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APPLIED NANO TECHNOLOGY SCIENCE, INC.

Video Contact Angle Analyzer (VCA)

Image recording and analysis

This technical note explains the optical consideration, image recording and image analysis in VCA. The basic concept of baseline determination, droplet edge detection, as well as the algorithm to determine contact angle will be introducing. The uncertainty, errors and limitations will be discussed in the last session of the technical note.

發行版本：V1.00

TRUTH

GOODNESS

BEAUTY

Introduction

Engineering surfaces wettability unleashed numerous useful applications. For example, a highly hydrophobic surface can shed water, be self-cleaning, and prevent fogging [1]–[3]. Surface wettability is generally characterized with contact angle (CA) goniometry.

With a history of more than 200 years, the measurement of CAs was and still is considered the gold standard in wettability characterization, serving to benchmark surfaces across the entire wettability spectrum from superhydrophilic (CA of 0°) to superhydrophobic (CA of 150° to 180°)[1], [4], [5].

To obtain CA rapidly and accurately, several methods were developed, namely: the optical methods, the tilting plate method and the Wilhelm plate method [1]. All these measurements of CA involve taking a profile image of the droplet followed by image analysis. The optical method is still the most popular technique up to date. Since it is the most fundamental technique among all the method mentioned above, and is based on the direct droplet shape analysis, and has advantages of ease of use, intuitive visualization, and data collection. With designed optical path and high-resolution camera installed, a small volume of liquid and surface sample is required, making performing the experiment affordable and inexpensive [1], [4], [5].

In the following sections, basic instrumentation of video contact angle analyser (VCA) will be introduced, the state-of-art optical path design for droplet image recording will be discussed. Followed by image analysis for contact angle measurement, the detailed uncertainty factors will be deliberated in the technical note.

The instrumentation

In general, the Video Contact Angle Analyser (VCA) consists of two subsystems. (1) The sampling system, also known as the hardware subsystem, which is designed to hold the solid surface, generate droplet, and capture the drop image on a solid surface. (2) The analysis subsystem, which is specifically used for image analysis and contact angle calculation. The basic instrumentation structure of VCA is schematically illustrated in Figure 1.

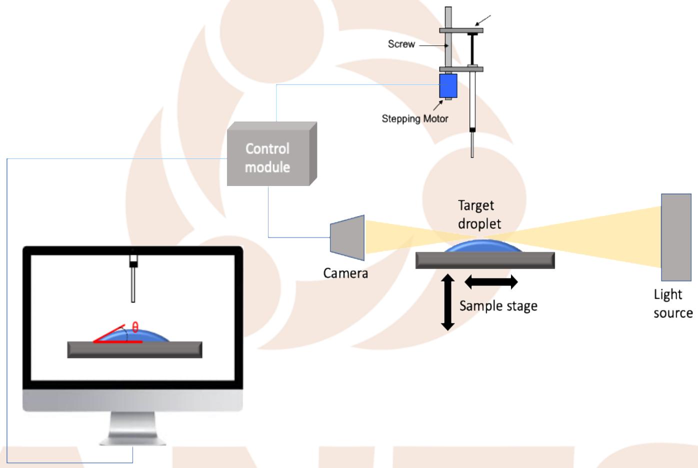

Figure 1: *Schematically illustrate the basic instrumentation structure of VCA.*

Recording image for contact angle analysing

The precision and accuracy of contact angle (CA) measurement are highly depending on the image quality of the droplet on a flat surface. There are several factors to consider when adjusting the optics of the measurement system. In the following paragraphs, the most important aspects of the image for the purposes of CA measurement will be introduced. Some of the variables can affect the quality of the droplet image, as well as the precision of CA measurement, which will be discussed in the section.

