Principle of a submerged freeze microgripper.

Beatriz Lopez Walle, Michaël Gauthier, Nicolas Chaillet

Principle of a Submerged Freeze Microgripper

Beatriz López Walle, Michaël Gauthier and Nicolas Chaillet
Laboratoire d'Automatique de Besançon - UMR CNRS 6596 - ENSMM - UFC
24, rue Alain Savary - 25000 Besançon, France
Email: {blopez,gauthier,chaillet}@ens2m.fr, Telephone: (33) (0) 381408801, Fax: (33) (0) 381402809
web site: www.lab.cnrs.fr/pronomia

***Abstract*— Manipulating microscopic objects still remains a very challenging task. In this paper, we propose a freeze microgripper working in an innovative environment, i.e. liquid medium. We first review a comparative analyse of the influences of dry and liquid media on contact and non contact forces. It clearly shows the interest of the liquid medium. A survey of different microhandling systems based on the use of ice is also given. The proposed submerged microgripper exploits the liquid surroundings to generate an ice microvolume as an active end-effector. Its principle based on Peltier effect is described and the physical characteristics of the prototype are detailed. We present the results of the numerical modelling of the prototype developed. Experimentations validate the thermal principle. Using it for micromanipulation tasks is the purpose of further work.**

I. Introduction

The main difficulties for manipulating and assembling micro-objects lie in the efficiency, reliability and precision of handling [1]. Actually, no repeatable and reliable automated micromanipulator exists for micro-objects sized under 100 μm. In addition, surface forces, preponderant compared to volumic forces, affect the micromanipulation task, especially the release [2]. The development of efficient micromanipulations under 100 μm is thus particularly relevant.

In this paper, we propose to manipulate and assembly artificial low thermal conductive micro-objects at this scale being submerged in a liquid medium.

A comparative analysis of micromanipulation conditions in dry and liquid media in terms of contact and non contact forces and hydrodynamic forces shows the interest of submerged micromanipulations.

First, the pull-off force which represents the necessary force to detach an object from a substrate is proportional to the surface energy between two objects. This energy decreases for submerged objects [3]; consequently, pull-off force reduces in liquid compared to air.

Secondly, the van der Waals (vdW) force, which is proportional to the Hamaker constant, is reduced in a liquid medium [3]. Moreover, the extended DVLO theory [4], [5], shows that double layer force, solvation force, steric force (particular forces in such medium) are repulsive in most cases, reducing thus the effect of the attractive vdW force.

Third, the electrostatic force is greatly reduced in submerged conditions because water has higher dielectric constant and better electric conductivity.

Fourth, the capillary force induced by the surface between the liquid and the air near to the object is naturally cancelled in a submerged medium [2].

Finally, the hydrodynamic force drastically limits the maximal velocity of the micro-objects reducing significantly their loss rate. Considering the same effect, the velocity of the microgripper end-effectors has to be limited in order to avoid disturbances. Nevertheless, during experiments the effector velocity stays high compared to the size of the objects [6].

Then contact and non contact forces are reduced in liquid while hydrodynamic force increases. Both phenomena bring advantages to submerged manipulation under the limit of 100 μm [2], [6]. First experimental comparative micromanipulation tests confirm it. However, the reliability of the release task remains a critical problem for so small objects.

The proposed submerged freeze gripper exploits the liquid environment to generate an ice microsurface whose adhesive properties allow handling, manipulation and assembling of micro-objects. Aditionnally, when ice is thawed, it naturally disappears in the aqueous surroundings cancelling capillary force. Potential applications of this principle are optical, mechanical and electrical microcomponents assembly [1].

Section II presents a brief overview of several kinds of manipulation strategies. Then the experimental device is described in section III and its modelling in section IV. Finally, section V presents experimentations.

II. Micromanipulation Strategies

A. Gripping Strategies

Above all, any micromanipulator must be able to pick up, move, and release the manipulated object. The two first actions can be generally accomplished, but a reliable and accurate release is still critical [7]. We distinguish three strategies, presented in Fig. 1, to tackle adhesion forces during the release phase.

