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Capillary Pick-and-Place of Glass Microfibers

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ABSTRACT Microfibers are key components in construction of fiber-based materials, biomimetic materials, microsensors, and other fiber-based microstructures. Due to the scaling law, the adhesion forces such as van der Waals force or electrostatic force in the micro world play a more dominant role than the gravity, causing difficulties in precise pick-and-place of the micro objects. In this paper, we propose a capillary force-based pick-and-place method for handling microfibers. The method combines the typical robotic transportation technique and capillary gripping method to achieve fast and accurate pick-and-place of microfibers. We quantitatively analyzed the critical conditions for capillary pick-up and placement of microfibers and validated the technique experimentally. The theoretical analysis indicates that both pick-up and the placement of microfibers are largely dependent on the contact length on the fiber or the contact angle of the meniscus on the substrate. The experimental results show that the microfibers can be reliably picked up from and placed on the substrate of different materials including paper tissue, glass, silicon, stainless steel, copper with droplet volume of 0.1 nL and 0.3 nL. We further applied the method to the placement of the microfibers on super hydrophilic-super hydrophobic grooves and studied its placement speed and accuracy. We demonstrated that microfiber can be placed in such grooves in less than 0.1 seconds, with linear placement accuracy of 10 μm and angular placement accuracy of 0.5°. The proposed method is fast and simple, and it is especially suitable for handling fragile and flexible micro sized objects and construction of fiber-based materials.

INDEX TERMS Microassembly, capillary pick-and-place, capillary gripper, micro manipulation, microfibers, micro grooves, super hydrophilic-superhydrophobic patterned surfaces.

I. INTRODUCTION

Microfibers are key components for the construction of fiber-enhanced materials, fiber-based microsensors, and other fiber-based microstructures. Due to the scaling law, the adhesion forces such as van der Waals force or electrostatic force in the micro-world play a more dominant role than the gravity, which causing difficulties in the precise pick-and-place of micro-sized objects. Especially, the placement of the micro-sized object is challenging due to the large adhesion force between the handling tool and the micro-sized objects. To solve the problem of precise pick-and-place of micro objects, researchers have developed different gripping methods based on electrostatic force [1], [2], van der Waals force [3], capillary force [4]–[8], friction force [9], magnetic force [10], [11], optical trapping force [12], [13], etc. Capillary force-based gripper has attracted great interest because capillary force is dominant in a great range from micro scale to millimeter scale and suitable for handling flexible, fragile, and micro-sized objects with complex shapes. including spherical objects [4], [14], [15], cylinders, cubes, and cones [16].

In our previous study, we have developed a capillary force based self-alignment method for the assembly of microchips on hydrophilic/superhydrophobic patterned surfaces [17]–[21]. We have also developed a capillary gripper and demonstrated that the capillary gripper can be used to pick-and-place microchips [22] and transport miniaturized soft ribbons made of polydimethylsiloxane (PDMS) [23]. We further demonstrated that the self-alignment of microfibers using capillary force on hydrophilic/superhydrophobic grooved surfaces [24]. So far, the reported capillary force based methods and capillary grippers have shown great potentials in the construction of

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microstructures. However, little has been done on studying the pick-and-place of microfibers using the capillary force based methods.

This paper studies capillary force-based pick-and-place of glass microfibers. The method combines the typical robotic transportation technique and the capillary gripping method to achieve fast and accurate pick-and-place of glass microfibers. We quantitatively analyze the capillary pick-up and placement of microfibers and investigate the critical conditions for capillary pick-and-place of glass microfibers and validate the methods on different substrates experimentally. Additionally, we apply the method to the placement of the microfibers on super hydrophilic-superhydrophobic grooves and study its placement accuracy and speed.

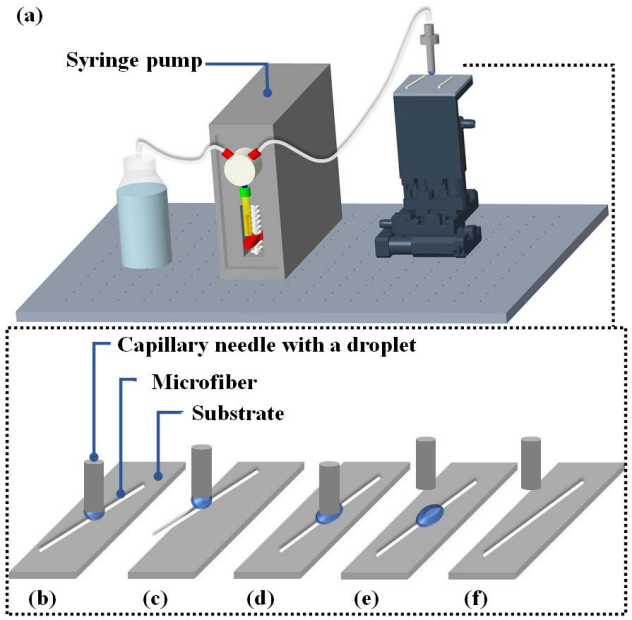

FIGURE 1. Schematic of capillary pick-and-place of a microfiber: (a) a needle connected to a syringe pump produces a liquid droplet at the bottom of the needle; (b) a needle with a droplet moves towards a microfiber; (c) the droplet picks up the microfiber; (d) the microfiber is moved towards the target position; (e) the droplet is in contact with the substrate and the microfiber is placed on the target position; (f) the droplet evaporates leaving the microfiber on the target.

II. METHODS AND MATERIALS

The schematic of the proposed capillary pick-and-place method is shown in Fig. 1. To pick up a glass microfiber, a needle connected to a syringe pump is employed to produce a liquid droplet at the bottom of the needle prior to picking (Fig. 1 (a)). The syringe pump is driven by a DC motor and connected to a liquid bottle, a needle, and a piston through a three-way valve. The pump sucks the liquid from the liquid bottle and produces a liquid droplet through the needle. The needle with the droplet moves towards a microfiber, and the droplet contacts the microfiber where a meniscus is formed between the needle and the microfiber (Fig. 1 (b)). Then, the microfiber is picked up by the meniscus (Fig. 1 (c)). To place a microfiber to a target position, the microfiber is first moved to the target position by the needle with a droplet, and then the droplet is in contact with the substrate and a liquid meniscus is formed between the microfiber and the substrate (Fig. 1 (d)). When the capillary force of the meniscus with the substrate is larger than the capillary force of the meniscus with the needle, the microfiber can be placed on the target position (Fig. 1 (e) - (f)).

