公開

研 究 終 了 報 告 書

「タッチ IoT：触れるインターネット実現のための肌感覚送受信機の開発」

研究期間： 2020 年 11 月～2024 年 3 月
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1. 研究のねらい

Touch holds significant meaning as a complex form of communication in human-environment, human-machine interactions within the cyber-physical system (CPS). On the Internet of Things (IoT) era, smart devices exchange vast amounts of digital data to enhance physical spaces, yet human interaction remains limited. The concept of the **Tactile Internet**, a concept within the IoT framework, emphasizes the importance of real-time, high-fidelity touch communication in various applications. Given the diverse ways humans interact with cyber/physical devices and space, touch plays a vital role in providing input data for controlling and optimizing CPS operations. Despite touch's crucial role, the understanding of touch sensation in the IoT ecosystem is insufficient, and methods for **interpreting large touch data influx** lack maturity. Practical hardware for widely applicable tactile interfaces with appropriate data structures is missing, along with solutions for low-latency internet transfer of multi-point tactile data. Our long-term research on human and robot touch senses identifies **the target**: immersing touch in the IoT ecosystem to create new values through extensive tactile information.

In this research, our aim is to develop a versatile smart sensing enabler tailored for the Tactile Internet, featuring a soft interface for human-machine interaction. This enabler will possess the capability to detect touch across a large area, gather substantial tactile image data, transfer data over the internet, and generate new values through an appropriate data structure. The objectives are:

1. **Platform Development**: Create a platform for designing soft haptic sensing interfaces characterized by high resolution, softness, and scalability. This hardware is designed for human interaction but can be applied broadly across diverse objects/robots.
2. **Real-time Tactile Data Acquisition**: Propose a method for real-time acquisition of tactile data at a large area. Processing and interpreting tactile information must match human tactile perception speed (approximately one-tenth of a second).
3. **Transmission of Large-Area Tactile Data**: Develop a "tactile codec" machine to compress or decompress digital tactile data, particularly at multi-sensing points. This codec aims to be widely applicable in IoT systems, considering the dynamic and unique nature of tactile information across various actions.
4. **Tactile Data Structure for AI-Driven Interpretation**: Construct a data structure with *ontological* relations to facilitate the AI-driven interpretation of human touch. This involves registering specific touch data from sensors and related user actions/intentions using machine learning/AI and a vast dataset of supervised tactile interactions. The goal is to establish a foundation for high-level applications based on contextual information derived from touch data.

2. 研究成果

(1)概要

Aligned with our proposed objectives, a thorough and ongoing evaluation process has enabled us to **successfully achieve all milestones**. Collaboration with researchers both within and beyond our fields has been instrumental in maximizing the practical applications of our findings. In summary:

1. We have established a design pipeline for developing a soft interface, facilitating human interaction with the Cyber-Physical System (CPS) on a large scale while maintaining simplicity in implementation. Utilizing vision-based tactile sensing principles, we leveraged these into a versatile platform for design and testing purposes by creation of a **digital twin** of the device in the simulated environment.
2. A real-time data acquisition method for large-area tactile sensing has been successfully proposed, employing both analytical and data-driven approaches based on the **digital twin**. The resulting **open-source** pipeline is adaptable to various shapes and sizes, boasting processing speeds of up to nearly 120Hz. Furthermore, it can be implemented on a range of hardware platforms, such as PCs, microcomputers.
3. We constructed an ***ontological*** **model** for tactile data, facilitating the expression of touch data at large-area for application in high-level contexts. Our substantial dataset of human interactions on the soft sensing interface has enabled the development and evaluation of a method for registering human actions and intentions.
4. Building upon the ontological model of tactile data, we introduced **WoTT (Web of Tactile Things)**, a framework allowing the transfer of tactile data across large areas through the internet and various hardware platforms.

(2)詳細

A) Hardware Enabler for Tactile Internet at Large Scale (see Ref. [1])

***What:** In this project, we focus on the development of scalable tactile sensing skin that can bring in large influx of touch information on a large area.

