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A Real-time Double Emulsion Droplets Detection System using Hough Circle Transform and Color Detection

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Abstract— The object detection based on computer vision algorithms has a wide range of applications in many domains. This paper introduces a real-time detection methodology of 3D printed double emulsion droplets. The first step is to directly segment and extract the color of the inner droplets from the current field of view using thresholding operations of inRange functions of OpenCV in YUV space, so that the droplets color and background color can be obtained separately. Secondly, a binary masking has been employed to locate the centre of the mass of droplets and also distinguish the droplets from surroundings. Next, the Hough circle transform is used to fit a circle to extract the true edge when identifying the contour of the external droplet. The droplet size, generated frequency, and determine whether the droplet is successfully formed can also be obtained using Hough circle transform. A series of experiments have been conducted and indicated that our proposed detection system works well on different double emulsion microfluidic devices with different background and droplet colors.

I. INTRODUCTION

Double emulsion droplet is a highly structured fluid in which smaller droplets are wrapped in dispersed phase droplets[1]. The outer droplet forms a shielding layer around the inner droplet, which can effectively isolate the inner droplet from the continuous phase. Double emulsion droplets as a closed reaction system, avoiding the change of reactant concentration and cross-contamination between different reactions; the inside of the double emulsion droplet can carry out a variety of biological and chemical reactions, and has the advantages of the small amount of sample reagents and low consumption[1]. With these specific advantages, double emulsion droplets are widely used in cosmetics, pharmaceutical production, cell medicine, food science, petroleum industry, chemical synthesis, environmental monitoring and some other fields.[2].

In the specific application process, sometimes it is necessary to detect the double emulsion droplet to obtain the droplet size, frequency and other parameters. In this case, it is not easy to identify the edge of the inner droplet, mainly because the inner droplet will not exactly at the centre of the wrap; and even if the inner droplet is in the center of the wrap, the Canny algorithm is not that easy to recognize it [3]. However, the size and frequency of droplets must be accurately monitored during the production process. Therefore, this paper proposed a double-droplet detection method based on color space, which can get the information of the contour, size, frequency of the double emulsion at one time.

Redmon et al. proposed a real-time object detection method, the principle of which is that a single neural network can directly predict bounding boxes and class probabilities from the complete image in one evaluation. This unified system has a fast detection speed, but the YOLO model used may produce some localization errors [4]. Bao et al. analyzed the proportional multiplication technology under the framework of Canny edge detection, which can greatly improve the positioning criteria through proportional multiplication when the loss of the detection criteria is small [5]. This technique is more accurate than the traditional Canny algorithm, but the detection speed is relatively slow. Zhan et al. proposed an improved algorithm based on the frame difference method and edge detection for the detection of moving targets. This method can mark the connected components of the block to obtain the smallest rectangle that contains the moving object. It has a fast detection speed and a high recognition rate, but it cannot obtain accurate object edges [6].

In the traditional droplet recognition method, the color image will be converted into a grey image, and then the grey image will be preprocessed to remove noise [7]. The next step is to use the canny operator or threshold segmentation method to process it and then go through suitable post-processing to get the information of the droplets [8]. Zhao etc. from Beijing Information Science and Technology University introduced four algorithms through Open CV programming, which can visually display the detection results under different thresholds to facilitate image edge detection [9]. But this method is not ideal for double emulsion. This paper intends to find a way to directly extracts and divides the color of the color image, then the information can be obtained after post-processing. Compared with the traditional method, the pre-processing and post-processing work of this method is relatively simple, which can greatly increase the processing speed. This method requires the use of a color camera and dyeing the droplets. With the development of imaging technology, the cost of color cameras is not expensive, and the algorithm itself has a strong tolerance for chromatic aberration.

In computer vision, color components are best separated from intensity due to reasons such as lighting changes or eliminating shadows. YUV is a color coding system, mainly used in video and graphics processing pipelines. Y stands for the luma component (the brightness), U and V are the chrominance (color) components [10]. It can make the encoding and transmission more convenience,

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reducing bandwidth occupation and information errors [11]. The conversion matrix of YUV and RGB sapce is shown as follows, wherein the YUV is an advanced option for color processing while the RGB is the most commonly used color display method [12]. OpenCV is a computer vision library developed by Intel. Its main role is for real-time image processing, computer vision and pattern detection programs. It is completely open-source and can be used well in engineering practice [13].