In the first one, named contactless manipulation, the handling task is not influenced by adhesion forces. The gap between the object and the gripper remains larger than

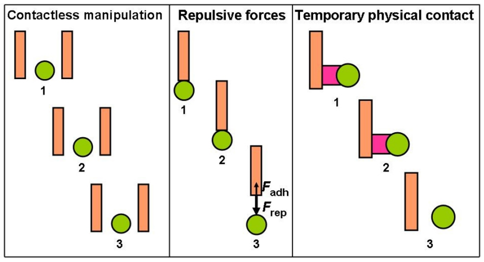

Fig. 1. Release strategies to overcome the adhesion forces.

the action range of adhesion forces, like in laser trapping [8] and dielectrophoresis [9]. These strategies need specific conditions for the objects and the surroundings.

The electrostatic handling [10] and the release by acceleration [7] are a second strategy. The repulsive forces F_{rep} are bigger than the adhesion forces F_{adh} to detach the object from the gripper; but most often the final position of the object is not totally controlled.

The capillary based gripper illustrates the third strategy [10]. It uses the surface tension force of a liquid droplet between the gripper and the object. To release it, the droplet is evaporated, eliminating the physical contact. However, capillary forces could not disappear completely then it is necessary to combine with other strategies, like adhesive substrates [10], [11].

In this work we chose the last principle, i.e. the temporary physical contact. The handling procedure appears simple. When the gripper is sufficiently close to the object, an ice microvolume is generated at the tip freezing just a small part of the object or completely covering it. The object is then handled. For the release phase, freezing is stopped, the ice droplet thaws liberating the object. As the gripper and the object are submerged, the melted ice surface mixes with the medium and capillary forces have no influence.

B. *Use of the Ice in Micromechatronics*

The ice in micromechatronics systems has two main applications: microfluidics and micromanipulation in air medium. In the first one, ice valves close or open a liquid flow in a microchannel [12], [13]. A thermoelectric device, such as a Peltier junction, is used to freeze the working fluid running inside the channel. Thereby the flow is blocked by the ice formation.

Adhesive properties of ice are also used for manipulating micro-objets in air. The cryogenic grippers based either on the Joule-Thompson effect [1], or on the Peltier effect [11], [14], freeze the water forming a thin ice film that connects the gripper to the object. The adhesive force generated by the ice allows to pick up the object. The release of the object is done by thawing the ice, stopping freezing or heating the gripper.

These cryogenic grippers look flexible and well-adapted to their applications. However, they work in air. To generate ice, the water is provided by a separated mechanism. In addition, particular conditions either environmental (low temperature and low humidity) or mechanical (release on adhesive surface) are needed. Finally, the size of the objects manipulated is bigger than 200 μm.

Despite the drawbacks, cryogenic grippers are a very promising approach. They warrant a reliable grip with no surface damaging, provide high holding forces without introducing additional stresses in the object and the handling process can be designed as almost independent of shape and material properties.

In order to overcome the drawbacks, we propose an innovative way which consists of the use of such a principle but totally submerged in a liquid medium.

III. Experimental Device

The submerged freeze gripper proposed and developed is based on Peltier effect. In this section, we describe the whole system principle. Then we present the physical characteristics of the prototype.

A. *Submerged Freeze Gripper Principle*

Cryogenic grippers presented above work in the air medium, so the water required to generate ice is supplied by an external device. The submerged freeze gripper utilizes the aqueous environment to create an ice droplet to catch objects with a low thermal conductivity. The cooling energy for freezing water is provided by the Peltier thermoelectric components.

The submerged freeze system, as shown in Fig. 2, consists of two Peltier module stages. The first one is a Peltier micromodule named MicroPelt (μP). The gripper is directly attached to its cold side. So the MicroPelt can cool the gripper and consequently generates the ice microvolume on its acting part. The convection heat flow in water is so important than it could warm up the system (liquid, gripper and Peltier module) instead to cool it. A second Peltier element is thus connected to decrease the temperature at the hot face of the MicroPelt. The second Peltier module, called MiniPeltier (mP), guarantees a constant temperature on the MicroPelt's heat sink. The MiniPeltier and its heat sink stay in air so that the heat is dissipated outside the water. The end-effector and the MicroPelt are completely submerged, requiring thus an electrical insulation.

