Graduate School of Creative Science and Engineering
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博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme

Development and Implementation of a Tactile Feedback System Using End-to-end Tactile Sensor Data Projections for Wearable Human-Robot Interaction

触覚データのエンドツーエンド射影に基づく装着型触覚フィードバックシステムの開発

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The sense of touch enables humans to perform a great variety of exploration and manipulation tasks in the physical world. In unstructured environments, tactile information constitutes a key sensory channel that is especially important. In this regard, tactile sensor skin has been widely adopted in robot design and control. The integration of distributed tactile sensors enables information-rich feedback from the robot's environment and makes robot manipulators increasingly capable of dexterous object manipulation and even active (tactile) exploration. For this reason, not only modern industrial robots but especially emerging robot applications like social and service robots benefit from the deployment of soft, distributed tactile skin sensors, because they enable higher manipulation capabilities, a higher flexibility, and in turn, possess a tremendous potential for versatile, human-like interaction with the physical world. However, in human-centered applications, e.g. robot-teleoperation or human-robot interaction, this massive tactile sensor data must be projected to the skin of a human operator in order to create meaningful, yet efficient tactile feedback that allows either for highly-efficient teleoperation of the robot or for tactile immersion while remotely interacting with the robot. In addressing these challenges, this thesis seeks to develop a vastly applicable end-to-end tactile feedback system for wearable human-robot interaction that provides tactile feedback from massive tactile sensor data by means of compact tactile displays with sparse actuator distributions.

Chapter 1 lays the groundwork to this thesis: First, insight into the mechanisms of tactile stimuli perception is provided. Second, existing tactile sensors, their large-scale implementations into (anthropomorphic) robots, and algorithms for tactile data processing are extensively reviewed in regard to state-of-the-art tactile feedback systems. Based on this review, chapter 1 derives the objectives for the development of a novel data-driven tactile feedback system that uses end-to-end tactile data projections in combination with illusory tactile sensations to mitigate space and energy restrictions of tactile display hardware. Finally, the implementation of this tactile feedback system into a wearable fingertip module with ultra-compact, energy-dense shape memory alloy (SMA)-based micro-vibrators is outlined.

Chapter 2 introduces the complete system architecture for the experiments and evaluations of the proposed data-driven tactile feedback system and the first fingertip module prototype. The system architecture involves the anthropomorphic *Allegro* robot hand covered with soft, distributed *uSkin* tactile sensor skin, a host PC running resource-intensive algorithms on the tactile data, a compact microcontroller unit that manages the computed spatio-temporal actuation patterns, an I^2C-enabled custom-made tactile display driver circuit for the generation of pulsed current signals, and the SMA-based tactile display prototypes to create vibro-mechanical stimuli on the human skin. Even though soft- and hardware developments considerably evolved throughout the experimental trials, chapter 2 also reviews fundamental design and operational principles of the SMA-based micro-vibrators, thereby, characterizes the potential applications and inherent limitations of the tactile display prototype. An important *a priori* limitation of the SMA-based prototype is the restriction to a subset of tactile stimuli in accordance with the frequency/ stimuli response of the cutaneous mechanoreceptors and the absence of proprioceptive feedback, i.e. stimuli that inform the brain on dynamic positioning/loading of articulated body segments. The SMA-based micro-vibrator generates mechanical vibrations perceived by the *Meissner* and *Pacinian* corpuscles and therefore allows for the construction of tactile illusions. The realization of sustained pressure (*Merkel*), skin shear (*Ruffini*) or proprioceptive feedback, however, would necessitate a different embodiment of the SMA actuators or the complementation with a different actuator. In conclusion, chapter 2 implements the outlined design objectives from chapter 1 for experimental analysis and evaluation.