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad \begin{matrix} Y \in [0, 255] \\ U \in [-111, 111] \\ V \in [-157, 157] \end{matrix}$$
(1)

Hough circle transform is an image transform can extract circular objects from the image. This transformation can effectively search for objects with high radial symmetry, with each degree of symmetry receiving one "vot" in the search space [14]. Grycuk and etc. used the Canny edge detection method and quadrilateral detection algorithm to obtain a list of objects of interest, but this method can only be applied to a single picture [15]. Therefore, this paper intends to find a double emulsion detection method that can be applied to fast cameras and can be monitored in realtime. The contribution of our proposed tracking system can be highlighted as follows:

1. There is no need to determine the color of droplets being tracked, the first two peaks of colors will be grabbed all at once, one is for the inner droplet the other is for background, which makes a faster detection speed and fulfils the district requirement of microfluidics detection.

2. Combining color thresholding with Hough circle algorithms, this paper provides an opportunity to online monitor the quality of microfluidics formation by selecting out those failed formed droplets which do not have the inner colored droplets.

3. The novelty is primarily in bringing together existing technologies to a complex task. The novelty and innovation required in this kind of work is not to be underestimated - whilst the system will be based on a number of existing technologies, combining these in a way that makes a reliable, coherent and effective system is a complex research challenge in its own right.

II. COMPARISON WITH TRADITIONAL ALGORITHMS

The Canny algorithm is a relatively straightforward algorithm, but the degree of freedom is relatively low, which requires manual debugging of a large number of parameters (two thresholds) to select the edge [9]. And the first step of Canny edge detection is to use Gaussian blur to remove noise, but this step will smooth the edges, making the edge information weaker, which may cause some required edges information to be missed in the subsequent steps, especially weak edges and isolated edges [16]. It can be eliminated in the calculation of the double threshold [17]. The Sobel operator is not very accurate in positioning edges, and the edges of an image are more than one pixel [18].

The detection is not stable enough when the traditional edge detection algorithm is applied to high-speed cameras [19]. The detection algorithm we proposed can reach the point directly and has a strong purpose. At the same time, the detection speed and accuracy can also be guaranteed.

III. PROBLEM DESCRIPTION

The droplets need to be dyed, then the double emulsion can be detected by the color space. This method can detect the edges of the two droplets at one time. The outer droplet edge on the left side of the nozzle vector is drawn from the centre of the droplet outward, and the collection of the darkest point of each vector is considered to be the edge of the outer droplet. There may be darker particles in the outer area of the pipe, which may cause false detection. To solve this problem, the surrounding area of the pipe can be covered with white. If the inner droplet is darker than the wrapper, it may also cause false detection. Since we have the droplet mask from the previous step, we can also cover the droplet mask with white. The final edge is formed by merging all the darkest points on each vector. There may be some errors in this edge, so a normal window filter needs to be used.

After converting the image to YUV format, the frequency of each tone is recorded on the entire image. In this way, an image with two peaks can be obtained, where the first peak is the background, and the second peak is the inner droplet. Since the background creates many close peaks, the image must be filtered by the average window. However, multiple peak detections are still triggered in the background. Find the next peak through the points with a descending gradient on both sides of the first peak. When the largest peak has been found, a dead zone should be set around it, and this dead zone should be ignored after the second peak being found. After located the second peak, consider it as the chroma of droplets. All pixels whose colors are closer to the chroma of the droplet than the background color are marked as white on the droplet mask. In the next step, the image is morphologically filtered to remove noise.

The number of double emulsions needs to be detected. This method is mainly aimed at the situation where a large droplet wraps a small droplet. For the situation where one droplet wraps multiple droplets, it is easy to overlap during detection, which will lead to errors. While determining the number of double emulsions, it can also identify the edges of the two droplets inside and outside, then get the size of the droplets.

The frequency of droplet generation can be also directly derived. It can measure the production time of a single droplet without the need for similarity conversion. By achieving the above goals, the production of the double emulsion can be well monitored, so that it can stably produce large droplet wrap small droplet.