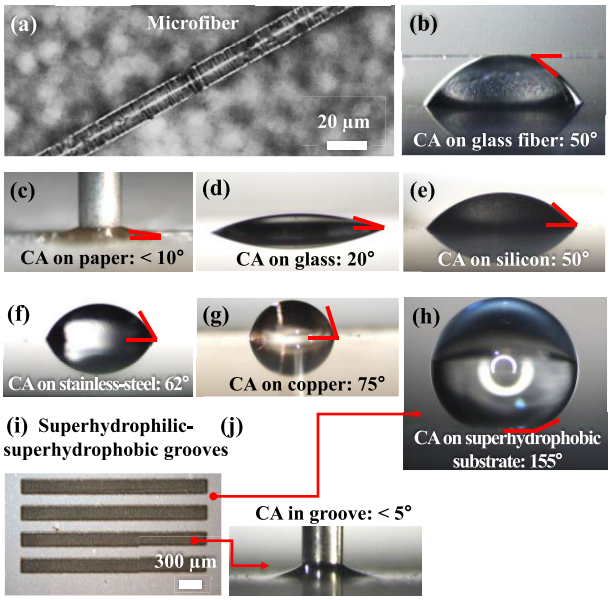

FIGURE 2. Microfiber and pick-and-place substrates: (a) microscopic image of microfiber with a diameter of 13 μm; water contact angle on (b) glass fiber (50°), (c) paper tissue (less than 10°), (d) glass substrate (20°), (e) silicon substrate (50°), (f) stainless steel substrate (62°), (g) copper substrate (75°), (h) superhydrophobic substrate (155°); (i) fabricated hydrophilic-superhydrophobic grooves of 4 mm in length, 300 μm in width, 15 μm in-depth; (j) water contact angle in the groove less than 5°.

A. MATERIALS

To carry out a study on capillary pick-and-place of microfibers, we used microfibers made of glass and with a size of 13 μm in diameter and 4.1±0.1 mm in length. We have prepared substrates made of different materials as the pick-and-place substrates, including paper tissue, glass, silicon, stainless steel, copper, and substrates with superhydrophobic coating, and super hydrophilic-superhydrophobic grooved surfaces. Figure 2 shows a microscopic image of a glass microfiber and water contact angles on the microfiber and on different substrates. Fig. 2 (a) represents the microscopic view of glass fiber, and the diameter of the glass fiber is around 13 μm, which is about a fifth of a human hair in diameter. The measured water contact angles on the glass fiber, paper tissue, glass, silicon, stainless steel, copper, and the substrate with the superhydrophobic coating are 50°, <10°, 20°, 50°, 62°, 75°, 155° respectively, see Fig. 2 (b)-(h). The hydrophilic -superhydrophobic grooved surfaces were fabricated on a silicon substrate using an ultraviolet laser cutting machine (HGTECH LU-5, China) with

a power of 5 W, wavelength of 355 nm. The fabrication process for grooved surface started with spraying a layer of superhydrophobic coating (Whole-Nano, SPN-62, China) on the silicon substrate and dried at room temperature for 24 hours; then the groove structures were fabricated using the laser cutting machine at a speed of 2000 mm/s, frequency of 100 kHz, pulse width of 1 μs, spot size of 50 μm and current of 1 A. Fig. 2 (i) shows the fabricated grooved silicon substrate, where the size of the grooves is 4 mm (length) $\times$ 300 μm (width) $\times$ 15 μm (depth). The water contact angle is less than $< 5°$ (Fig. 2 (j)) in the groove and 155° on the superhydrophobic substrate (Fig. 2 (h)).

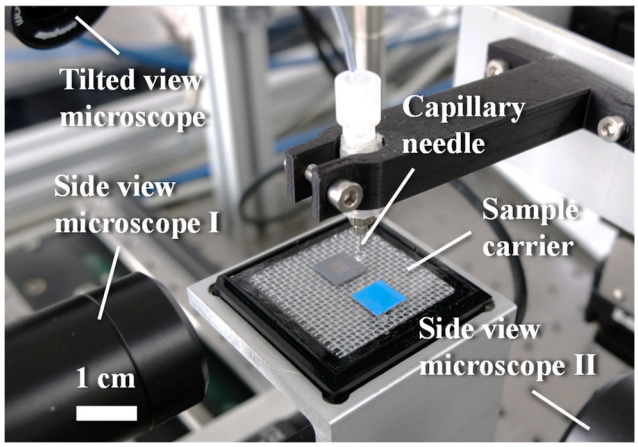

FIGURE 3. Robotic system for capillary pick-and-place microfibers includes a syringe pump with a capillary needle, a sample carrier and three microscopes with CCD cameras.

B. EXPERIMENTAL SETUP

We have set up a robotic system (Fig. 3) to study the capillary pick-and-place of glass microfibers. The robotic system consists of three subsystems: a microscopic vision system for observation, a syringe pump system with a capillary needle for liquid dispensing, and a sample carrier system. The microscopic vision system consists of two side view microscopes (side view microscope I & II) and one tilted view microscope together with three CCD cameras (Point Grey BFLY-U3-23S6C, Edmund Optics, USA) providing two side views and a tilted view of the capillary manipulation. A capillary needle is attached to a syringe pump system (Tecan Cavro Centris, USA) to produce droplets for pick-and-place of microfibers, with a resolution of 0.05% at full stroke. The outer and inner diameter of the capillary needle is 400 μm and 210 μm respectively. The sample carrier consists of three motorized stages (two M-122.2DD1 and one M-414.3PD by Physik Instrumente Germany) allowing the movement of the test samples in three dimensions.

