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Author(s)	NGUYEN, VAN PHO
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Description	Supervisor:HO Anh Van, 先端科学技術研究科, 博士

氏　　　　　名	NGUYEN Van-Pho
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論 文 題 目	Mechanics of Wet Adhesion on Patterned Soft Surface, and Application to Development of Soft Robotic Hand
論文審査委員	主査　HO Anh-Van　北陸先端科学技術大学院大学　准教授
	高村　禅　同　教授
	水田　博　同　教授
	小矢野　幹夫　同　教授
	平井　慎一　立命館大学　教授

論文の内容の要旨

1. Research Content

The sole toe of the tree frog has a microstructure in the contact interface comprising from a vast number of cells interspaced by a channel system. When contacting with surrounding environments, fluid inside the grooves is ejected to produce the wet adhesion, helping this animal to secure the substrate. Wet interfaces can facilitate the soft robotic fingers to archive an effect grasping thanks to increment of the adhesion interactions with the gripped object. Hence, the wet adhesion mechanism of the tree frog toe hinted us to develop the soft robotic hands for grasping the soft-fragile objects in wet environments. Thus, my thesis illustrates a mechanical approach understand the significant role of morphological design on rising the wet adhesion for secure grasping by the soft pads attached on the robotic finger’s tips. To answer the given question, we firstly constructed a model of contact mechanics for the wet interface between the soft pad and its surrounding substrates. Then, two conditions of these such pads were carried out in comparisons between: a pad with a normal surface (n-pad), and a pad with a micropatterned surface (m-pad). The latter was designed and estimated inspired by the wet adhesion principle between the surface of the tree frog’s sole toes and their environments. In this analytical model, we proposed a method to investigate the contact force for two geometries of the substrates having: flat and curve contact interfaces.

For the flat contact interface, the adhesion and contact forces between the n- and m-pads with their substrate were estimated for both normal and tangential directions. In this scenario, these pads were cast from silicon rubbers. Additionally, a square-patterned mold, as the m-pad mold, comprising from 3600 85µm×85µm cells interspaced by a channel network with 15µm wide and 15µm deep was fabricated from the electron beam lithography (EBL) technology. The obtained results of the normal and tangential contact forces for the m-pad and the n-pad were verified through the measurements in wet conditions.

Validated results illustrated a good agreement with those of the estimation, revealing that the micropatterned morphology can enhance the contact force for the m-pad by two-fold in case the normal and 1.2- to 1.4-fold in case the tangential force.

The model of contact mechanics with adhesion in flat interface was applied to the flat contact interface. Herein, the adhesion force was focused on the normal direction in different contact scenarios. In addition, the micropatterned pad used in this analysis has 3600 cells each 85 μm×85 μm separated by grooves 15μm wide×44μm deep. This micropattern soft pad is able to change its form into a concave or a convex surface. We estimated the normal contact force in detachment and attachment phases between the micropattern soft pad and a substrate (environment). This micropattern pad was compared with a similar pad without a micropattern for their adhesion ability at the interface between the pad and the substrate. Obtained results, have good agreement with the estimations, demonstrated the surface of the micro-patterned pad enhanced contact force at the interface approximately 1÷2 times than that the normal surface. This approach can be utilized in evaluation of wet adhesion in grasping curved surfaces of objects using soft pads with patterned surfaces.

Based on the results obtained from the model of the contact mechanics with adhesion, we proposed applications of the soft robotic hands. The first of them is a project of a manipulating robot in automatically attaching and detaching a contact lens from a 'human eye'. A contact lens presented a hemispherical thin shell was grasped by the soft fingers in three different environments: inside/outside the preservative liquid and as the contact lens stuck a hemispherical substrate mimicking a human eye. The experimental and estimated results were compared for two kinds of the finger's tips surfaces: normal and micropattern. The tested results illustrated a good contract with the calculation as the m-pad reduced the preload and deformation of the thin hemispherical shell 1.1-2 times lower than that of the n-pad. The next application is a soft robotic hand approaches to grasp and then release a food sample in wet condition. We showcased this scenario with a small block of fresh tofu 19.6mm×19.6mm×15mm which is soft, fragile object that was grasped by a soft robotic hand including two symmetrical pressurized fingers which their tips deposited with two types of soft pads: a n- or m-pads. The micro-machined pattern comprises of 14400 square cells same dimensions as the previous m-pad, whereas each groove has its cross section 15μm in width and 44μm in depth. Our estimation of the grasped force for both types of soft pads were conducted, then verified by actual application in griping the tofu block. Both estimated and experimental results reveal that the micropattern pad decreased the preload and deformation of the tofu block's surface 2.2 times lower than that of the flat one, for stable grasping of the tofu. The showcase in my thesis confirmed the potential of micro patterns grasping soft-fragile objects in wet environments without complicated control strategy, promising wider applications for robot in medical, human, service or food industry.