IV. PROPOSED METHODOLOGIES

A. Principle of Droplet Detection

Compared with the traditional method, this method is to extract a specific color by extracting the value of U

and V, reference data needs to be checked to find the U, V valuesrange of a certain color. This method needs to manually set an initial value and a value range. The first step is to use chroma values to perform color segmentation on the target. The algorithm associates different color pixels in the visible range of the field of view with their corresponding colors. As shown in figure 1, the most distribution is taken as the background color; the second most distribution is taken as the color of the droplet. This method can quickly extract the droplet color and background color no matter what colors they are.
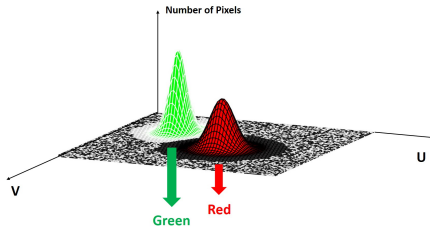

Fig. 1. YUV space diagram. Green is the most distributed chroma, which is the background color; red is the second most distributed chroma, which is the droplet color.

The second step is to perform droplet detection through binarization. Randomly select a pixel in the visible range of the field of view and determine whether the point is a background color or a droplet color. If it is the background color then gives it black color, while the droplet color gives it white color. So the droplet detection can become spot detection. Before this process, noise reduction is required through filtering. Then by determining the centre of the mass point to identify the centre point of the spot (inner droplet), this centre point is a necessary condition for subsequent identification of the outer edge and calculation of the size.
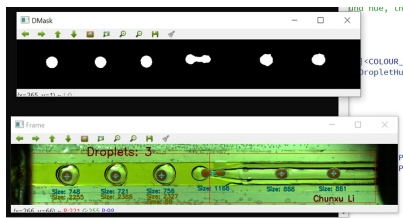

Fig. 2. Field of view obtained by binarization. Give the background color black and the droplets color white.

B. Determine If the Droplet is Successfully Formed

If the double emulsion has successfully formed, its shape close to a circle; if it fails, it has an irregular shape. First, find the centre point of the inner droplet, then find the farthest point on its outer droplet from this centre point. Calculate the area of the fitted circle with the connecting segment of these two points as the radius, and compare this area with the actual area obtained by calculating the sum of pixels. In Figure 3, if the droplet is formed successfully, the area obtained by fitting is not much different from the actual

area; if it fails, the area obtained by fitting will be much larger than the actual area. Assuming S_0 is the size of the outer droplet,obtained by counting the pixels numbers.The following equation can be derived:

$$\xi = \pi r^2 - S_0 \tag{2}$$

$$sign\left(\xi\right) = \begin{cases} -1, & \xi < -a \\ 0, & -a < \xi < a \\ 1, & \xi > a \end{cases} \tag{3}$$

Where r is the radius of the fitted circle; a is the preset gap factor, which can be adjusted according to the difference allowed by different experiments. When the output of the $sign$ function is 0, the droplet is successfully formed.
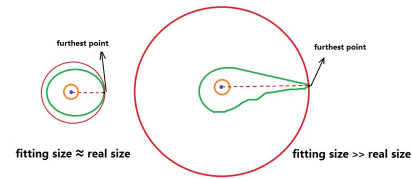

Fig. 3. The area of the fitted circle has been calculated and compared with the real size. The green line represents the true outer edge of the droplet, and the red line represents the circle formed by the fitting.

C. Wrap Detection Principle

The traditional method is to determine the centre point of the entire double emulsion droplet through the droplet inside[19]. In this paper, we present two methods to detect the outer edge of the droplet. First, as shown in figure 4, the centre of the inner droplet should be taken as the starting point, and use a vector of a certain length to make the half-line. The length of the half-line can be defined by yourself. Find the darkest point on each ray and circle it to form an external contour detection. Then the inner and outer edges of the droplet can be identified and extracted. In this case, the formula can be expressed as:

$$\vec{S_n} = \vec{j} \cdot r \cdot sin\left(n \cdot \theta\right) + \vec{l} \cdot r \cdot cos\left(n \cdot \theta\right) \tag{4}$$

Where r is the preset vector length; n is a geometric multiple, which represents the number of iterations. The unit vectors $\vec{j}$ and $\vec{l}$ can be synthesized into the required vector $\vec{S_n}$ when the angle θ given, where angle θ is the angle between the sum vector and the positive direction of the vector $\vec{j}$.