III. THEORETICAL ANALYSIS

In this section, we quantitatively analyze critical conditions for capillary pick-up and placement of glass microfibers. We investigate the influence of the liquid contact length and liquid contact angle of the meniscus on the substrate on pick-up and placement of microfibers with a droplet.

A. CAPILLARY PICK-UP OF MICROFIBER

We investigated the critical conditions for the pick-up of a microfiber under two schemes. One is that the droplet is only in contact with the microfiber and the other is that the droplet is in contact with both the microfiber and the substrate. In the first scheme, the droplet is only in contact with the fiber and a liquid meniscus is formed between the needle and the microfiber as shown in Fig. 4.

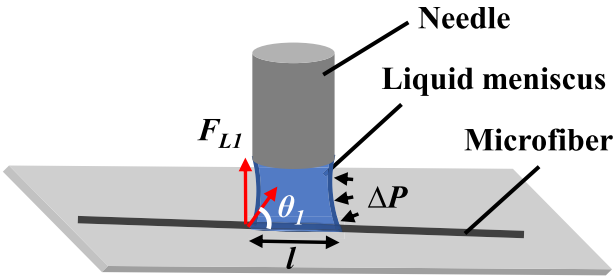

FIGURE 4. Capillary pick-up scheme I: The droplet is in contact with the microfiber and a meniscus is formed between the needle and the microfiber.

The capillary force for picking up a microfiber $F_{pick-up}$ can be expressed as:

$$F_{pick-up} = F_{L1} + F_{A1} = L_1\gamma\sin(\theta_1) + A_1\Delta P \qquad (1)$$

where F_{L1} is the surface tension force of the meniscus along the contact line when the droplet is in contact with the microfiber, F_{A1} is the Laplace pressure over the contact area between the liquid meniscus and the microfiber, which is originated from the pressure difference between the inside and the outside of the liquid meniscus. γ is the surface tension of the liquid per unit length (72.8 mN/m for water), θ_1 is the liquid contact angle on the microfiber, L_1 and A_1 is the perimeter and the contact area of the meniscus with the microfiber respectively, and ΔP is the pressure difference determined from Young-Laplace equation. In the case of picking up a microfiber, the contact area between the microfiber and the needle is very small due to the small width of the microfiber, so the effect of Laplace pressure over the contact area F_{A1} is neglected and the capillary pick-up force can be simplified as the surface tension along the contact line L_1. The contact line L_1 is calculated using $L_1 = 2(d + l)$, where d is the diameter of the microfiber and l is the contact length of the meniscus with the microfiber. Given that the diameter of the microfiber is 13 μm and the contact length equals the inner diameter of the needle of 210 μm, the measured water contact angle on the microfiber is around 50° (Fig. 2(b)), the surface tension along the contact line should be

$$F_{L1} = L_1\gamma\sin(\theta_1) = 2 \times 223 \times 72.8 \times \sin(50°) = 25\mu N \qquad (2)$$

In the capillary pick-up scheme I, the pick-up force only needs to be larger than the gravity of the microfiber to pick up a microfiber. Given the length of the microfiber $l_0 = 4mm$, the mass density of glass $\rho = 2500\ \mathrm{kg/m^3}$, the gravity of the microfiber can be calculated using

$$G = \rho l_0 \pi (\frac{d}{2})^2 g = 1.3 \times 10^{-2} \mu N \tag{3}$$

where g is the gravity acceleration $g = 9.8\ \mathrm{m/s^2}$. The gravitational force on the microfiber is about 13 nN which is about 1/2000 of the capillary pick-up force. Therefore, the microfiber should be easy to be picked up.

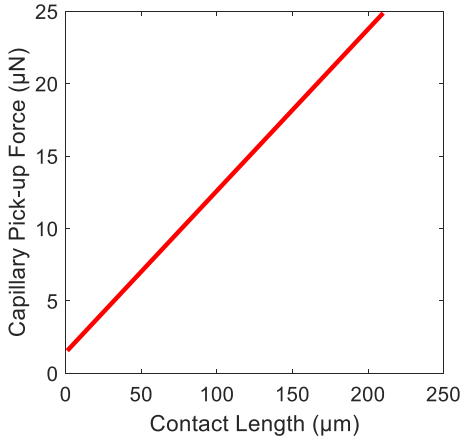

FIGURE 5. Capillary pick-up force as a function of contact length of the liquid meniscus on the microfiber. The capillary pick-up force increases as the contact length increases.

Fig. 5 shows the relationship between the capillary pick-up force and the contact length of the meniscus on the microfiber, where the x-axis represents the contact length, and the y-axis represents the capillary pick-up force. The results indicate that the capillary pick-up force increases as the contact length increases.

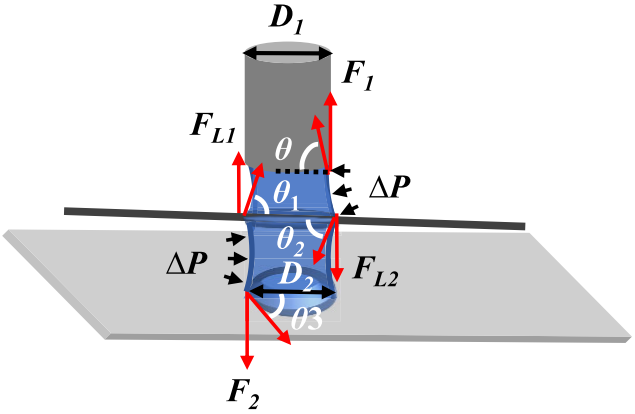

FIGURE 6. Capillary pick-up scheme II: the droplet is in contact with both the microfiber and the substrate.

