# Manipulation of Capillary Force by Electrowetting for Micromanipulation

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## ABSTRACT

The objective of this paper is to study the utility of capillary forces for micromanipulation. Due to the scaling effect adhesion forces like capillary force and surface tension force are prominent in the micro scale. Control and proper exploitation of these adhesion forces are an important issue for a design of a capillary gripper prototype. In this paper a novel method to control the capillary force by using electrowetting is proposed. Electrowetting is a process by which contact angle of surface is changed by application of electrical energy. Contact angle change facilitates the control of the capillary force and surface tension forces. A Numerical study of formation of the liquid bridge with volume constraint is presented and the feasibility of the micromanipulation scheme is discussed.

***Keywords***: micromanipulation, capillary force, liquid bridge, electrowetting, contact angle.

## 1 INTRODUCTION

Microassembly is the future of MEMS and NEMS technology. The primary difficulty to the idea of micro assembly is micromanipulation. The three major steps in micromanipulation are pickup, transport and release and the most difficult part is the release of the object. Releasing the object against the sticking effect due to large adhesion forces in micro scale is a challenge. From the comparative study of adhesion forces [1] it is understood that capillary force and surface tension forces are the most prominent forces in micro scale. These large forces, if exploited and controlled can become the perfect tool for manipulation. A number of schemes for manipulating this capillary force have been introduced in recent papers. Obata et. al [2] proposed to control the capillary force by changing the liquid bridge volume. Concepts like changes in the probe geometry or the use of a Peltier device to manipulate the liquid bridge evaporation and condensation has also been proposed. In this paper we are proposing a novel way of manipulating the capillary force by changing the contact angle of the probe surface by using electrowetting methods.

## 2 FORMATION OF CAPILLARY BRIDGE

The use of capillary principles for manipulation depends mainly on the formation of capillary bridge between two solids. There are various numerical methods for formation of the liquid bridge, thermodynamic approach of minimization of energy, solving for Laplace equation, geometric approximation of the meniscus are some of them.

The problem here is to determine the force acting between a flat probe surface and a spherical object as shown in Figure 1 and study the effect of contact angle change on the attraction force. In this work we will be using the solution of Laplace equation by iteration method [3]. The Laplace equation expresses the pressure difference across the meniscus as a function of mean curvature of the meniscus. The meniscus profile $x = \boldsymbol{x}\ (y)$ of the liquid bridge can be obtained by solving the Laplace equation with boundary conditions as expressed in equation 3. The Laplace equation is

$$\frac{\Delta p}{\gamma_{lv}} = \frac{\dfrac{d^2 y}{dx^2}}{\left[1+\left(\dfrac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} + \frac{\dfrac{dy}{dx}}{x\left[1+\left(\dfrac{dy}{dx}\right)^2\right]^{\frac{1}{2}}} \quad , \tag{1}$$

which can be rewritten as

$$\frac{\Delta p}{\gamma_{lv}} = \frac{1}{x}\frac{d}{dx}\left(x\sin\varepsilon\right) \ , \tag{2}$$

where $\varepsilon$ is defined by $\boldsymbol{x}'(y) = \cot\ \varepsilon$ , $\gamma_{lv}$ is the liquid vapor surface tension . The boundary conditions for the equation are

$$x_1' = \cot(180-\theta_1) \quad x_2' = \cot(\theta_2+\varphi) \quad . \tag{3}$$

The algorithm follows iteration method to satisfy the contact angle constraints and volume constraint and produces final meniscus geometry.

Once the meniscus is obtained the attractive force is calculated by adding the capillary force and surface tension force exerted on the probe by the liquid bridge. The force terms are expressed in equation 4.

$$F = \pi x_1^2 \Delta p - 2\pi\gamma x_1 \sin\theta_1 \quad (4)$$

$\Delta p$ is the pressure difference across the meniscus and $\gamma$ the surface tension of the liquid. The geometric parameters $x_1$ and $\theta_1$ are described in the axis-symmetric diagram of the probe, object and meniscus geometry provided in Figure 1. Negative force is considered to be attractive force.