However, if the inner droplet did not successfully enter the outer droplet, the detection would not succeed. The second method is to apply the Hough transform algorithm for detection. Specifically, it is the curve transformation applied to the Hough line transformation. For a certain point in the pixel space, through the Hough transform, it is possible to find all the specific linear shapes of this point. In this experiment, the edge shape is close to a circle, so find all n circles passing through this point. If the point is on the real edge of the outer droplet, then there are one and only one of these n circles, which is the real edge of the outer droplet. So we need to constantly change the position of the point to
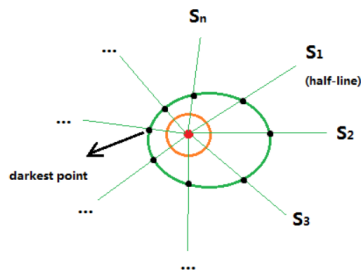
Fig. 4. The yellow circle indicates the contour of the inner droplet that has been identified, and the red point is the centre point of the inner droplet. The half-line is emitted with the red point as the centre, and the collection of the darkest points on each half-line is the outline of the outer droplet, which represent in green.

find the circle with the highest repetition rate, which is the outer droplet edge.

For the known circle, the general equation in the rectangular coordinate system is:

$$(x - a)^2 + (y - b)^2 = r^2 \quad (5)$$

Where (a, b) is the coordinates of the centre of the circle, and r is the radius of the circle[20]. Then the parameter space can be expressed as (a, b, r), and a circle in the image coordinate space corresponds to a point in the parameter space. The calculation process is to increase a and b within the range of values, and solve the r value that satisfies the above formula. Each time a value of (a, b, r) is calculated, the corresponding array element $A(a, b, r)$ plus 1. After the calculation, the (a, b, r) corresponding to the largest $A(a, b, r)$ are the parameters of the desired circle [21].

The Hough transform algorithm has been used to scan all points within the visible range of the screen, then the edges of the outer droplets can be extracted. This circle is obtained
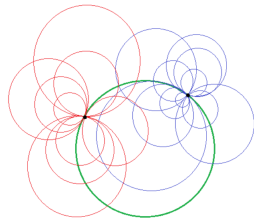

Fig. 5. The Hough transform has been used to find the circle with the highest repetition rate is the outer droplet edge, which represents in green.

by the Hough transform fitting. However, this circle is still different from the real shape of the droplet. The next step is to use the fitted circle to extract its true outer edge. The method is similar to the previous method. Two thresholds are added so that the vector only scans the area within the threshold to get the set of the darkest points, which is the real outer droplet edge. This method can extract empty droplets, which is the inner droplet did not successfully enter the outer droplet. The size of the droplets can be measured by counting the total number of pixels in the edge that has been identified, the total number of pixels can be converted into area units

after getting the scale factor data. In this case the equation is expressed as:

$$\vec{S_n}' = \vec{j} \cdot (R - r') \cdot sin\,(n \cdot \theta) + \vec{l} \cdot (R - r') \cdot cos\,(n \cdot \theta) \quad (6)$$

where the large threshold is represented by R, small threshold is represented by r'. The meanings of other parameters are the same as in equation (4).
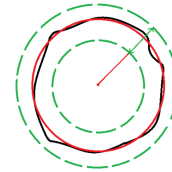

Fig. 6. The red circle is the fitted circle, and the green dashed line is the two thresholds based on the fitting circle after scaling and expansion. By scanning the area within the threshold, the true edge of the outer droplet can be obtained, which represent in black.

D. Principle of Frequency Identification

The frequency of droplet generation is obtained by calculating how long it takes for the droplet to pass through the nozzle. A line has been drawn from the centre of the inner droplet to the nozzle, then check if there is an edge that exists along the line to judge the rupture. The frequency of droplet generation has been determined by counting the number of frames. The start frame is when the droplet begins to form, and the end frame is when the droplet just formed. Therefore, the key point to this algorithm is to determine when the droplet begins to form and when the droplet has just formed. If the droplet is in the forming state, the number of frames is increased by 1; if it is already formed, the number of frames is increased by 0, and the number of frames should be output as the frequency at the same time.