The second scheme of the capillary pick-up is much more complicated, in the capillary pick-up scheme II as illustrated in Fig. 6, the droplet is in contact with both the microfiber and the substrate, and a meniscus is formed between the needle and the substrate. The microfiber immerses inside the meniscus. The capillary force of the meniscus acting on the microfiber consists of four components, including the capillary force of the meniscus with the needle F_1, the capillary force of the meniscus with the upper side of the microfiber F_{L1} and with the lower side of the microfiber F_{L2}, and the capillary force of the meniscus with the substrate F_2. The capillary force of the meniscus with the needle can be calculated as:

$$F_1 = \pi D_1 \gamma \sin(\theta) + \pi \left(\frac{D_1}{2}\right)^2 \Delta P \tag{4}$$

where θ is the contact angle of the meniscus with the needle, and D_1 is the diameter of the needle. The capillary force of the meniscus on the substrate can be calculated as:

$$F_2 = \pi D_2 \gamma \sin(\theta_3) + \pi \left(\frac{D_2}{2}\right)^2 \Delta P \tag{5}$$

where D_2 is the diameter of the meniscus on the substrate, θ_3 is the liquid contact angle on the substrate. In the second scheme, the microfiber immerses inside the meniscus, and the surface tension force acting on the microfiber along the contact line are F_{L1} and F_{L2}. Due to the small contact area between the microfiber and the meniscus, the Laplace pressure over the contact area can be neglected. The surface tension along the contact line can be calculated using (2). According to the observation from the experiments, when a liquid droplet is in contact with a fiber and the fiber immerses inside the droplet, the contact angle on the upper side of the microfiber θ_1 is about the same as the contact angle on the lower side of the microfiber θ_2. Therefore, we have $F_{L1} \approx F_{L2}$, and the two forces acting on the microfiber cancel each other, indicating that only the capillary force of the meniscus between the needle and the substrate need to be considered during pick-up process.

Given the volume of the liquid is 0.1 nL - 0.3 nL, we calculated the capillary force of the meniscus between the needle and the substrate using a double iteration algorithm developed previously [23]. If the volume of the liquid, the contact angle of the liquid with the needle, and the contact angle of the liquid with the substrate are known, the algorithm can estimate the shape of the meniscus and calculate the capillary force of the meniscus between the needle and the substrate. Fig. 7 shows the capillary force of the liquid meniscus between the needle and the substrate as a function of the liquid contact angle on the substrate with respect to different volumes of the droplet. In the simulation, the contact angle with the needle is set to be 90°. The results show that the capillary force of the meniscus decreases as the contact angle of the substrate increases. The volume of the droplet also plays an important role, the capillary force of the meniscus on the substrate increases as the volume of the droplet increases.

In the capillary pick-up scheme II, whether the microfiber can be picked up is also depending on the rupture of the liquid meniscus between the needle and the substrate.

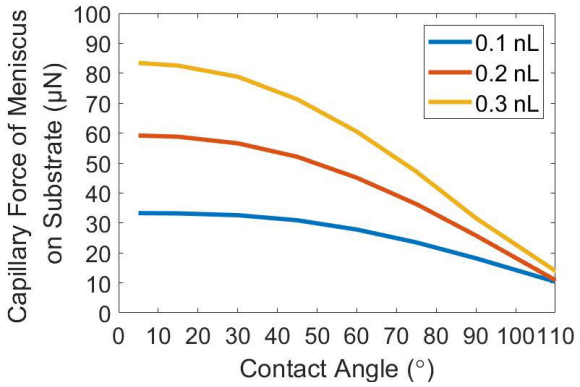

FIGURE 7. Capillary force of the liquid meniscus on the substrate as a function of liquid contact angle on the substrate when the volume of the droplet is 0.1 nL, 0.2 nL, 0.3 nL. The capillary force of the meniscus on the substrate decreases as the contact angle of the substrate increases and the volume of the droplet decreases.

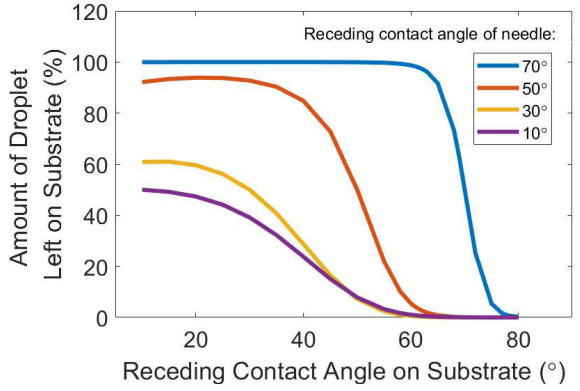

FIGURE 8. Amount of the droplet transferred to the substrate as a function of the receding contact angle on the substrate when the receding contact angle of the needle is 70°, 50°, 30°, 10°. The amount of the liquid transferred to the substrate decreases as the receding contact angle of the substrate increases.

To estimate the rupture, we use the method proposed previously [25]–[27], where the amount of the liquid transferred to a substrate after the rupture of the liquid meniscus between two surfaces can be calculated as [27]:

$$\alpha = \frac{1}{1 + e^{-m(\theta_{r_n} + \theta_{r_{sub}})^n \times (\theta_{r_n} - \theta_{r_{sub}})}} \tag{6}$$

where α is the amount of the liquid transferred to the substrate in percentage, θ_{r_n} is the receding contact angle of the meniscus with the needle, $\theta_{r_{sub}}$ is the receding contact angle of the meniscus on the substrate, m and n are the coefficients which are universal to all surfaces and liquids. The value of m and n are 3.142 and 2.528 obtained through experiments [27]. Fig. 8 shows the relationship between the amount of the liquid transferred onto the substrate and the receding contact angle on the substrate regarding different receding contact angles with the needle. Fig. 8 indicates that when the receding contact angle on the substrate is less than 20°, there are more than 50% of the droplet transferred onto the substrate after the rupture of the liquid meniscus, which will most likely lead to the failed pick-up of the microfiber due to the large contact area of the liquid meniscus with the substrate and large capillary force of the meniscus on the substrate. On the other hand, when the receding contact angle on the substrate is larger than 75°, less than 20% of the liquid are transferred to the substrate, indicating that the microfiber will most likely successfully be picked up from the substrate. Therefore, to pick up a microfiber from the substrate, the substrate should be as hydrophobic as possible so that the amount of the liquid transferred to the substrate is as small as possible. On the other hand, if the substrate is hydrophilic or super hydrophilic, it is suggested that the volume of the droplet should be as small as possible to decrease the contact area with the substrate.