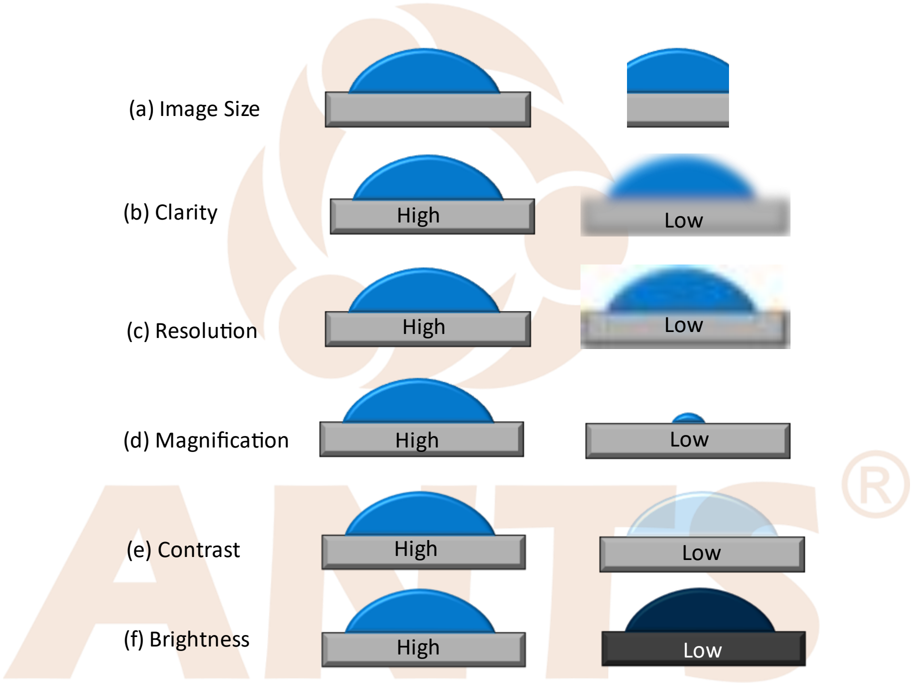

***Figure 2**: Variables that determine image quality for contact angle analyse.*

Figure 2 shows the most important aspects of the image for the purposes of contact angle measurement. The image size is one of the most important factors, as shown in figure 2 (a), the image must contain the entire droplet; the software would not be able to measure the contact angle if the image does not contain the angle formed by the liquid droplet at the three-phase boundary.

Clarity is another important factor for image recording. Shown in figure 2(b), the droplet needs to be seen clearly, so that edge can be identified rigorously, and the more accurate CA can be obtained. A 'fuzzy' droplet edge will make it harder for image analysis software to identify the slope of the baseline, the edge of droplet and the place at which it meets the solid surface. Clarity can be affected by factors such as camera resolution, image magnification, light levels, and contrast with the background.

The image resolution is also important. As shown in figure 2(c), it determines how many pixels represent the droplet edge. If an image is highly pixelated (the spatial resolution is low), it is hard to determine where the edge of the droplet is. For polynomial fitting [6], [7], the fewer the data-points, the less accurate the fit. In fact, image magnification has an impact on image resolution. As shown in figure 2(d), the larger an optical image is, the more pixels it will cover and the higher resolution the image will be.

The image contrast is the next important factor to be consider. Since the image analysis for contact angle measurement is based on finding the droplet edge. As shown in figure 2(e), if the contrast is low, then it will be difficult to distinguish the droplet from its background. Since the software algorithm highly depends on image edge-detection technique, the image contrast would significantly affect detection accuracy. Also, the light level is one considerable parameter that effect the image contrast. As shown in figure 2(f), if the lighting is too light or too dark, the contrast of the droplet and background can be affected.

The optical path is important to take into consideration. The entire depth of the droplet needs to be in focus, otherwise it will be difficult to find the baseline through the blurry front of the droplet. This can be achieved by altering the ‘depth of field’ of the imaging system. The actual focal point of a lens is a specific distance from it. However, there is an area either side of the focal point which you consider to be in focus. This is known as the 'depth of field'. The depth of field can be altered by using an aperture. Figure 3 the effect of an aperture on the light entering a camera. As the aperture is reduced in size, the light entering the camera is narrowed. This results in two changes:

1. There is less overall light, so you need a bright background light.

2. The depth of field is increased and the ‘in focus’ region becomes longer.

As the aperture is narrowed, the size of the beam changes. If you consider the focal region to be within a certain beam width, you can extend this focal region away from the camera by narrowing the beam. The result of this is shown in Figure 3. In figure 3(a), the depth of field starts and ends inside the droplet, so the front and back of the droplet are blurry. In figure 3(b), the depth of field is wider than the whole droplet, so the entire droplet is within focus.