B. *Physical and Technical Characteristics*

The experimental device shown in Fig. 3 presents the two Peltier modules with their respective heat sinks and the support for the MicroPelt's electrical connection.

The MicroPelt (Infineon Technologies AG), whose dimensions are 720 $\times$ 720 $\times$ 428 μm^3, is fastened to a copper heat sink with silver glue that provides excellent thermal conductivity. The MiniPeltier's (Melcor FC0.6-18-05) dimensions are 6.2 $\times$ 6.2 $\times$ 2.4 mm^3. Its cold face is

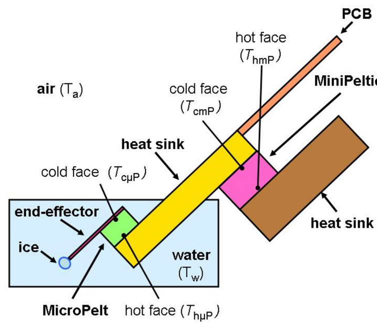

Fig. 2. Submerged freeze system principle.

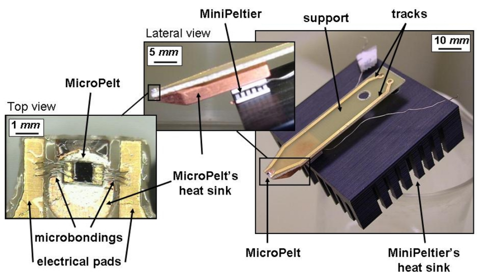

Fig. 3. Experimental freeze system.

fixed to the MicroPelts' heat sink while its hot face is fixed to an Aluminium heat sink.

Because of the dimensions of the MicroPelt, the electrical connections between the MicroPelt's electrical contacts and a support specially designed for this purpose, have been established using microbonding technology.

The micro-end-effector is a $1500 \times 3500 \times 20\ \mu m^3$ Nickel sheet. Its body covers all the surface of the MicroPelt's cold face to take advantage of its whole cooling power, as well as the tip corresponds to the size of the objects that will be gripped.

IV. Microgripper modelling

The thickness of the ice surface on the end-effector tip depends thus on both the electrical current of the MicroPelt, $i_{\mu P}$, and the electrical current of the MiniPeltier, i_{mP} [1]. The objective of this section is to determine the optimal values of these electrical currents.

The Peltier modules represent the active elements of the submerged freeze gripper. Every Peltier module provides a cooling capacity (Q_c) and a heating capacity (Q_h), which depend on its geometric and physical characteristics. The cooling and heating capacity expressions include the Peltier effect ($\alpha T_{c,h} i$), the Joule effect ($Ri^2/2$) and the heat flow through heat conductivity ($k\Delta T$), and can be written as:

$$Q_c = -\alpha T_c i + Ri^2/2 + k\Delta T \quad (1)$$

$$Q_h = \alpha T_h i + Ri^2/2 - k\Delta T \quad (2)$$

where α is the Peltier coefficient, R is the electrical resistance, k is the thermal conductivity coefficient of the module, i is the electrical current supplied, T_c is the temperature at the cold face, T_h is the temperature at the hot face, and ΔT is the difference of temperature between the two faces.

Table IV gives the physical parameters for the MicroPelt and the MiniPeltier.

Coefficient	**MicroPelt** (μP)	**MiniPetier** (mP)
Peltier coefficient α (V/K)	1.0×10^{-3}	7.0×10^{-3}
Electrical resisitance R (Ω)	0.2	1.158
Heat conductivity k (W/mK)	0.0082	0.017

TABLE I

Physical parameters for the Peltier elements

For the thermal study as well as for the examination of the working principles, the whole system has been modelled, using the finite elements (FE) software COMSOL Multiphysics 3.2, in two parts: in the first one, we calculated the optimal electrical current for every Peltier module using static modelling; in the second one, we examined the dynamical behaviour of the system.