B. CAPILLARY PLACEMENT OF MICROFIBER

For placement of a microfiber using capillary force, we use hydrophilic substrate. When the droplet at the end of the needle is in contact with a hydrophilic substrate, the water droplet wets the substrate, and a liquid meniscus is formed between the needle and the hydrophilic substrate. The scheme for placement of microfiber on a substrate is the same as the scheme II showed in Fig. 6. Whether the microfiber can be placed onto the substrate is depending on the amount of the liquid transferred to the substrate after the meniscus ruptures. The amount of the liquid transferred to the substrate is largely depending on the receding contact angle of the substrate, where a smaller the receding contact angle of the substrate leads to a larger amount of liquid being transferred to the substrate (Fig. 8). Therefore, in order to successfully place a microfiber on a substrate, the substrate should be as hydrophilic as possible, such that a large amount of the liquid will be transferred to the substrate creating a large contact area and large capillary placement force. For the hydrophobic substrate or the substrate with poor wetting properties, it is preferable to apply a large amount of the droplet to forcedly increase the contact area of the meniscus with the substrate.

IV. EXPERIMENTAL RESULTS

We carried out a series of experiments to study the critical factors influencing the capillary pick-up and placement of microfibers, respectively. For pick-up of the microfibers, we investigated the influence of the volume of the water droplet and water contact angle on the pick-up success rate. For placement of microfibers, we studied the influences of the volume of the water droplet and the water contact angle on the placement success rate. We further investigated the placement accuracy and the placement speed of microfibers on hydrophilic/superhydrophobic grooved surfaces.

A. INFLUENCE OF DROPLET VOLUME ON PICK-UP

We have carried out a series of tests to study the influence of the volume of the water droplet on the pick-up of the microfiber. In the tests, the initial apparent volume of the droplet ranges from 0.1 nL to 0.3 nL, defined as the size of the droplet below the needle. The length of the microfiber

used in the tests is 4 mm, and the diameter of the microfiber is 13 μm. According to the theoretical analysis in Fig. 7, when the volume of the liquid is 0.1 nL and the liquid contact angle on the substrate is 75°, the capillary force of the meniscus on the substrate drops to 30 μN, indicating a better chance of successful pick-up. Therefore, the pick-up tests were carried out on a copper substrate where the measured water contact angle is about 75°.

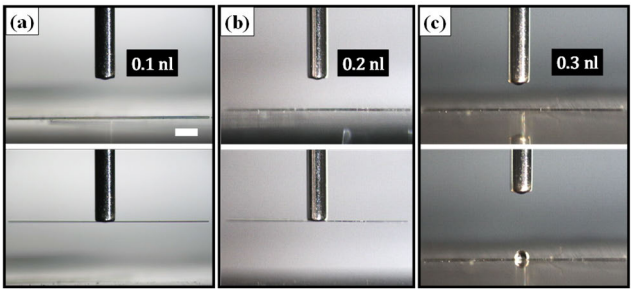

FIGURE 9. Pick-up of microfiber from a copper substrate with the volume of the droplet ranging from 0.1 nL to 0.3 nL. (a) Successfully pick-up of microfiber with a droplet of 0.1 nL; (b) Successful pick-up of microfiber with a droplet of 0.2 nL; (c) Unsuccessful pick-up of microfiber with a droplet of 0.3 nL. Scalar bar: 400 μm.

TABLE 1. Volume of water droplet vs. pick-up success rate.

Volume of Droplet	Pick-up Success Rate [a]	Droplet Transferred to Substrate
0.1 nL	5/5	0 nL
0.2 nL	5/5	0 nL
0.3 nL	2/5	~ 2 nL

[a] Pick-up test for each volume was repeated 5 times, the water contact angle on the copper substrate is 75°.

The pick-up test for each volume was repeated 5 times. Fig. 9 shows examples of the pick-up of microfibers with a droplet of 0.1 nL, 0.2 nL and 0.3 nL, respectively. The microfiber can be successfully picked up with a droplet of 0.1 nL (Fig. 9 (a)) and 0.2 nL (Fig. 9 (b)). The pick-up of microfiber was failed with a droplet of 0.3 nL in this example (Fig. 9 (c)). The results are summarized in Table 1, when the volume is 0.1 nL and 0.2 nL, the pick-up of the fiber took place under capillary pick-up scheme I as shown in Fig. 4, where the droplet was only in contact with the microfiber during the pick-up process, the success rate reaches to 100%. When the volume of the droplet increases to 0.3 nL, the pick-up of the microfiber becomes less reliable, and the success rate drops to 40%. In that case, the 3/5 pick-up test took place under scheme II, where the droplet was both in contact with the microfiber and the substrate, and it can be clearly seen in Fig. 9 (c) that there was a droplet of about 2 nL transferred to the substrate after the pick-up. It appears that the droplet transferred to the substrate is much more than the original volume of the droplet of 0.3 nL, the reason is that the needle is connected to a syringe pump, more water can be dragged out from the needle if the substrate is highly wettable. The reason for the failed pick-up is mainly caused by the liquid transferred to the substrate leading to the large capillary force of the meniscus on the substrate. The results are consistent with the theoretical analysis in Fig. 7, indicating that the volume used for pick-up of a microfiber should be as small as possible to avoid large liquid contact area and large capillary force on the substrate.

TABLE 2. Water contact angle vs. pick-up success rate.

