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

論 文 題 目
Thesis Theme

Designing Serpentine-Shaped Robotic Appendages for Augmenting Daily Interactions

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Augmenting humans with robotic appendages has long been envisioned in sci-fi and pop-media. Recent advances in robotics have also demonstrated prototypes that could satisfy such vision. However, existing research literatures have several limitations. First, most works are very focused on specific domains, such as industrial applications or rehabilitation. While these tasks are useful, daily usage constitutes other use cases that are more relevant to such usage contexts. Secondly, knowledge from wearable systems and human-computer interactions research indicate that daily worn devices constitutes additional set of design requirements and challenges, such as wearability and ergonomics, social and user acceptability and user experience design. These challenges were not addressed in surveyed related literatures.
Therefore, this dissertation takes the first step to bridge the gap in addressing mentioned challenges. To realize appendages that fulfil the requirements of daily use, this dissertation focuses on the serpentine morphology (Snake-like). The serpentine morphology was chosen as it has established flexibility and versatility in various application domains. Accordingly, its versatility is also demonstrated through the four case studies that were developed and evaluated, further demonstrating its potential as robust wearable structure. This dissertation is the first to examine wearable serpentine-robotic appendages for everyday use.

Accordingly, this dissertation makes four contributions, which are as follows:

1- *Identification, analysis and classification of daily usage expectations and domains of serpentine-shaped robotic appendages within everyday contexts:* The conducted work addresses the fact that the usage domain, requirements and expectations of a physical augmentation wearable are not formally investigated or identified in surveyed works. This contribution is addressed by conducting two evaluations that addressed daily usability expectations, where the resulting use cases are analyzed, structured and classified. The resulting use case distributions enable identifying various domains of daily interaction expectations. This contribution is significant; it is the first to provide insights about the interaction expectations, which in turn forms a broad understanding of the main usage expectations and potential challenges of serpentine-shaped robotic appendages. The provided data, analysis and insights contributes with a comprehensive resource from which design considerations, implementation methods and evaluation criterion can be derived.

2- *Identification of social and user acceptability challenges, and the methods to address and accommodate these challenges and requirements:* Previous works within wearable systems provide a number of insights to address various acceptability requirements, yet identified factors are applicable to standard wearable systems. Serpentine-shaped robotic appendages present new challenges for public and personal acceptability that have not been previously identified. Accordingly, this dissertation contributes with new knowledge about the main factors affecting personal and social acceptability, which are extracted through a series of case studies and evaluations results. The significance of this contribution lies in the presented insights and methodologies on which social and personal acceptance are addressed, where these insights contributes to addressing social challenges as well as ensuring user adoption. Previous efforts within the area have focus on functional efficiency and technical novelty, therefore, there is a dearth of works that tackled essential social and personal acceptability challenges that would equally effect a wearable's daily use.

3- *Design and Implementation of novel user experiences that demonstrate how cohesive multipurpose user experiences can be designed, and identification and classification of novel cross device user experiences involving this form of wearable systems:* The multipurpose nature of these robots present challenges that were not addressed in single purpose wearable systems. Therefore, insights are extracted from the design, development and evaluations of the case studies, where they are structured and presented. These insights provide valuable considerations and methodologies for developing multipurpose user experiences that target daily use. Previous research efforts in multipurpose wearable systems have presented various interaction possibilities, yet these works do not address the mean of enabling multipurpose user experiences. Therefore, this contribution constitutes design insights about the design methodology of cohesive multipurpose user experiences, as well as a classification and embodiment of novel user experiences that were not previously investigated in related research literatures.

4- *Identify and discuss the main user-centered design considerations for creating daily used serpentine-shaped robotic appendages:* The fourth contribution comprise an effort to structure gathered insights from the

design, implementation and evaluation procedures of the case studies, by providing a multi-dimensional set of essential user-centered design considerations for constructing serpentine-shaped robotic appendages. The design dimensions include four main sub-domains, which are multipurpose use, interaction and control, wearability and ergonomics, and unobtrusiveness and social acceptability. These design considerations provide both design guidelines and implementation methods based on the culmination extracted insights from case studies and their evaluations.