***Why:** Humans' touch serves both task-oriented and social purposes. In the context of the Tactile Internet, conventional haptic interfaces are frequently crafted to acquire single-channel kinesthetic, or point-contact based tactile data. With the advent of the Metaverse or Cybenetic/Avatar robots, the interaction between users and the CPS extends beyond small-scale interactions (joints, fingers) to encompass larger areas (whole body). This touch information can be beneficial in implementing safety measures for robots, controlling remote machinery, and conveying users' intentions and motions. Nevertheless, the implementation of large-area tactile sensing has been deemed challenging, primarily due to the requirement for a substantial number of embedded sensors, intricate hardware setups, and complex data acquisition processes. Consequently, the development of efficient hardware for large-area tactile sensing assumes a crucial role as a facilitator in advancing the capabilities of the Tactile Internet.

***How:** Based on vision-based tactile sensation, we proposed a research framework for design, fabrication, and evaluation of soft interfaces. Especially, we succeeded in proposing soft, barrel-shaped tactile sensing system (called **TacLink**) that can be easily scaled to various shape and size. **This technology has been patented**. The basic design can be seen in Figure 1.

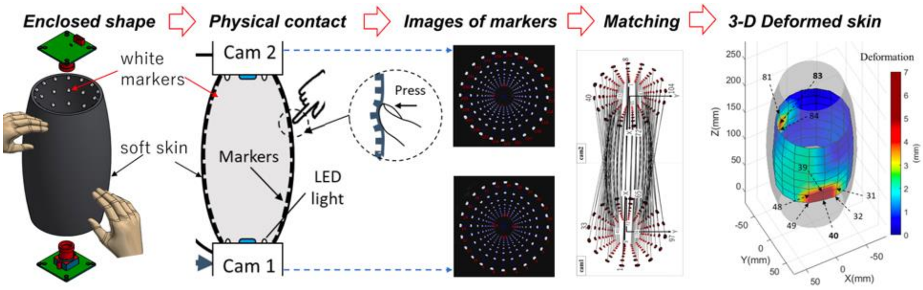

Fig. 1: Design principle of the **patented** soft tactile sensing TacLink using built-in cameras

B) Data-driven Realtime Data Acquisition: (see Ref. [1])

***What**: We have successfully implemented real-time data acquisition on the TacLink device, pushing the sampling rate close to the camera's frame rate. During this project, we achieved a significant milestone by attaining a data acquisition speed of nearly 120 Hz.

***Why**: Common haptic data acquisition typically occurs at a single point or channel with a high sampling rate. However, obtaining tactile data across a large area at such a rate presents a challenge. While the TacLink data initially consist of images, extracting tactile data, including contact location, contact depth, and contact forces, requires acquiring information at multiple points across the surface. Therefore, the development of a technique to enhance tactile data acquisition speed is crucial for this purpose.

***How**: We developed a holistic pipeline for data acquisition, learning, and transferring to the sensing performance of the TacLink, called as **SimTacLS.** The summary can be found below:

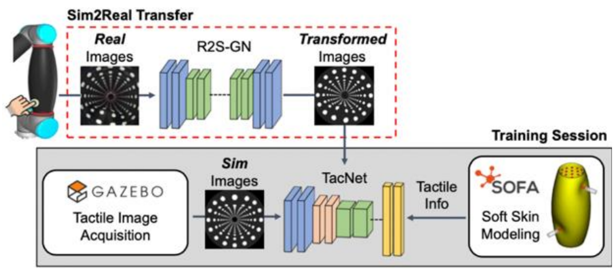

Fig. 2: **SimTacLS** pipeline for learning/transferring

1. ***Data acquisition***: Based on the Digital Twin of each TacLink device, diverse contact states occurring on the TacLink can be simulated, and *virtual* tactile images can be collecte.
2. ***Training:*** Deployment of a supervised learning-based multi-output regression model called **TacNet** on virtual tactile images. As a result, the process is based on the simulated data.
3. ***Sim-to-Real Transfer Learning:*** A generative AI tool (R2S-GN), which translates real tactile images into look-alike simulated images before feeding to the **TacNet**. As a result, the accuracy of the regression can be improved significantly.

*__Conclusion remark__: The proposed **SimTacLS** pipeline is a substantial effort toward implementing the high-rate tactile sensing on large area. Currently, maximum 120Hz can be achieved with 120fps camera.