Chapter 3 describes the algorithm *end-to-end tactile texture projection* with psycho-physically meaningful latent space coordinates. This algorithm deploys a deep gated recurrent unit-based autoencoder (GRU-AE) to capture the perceptual dimensions of tactile textures in latent space coordinates that coincided with the psychophysical layer of human material perception. The auto-compression of tactile sensor data enabled an end-to-end mapping from tactile sensor data to tactile actuator driving signal by modulating the tactile display actuator driving signal in accordance with the latent space coordinates of explored surfaces. The approach was experimentally verified by evaluating the prediction performance of the GRU-AE on seen and unseen tactile data that were gathered during active tactile exploration of objects commonly encountered in daily living using a *uSkin* tactile sensor module. Additionally, a user study on the first prototype of the custom-made tactile display was conducted in which real tactile perceptions in response to active tactile object exploration were compared to the emulated tactile feedback using the proposed GRU-AE approach. The algorithm was able to drive the tactile display module and generated convincing tactile illusory stimuli even for new, unseen textures alone from the *uSkin* tactile sensor readouts. The experimental results revealed that the GRU-AE, or AE approaches in general, allows for finding an end-to-end mapping between tactile sensor and tactile display space over a wide range of tactile sensor and actuator combinations. However, the experiments revealed that the specifics of tactile sensor and tactile display must be accounted for, because their respective hardware characteristics, e.g. frequency response or material properties, in capturing and projecting relevant surface features impact the quality and integrity of the tactile stimulus. Finally, another important limitation is the pre-definition of the moving contact pattern that was necessary to emulate the sensation of moving object surfaces by means of tactile illusions.

Chapter 4 introduces *sequential tactile data compression*, which resolves the dimensional mismatch between tactile sensor space and tactile display space by performing two stages of modified *k*-means++ clustering on the raw tactile sensor data at each time instant. This dynamic compression allows for the identification of discrete contact locations and stimulus intensities thereby enables the representation of the tactile data by tactile illusions. The algorithm compresses the tactile sensor data into a number of representative discrete contact locations and stimuli intensities to match the tactile display specifications. In this manner, the compressed tactile data preserves its physical meaning and enables direct adaptive feedback with regard to the design and transduction principles of the tactile display. The algorithm is experimentally verified within an extensive parameter study by evaluating the original and compressed tactile data that was gathered during the active tactile exploration of several objects of daily living by the *Allegro* robot hand that was covered with 15 *uSkin* tactile sensor modules providing 240 *x,y,z*-axis force vector measurements at each time instant. The algorithm deploys *k*-means++ clustering and is therefore an iterative algorithm. For this reason, chapter 4 also investigates the algorithm performance under varying conditions and discusses multiprocessing-implementations to alleviate the speed problem that may become relevant for extremely large amounts of sensor data. In conclusion, the algorithm allows for the direct feedback from massive tactile sensor data for a broad variety of tactile sensors and tactile displays therefore enables the compressed yet intuitive representation of massive tactile sensor information by means of tactile illusions. Since the algorithm produces discrete contact points of varying intensity, it could be combined with the algorithm from chapter 3 to attribute arbitrarily moving contact points with textural properties.

Chapter 5 is concerned with the implementation of the system architecture as introduced in chapter 2, 3, and 4 into a compact and wearable human-machine interface. Chapter 5 is therefore application-oriented and describes the mechanical (wearable fingertip module) and electronic (compact PCB of the I^2C-enabled driver circuit) implementation of the system components with optimized wiring into a compact, ergonomic fingertip module. As a result, chapter 5 arrives at a novel, scalable tactile fingertip module that successfully implements the in chapter 1 initially outlined design paradigms: a scalable solution with an end-to-end design in a compact form factor that deploys tactile illusions to alleviate energy and space restrictions inherent to tactile display hardware. The tactile fingertip display module prototype was successfully tested in experiments: The contact trajectories of an object that moved across a *uSkin* tactile sensor module were transmitted to human users by deploying the algorithm from chapter 4 and quasi-dynamic, consecutive projections of compressed contact locations by means of tactile illusions. Hence, the proposed human-machine interface solves the unknown transformation from tactile sensor space to tactile actuator space and utilizes tactile illusions to mitigate limitations of tactile display actuators in terms of energy consumption and actuator density. In this respect, the developed fingertip module exhibits similar limitations as described in the previous chapters, i.e., the projection of tactile stimuli using SMA-based micro-vibrators is limited to a subset of perceivable tactile stimuli, excluding static protrusion, shear, and heat flux. Moreover, the generation of robust tactile illusions is still a matter of research: The experiments on the feedback of moving contacts patterns revealed inconsistencies of the perceived stimuli with respect to the desired contact trajectory due to the SMA-based actuator's limited range of producible stimulus intensities and relative movements between finger pad and display module. However, the experiments on both the hard- and software components have shown that the proposed data-driven tactile feedback system effectively utilizes end-to-end tactile data projections to efficiently convey physical contact information.