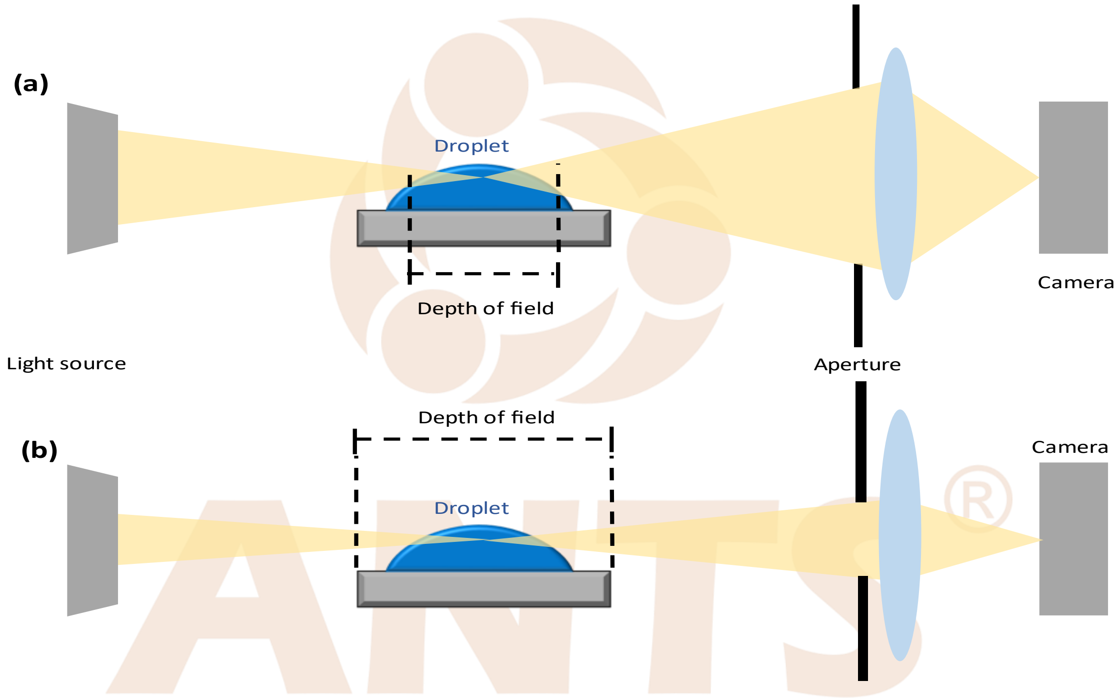

Figure 3: Schematically illustrates the effect of an aperture on depth of field.

Image analysis

Image processing and analysis is the crucial step once an image has been obtained. Most image analysis algorithms for contact angle measurement follow four basic steps, as shown in the figure 4. The first step is shown in figure 4(a), define a baseline: the baseline of the measurement is the horizontal line that represents the solid on which the droplet is being deposited. The contact angle is the angle at the point where this baseline meets the droplet edge. (b) Trace the droplet edge: the CA cannot be calculated without knowing where the droplet edge meets the baseline. The droplet edge can be drawn by hand, detected programmatically, or estimated based on some models about typical droplet shapes. (c) Determination of the gradient: the gradient of the tangent of the droplet edge at the point where it meets the baseline needs to be determined. With the edge tracing, the gradient determination can be done by the software. (d) Calculate the contact angle. Once the baseline and a gradient were determined, the angle can be between them can be calculated. To do this, the trigonometric functions will be used. The detailed calculation will be introduced in the following section.