*__Outcomes__: We also open sourced: https://github.com/Ho-lab-jaist/SimTacLS

C) Web of Tactile Thing (WoTT) (see Ref. [2])

***What:** We proposed an open platform specifically designed for tactile entities, referred to as the Web of Tactile Things (**WoTT**). WoTT extends the W3C Web of Things (WoT) framework to enable the exchange of haptic information from tactile sensing devices to cross-domain services, leveraging established Web technologies.

***Why:** In the pursuit of advancing the Tactile Internet, there arises a requirement for a platform facilitating the exchange of haptic information among human and cyber-physical systems, <u>especially for large area tactile sensing devices</u>. Therefore, an open and standard platform to enable the **seamless interoperability** of the diverse tactile devices and applications is a crucial question that needs to be addressed in the early stage toward the of the Tactile Internet.

*__How:__ We succeeded in building a whole pipeline of Web of Tactle Things for sharing tactile data, based on the well-known W3C Web of Things ecosystem. The semantic enabler of the WoT is the Thing Description (TD), which can map any physical thing into a *WoT Thing* so that human and machines can understand and interact easily with it via sets of standardized APIs:

1. ***Tactile Thing Description*** (**TTD**): Based on the ontological model of TacLink, TTD, which is the most important part of the WoTT platform, is designed and implemented for encoding tactile data obtained from TacLink.
2. ***WoTT Thing Producer*** **(Server)**
   This middleware is implemented in Python, utilizing the *wotPY* library to encompass the W3C WoT run-time, WoT Scripting API, and protocol bindings. During regular operation, events such as interactions are emitted to interested *clients* through predefined events.
3. ***WoTT Thing Consumer*** **(Client)**
   A WoTT client was implemented to make use of tactile information from the *server* to reproduce a digital twin (static and dynamic information) of the device. Moreover, the client also subscribes to tactile events and reflect the event via a 3D model of the tactile sensing device.

*__Conclusion remark:__ In accordance with the ontological model, the WoTT protocol has demonstrated a straightforward yet effective method for encoding tactile data and transmitting it over the internet with less computation burden. Currently, latency is notably influenced by the infrastructure; while experimental results indicate that encoding based on TTD and transmission through WoTT result in short latency, thus promising for use in Tactile Internet.

*__Outcomes__: We also open sourced the WoTT for co-development (for client):
https://github.com/Ho-lab-jaist/wott-client

D) Acquisition of Touch Data Embedded with Action/Emotion:

***What:** A substantial dataset of tactile information was gathered through the TacLink interface, encompassing a variety of touch actions performed by users and representing several typical emotions. The experiment involved the participation of nearly 80 subjects, and the dataset is prepared for release soon.

***Why:** Currently, there is a lack of available data for a comprehensive examination of user interactions with the CPS. The TacLink is deemed suitable for acquiring interactive data due to its expansive and soft skin equipped with tactile sensing, resembling the human skin organ. The dataset holds potential for studying task-oriented and social touches from users within CPS.

***How:** In this project, we have conducted two sets of experiments with collaborations from large set of subjects. The experiments <u>were verified</u> by the JAIST's Committee for Life Science Research. Subjects were students/staffs in JAIST at their 20s and 30s ages, exhibiting diversity in terms of gender and nationality. There are two datasets have been collected:

1. ***Touch Action Dataset***: Forty-eight participants were selected to perform a range of touch primitive actions on TacLink devices, with the resulting tactile images recorded as data.
2. **Emotion-included Touch**: Emotions are inherently private and vary among individuals, posing a ***challenge*** in terms of data collection and evaluation. In anticipation of the experiment, thirty-four subjects were recommended to contemplate touch actions they might employ in response to changes in their emotions. Post-experiment interviews with subjects disclosed that participants were uncertain about how to appropriately employ touch to express their emotions accurately. Also, some video could not evoke subjects' emotion. Further experiments with additional constraints are warranted in future investigations.