Chapter 6 draws conclusion and summarizes the achievements and limitations of the presented developments of the end-to-end tactile feedback system for wearable human-robot interaction. The tactile feedback system uses tactile sensor data projections to provide cutaneous feedback from massive tactile sensor raw data by compact tactile displays with sparse actuator distributions in an end-to-end manner. The presented hard- and software solutions were experimentally verified and implemented into a prototype of a compact, wearable fingertip module with networking capabilities. Further developments should address the robustness of the generated tactile illusions and improvements for increased ergonomics. Moreover, due to the need for extensive experimental field testing in unstructured environments, the algorithms that enabled the data projections and were run on a stationary host PC with GPU should be migrated to mobile, embedded computing boards with GPU, e.g. the *Nvidia Jetson Family*, which is currently in progress. In this context, the overall system integration with a data glove and, e.g., the *Allegro* robot hand for closed-loop robot-teleoperation poses the next logical challenge. Due to the compactness and modularity of the developed hard- and software, several fingertip modules, e.g. four tactile display modules matching the four fingertips of the *Allegro* robot hand, can be seamlessly integrated into a glove like wearable device that covers only the finger tips and allows to be simultaneously worn with a data glove. For a greater coverage of perceivable stimulus modalities, the deployment of merely one type of actuator (embodiment) is not sufficient. The integration of heat flux feedback and the complementation of the cutaneous feedback with kinesthetic feedback, i.e. the implementation of actuators that target the proprioceptive receptors in the joints and muscles of articulating body segments, should be addressed in the future.

早稲田大学　博士（工学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Engineering), Waseda University)

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a Academic Conference Paper	**(O) A. Geier**, G. Yan, T. P. Tomo, S. Somlor, and S. Sugano, "Deep GRU-ensembles for active tactile texture recognition with soft, distributed skin sensors in dynamic contact scenarios," 2020 IEEE/SICE International Symposium on System Integration (SII), Honolulu, HI, USA, 2020, pp. 127-132, doi: 10.1109/SII46433.2020.9025993
a Academic Conference Paper	**(O) A. Geier**, G. Yan, T. P. Tomo, S. Ogasa, S. Somlor, A. Schmitz, and S. Sugano, "Sequential clustering for tactile image compression to enable direct adaptive feedback," 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Macau, China, 2019, pp. 8117-8124, doi: 10.1109/IROS40897.2019.8968493.
e Academic Conference Paper	S. Funabashi, G. Yan, **A. Geier**, A. Schmitz, T. Ogata, and S. Sugano, "Morphology-Specific Convolutional Neural Networks for Tactile Object Recognition with a Multi-Fingered Hand," 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 57-63, doi: 10.1109/ICRA.2019.8793901.
e Academic Conference Paper	S. Funabashi, S. Morikuni, **A. Geier**, A. Schmitz, S. Ogasa, T. P. Tomo, S. Somlor, and S. Sugano, "Object Recognition Through Active Sensing Using a Multi-Fingered Robot Hand with 3D Tactile Sensors," 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, 2018, pp. 2589-2595, doi: 10.1109/IROS.2018.8594159.