A. Static modelling

The cooling capacity Q_c of the Peltier elements is a parabolic function of the current i according to (1).

In the case of the MicroPelt, an optimal current $i^*_{\mu P}$ exists when this cooling capacity $Q_{c\mu P}$ is maximal and when the temperature on its cold side $T_{c\mu P}$ is minimal, being the temperature on the tip surface also minimal.

The MicroPelt injects the cooling capacity to the gripper in order to create the ice surface as we explained below. To warrant the maximal cooling of the MicroPelt, its hot face temperature must be slightly above $0\ ^oC$. Because of this, the MiniPeltier's cold side temperature T_{cmP} keeps at $2\ ^oC$. This temperature is sufficiently close to $0\ ^oC$ but it prevents from freezing the MicroPelt's heat sink.

To determine the optimal current of the MicroPelt, the MiniPeltier's cold side temperature T_{cmP} is fixed at $2\ ^oC$, the behaviour of the surroundings medium is simulated by FE and we range $i_{\mu P}$ to obtain the minimal temperature $T_{c\mu P}$. Fig. 4 shows that this optimal current $i^*_{\mu P}$ is $1.1\ A$.

Knowing the optimal current of the MicroPelt, we can establish the optimal current in the MiniPeltier i^*_{mP} that must warranties the temperature of its cold side T_{cmP} at $2\ ^oC$ as we referred below. In Fig. 5 we note that this temperature is reached at $i^*_{mP} = 0.8\ A$.

[1]The electrical current i is noted $i_{\mu P}$ or i_{mP} if it corresponds to the current applied to the MicroPelt or the MiniPeltier respectively.

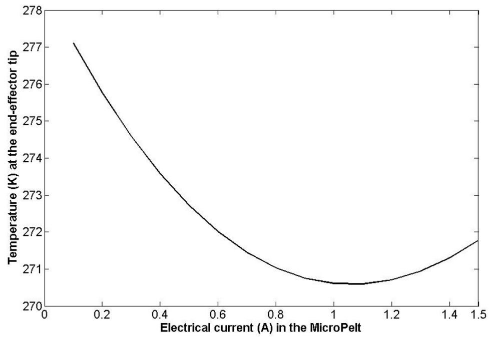

Fig. 4. Temperature at the active surface of the gripper as a function of MicroPelt's electrical current.

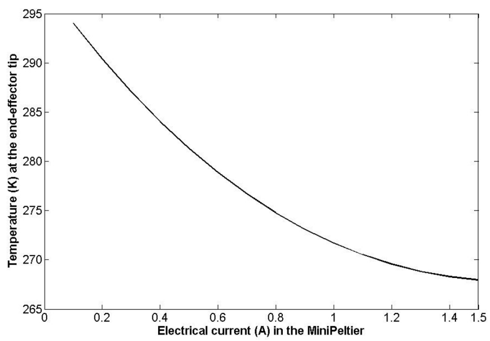

Fig. 5. Temperature at cold surface of the MiniPeltier as a function of MiniPeltier's electrical current.

B. Dynamical modelling

The dynamical modelling of the submerged freeze gripper allows us first to design the geometry of the Nickel end-effector to obtain the best cooling flow; secondly to observe ice generation and its shape on the active surface; and finally to obtain the cycle times of the system. In the dynamical FE model, current i_{mP} is set at its optimal value i^*_{mP}, while current $i_{\mu P}$ is ranged between zero and its optimal value $i^*_{\mu P}$.

So first, as the thermal performance of the gripper was a critical parameter, the Nickel end-effector has been designed using FE modelling with the aim of optimizing heat distribution while keeping a reduced size of the tip. Fig. 6 presents the design of the end-effector used in the experiments.