E) Use case

We have conducted a set of use-cases for application of proposed methods into actual scenarios to show their potentials. Two representative ones are below:

1. ***Internet of skill***:

   ***How**: In this context, we utilized TacLink and the associated WoTT transmission to establish a massage training system. This system enables trainees to follow the tactile information provided by experts, allowing for evaluation by the experts in both online and offline modes. This work is an **ongoing collaboration** with Prof. Yoneda of Kanazawa University Hospital.

2. **Multimodal Sensing for Safety robot:**

   ***How**: We have introduced a distinctive method for <u>integrating proximity sensing into the existing design of TacLin</u>k by incorporating a soft skin with optical properties that can switch between transparency and opacity. Development of multimodal sensing in one structure of TacLink is considered crucial toward implementation of future **cybernetic/avatar robots** that can represent the users to interact with the remote surroundings safely.

3. 今後の展開

Although the findings from the PRESTO projects laid the groundwork for the co-design of TacLink hardware (sensing) and software (perception, communication), the latency issue is still challenging due to the constraints imposed by the sampling rate of the embedded camera, network infrastructure. Consequently, we aim to **leverage the capabilities of the WoTT framework** to achieve near-instantaneous end-to-end (E2E) communication for multi-channel tactile data. This communication will be further enhanced through the integration of artificial intelligence technologies, contributing to the development of a robust and reliable sensing and communication protocol for the TI, called **RESPECT-I** (**Re**liable **S**ensing and **P**roactive **C**ommunication **T**actile- internet).

4. 自己評価

This research proposal aims to **align with the vision** of Society 5.0 in Japan and the emerging concept of **Industry 5.0**. Both visions focus on the development of a smart society and manufacturing characterized by the collaboration and interaction of humans with Cyber-Physical Systems (CPS), including robotic and cybernetic/avatar robots. In this context, our project「TouchIoT」seeks to advance basic technology by enhancing large-area interaction through hardware and software enablers. These **enablers** possess the capability to detect touch across expansive surfaces, collect substantial tactile image data, facilitate internet data transfer, and create new value by optimizing interactive behavior through a suitable data structure. Therefore, the outcomes of this research could contribute to the science and social-economy as follows:

i. 科学技術への波及効果: this research **addresses a challenging topic** in implementation of soft tactile sensing at large areas with high sampling rate and sensing reliability and durability. Current technology on large area sensing exploited embedding multiple sensing elements, which cause difficulties in implementation, data acquisition, and durability. In fact, our design pipeline **paves a way** to create various tangible interfaces for IoT and Tactile Internet.

・Furthermore, the proposed transmission method utilizing WoTT and Tactile Thing Description presents a simple yet efficient solution for transferring a substantial influx of tactile data over the internet. This **lays the groundwork** for proactive communication with very low latency in the Tactile Internet in the future. The anticipated outcomes are also expected to contribute to the standardization of the Tactile Internet, particularly for multiple, large-area contacts.

・The projects published many high impact papers, which now already **attract about 100 citations** from the research community (according to Google Scholars).

ii. 社会・経済への波及効果: The results of this research align with the vision of Society 5.0 and Industry 5.0, contributing to the development of new enablers for the immersive interaction of humans with Cyber-Physical Systems (CPS), including cybernic/avatar robots. This encompasses considerations for both large-area tactile sensing and safety. Presently, we are actively engaged in conducting showcases and applications in collaboration with companies and hospitals, demonstrating the **potential socio-economic impacts** of this research.

5. 主な研究成果リスト

(1)代表的な論文(原著論文)発表

研究期間累積件数: 19件(論文:6件、国際会議発表:13件)

[1] Quan Luu, N. Nguyen, and Van Anh Ho*, *Simulation, Learning, and Application of Vision-Based Tactile Sensing at Large Scale*, **IEEE Transactions on Robotics**, Vol. 39, Issue 3, pp. 2003-2019, February 2023

Abstract: This study introduces a Multiphysics simulation pipeline, called **SimTacLS**, which considers not only the mechanical properties of external physical contact but also the realistic rendering of tactile images in a simulation environment. The system utilizes the obtained simulation dataset, including virtual images and skin deformation, to train a tactile deep neural network to extract high-level tactile information. Moreover, we adopt a generative network to minimize sim2real inaccuracy, preserving the simulation-based tactile sensing performance. Last but not least, we showcase this sim2real sensing method for our large-scale tactile sensor (TacLink) by demonstrating its use in two trial cases, namely, whole arm nonprehensile manipulation and intuitive motion guidance, using a custom-built tactile robot arm integrated with TacLink. This article opens new possibilities in the learning of transferable tactile-driven robotics tasks from virtual worlds to actual scenarios without compromising accuracy.