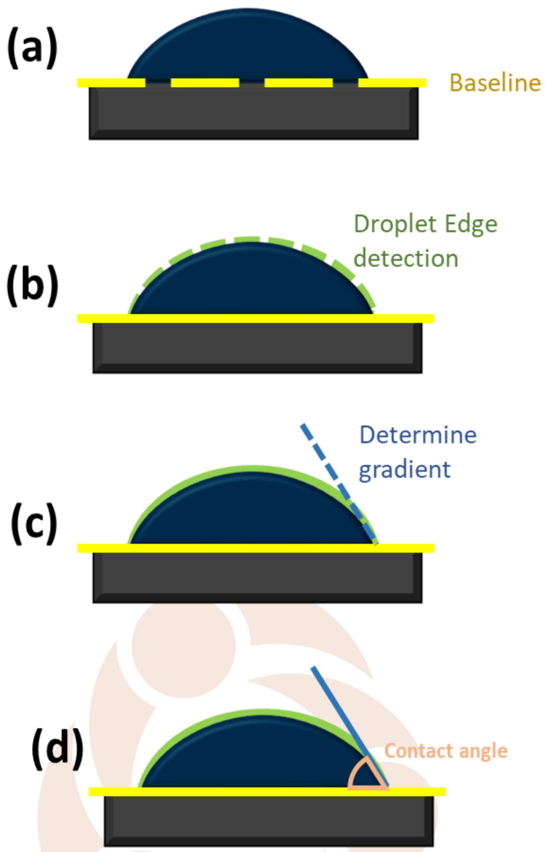

Figure 4: Schematically shows different stages of contact angle analysis. The analyse process are: (a) Baseline detection, (b) droplet edge detection, (c) determine gradient and (d) calculate contact angle.

How does the AutoFast© image analysis work?

In this section, we will explain how the image analysis step was performed by the ANTS Video Contact Angle Analyzer (VCA), along with some tips and tricks to help you get the most out of your contact angle measurements.

AutoFast© is a stable, well-established software developed specifically for contact angle measurement in VCA. The state-of-art algorithm captures automatically detects the droplet image, defining region of interests (ROI) and the baseline with a quick snapshot. To accurately perform contact angle measurement in various situation, three different image analysis algorithms are developed, namely (a) Snapshot, (b) Reflect and (C) LowAngle, as demonstrated in Figure 5.

