liquid sample in order to calculate the contact angle, whereas Dropsnake traces the droplet edge and performs polynomial fitting, which does not require additional information of the samples [14]. The liquid droplets were placed on PDMS and the photos were taken using an iPhone 12 Pro Max (Fig. 14). The ANOVA test of the contact angles of Lipton Iced Tea (p value = 0.457), Gatorade (p value = 0.657) and milk (p value = 0.570) all suggest that the contact angle measured using the open source analyzer is consistent what that measured by using the commercial instrument.



Fig. 14. Beverage drop in volume of 5 μ L on PDMS A) Lipton Iced Tea, B) Gatorade and C) milk.

Dynamic contact angle measurement

Aside from the static contact angle, measurement of dynamic contact angle is another parameter of great interest. To measure the dynamic contact angle, the needle method (Fig. 1C) was used. The location of the O-ring of the volume metering module was adjusted so that total of 15 μ L can be discharged manually during dynamic contact angle measurement. The total volume was dispensed over the course of 10 s to dispense and withdraw the liquid at 1.5 μ L/s, similar to previously reported manual dispensing method [12]. iPhone 12 pro max's high definition (HD) video recording (30 frames/s) was used to record the water droplet on PDMS (Fig. 15A and B). To measure the advancing contact angle and receding contact angle, each frame (image) from the recording needs to be flipped through to identify the moment when the length of baseline begins to change. A baseline is the line between two edges of the droplet, or the side view view of area where the liquid and solid surface contact. Advancing contact angle was determined by measuring the contact angle from a frame just before the length of the baseline began to increase. Similarly, for receding contact angle, it was measured just before the length of the baseline began to decrease. To compare the measurement results with commercial instrument, the dynamic contact angle was measured using the needle method using Phoenix-MT(T) (Fig. 15C and D). The measurement results are shown in Table 2. The mean value of the advancing contact angle measured by the open source instrument was consistent with that measured using a commercial instrument (p value = 0.241). The mean value of the receding contact angle was also consistent between the two instruments (p value = 0.819), suggesting that the open source contact angle analyzer not only is capable of measuring static contact angles, but also dynamic contact angles.

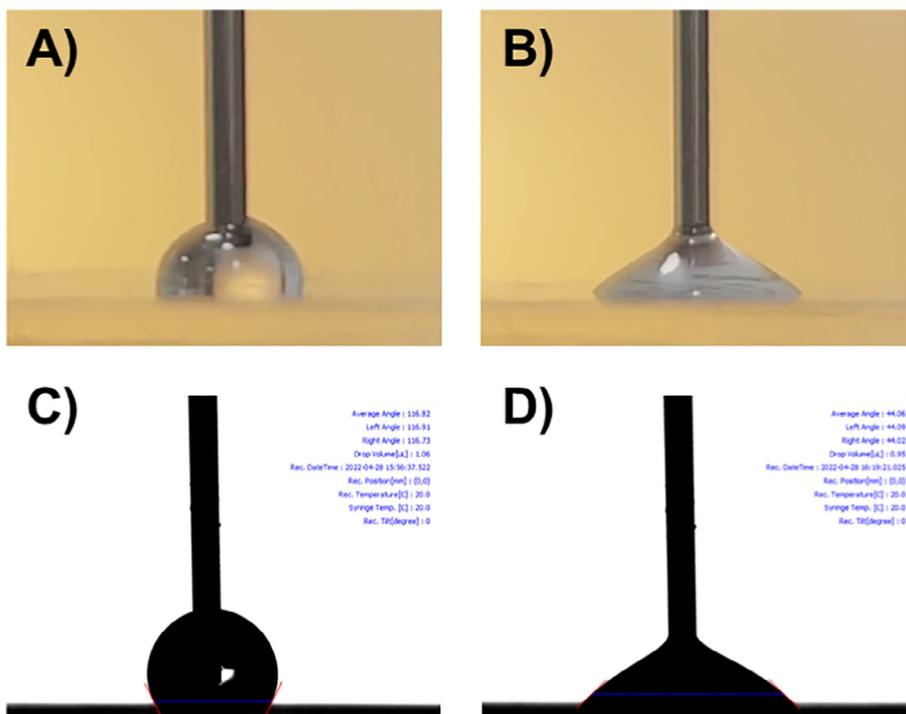


Fig. 15. Images taken during the measurement of A) advancing contact angle and B) receding contact angle of water droplet using propose analyzer. Images taken during the measurement of C) advancing contact angle and D) receding contact angle water droplet imaged using Phoenix MT(T).

Table 2

Advancing contact angle, receding contact angle, standard deviation and coefficient of variation of DI water loaded into PDMS measured using the open source instrument and a commercial instrument.

	Advancing contact angle		Receding contact angle	
	Open source instrument	Commercial instrument	Open source instrument	Commercial instrument
Mean contact angle	113.02	116.44	41.77	41.92
Standard deviation	2.40	2.59	0.53	0.73
Coefficient of variation	0.021	0.022	0.013	0.017

Discussion

In this paper we proposed a contact angle analyzer that can be built using 3D printed parts and commercial camera tripods. We take advantage of the height and angle adjustment features of the tripods for substrate leveling and imaging. The tripods are used as platforms on which light box module, sample plate module, volume metering module and camera holder modules are built upon. Each module can be detached and reattached from the tripod easily by unscrewing and screwing the mounting screws of the commercial tripods. Because of this feature, we expect that users can easily upgrade and modify the modules to meet their specific needs. For example, the volume metering module can be upgraded to automate and connect wirelessly to mobile phones so that users can more easily set target droplet volume and dispense it. Lastly, the current set up also allows users to measure additional parameters, for example, surface tension of liquid, by using open source ImageJ plugins such as Pendent_Drop [20,21]. Such an expandability and compatibility with open source software, the proposed contact angle analyzer is expected to help facilitate science and engineering in many areas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ohx.2022.e00327>.

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