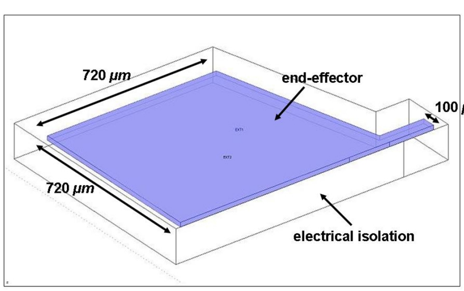

Fig. 6. Nickel microtip design.

Secondly, in order to study the working of the gripper, the ice generation on the active surface of the gripper was modelled at different times applying the optimal electrical currents. We observed that the ice was ellipsoidal in shape and depends on cooling time. In Fig. 7 we see the ice shape at the tip after 1 second when the temperature of the water surrounding was 2 ^oC.

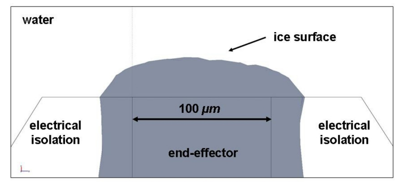

Fig. 7. Ice surface at the tip after 1 second of cooling.

Finally, the dynamical modelling allowed us to obtain both maximal cycle time and stable working cycle of the gripper. The electrical current of the MiniPeltier stays constant at its optimal value i^*_{mP}. The current through the MicroPelt $i_{\mu P}$ ranges between zero and its optimal value $i^*_{\mu P} = 1.1\ A$. The maximal cycle time for a freezing-thawing cycle was 0.2 s and the stable working cycle is found at 2 s.

Numerical modelling was used to study and validate our submerged freeze gripper. Modelling interactivity between the end-effector and different material objects confirms that manipulation is better for objects with a low thermal conductivity. Moreover, optimal parameters for the experimental micromanipulations were obtained. In addition, the working cycle found (0.3 s) is very short and can be compared with the cycle times of mechanical tweezers and vacuum grippers [11].

V. Experimental Validation

The process steps and the cycle time were observed thanks to the experimentations.

Fig. 8 shows the three phases of the process: (a) precooling, (b) cooling under 0 ^oC and (c) heating over 0 ^oC. In fact, the MiniPeltier is activated at $t = 0\ s$ to decrease the temperature of the MicroPelt's heat sink during the precooling phase (a). The MicroPelt is then activated and the temperature on the end-effector tip decreases under 0 ^oC as shown in phase (b). Finally, if the electrical current of the MicroPelt is cancelled, as observed in phase (c), the temperature on the end-effector tip increases over 0 ^oC.

In this experimentation, the current i_{mP} is set constant at $i^*_{mP} = 0.8\ A$. To test the validity of the microgripper, the current $i_{\mu P}$ is first limited to 0.2 A. The temperature is measured with a microthermocouple. Its effects as a source of thermal conduction are not considered.

The working cycle of the MicroPelt is presented in Fig. 9. The temperature at the active area of the microgripper decreases under 0 ^oC in 0.5 s after the activation of the

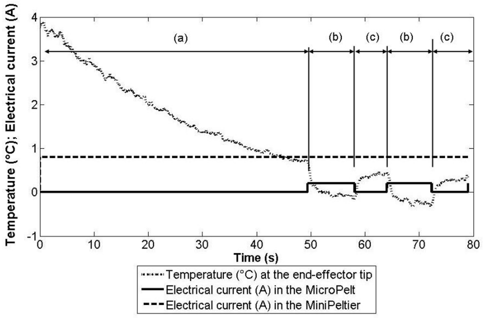

Fig. 8. Temperature at the active area of the microgripper, electrical current in the MicroPelt, and electrical current in the MiniPeltier as a function of time.

MicroPelt. However, after cancelling MicroPelt's electrical current, the end-effector takes more than 0.6 s to pass over 0 ^oC.

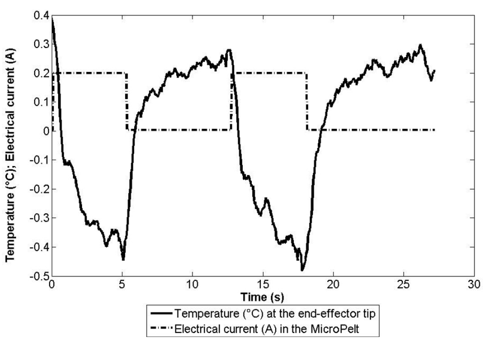

Fig. 9. Temperature at the active area of the microgripper and electrical current in the MicroPelt as a function of time.