The state of the droplet is judged by the leading point and the tailing point. In Figure 6 to Figure 9, the m-line is the line segment where the droplet nozzle is located, perpendicular to the direction in which the droplets are generated. The following situations can be analyzed:

1. In Figure 7, the leading point has not reached the droplet nozzle yet, the number of frames should be output as the frequency; if the leading point has passed the droplet nozzle, the number of frames should be increased by 1.
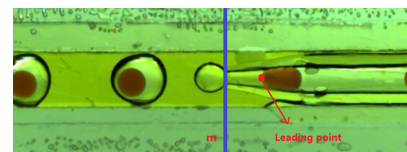

Fig. 7. Leading point has not reached m-line.

2. In Figure 8, the leading point has passed the droplet nozzle and tailing point has not reached the droplet nozzle, the number of frames should be increased by 1.

3. In Figure 9, if the second leading point can be found between the previous leading point and droplet nozzle, the
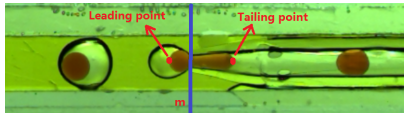
Fig. 8. Leading point on the left side of m-line and tailing point on the right of m-line.

number of frames should be increased by 1. If the second leading point cannot be found, it may also be in the forming state, so further verification statements need to be added.
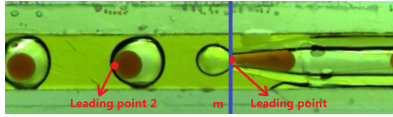

Fig. 9. Whether there is a new leading point between leading point 2 and m-line. Leading point 2 means the previous leading point.

4. In Figure 10, the centre of the inner droplet to the midpoint of the m-line has been connected to see if there are two edges on this line segment. If yes, it means that the droplet has been formed, the number of frames should be output as the frequency; if there is only one edge on the line segment, it means that the droplet is still forming, so the number of frames should be increased by 1.
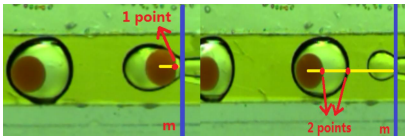

Fig. 10. Whether the droplet is formed should be determined by the number of edges on the line segment, which connects the centre point of the inner droplet and the midpoint of the m-line.

V. EXPERIMENTAL RESULTS AND ANALYSIS: SPECIFIC DETECTION METHODS FOR DIFFERENT TYPES OF MICROFLUIDIC DEVICES

The video in the experiment runs at a frame rate of 30fps, and the program needs about 7-11 milliseconds per frame to track all droplets, so it can track in real time at about 100 fps. This can be optimized through better hardware, optimization, GPU acceleration, etc.In the experiment, the accuracy of the system was close to 100%, but the situation of the experiment video was relatively ideal.

When extracting the color space, a one-step process method has been considered in this paper, which is to determine the background color and the color of the droplet by catching the two peaks of the ordinate. This method does not need to consider what colors they are, but only needs to find the peaks. Another advantage of this method is that the detection is accurate, and multiple colors can be extracted in the user interface, which is very flexible. Different microfluidic devices have been used to validate our proposed detection system.

A. Transparent Background with colored Inner Droplet

In this case, the statistically calculated YUV curve has only one peak. In Figure 11, the background is nearly transparent and the droplets are blue. To extract the colure blue, the U value needs to exceed the peak. Its value range is [133,255]. If a cleaner extraction is needed, the V value can reduce to meet the requirements, then the effect of red can be eliminated. The value does not include the main peak and the range is [1,123].
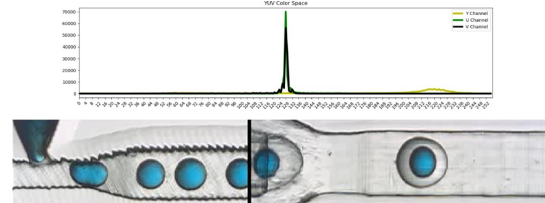

Fig. 11. The background is nearly transparent and the inner droplet has one color.