Substrate	Contact Angle / Receding Contact Angle	Pick-up Success Rate [a]	Droplet Transferred to Substrate
Paper tissue	10°/5°	1/5	> 10 nL
Glass	20°/16°	1/5	~ 7 nL
Silicon	50°/19°	2/5	~ 4 nL
Stainless Steel	62°/32°	5/5	0 nL
Copper	75°/34°	5/5	0 nL
Superhydrophobic coating	155°/130°	5/5	0 nL

[a] Pick-up test on each substrate was repeated 5 times and the volume of the droplet was kept as 0.1 nL

B. INFLUENCE OF CONTACT ANGLE ON PICK-UP

A series of tests have been carried out to study the influence of the contact angles of water droplets on the pick-up process. In the tests, we investigated the pick-up of the microfiber from substrates made of different materials, including paper tissue, glass, silicon, stainless steel, copper, and the substrate with the superhydrophobic coating. The measured apparent water contact angles and the receding water contact angles on the paper tissue, glass, silicon, stainless steel, copper, paper tissue, and the substrate with the superhydrophobic coating are 10°/ 5°, 20°/16°, 50°/19°, 62°/32°, 75°/34°, 155°/130° respectively. Each test was repeated 5 times. Based on the investigations of the suitable volume used for pick-up as shown in Table 1, the volume of the droplet for picking up microfiber should be as small as possible. Therefore, in the tests for picking up microfibers on different substrates, the volume of the water droplet was kept as 0.1 nL. The experimental results are shown in Table 2, where the left column represents the type of the substrates and the corresponding water contact angle and the receding contact angle of different substrates, and the right column represents the success rate of the pick-up and the amount of the droplet transferred to the substrate. Table 2 shows that the microfiber can be picked-up reliably on the copper, stainless steel, and substrate with the superhydrophobic coating. The pick-up success rate drops to 40%, 20%, 20% on the silicon, glass and the super hydrophilic paper tissue, respectively. Based on the observation, the smaller the water contact angle on the substrate, the more quickly the water droplet spreads on the substrate, generating a larger contact area and larger capillary force of the meniscus on the substrate.

The experiment results are consistent with the theoretical analysis in Fig. 7, which suggests that a larger contact angle of

the substrate leads to a smaller capillary force on the substrate and a better chance of successful pick-up. In the cases of the unsuccessful pick-up of microfibers on the more hydrophilic substrate, the results are consistent with the theoretical analysis in Fig. 8, which suggests that a smaller receding contact angle on the substrate leads to a larger amount of the droplet transferred to the substrate. The microfibers are less likely to be picked up from the more hydrophilic substrate because of the large number volume of droplet transferred to the substrate. To achieve reliable pick-up of microfibers on the more hydrophilic substrate, it is preferable to use a smaller volume of the droplet and avoid the liquid contacts with the hydrophilic substrate.

C. INFLUENCE OF VOLUME ON PLACEMENT

We have carried out a series of tests to study the influence of the volume of the water droplet on the placement of the microfiber. In the tests, the volume of the droplet is ranging from 0.1 nL to 0.3 nL. We choose to use copper as the substrate for the placement of the microfiber, because the water contact angle on the copper substrate is 75° and it is important to find out the critical conditions for the placement of a microfiber on a substrate with a poor wetting property. Each test was repeated 5 times. The experimental results are shown in Table 3, when the volume of the droplet is 0.1 nL and 0.2 nL, the placement success rate drops to 0% and 20% respectively. The reason for the low placement success rate is mainly due to the poor wetting property of the substrate leading to the small liquid contact area of water meniscus on the substrate and the small capillary force on the substrate.

TABLE 3. Volume of water droplet vs. placement success rate.

Volume of Droplet	Placement Success Rate [a]	Droplet Transferred to Substrate
0.1 nL	0/5	~ 0.1 nL
0.2 nL	1/5	~ 1 nL
0.3 nL	5/5	~ 3 nL

[a] Placement test for each volume was repeated 5 times and the tests were carried out on the copper substrate.

Fig. 10 shows examples of an unsuccessful and a successful placement of microfiber on a copper substrate with a droplet of 0.1 nL and 0.3 nL, respectively. It can be seen clearly that the volume of the droplet transferred to the substrate with a 0.1 nL droplet is much less than the droplet transferred to the substrate with a 0.3 nL droplet. The large volume of the droplet transferred to the copper substrate with a droplet of 0.3 nL leads to the large capillary force, therefore the fiber was able to be placed on the copper substrate. The experimental results are consistent with the theoretical analysis in Fig. 7, indicating that the capillary force of a 0.1 nL meniscus is much smaller than the capillary force of a 0.3 nL meniscus on the same substrate. The experimental results suggest that we should consider increasing the volume of the droplet to achieve successful placement of the microfiber on the substrate with the poor wetting property.

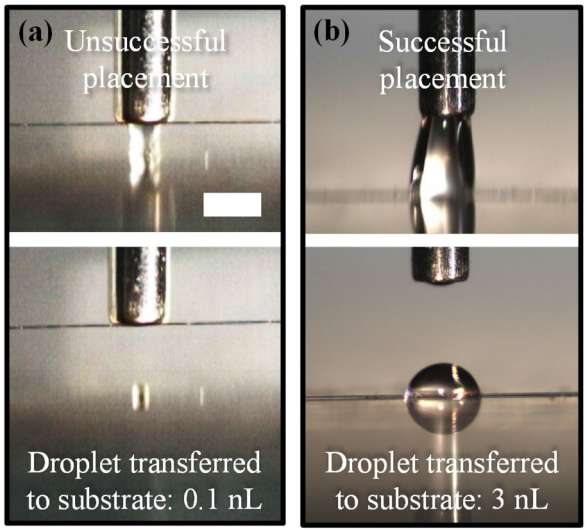

FIGURE 10. Examples of unsuccessful and successful placement of a microfiber on a copper substrate with (a) 0.1 nL and (b) 0.3 nL droplet. Scalar bar: 400 μm.

TABLE 4. Water contact angle vs. placement success rate.

Substrate	Contact Angle / Receding Contact Angle	Placement Success Rate [a]	Droplet Transferred to Substrate
Paper tissue	10°/5°	5/5	> 15 nL
Glass	20°/16°	5/5	~ 10 nL
Silicon	50°/19°	5/5	~ 8 nL
Stainless Steel	62°/32°	5/5	~ 5 nL
Copper	75°/34°	5/5	~ 3 nL
Superhydrophobic coating	155°/130°	0/5	0 nL

[a] Placement test on each substrate was repeated 5 times and the volume of the droplet was kept as 0.3 nL.