Chapter 1 introduces our work. First, we discuss the motivation of our work, which is essentially based on the realization of daily worn robotic appendages for everyday use, which is a research domain that has not been tackled from a user-centered perspective. Second, the research questions addressed within this dissertation are discussed, indicating how they yield the main contributions of this dissertation. The user-centered research method used to address the research questions is also introduced and discussed, highlighting the methodology of applying such research approach to provide the mentioned dissertation contributions.

Chapter 2 presents a background of related research and a discussion of such research with respect to the development serpentine-shaped robotic appendages. This dissertation builds upon four main research domains. Accordingly, this chapter starts with a discussion of the methods and challenges of designing interactions and wearable devices that target the daily interaction context. Moreover, the area of shape-changing interfaces is discussed, highlighting prominent differences between the serpentine-shaped robotic appendages and this research domain. Next, I touch upon different domains of wearable systems, including supernumerary robotic limbs (SRLs), kinetic and fashion wearables, and actuated wearables, all of which serpentine-shaped robotic appendages extends various design directions and considerations. This chapter ends with a discussion of the concept of serpentine-shaped robotic appendages and how it relates to the mentioned research domains.

Chapter 3 covers the preliminary studies conducted to address contextual factors and requirements for designing serpentine-shaped robotic appendages. Two user studies are discussed. The first user study is concerned with investigating the requirements and expectations of using serpentine-shaped robotic appendages within daily contexts. The second user study investigates the research challenges and opportunities for designing serpentine-shaped robotic appendages from the perspectives of Robotics and HCI. The outcomes of these studies enabled extracting insights about the main usage requirements, challenges and expectations that were further investigated in the case studies.

Chapter 4 discusses four case studies, their evaluations and analysis. The first case study, called Orochi, builds upon the findings in the preliminary works to establish the design considerations, embody them in a prototype and evaluate them. The second case study, called HapticSerpent, focuses on exploring novel haptic feedback enabled by serpentine-shaped robotic appendages, and follows with an investigation of the acceptability of receiving various types of feedback throughout the user's body. The third case study, weARable, explores how user experiences can be designed for serpentine-shaped robotic appendages, presenting a design space, a technical-integration architecture and a preliminary evaluation of various user experiences. The last case study, called HapticSnakes, presents a system for delivering novel feedback to users. Moroever, a design space that comprises dimensions for constructing novel experiences is constructed, followed by two evaluations targeting taps and novel haptic feedback which can be applied to a variety of daily interaction contexts.

Chapter 5 focuses on extracting the insights from the preliminary evaluations and the case studies. Accordingly these insights categorized, analyzed and presented under three main section to correspond to the first, second and third research questions, respectively. First, daily usage expectations. The data gathered from preliminary studies and the first case study are combined and analyzed to form a use-case distribution comprising 457 use cases, where they are discussed and classified under three primary categories: physical interactions, digital interactions, and others, thereby underlining the requirement of multipurpose use. The second section is concerned with social and personal acceptance. Social acceptance comprise challenges in unobtrusiveness, therefore, methods to decrease obtrusiveness are extracted and discussed, such as to resemble garments and accessories. Another aspect is social acceptability, where insights from the case studies highlighted several interleaved challenges for public usability of serpentine-shaped robotic appendages. Extracted insights showed personal acceptability challenges in undesired and controversial use cases, as well as undesired interactions. Accordingly, these aspects are analyzed and discussed with respect to the case studies, underlining their importance in contributing to user adoption in future deployments. The third section is concerned with user experience design. Design and

implementation insights emphasizing methods of enabling multipurpose user experiences and designing user experiences with multiple interaction paradigms. Moreover, a classification of cross-device digital interactions is provided, citing example implementations extracted from the case studies. Such classification enables designers to identify and implement cross-device user experiences that seamlessly combine serpentine-robotic appendages and various digital devices.