[2] V. Pham, Q. Luu, Yasuo Tan, and Van Anh Ho*, *Web of Tactile Things: Towards an Open and Standardized Platform for Tactile Things via the W3C Web of Things,* **CAiSE 2022: Intelligent Information System**, pp. 92-99, In: De Weerdt, J., Polyvyanyy, A. (eds) Intelligent Information Systems. CAiSE 2022. Lecture Notes in Business Information Processing, vol 452. Springer, Cham. https://doi.org/10.1007/978-3-031-07481-3_11

Abstract: Toward the development of the Tactile Internet beyond the 5G era and the recently introduced Metaverse, a need for standardized platforms to exchange haptics information for human and cyber-physical systems is emerging. This paper introduces our attempt for an open and standardized platform for tactile things, namely Web of Tactile Thing (WoTT). The WoTT extends the W3C Web of Things (WoT) to exchange haptic information from tactile sensing devices to cross-domain services via already proven Web technologies. This paper proposes (i) haptic vocabularies to generate the WoT Thing Description for vision-based tactile sensing devices, as well as (ii) mechanisms to connect, update, and exchange tactile information efficiently. To prove the feasibility of the platform, a proof of concept includes (i) a tactile sensing device to produce tactile information and (ii) a WoT client that consumes proposed vocabularies to create a digital twin of the physical device, have been implemented. The feasibility of the proposed platform has been verified by abilities to reproduce the digital twin and reflect touch events timely and correctly

（2）特許出願

研究期間全出願件数： 5件（特許公開前のものも含む）

	発明者	ホ アンヴァン、ツオン ヴァンラク、朝比奈 励
	発明の名称	触覚検知装置及び触覚検知方法
	出願人	北陸先端科学技術大学院大学
1	登録番号	特許第 7242036 号
	登録日	令和 5 年 3 月 10 日
	概要	本発明は、検知精度の高い触覚検知装置及び触覚検知方法を提供することを目的とする。
	発明者	ホ アンヴァン、リュウ カンクアン
	発明の名称	接触近接検知装置、ロボットアーム及び接触近接検知方法
	出願人	北陸先端科学技術大学院大学
2	出願日	令和 4 年 7 月 26 日
	出願番号	特願 2022-118796
	概要	本発明は、接触と近接とを検知する接触近接検知装置、ロボットアーム及び接触近接検知方法を提供することを目的とする。

	発明者	ホ アンヴァン、グエン ディン クアング
	発明の名称	触覚提示装置及び触覚提示方法
	出願人	北陸先端科学技術大学院大学
	出願日	令和 3 年 10 月 13 日
3	出願番号	特願 2021-168206
	概要	本発明は、特定の箇所の触覚と連続的に移動する触覚の両方を提示することができる触覚提示装置及び触覚提示方法を提供することを目的とする。
	発明者	ホ アンヴァン、リュウ カンクアン
	発明の名称	接触近接検知装置及び接触近接検知方法
	出願人	北陸先端科学技術大学院大学
4	出願日	令和 3 年 7 月 27 日
	出願番号	特願 2021-122314
	概要	本発明は、接触と近接とを検知する接触近接検知装置、接触近接検知方法を提供することを目的とする。

（3）その他の成果（主要な学会発表、受賞、著作物、プレスリリース等）

・受賞： 1) 2024 IEEE/SICE International Symposium on System Integration (SII 2024) Best Paper Award Finalist

2) 2022 IEEE Senior Member 昇格

・プレスリリース：

1) 協調ロボットの未来：広範囲触覚・近接センシングの簡易な実現に成功

https://www.jaist.ac.jp/whatsnew/press/2023/04/12-1.html

・新聞の記事掲載

1)【掲載誌】 令和 5 年 4 月 14 日付 日刊工業新聞 21 面

【電子版】 https://www.nikkan.co.jp/articles/view/669788