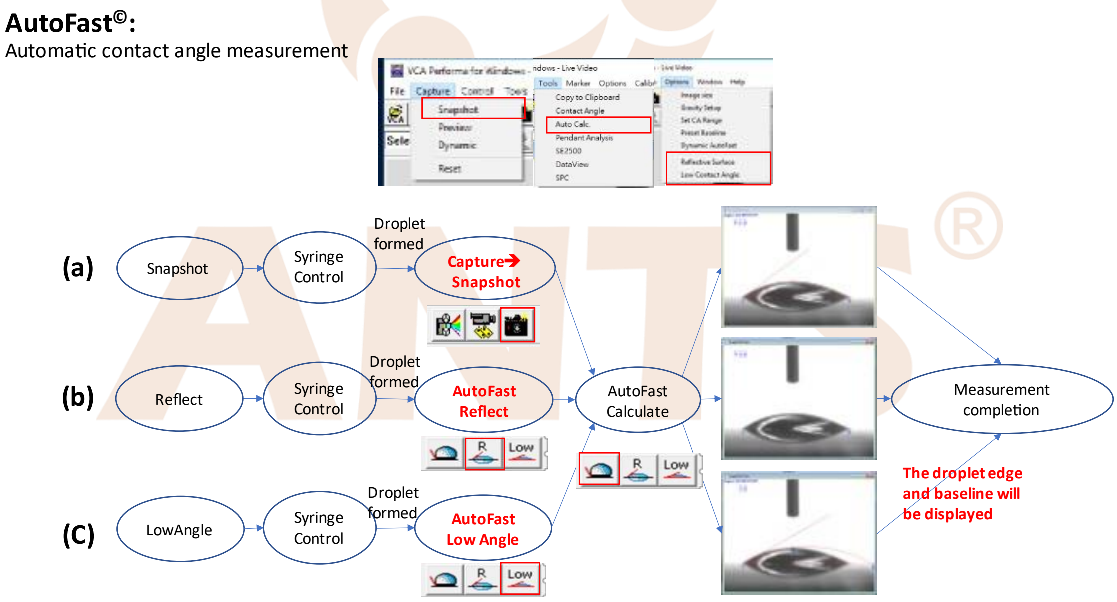

Figure 5: Schematically shows the interface of AutoFast©. In AutoFast© , there are three different image analysis algorithms: (a) Snapshot, (b) Reflect and (C) LowAngle, designed to be used in various scenarios.

The Snapshot is the default mode in AutoFast© , and is designed for measuring CA in general condition : CA >20° and the substrate reflection is minor. On the other hand, when the sample substrate reflection is significant (i.e., droplets on silicon wafer, glasses, or mirror-like surface), the reflect mode should be used, so that the baseline and droplet shape can be correctly selected. The LowAngle mode is specifically designed to obtain super hydrophilic surface. The image analysis process can be challenging when CA is low, but with the LowAngle mode in AutoFast©, CA as low as 10° can be repeatably identified.

In general, these image analysis algorithms share similar procedure. The algorithm first defines boundaries of a region of interest (ROI), meaning which portion of the image that will be used for edge detection. After the ROI is determined, the image was then transformed to binary (i.e., the colour of the image was transformed into pixel intensity), followed by applying edge detection algorithm. As shown figure 6, (a) The outline was extracted from the binary image after the edge detection algorithm was applied. The baseline and the outline of the droplet was identified via Hough line transformation and Hough circle transformation respectively, labeled in red and black lines in Figure 6(b). Once the baseline and droplet outline were identified, the contact angle can be calculated using the ball crown model.

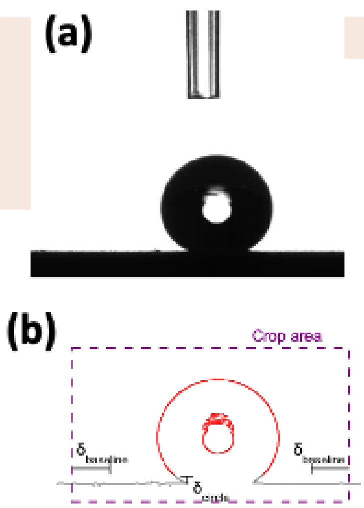

Figure 6: (a) Original example image of a droplet on a surface with a contact angle ϑ > 90°. (b) Result of the Canny edge detection algorithm processing of the image file with the standard deviation of the Gaussian blur, σ = 0.3, showing the most important user-specified thresholds and crop area provided.

The contact angle determination is also an important process in image analysis, which not only involving finding the edge of the droplet, but also fitting the edge data to a established mathematical model (see figure 7(b)). To extract the CA accurately, several mathematical models were proposed. Up to date, the ball crown model is one of the most popular method to describe the profile of the droplet, even though the method can be inaccurate in many situations.

Traditional ball crown model assumes the water droplet is a small part of a three-dimensional sphere, where the gravity effect was neglected. The droplet is simply approach as a spherical projection, where the contact angle is calculated as, as illustrated in figure 7(a):

$$\theta_\gamma = 90 - tan^{-1}\left(\frac{r-b}{\sqrt{2rb-b^2}}\right)$$

However, the reality is that unless the droplet is small enough, the droplet is never a true sphene, so the method can over-estimate the CA compared to reality droplet (over-estimate the b value)[8], [9] .

Fortunately, AutoFast© uses improved ball crown model, as known as High-precision droplet shape analysis (HPDSA), in which only very small portion of the droplet profile is needed to fit into the ball crown model. The calculation of the contact angle θm is performed not by some tangent on the triple point but by the sine theorem for a right-angled triangle,

$$\theta_m = 90° + sin^{-1}\left(\frac{\Delta y}{R}\right) \pm \alpha_{BL}$$

The principal radius R, the inclination angle αBL of the baseline (= arc tangent from the slope), and the difference in height coordinates Δy between the center of the circles with XCC and YCC and the triple points with XTP and YTP are calculated for both sides of the drop for every image, as shown in Figure 7 (b) [10], [11].