Chapter 6 addresses the fourth research question. I identify a set of design considerations for designing serpentine-shaped robotic appendages targeting daily usage contexts. These design considerations are based on the design, implementation and evaluation of the case studies. These design considerations are classified into four main categories. The first consideration is multipurpose use, which is concerned with designating which interactions designers should consider when creating serpentine-shaped robotic appendages. The second consideration is interaction design, which presents design dimensions and methodologies for constructing cohesive user experiences that cope with user's expectations and multipurpose use. Third, wearability and ergonomics, which is concerned with addressing wearability paradigms that can provide varied levels of flexibility during daily use. Various wearability methods are extracted from the use cases to exemplify the variety of implementation approaches with respect to required flexibility. Fourth, unobtrusiveness and social acceptability. This section emphasizes the importance of attaining unobtrusive designs to decrease obtrusiveness and social pressure commonly associated with novel wearables. Moreover, the importance of evaluating the social acceptability during active use of the wearables are also discussed. Accordingly, each section comprise implementation methods based on the case studies are discussed within each design consideration, which provides researchers with methods of embodying these considerations. Finally, design implications of embodying the design considerations are discussed, including some trade-offs that may arise from embodying various considerations.

Chapter 7 discusses limitations and future research directions. A number of aspects related to the research questions are discussed. First, the limitations to the domain of multipurpose use is discussed, as there are unconsidered use cases that fall beyond functional requirements or difficult to extract from a user-centered methodology. For example, using the robot for fashion, hedonic purposes or as a wearable teleoperation platform. Similarly, difficulties in social acceptability presents a number of challenges, some of which bear similarities to those of novel wearable systems. Therefore, established evaluation methods of wearable systems can be the foundation from which social acceptability research about serpentine-shaped robotic appendage are built upon. While the extracted results and insights in this dissertation mainly emphasize serpentine-shaped robotic appendages, the design considerations can be generalized. The design considerations can be realized in different methods, thereby resulting in other intriguing methods of fulfilling the considerations. Further aspects related to the technical implementations are also presented. Most importantly, the need to develop technical considerations that examine the design dimensions from an implementation perspective. Also, aspects related to actuation, mechanical design, safety are also discussed in light serpentine-shaped robotic appendages. The feasibility of implementing wearables based on the presented case studies is discussed, given that the level of fulfillment of the design consideration is relatively scaled down. Finally, Chapter 8 discusses the conclusion and summarizes the dissertation.

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Journal Papers	○ M Al Sada, K. Jiang, S. Ranade, M. Kalkattawi & T. Nakajima, (2019). HapticSnakes: multi-haptic feedback wearable robots for immersive virtual reality. Virtual Reality, 1 – 19 (to Appear) DOI: https://doi.org/10.1007/s10055-019-00404-x
Conference Proceedings	○ Mohammed Al-Sada, Thomas Höglund, Mohamed Khamis, Jaryd Urbani, and Tatsuo Nakajima. 2019. Orochi: Investigating Requirements and Expectations for Multipurpose Daily Used Supernumerary Robotic Limbs. In Proceedings of the 10th Augmented Human International Conference 2019 (AH2019). ACM, New York, NY, USA, Article 37, 9 pages. DOI:https://doi.org/10.1145/3311823.3311850 ○ Mohammed Al-Sada, Keren Jiang, Shubhankar Ranade, Xinlei Piao, Thomas Höglund, and Tatsuo Nakajima. 2018. HapticSerpent: A Wearable Haptic Feedback Robot for VR. In Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems (CHI EA '18). ACM, New York, NY, USA, Paper LBW624, 6 pages. DOI:https://doi.org/10.1145/3170427.3188518 ○ J. Urbani, M. Al-Sada, T. Nakajima and T. Höglund, "Exploring Augmented Reality Interaction for Everyday Multipurpose Wearable Robots," 2018 IEEE 24th International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA), Hakodate, 2018, pp. 209-216. DOI: 10.1109/RTCSA.2018.00033 ○ Mohammed Al Sada, Mohamed Khamis, Akira Kato, Shigeki Sugano, Tatsuo Nakajima, Florian Alt. Challenges and Opportunities of Supernumerary Robotic Limbs, In Amplify '17: Proc. of CHI 2017 Workshop on Amplification and Augmentation of Human Perception. May 6 - 11, 2017. ACM, New York, USA. ○ Jiang K., Piao X., Al-Sada M., Höglund T., Ranade S., Nakajima T. (2019) A Robotic Haptic Feedback Device for Immersive Virtual Reality Applications. In Ambient Intelligence – Software and Applications –, 9th International Symposium on Ambient Intelligence. ISAmI2018 2018. Advances in Intelligent Systems and Computing, vol 806. Springer, Cham DOI:https://doi.org/10.1007/978-3-030-01746-0_17 ○ M. Al-Sada, "Design Space of Multipurpose Daily Worn Snake-Shaped Robotic Appendages," 2019 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), Kyoto, Japan, 2019, pp. 455-456. DOI: 10.1109/PERCOMW.2019.8730745