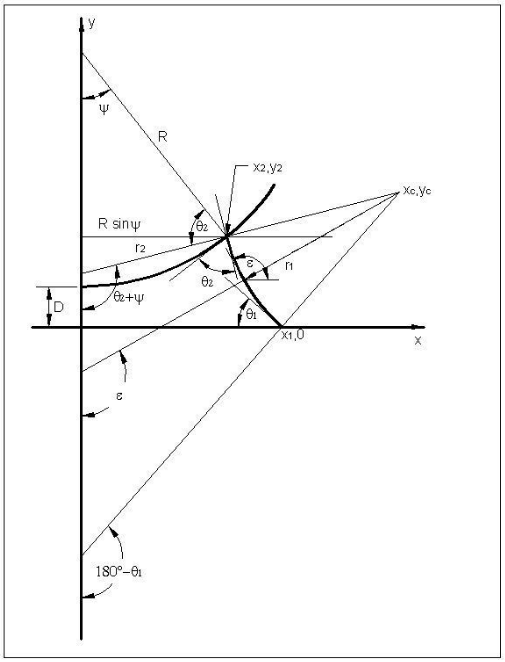


Figure 1: Axis-symmetric diagram of the flat probe, spherical object and the liquid bridge meniscus.

## 3 ELECTROWETTING

Electrowetting is a phenomenon where the contact angle of a solid liquid interface changes when the surface is charged with electrical energy. This is due to additional electric free energy contributed by the capacitor formed by the solid liquid interface and the flat electrode. The contact angle θ decreases with increase in applied voltage following the Lippman's equation expressed as:

$$\cos\theta = \cos\theta_0 + \frac{\varepsilon_0 \varepsilon_r V^2}{2\gamma_{lv}\delta} , \quad (5)$$

where $\varepsilon_0$ is electric susceptibility of vacuum, $\varepsilon_r$ is the dielectric constant of the insulator , $\delta$ is the thickness of the insulator and $\gamma_{lv}$ is surface tension of liquid

In an experiment Lee et. al [5] showed that liquid bridge can be splitted or merged by using electrowetting on dielectric [EWOD] materials. From this work it is evident that this method can be used in micro scale to deal with micro volume of liquid.

Our design proposes the use of the EWOD method and implements it on the probe tip so that by applying voltage we can control the contact angle of liquid probe interface. As the contact angle will changes it will change the capillary force exerted by the liquid bridge between two objects. Figure 2 is a plot of decrease in contact angle with increase in applied voltage. It is found that the decrease of contact angle saturates when the voltage reaches a saturation voltage. So saturation effect of electrowetting will confine the working range of contact angles from approximately 60° to 150°.

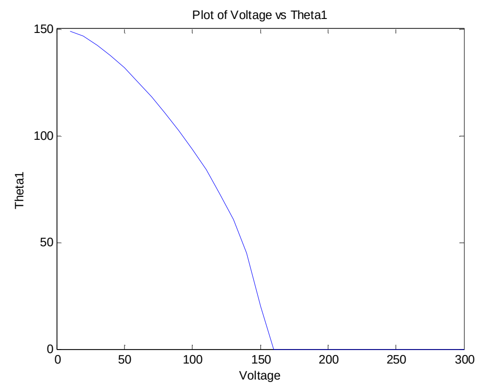


Figure 2: Plot of contact angle $\theta_1$ with applied voltage V for a Parylene (2um thickness) and water interface by using Lippman's equation.

## 4 MANIPULATION SCHEME

The manipulation scheme constitutes of two main processes, pickup and release. For pickup the attraction force exerted on the object by the liquid bridge should be greater than the weight of the object and any adhesion force acting on the object by the surface on which it is placed. The contact angle $\theta_2$ is considered to be zero for full wetting and the contact angle $\theta_1$ is manipulated by applying the voltage. Lower contact angle produces greater attraction force, so the probe surface will be charged with high voltage to reduce the contact angle and moved to close proximity of the object for pick up.

At the time of release the capillary force between the probe and sphere is controlled and made less than any adhesion force acting between the object and the target surface so that the object can be landed on the surface smoothly and with precision. The release mechanism can also be studied on the basis of stability of the bridge which is our future research project.

## 5 RESULTS

### 5.1 Pickup Procedure

The step by step pickup procedure is described below. Initially the probe surface would be hydrophobic with contact angle around 150°. By applying voltage to the probe surface the contact angle will be reduced .For this study the contact angle $\theta_1$ is kept at 60°. A liquid droplet of known volume will be placed on the probe tip. The gripper would then be ready for pickup. When the gripper will approach the object, liquid bridge will be formed between the probe and the object and capillary attraction force will lift off the object from the surface. The adhesion force exerted on the object by the surface is expressed as $F_{adh} = 1.5\pi R\Delta\gamma$ in [2]. The meniscus geometry and forces are obtained from the numerical analysis for study. The forces are then normalized with respect to $\pi R\gamma$ where $R$ is the radius of the spherical object. For a predefined volume with fixed contact angle the plot of total attraction force with increasing gap is presented in Figure 3. It can be observed that as the gap decreases the force increases and when the force is greater than the adhesion force the object is ready to be picked up. The volume of the liquid required for pickup depends on the adhesion force it needs to overcome. Two distinct normalized adhesion forces of 0.4 and 0.75 are utilized to demonstrate the force curves. The liquid is water and the volumes used are 0.1 µl and 0.01 µl.