In recent years, advanced contact angle analysis algorithm uses elliptical spherical crown model to simulate the effect of gravity, but such method is more computational power-hungry, and thus not suitable for commercial CA analysis yet [12], [13].

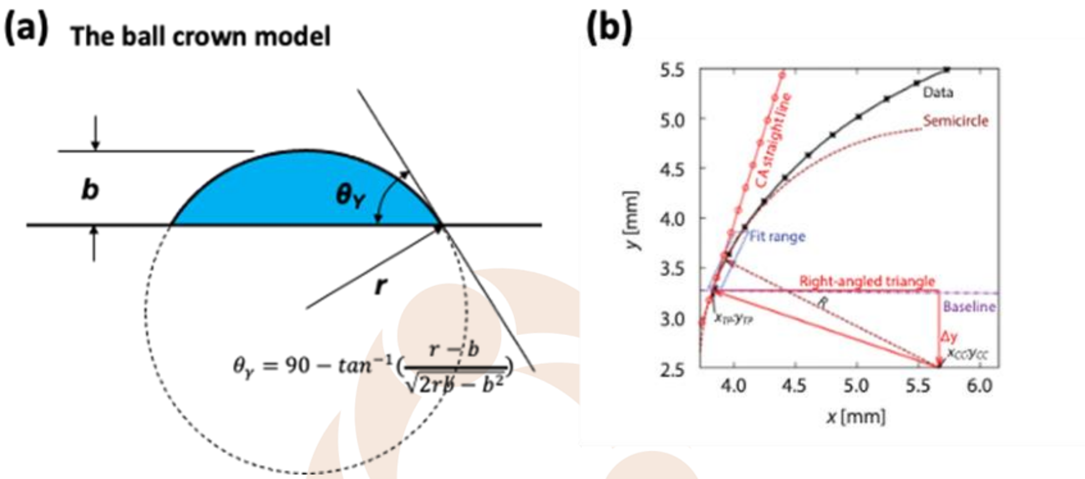

Figure 7: Illustrate the algorithm used to determine contact angle (a) shows traditional ball-crown model (b) the High-precision droplet shape analysis (HPDSA) method [12], [13].

Uncertainties, Inaccuracies, and Limitations

As mentioned earlier in the technical note, all measurements of CA involve taking a profile image of the droplet followed by image analysis [10]–[13]. However, the simple method for determining surface wetting, measuring contact angles (CAs) of water droplets, can be misleading for superhydrophobic surfaces because of difficulties in positioning the baseline (see figure 8). The inaccuracies mainly originate from optical distortions and are affected by experimental parameters such as magnification, lighting, contrast, and camera resolution.

The optical distortions are large near the baseline (i.e., the boundary between the solid surface and the liquid droplet in the two-dimensional image; see the figure, top). Not only is the droplet edge diffuse, but it also becomes heavily pixelated, even when a goniometer with a high-resolution camera is used. As shown in figure 8, the diffuse edge and pixilation necessarily introduce a substantial systematic error in CA from about 1° to beyond 10°, due to the uncertainty in baseline placement, which becomes subjective. Even the automatic baseline detection feature in CA analysis software often fails, likely because of the short baseline length on highly hydrophobic surface. Despite the continuous improvement of experimental procedures, and analysis methods, of CA equipment, these problems kept persist.

Figure 8(d) shows the error in CA resulting from one-pixel displacement of the baseline. V.Konduru et al. has experimentally and theoretically demonstrated how the error increases substantially for increasing CA, especially upon reaching the superhydrophobic regime. The uncertainty range in CA corresponds to ~1° for Cas less than 120°, ~2° for CAs of ~150°, and ~5° for Cas of ~162°. Propagation of errors in subtraction makes the uncertainty of contact angle hysteresis even worse, which can be up to √2 times greater than for static CA values. Surface reflection (as shown in the figure 8 (a)) can somehow cause uncertainty to the baseline determination. Moreover, macroscopically rough surfaces, such as woven textiles, have an irregular baseline and the contact angle can be ill-defined [10]–[13].