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	Mohammed Al-Sada, Fumiko Ishizawa, Junichi Tsurukawa, and Tatsuo Nakajima. 2016. Input Forager: a user-driven interaction adaptation approach for head worn displays. In Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia (MUM '16). Association for Computing Machinery, New York, NY, USA, 115–122. DOI:https://doi.org/10.1145/3012709.3012719 Urbani, Jaryd, Mohammed Al-Sada, Shubhankar Ranade, Mingshu Zhang, and Tatsuo Nakajima. "WAR Bots: Combining Virtual and Augmented Realities for an Immersive and Enjoyable Gaming Experience." In International Conference on Entertainment Computing, pp. 379-382. Springer, Cham, 2017. DOI:https://doi.org/10.1007/978-3-319-66715-7_44 Keisuke Irie, Mohammed Al Sada, Yuki Yamada, Kota Gushima, and Tatsuo Nakajima. 2017. Pervasive HoloMoL: A Mobile Pervasive Game with Mixed Reality Enhanced Method of Loci. In Proceedings of the 15th International Conference on Advances in Mobile Computing & Multimedia (MoMM2017). Association for Computing Machinery, New York, NY, USA, 141–145. DOI:https://doi.org/10.1145/3151848.3151869 Ranade, Shubhankar, Mingshu Zhang, Mohammed Al-Sada, Jaryd Urbani, and Tatsuo Nakajima. "Clash tanks: An investigation of virtual and augmented reality gaming experience." In 2017 Tenth International Conference on Mobile Computing and Ubiquitous Network (ICMU), pp. 1-6. IEEE, 2017. DOI: https://doi.org/10.23919/ICMU.2017.8330112 Yamada, Yuki, Keisuke Irie, Kota Gushima, Fumiko Ishizawa, Mohammed Al Sada, and Tatsuo Nakajima. "HoloMoL: human memory augmentation with mixed-reality technologies." In Proceedings of the 21st International Academic Mindtrek Conference, pp. 235-238. ACM, 2017. DOI:https://doi.org/10.1145/3131085.3131097 Mohammed Al-Sada, Shuma Toyama, and Tatsuo Nakajima. 2016. A Mobile VR Input Adaptation Architecture. In Proceedings of the 13th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (MOBIQUITOUS 2016). ACM, New York, NY, USA, 286-287. DOI:https://doi.org/10.1145/2994374.3004073 Ikeuchi, Kohki, Mohammed AlSada, and Tatsuo Nakajima. "Providing ambient information as comfortable sound for reducing cognitive overload." In Proceedings of the 12th International Conference on Advances in Computer Entertainment Technology, p. 29. ACM, 2015. DOI:https://doi.org/10.1145/2832932.2832985 Toyama, Shuma, Mohammed Al Sada, and Tatsuo Nakajima. "VRowser: A Virtual Reality Parallel Web Browser." In International Conference on Virtual, Augmented and Mixed Reality, pp. 230-244. Springer, Cham, 2018. DOI:https://doi.org/10.1007/978-3-319-91581-4_17

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	Tsurukawa, Junichi, Mohammed Al-Sada, and Tatsuo Nakajima. "Filtering visual information for reducing visual cognitive load." In Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers, pp. 33-36. ACM, 2015. DOI:https://doi.org/10.1145/2800835.2800852 Mohammed AlSada and Tatsuo Nakajima. “Parallel Web Browsing in Tangible Augmented Reality Environments.” Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA ’15 (2015). DOI:https://doi.org/10.1145/2702613.2732746