2. Research Purpose

Motivation in solving the given problems, our study aimed to develop the novel soft robotic hand enabling grip/manipulation of the soft-fragile objects. In this scenario, the principle and morphological designs of the adhesive pads attached in the robotic fingers are inspired by the wet attachment of the tree frog's toe pad. Additionally, the role of micro pattern on enhancement of the grasp force/contact force was investigated through constructing theoretical model validated by experimental evidence. Our research makes meaningful contributions to science and tech as followed:

1. Studied the wet attachment mechanism of tree frog' toe pads for improving the adhesive ability of the pad in robotic finger.
2. Came up with a theoretical model for estimating the wet adhesion force in normal and tangential direction for flat contact interface between the pads (m-and n-pad) and the substrate, which is potential for other related researchers to follow and develop their current works.
3. Developed the approximation of the wet adhesion in flat surface of the pads (m-and n-pad) to two parallel curved contact interfaces between those pads with the curved substrates. Studying curved contact interfaces is more suitable for utilizing the actual applications of soft robotic manipulation because the object's surfaces may be not completely flat.
4. Presented a theoretical approach for gripping thin hemispherical shell in wet environment by the pad having micropatterned morphology. Our work is useful for evaluating the manipulation of thin soft objects by robotic fingertips with patterned structure in wet or moisture conditions.
5. Showed an analytical model for evaluating the grasping ability of a soft robotic finger's tip attaching micropatterned pad (m-pad) over a wet, fragile object such as a tofu block. This work is potential for extending to grasping soft-fragile objects in wet conditions by micropattern interface fixed on the fingertips.
6. Demonstrated some ways to making a soft robotic finger's tips attaching the bioinspired pad with an array of the cells and grooves in microscale.

Keywords: Wet adhesion, dry adhesion, tree frog toe, micropattern, soft grasping and manipulation.

Publications and Awards

Peer-reviewed journals

[1] Pho Van Nguyen and Van Anh Ho, "Grasping Interface with Wet Adhesion and Patterned Morphology: Case of Thin Shell", IEEE Robotic and Automation Letters (RA-L), Vol. 4, Issue 2, pp. 792-9, 2019.

[2] Pho Van Nguyen and Van Anh Ho, "Mechanics of Wet Adhesion in Soft Interaction with Patterned Morphology", Bioinspiration & Biomimetics, Vol. 14, No. 1, 2018.

Other peer-reviewed journals

[1] Pham HH and Nguyen PV, "Dynamic analysis of cam manufacturing", J. of Applied Mechanical

Engineering, Vol. 6, No. 274, 2017.

Peer-reviewed international conference

[1] Pho Van Nguyen, Quan Luu and Van Anh Ho, “Wet Adhesion of Micropattern Interface in Grasping Fragile Objects”, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), No. 2080, Las Vegas, US, 2020.10. (Accepted)

[2] Pho Van Nguyen and Van Anh Ho, “Grasping Interface with Wet Adhesion and Patterned Morphology: Case of Thin Shell”, International Conference on Robotics and Automation (ICRA), No. 2711, Montreal, Canada, 2019.5.

[3] Pho Van Nguyen, Tue Trong Phan, Ngoc Van Huynh and Van Ho, “Soft Grasping with Wet Adhesion: Preliminary Evaluation", The first IEEE- RAS International Conference on Soft Robotics (RoboSoft), pp. 418-23, Livorno, Italy, 2018.4

Peer-reviewed international workshop

[1] Pho Van Nguyen, Van Anh Ho et al, “Toward a Platform for Simulation and Design
Optimization of Underwater Anguilliform Movement: Case of Soft Robotic Eel”, Interdisciplinary Collaborative Case-studies at the ICRA2020 workshop "Beyond Soft Robotics-International Conference on Robotics and Automation (ICRA), Paris, France, 2020.5.

[2] Pho Van Nguyen, “Grasping Interface with Wet Adhesion and Patterned Morphology: Case of Thin Shell”, ICRA 2019 Workshop on soft haptic Interaction, Canada, 2019.5.

[3] Pho Van Nguyen and Van Anh Ho, “Soft Grasping with Wet Adhesion: Preliminary Evaluation”, Workshop Soft haptics: what’s been done, be done, Italy, 2018.4

Domestic conferences, symposiums

[1] Pho Van Nguyen, “Grasping Curved Surfaces by Soft Robotic Finger with Micropattern Integrated Wet Adhesion”, Tokyo-Ishikawa Scientific Meeting, Tokyo, 2020.3.