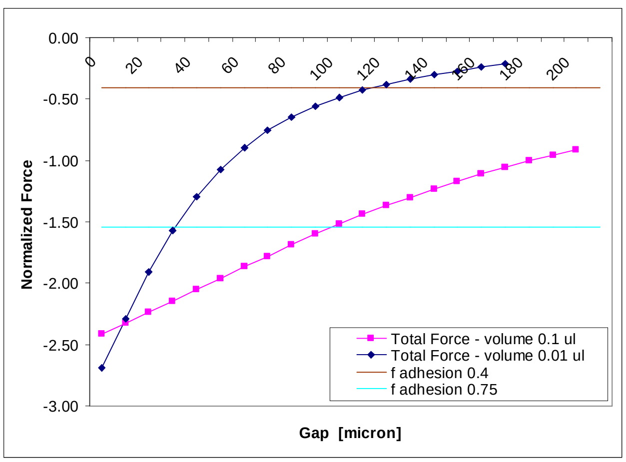


Figure 3: Plot of attractive force with increasing gap between a 1mm radius sphere and flat probe for 0.1 µl liquid and 0.01 µl water.( $\theta_1$ = 60° and $\theta_2$ =0° )

### 5.2 Release Procedure

At the time of release, the gripper is moved and placed above the target surface and the applied voltage is reduced to increase the contact angle. Figure 4 shows how the force decreases with increase in contact angle. When it is less than the adhesion force exerted by the target surface the object sticks to the surface and the probe can be removed easily. Increase in angle also changes the stability of the liquid bridge and forms necking which also can be facilitated to break the bond between the probe and the object.

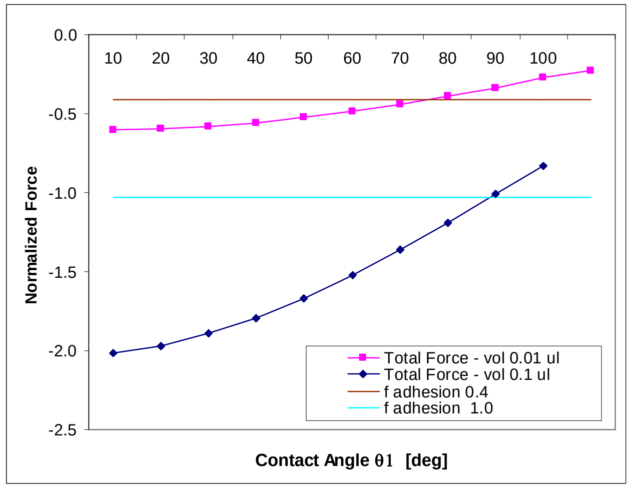


Figure 4: Plot of attractive force with increasing contact angle $\theta_1$ between a 1mm radius sphere and flat probe for 0.1 µl liquid and 0.01 µl liquid.( Gap = 100 µm)

## 6 CONCLUSION

A scheme for micromanipulation by exploiting the capillary and surface tension force is presented in this paper. A systematic study of pick up and release of the object is described. A novel method to control the contact angle by use of electrowetting method is proposed. From the results of the numerical simulation it can be seen by changing the contact angle through electrowetting the release of an object from the probe surface can be possible.. Further study on the volume requirements depending on the object size is needed as a manipulation guideline. Research is needed to understand the formation of neck during the release mechanism which can be another tool of release. Numerical procedure shows Increase in contact angle results in instability of the liquid bridge but the deformation of liquid bridge is yet to be understood.

## REFERENCES


[1] R. S. Fearing, "Survey of Sticking effects for micro parts handling" ,International Conference on Intelligent Robots and Systems, 2 ,2212,1995

[2] K. J.Obata, T. Mokotado, S. Saito, K. Takahasi, "A scheme for micro-manipulation based on capillary force", J. Fluid.Mech, 498, 113-121, 2004

[3] R. Aveyard , J. H. Clint, V. N. Paunov, D. Nees ,

”Capillary condensation of vapors between two solid surfaces: effects of line tension and surface forces”, Phys. Chem. Phys. Chem., 1, 155-163, 1998

[4] F. M. Orr, L. E. Scriven, A. P. Rivas ,” Pendular Rings between solids: meniscus properties and capillary force” , Journal of Fluid Mechanics, 67(4 ), 723-742, 1975

[5] J. Lee, H. Moon, J. Fowler, T. Schoellhammer, C. J. Kim , ”Electrowetting and electrowetting-on-dielectric for micro scale liquid handling”, Sensors and Actuator, 95,259-268,2002.