D. INFLUENCE OF CONTACT ANGLE ON PLACEMENT

A series of tests have also been carried out to study the influence of the contact angle of water droplets on the placement process. In the tests, we investigated the placement of microfiber on the paper tissue, glass, silicon, stainless steel, copper, and the substrate with superhydrophobic coating. Each test was repeated 5 times. Fig. 11 shows the placement of microfiber on different substrates and the amount of the droplet transferred to the substrate after the placement. The estimated volume of the droplet transferred is >15 nL, 10 nL, 8 nL, 5 nL, 3 nL and 0 nL on the paper tissue, glass, silicon, stainless steel, copper, and the substrate with superhydrophobic coating, respectively. The results show that the amount of the droplet transferred on the substrate decreases as the contact angle of the substrate increases. TABLE 4 summarizes the results of water contact angle versus placement success rate. The results show that the microfiber can be reliably

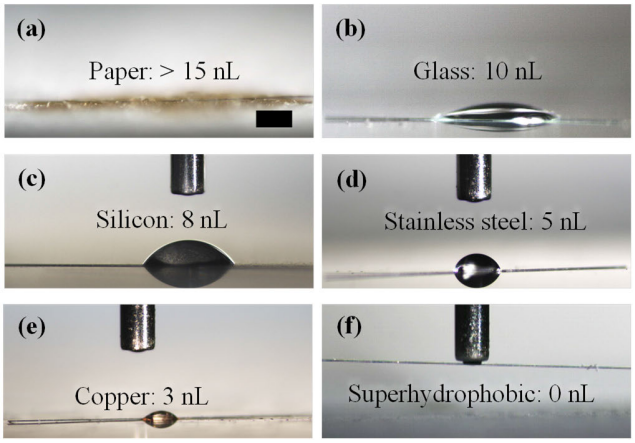

FIGURE 11. Placement of microfiber on a (a) paper tissue, (b) glass substrate, (c) silicon substrate, (d) stainless steel substrate, (e) copper substrate and (f) superhydrophobic substrate. Scalar bar: 400 μm.

placed on almost all the substrates excluding the substrate with superhydrophobic coating. The failed placement of the microfiber on the superhydrophobic substrate is expected because there was no droplet transferred to the superhydrophobic substrate, leading to an extremely small contact area and capillary force on the superhydrophobic substrate.

E. PLACEMENT OF MICROFIBER IN MICROGROOVE

We further studied the placement of microfibers on super hydrophilic/superhydrophobic grooved surfaces. It was previously reported that microfibers can self-align to the microgrooved structures [24] and the self-alignment has great potential for the alignment and distribution of microfibers, but the placement of the microfibers on the grooved structures have not been studied. This study mainly focuses on the placement accuracy and the placement speed of microfiber on hydrophilic-superhydrophobic microgrooves.

To study the placement accuracy of the microfiber on super hydrophilic-superhydrophobic grooves, we carried out a series of tests on the grooves with different widths. In the tests, the length of the microfiber is 4 mm, and the diameter of the microfiber is 13 μm. The water contact angle in the groove and on the substrate are 5°(Fig. 2(h)) and 155°(Fig. 2(i)) respectively. The length of the groove is 4 mm, and the width of the groove ranges from 100 μm to 500 μm. The placement procedure is shown in Fig. 12, firstly, a needle carrying a microfiber moves towards a target groove (Fig. 12 (a)); and then the needle produces a small droplet and the droplet is in contact with the groove (Fig. 12 (b)); finally, the microfiber is successfully placed in the groove (Fig. 12 (c)). The placement accuracy is divided into linear placement accuracy and angular placement accuracy. The linear placement accuracy is defined as the difference between the center of the microfiber and the center of the groove along the width of the groove. The angular accuracy is defined as the angular difference between the microfiber and the groove along the length of the groove. The results are shown

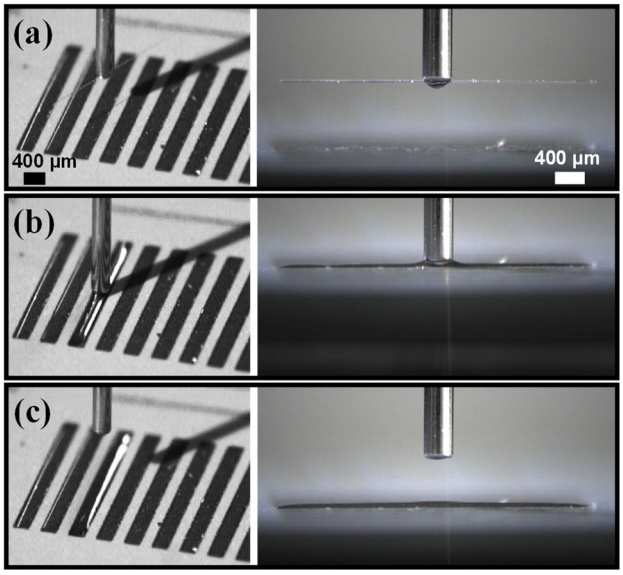

FIGURE 12. Titled view and side view of the placement of a microfiber in a 300 μm wide hydrophilic-superhydrophobic groove: (a) a needle carrying a microfiber moves above a target groove; (b) the droplet is in contact with the groove; (c) the microfiber is successfully placed in the 300 μm wide groove.

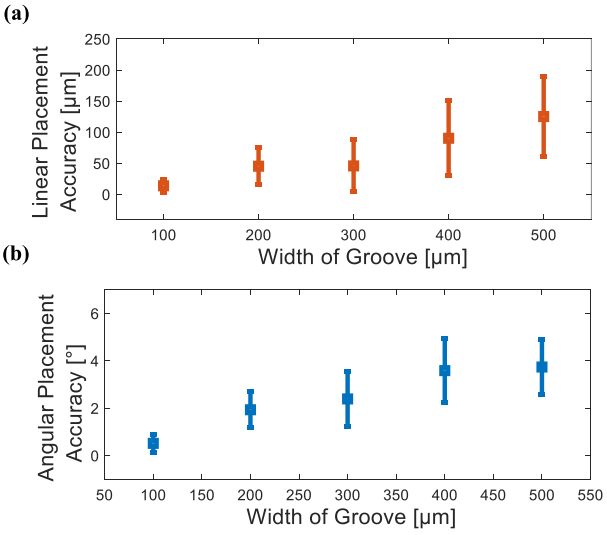

FIGURE 13. Placement accuracy of microfibers as the function of the widths of grooves. (a) linear placement accuracy as the function of the width of the groove; (b) angular placement accuracy as the function of the width of the groove.