Experimentations allow thus validating the thermal principle of the submerged freeze gripper. Controlling both Peltier modules temperature through their electrical currents and micro-object manipulations will be the objective of further work.

VI. Conclusion

Reliable manipulations for micro-objects sized under the 100 μm require novel gripping strategies. The analysis of contact forces, distance forces and hydrodynamic forces shows that performing micromanipulations in a liquid medium is more interesting than dry micromanipulations. We develop an innovative micromanipulation strategy adapted to the aquatic medium. Effectively, the submerged freeze gripper presented in this paper, exploits the liquid medium to generate an ice microsurface to manipulate micro-objects. Furthermore, it takes advantages of the environment mixing the micro-ice formation in this aqueous medium when it thaws to release the object, overcoming thus the capillary force. Modelling the acting principle based on Peltier effect brings out process parameters like optimal electrical currents and cycle times. The principle has been also validated by experimentations. Further works will focus on manipulating micro-objects, improving the control of the temperature and thickness of the ice microsurface, and the miniaturization of the system to manipulate micro-objects sized under the 50 μm.

References

[1] J. Liu, Y.-X. Zhou, and T.-H. Yu, "Freeze tweezer to manipulate mini/micro objects," *Journal of Micromechanics and Microengineering*, vol. 14, no. 2, pp. 269–276, February 2004.

[2] M. Gauthier, B. López-Walle, and C. Clévy, "Comparison between micro-objects manipulations in dry and liquid mediums," in *In Proc. of the 6th CIRA*, Espoo, Finland, June 2005.

[3] J. Israelachvili, *Intermolecular and surfaces forces.* Academic Press, 1991.

[4] Z. Xu and R. H. Yoon, "The role of hydrophobic interactions in coagulation," *Journal of Colloid Interface Science*, vol. 44, no. 132, pp. 532–541, 1989.

[5] ——, "A study of hydrophobic coagulation," *Journal of Colloid Interface Science*, vol. 45, no. 134, pp. 427–434, 1990.

[6] M. Gauthier et al., "Forces analyses for micromanipulations in dry and liquid media," *Journal of Micromechatronics*, vol. 3, no. 3-4, pp. 389–413, September 2006.

[7] D. S. Haliyo and S. Régnier, "Advanced applications using micromad, the adhesion based dynamic micro-manipulator," in *In Proc. of AIM*, Port Island, Japan, July 2003, pp. 880–885.

[8] F. Arai et al., "Synchronized laser micromanipulation of microtools for assembly of microbeads and indirect manipulation of microbe," in *In Proc.of IROS*, Las Vegas, USA, October 2003, pp. 2121–2126.

[9] A. Rosenthal and J. Voldman, "Dielectrophoretic traps for single-particle patterning," *Biophysical Journal*, vol. 88, March 2005.

[10] P. Lambert, "A contribution to microassembly: a study of capillary forces as a gripping principle," Ph.D. dissertation, Université Libre de Bruxelles, 2004.

[11] S. Droz et al., "New generation of grippers for the manipulation of miniaturized components," in *Proc. of Mechatronics*, Besançon, France, October 2001, pp. 572–575.

[12] L. Gui and J. Liu, "Ice valve for a mini/micro flow channel," *Journal of Micromechanics and Microengineering*, vol. 14, pp. 242–246, November 2004.

[13] R. P. Welle and B. S. Hardy, "Fabrication and charaterization of fast-acting peltier-actuated microvalves," in *In Proc. of the 9th MicroTAS*, Boston, USA, October 2005, pp. 1078–1080.

[14] G. Seliger, J. Stephan, and S. Lange, "Hydroadhesive gripping by using peltier effect," in *In Proc. of IMECE*, Florida, USA, November 2000, pp. 3–8.