[2] Pho Van Nguyen, “Soft Robotics: Potential in Developing Digital Economy”, Vietnamese Young Global Forum 2th-Technology and Management in Digital Economy, Ha Noi, Viet Nam, 2019. 11.

[3] Pho Van Nguyen, “Soft Robotics: Perspective of Significant Contribution in Science and Technology”, Vietnamese Young Global Forum 2th-Vietnamese Sustainable Development, Ha Noi, Viet Nam, 2019. 11.

[4] Pho Van Nguyen, “Grasping Interface with Wet Adhesion and Patterned Morphology”, Japan-India Symposium on Materials Science, Ishikawa, Japan, 2019.3.

[5] Pho Van Nguyen, “Soft Robotics”, Scientific Meeting with Duy Tan University, Danang city, Viet Nam, 2018.12.

[6] Pho Van Nguyen, “Soft Grasping with Wet Adhesion”, Vietnam-Japan Scientific Meeting-Tohoku University, Sendai, Japan, 2018.9.

[7] Pho Van Nguyen, “Soft Robot in Grasping”, Tokyo-Ishikawa Scientific Meeting, Tokyo, 2018.3

Awards

[1] 2020 IEEE Nagoya Chapter International Conference Research Presentation Awards, 2020.4.

[2] JSPS (Japan Society for the Promotion of Science) DC2 in 2020.4-2022.3.

[3] JAIST Off-campus research grant for research in INRIA Institute, Lille, France, 2019.4-9.

[4] Student travel award by JAIST research grant, 2019.5

[5] JAIST President award, 2018.9.

[6] Student travel award by JAIST research grant, 2018.4.

[7] Doctoral Research Fellow scholarship, 2017.10-2020.9.

[8] Monbukagakusho honors scholarship, 2017.10-2018.3.

論文審査の結果の要旨

Object grasping/manipulation is a traditional topic in robotics, but still remains many challenges, thanks to the diversity of grasped objects in an unconstructed environment. Especially, grasping wet, deformable objects, such as food product, is extremely difficult. It is due to the low friction at the contact interface, and high gripping force may damage the object. Therefore, utilization of wet adhesion in such scenario is a potential solution. However, there is no theoretical background for designing robotic hand with wet adhesion, as well as actual showcases of gripping wet, soft objects.

This thesis starts with a bio-mimetic solution to the aforementioned challenge by looking at the structure of the tree frog’s toe pad, which has micro-scaled cells and grooves that are considered helpful to increment of the pad’s adhesion in wet environment.

1.First, this research constructs an analytical model of a micro-patterned soft pad for clarification of underlying mechanics of the wet adhesion. Based on comprehensive combination of known contact forces, taking in account Laplace pressure and related surface tension, the model is capable of quantitatively explaining the increment of wet adhesion in both normal and tangential direction when the micro-patterned pad is used. The model reveals that the wet adhesion strongly depends on many factors of the contact interface, and one can adopt this model to evaluate the wet adhesion of a specific interface. The thesis also presents how the deformed states (convex and concave) of the pad may affect the wet adhesion ability. This is considered important since such states are usually observed in robotic grasping/manipulation.

2. Second, the thesis also illustrates a fabrication process for creation of a soft pad with

pre-determined pattern. In this scenario, these pads were cast from silicon rubbers. Additionally, a square-patterned mold, as the m-pad mold, comprising from 3600 85μm×85μm cells interspaced by a channel network with 15μm wide and 15μm deep was fabricated from the electron beam lithography (EBL) technology. Validated results illustrated a good agreement with those of the estimation, revealing that the micro-patterned morphology can enhance the contact force for the m-pad by two-fold in case the normal and 1.2- to 1.4-fold in case the tangential force.

3. Third, the thesis showcases two scenarios of object grasping: soft contact lens, and a block of tofu. These objects were chosen since they are soft and thin (contact lens), and slippery (tofu). Based on the proposed analytical models, and taking into account deformation of a thin shell (contact lens) and a visco-elastic block (tofu), the micro-patterned pad is proved to reduce the generated deformation while maintaining the stability.

Overall, the thesis succeeds in proposal of an analytical model for evaluation of wet adhesion on a micro-patterned pad based on exhaustive combination of contact mechanics theories, and showcases how a robotic hand with micro-patterned pad could enhance the performance of gripping soft, deformable objects in wet environment. The research content in this research paves a way to wide application in robotics, especially grasping and manipulation of wet objects; and surely contribute to the robotics research. Therefore, this thesis contains large academic contribution, and is sufficient to be rewarded as doctoral thesis (in Material Science)