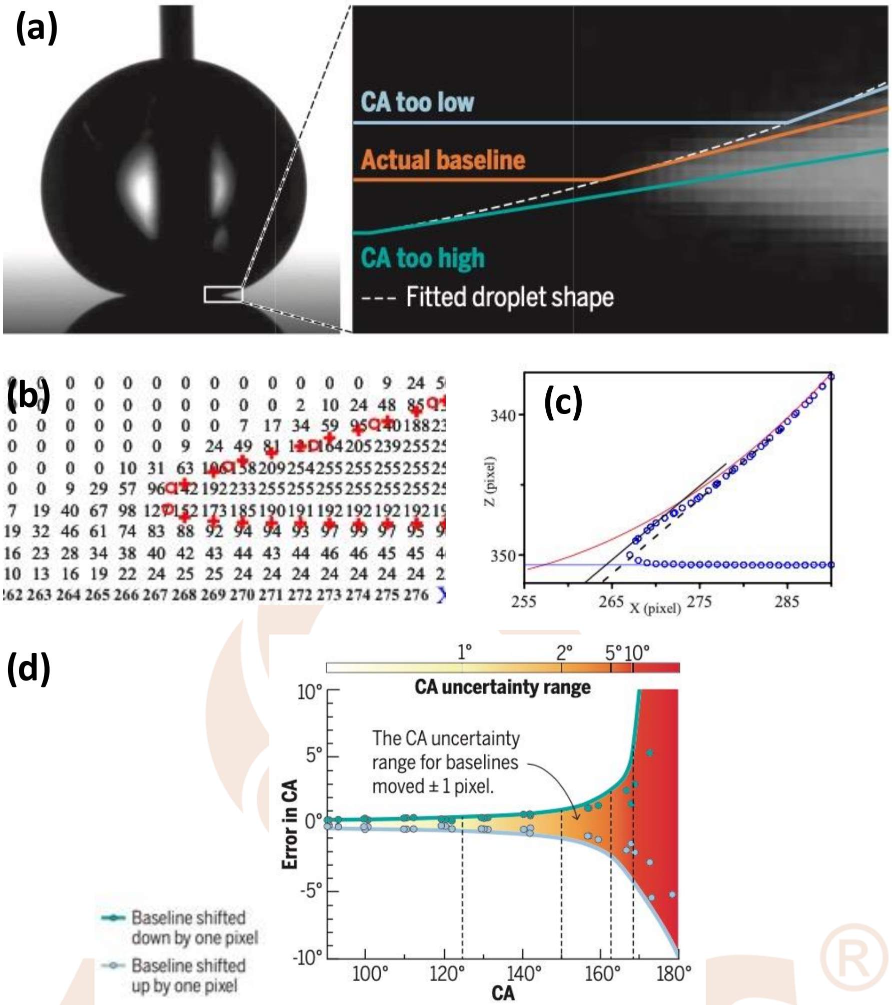

Figure 8 :Uncertainties in contact angle measurement. (a) A droplet image (camera resolution 1984 by 1264 pixels) during CA measurement on a superhydrophobic surface and high magnification zoom image. Inaccurate baseline position causes errors in CA measurement; baseline set too high decreases CA (light- blue lines), whereas baseline set too low increases CA (teal lines). (b) The gray level for the region around the detected contact point, showing the droplet edge diffuse and pixelated. (c) (Color online) Best-fit circle (curve), base line, and the edge points near the right detected contact point for the stainless-steel ball on the slide. The solid and dashed lines represent the tangent lines using the edge points of different regions near detected contact point. Both tangent lines resulted in a value of ϑ=152°. (d) A baseline shifts up or down by 1 pixel resulted in similar CA errors in both simulated and experimental data (resolution 1984 by 1264 pixels). Errors are dramatically increased for CA>150°.

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