B. Dyed Background with Darker colored Inner Droplet

The background color is caused by the dyeing of the outermost liquid, which interferes with the color extraction of the inner droplets. In Figure 12, the red color of the inner droplet needs to be extracted, which relatively darker. Then the V channel should be focused, there can find two peaks. The first peak is the green of the overall pipe background, and the second peak is the red of the inner droplet. The color green can be composed of red and blue, so red can also be detected in the background. If the second peak value is taken, the inner droplet size will be underestimated because the red color inside the droplet is uneven. The refraction of light caused by the droplet curve will also lead to uneven red, which will cause the red at the edge of the droplet to be less red, resulting in the identified droplet size being smaller than the actual size. It can be known from the experiment, the detection effect is better when the middle value of the two peaks has been taken.
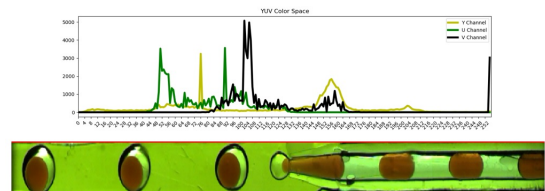

Fig. 12. The background has been dyed, the inner droplet has one darker color.

C. Dyed Background, colored Inner Droplet with Unevenly Distributed Illumination

In this case, the V channel should be focused to extract the red color and the YU channel should be ignored. As shown in Figure 13, two peaks have appeared. Regarding the value of V, the intermediate value 130 between the two peaks has been taken. Two methods can be used in the brighter area to

eliminate the impact, increasing the U value or decreasing the Y value. The interval of U value must cross the second peak, which can be determined as [56, 255]; the interval of Y value can be determined as [0, 196], because it belongs to the brighter area, only the two largest peaks need to be avoided.
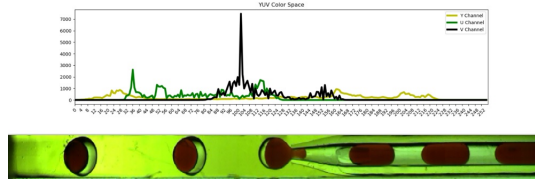

Fig. 13.   The light field is relatively uneven.

D. Dyed Background with Lighter colored Inner Droplet

In Figure 14, the inner droplet is red, and the color is relatively lighter. To extract the red color, the V channel should be focused on. There are two peaks in Figure 14, but the peaks are not very clear. The value interval of V is [104, 255], in the middle of the two peaks. However, there are shadows in the outer droplets. This problem can be solved by three methods: debugging U value separately, debugging Y value separately, and debugging U value and Y value at the same time. The U value range should include the main peak, so take the value just past the main peak. In this figure, the U value can be debugged in [0,110]; debugging the Y value alone is not very effective in this example, because the pixels of the droplet will be lost; debugging the U value and Y value at the same time can get a cleaner image, but the difference between this result and the result when debugging the U value alone is not much different.
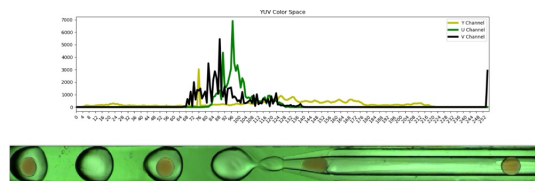

Fig. 14.   The inner droplet has one lighter color.

VI. Conclusion

Through the analysis of the experimental results, it can be concluded that this method can detect double emulsion and obtain accurate edges about inner and outer droplet. At the same time, information such as the size and frequency of droplets can also be accurately acquired. And it can effectively detect and mark the droplets that have failed to form. In the high-speed production process, this method is still very effective. This system currently only uses video for offline detection, the next step is to embed the model into a high-speed camera to achieve real-time monitoring. Our future work will also focus on the implementation of color tracking based algorithms into trajectory mapping of a Baxter robot with a moving colored item, which is also a further expansion of our previous work, to achieve user experience enhanced human-robot interaction[22]. And this method can play an important role in a production environment that requires real-time monitoring.

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