in Fig. 13, the x-axis represents the width of the groove, and the y-axis represents the angular placement accuracy (Fig. 13 (a)) and linear placement accuracy (Fig. 13 (b)). Both linear and angular placement accuracy consist of a mean of 5 tests with the standard derivation. The results show that both angular placement and linear placement accuracy worsens as the width of the groove decreases, which indicates that the better the width of the groove matches the diameter of the microfiber, the higher placement accuracy can be achieved. When the width of the groove is 100 μm wide, the linear placement accuracy can reach 10 μm and the angular

placement accuracy is better than 0.5°. The results indicate that the grooves can be used as a template to control the orientation and final position of the fibers. The better the size of the groove matches the size of the microfiber, the better the placement accuracy can be achieved.

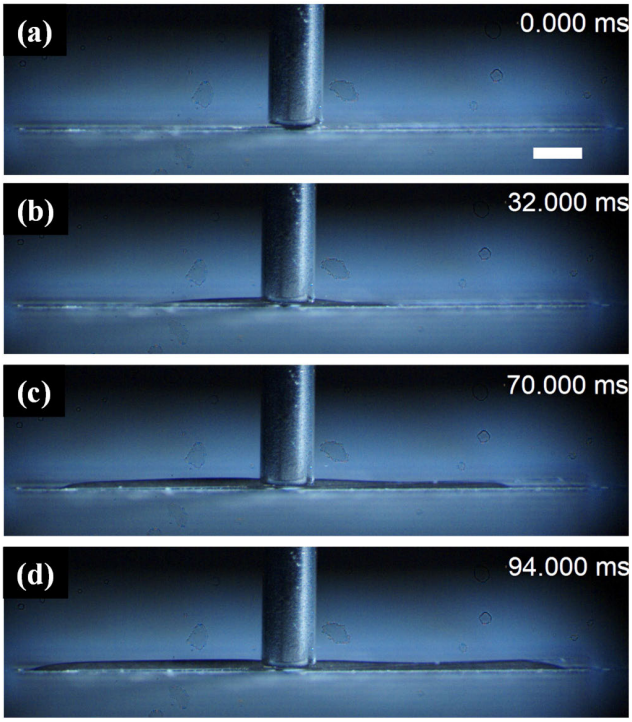

FIGURE 14. Sequences of placement of a microfiber in a super hydrophilic-superhydrophobic groove. (a) A needle with a microfiber is approaching the target groove; (b) and (c) the water droplet wets the groove immediately as it in contacts with the superhydrophobic groove; (d) the water droplet reaches the ends of the groove and the fiber was fully wetted by the liquid film and was successfully placed in the groove. Scalar bar: 400 μm.

The speed of the placement of the microfiber has been investigated using a high-speed camera (Phantom Miro R311, USA). A sequence of the placement of microfiber can be seen in Fig. 14, which are the images captured from a fast speed video of placement of microfiber in a 300 μm wide groove. Firstly, a capillary gripper needle with a water droplet carrying a microfiber is approaching a target groove (Fig. 14 (a)); then, the water droplet is in contact with the groove and quickly spread in the super hydrophilic groove (Fig. 14 (b)-(c)); finally, the water droplet reaches the two ends of the grooves and the fiber are successfully placed in the groove (Fig. 14 (d)). Fig. 14 shows that the microfiber can be placed in a groove within 100 milliseconds. The time needs for placing a microfiber in the groove largely depends on the wetting speed of the water droplet in the groove. Since the groove is super hydrophilic where the water contact angle in the groove is less than 5° (Fig. 2 (j)), once the water droplet is in contact with the groove the water droplet immediately spreads in the groove. When the water droplet reaches the ends of the groove (Fig. 14 (d)), the fiber is fully wetted by the liquid and placed in the groove. The results suggest that the smaller the contact angle on the groove or the better the wetting property of the groove the faster the placement of the microfiber can be achieved.

V. CONCLUSION

In this paper, we propose a capillary force-based method for pick-and-place of microfibers. The method combines the typical robotic transportation technique and capillary gripping method to achieve fast and accurate pick-and-place of microfibers. We quantitatively analyzed the critical conditions for capillary pick-up and placement of microfibers theoretically and experimentally. The theoretical analysis indicates that both the pick-up and the placement are largely dependent on the contact length and the contact angle of the droplet on the substrate. For picking up a microfiber from a substrate, the theoretical analyses suggest that the substrate should be as hydrophobic as possible, and the volume of the droplet should be as small as possible so that the amount of the liquid transferred to the substrate, the contact area with the substrate and the capillary force of the meniscus with the substrate is small. On the other hand, in order to successfully place a microfiber on a substrate, the substrate should be as hydrophilic as possible, so that a large amount of the liquid will be transferred to the substrate creating a large contact area and large capillary placement force. We further investigated the critical conditions for capillary pick-and-place through systematic experiments. The results are consistent with the theoretical estimation, showing that microfibers can be reliably picked up and placed on the substrate made of paper tissue, glass, silicon, stainless steel, copper when the volume of the droplet is 0.1 nL and 0.3 nL. We further studied the placement accuracy and placement speed of microfibers on super hydrophilic-superhydrophobic grooved surfaces. We demonstrated that microfiber can be placed in such grooves in less than 0.1 seconds, and the linear placement accuracy can reach 10 μm and the angular placement accuracy is better than 0.5°. The results suggest that the smaller the contact angle on the groove or the better the wetting property of the groove, the faster the placement of the microfiber can be achieved. The results also indicate that the grooves can be used as a template to control the orientation and final position of the fibers. The better the size of the groove matches the size of the microfiber, the better the placement accuracy can be achieved. Due to the scaling law in micro world, the proposed capillary force-based method can also be applied to handle smaller microfibers. The proposed method is fast and simple, it is especially suitable for handling of fragile components and construction of fiber-based materials.

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