Title	スケーラブルかつ伸縮可能な折り紙構造を用いた余剰肢ロボットの開発
Author(s)	楠木, 幹也
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Description	Supervisor: 謝 浩然, 先端科学技術研究科, 修士(知識科学)

Abstract

Human augmentation refers to the technology that enhances human physical abilities using technology. The targets for augmentation can be broadly categorized into four aspects: body, cognition, existence, and perception. Within the realm of body augmentation, the primary goal is to enhance human physical capabilities by using wearable devices. Examples include prosthetics, exoskeletons, and supernumerary robotic limbs. Supernumerary robotic limbs involve attaching a robotic arm to the human body to expand capabilities, allowing for the performance of various tasks that were previously challenging. This technology is expected to be useful for various applications in industries, rehabilitation, and daily life support. However, most of wearable robotic arms currently developed are designed with a specific focus and optimized for a particular purpose. They often lack consideration for user variations in body size and usage scenarios, leading to a lack of flexibility and versatility. Given the diverse needs and requirements from individual users, the absence of customization makes it challenging for users to effectively utilize these devices. Therefore, it is an important issue for the development of wearable robotic arms that possess flexibility to accommodate different users and tasks, enhancing their versatility. To achieve this goal, this thesis introduces mechanisms that allow users to freely adjust and customize the device. Building systems based on human centered design principles can enable adaptability to various applications, allowing each user to more effectively utilize the device. The ability for users to customize wearable robotic arms according to their preferences and needs has the potential to broaden their utilization in various applications of industry, rehabilitation, and daily life. The flexibility and customization offered by such devices are expected to improve their effectiveness, providing tailored support to meet user needs.

In this thesis, we propose supernumerary robotic limbs utilizing a scalable and foldable origami structure to address such issues. Inspired by origami, the extra limb robot allows for adjusting the device's scale to various applications, enhancing the wearer's capabilities by attaching it to different parts of the body such as hands, wrists, arms, and torso. The device's foldable structure can be unfolded during use and folded when not in use, preventing physical contact with the wearer and the surrounding environment, thus not restricting the user's movements. Furthermore, the robotic limb is made of lightweight and soft materials, ensuring safety and reducing fatigue even after prolonged use. In our proposed system, users first create an unfolding diagram for the desired origami structure using a user interface implemented in Grasshopper. Adjusting parameters of fabrication scale and layer, users can determine the size of the robotic arm. The unfolding diagram created using the user interface is then saved in SVG format. Next, the diagram is imported

into software designed for laser cutters, and the laser cutting process follows the pattern of the unfolding diagram. Users can fold the cut sheets along the unfolding diagram, and complete the module. This proposed approach allows for a scalable design by avoiding the complexities of traditional methods. Users can easily adjust the size of the robotic arm using the provided user interface, streamlining the fabrication process and enabling scalability.

In this study, several experiments were conducted in the fabrication of origami modules. First, to select a suitable origami structure, three representative cylindrical origami structures—namely, the “Twisted tower,” “Yoshimura pattern,” and “Kresling pattern”—were fabricated in a simplified manner, and their performance was compared. As a result, it was determined that the “Twisted tower” was the most suitable for the intended purpose. Additionally, user experiments using NASA-TLX were conducted to examine the fabrication burden of the three origami structures, revealing that the “Twisted tower” imposed the highest workload. To address this, a method utilizing a laser cutter is proposed. Furthermore, to determine the most suitable material, experiments were conducted to investigate the durability of three materials: polypropylene, Yupo paper, and regular paper. A load measuring device was employed to compress and restore origami modules created from different materials in the axial direction for 1,000 cycles, measuring both the rigidity and fatigue of the origami in the stretching and compressing motions. The results indicated that polypropylene was the most effective material in preventing origami fatigue. In experiments assessing durability with different layer counts, it was observed that as the number of layers increased, the rigidity decreased.

For the implementation details, a wire is attached to the top surface of the origami module created through several experiments, and it is connected to a motor equipped with a rotary encoder (Magnetic Encoder Pair Kit for Pololu Micro Metal Gearmotors, 12 CPR) through a spool mechanism (Pololu 380:1 Micro Metal Gearmotor HP 6V with Extended Motor Shaft). The microcontroller used is Arduino Mega 2560, and the motor driver is TB6612FNG. When the motors are activated, the wire is retracted, causing the origami module to contract. Conversely, reversing the direction of the motors allows the origami module to extend due to the spring-like characteristics of the structure. Additionally, by using a single motor, bending motion is achievable, and by appropriately controlling multiple motors, bending motions in any direction can be realized. In the prototype development, three sizes of supernumerary robotic limbs were created. Based on previous research, simulations were conducted with tasks suitable for each size. The small-scale device is attached to the hand as the “Sixth finger.” The medium-scale device is attached to the forearm as the “Third forearm.” The large-scale device is attached to the torso as the “Third arm.”

In the evaluation experiment of this system, tasks were performed using the proposed devices of three different sizes. Ten participants took part in the experiment. After the experiment, a questionnaire survey was conducted to assess usability. The tasks performed by participants in the experiment included lifting an object using the small-sized device, grasping an object by pinching with the medium-sized device, and soldering using the large-sized device. After completing these three tasks, participants responded to questionnaire items on a 5-point scale. The results confirmed the effectiveness of the proposed system. In addition, valuable insights were obtained through open-ended responses. The use of the proposed system suggests not only the potential for use in confined spaces and extended periods but also the ability to provide support tailored to user needs. Future improvements to the system may involve refining the origami structure. While the current system utilizes unfolding diagrams of existing origami structures, enhancing the design for increased robustness could elevate the payload capacity as a robotic limb, enabling it to handle a broader range of tasks.

This thesis has the following main contributions.

- We propose a fabrication technique of origami-inspired SRLs(Supernumerary robotic limbs) using a twisted tower structure with adjustable layers and scale.
- We verify the proposed SRLs for durability using different materials.
- We design SRLs that combine scalability and foldability in different use scenarios.