様式３

論　文　内　容　の　要　旨

氏　　名　（濵屋　政志　　　　　　）	
論文題名	Leveraging Physical User-robot Interactions for Modeling and Control of Exoskeleton Robots （物理的相互作用を利用した外骨格ロボットのモデル・運動支援制御器設計） ブツリテキソウゴサヨウ　リヨウ　ガイコッカク　ウンドウシエンセイギョキセッケイ

論文内容の要旨

Owing to recent breakthroughs of robotics technologies, physical assistive robots have attracted much attention.
Exoskeleton robots are one of them; can be used in various situations such as augmentation or rehabilitation.
Many studies have developed both of the hardware and software of exoskeleton robots.
The recent hardware studies have developed the exoskeleton robot with soft actuators and soft exosuits that enable safe and comfortable assistance. Meanwhile, designing software of the exoskeleton remains a challenging problem due to the complexity of the user-robot interactions. In this thesis, I propose to design the models and controllers of the exoskeleton robots that are suitable for the individual user by leveraging the physical user-robot interactions.
To achieve this goal, I tackle three problems: 1) design of a controller framework from the physical interaction, 2) model identification from the physical interaction, and 3) improvement of scalability of the assistive strategies.

First, I propose the control framework: learning assistive strategies of the exoskeleton robots from the physical user-robot interactions. Although many controllers have been proposed, most of them utilized approximated models that did not take the individuality and interactions into account. This proposed approach learns the user-robot interaction model that predicts the user's reaction given the robot's input from the physical interaction data. Based on the model, I employ a data-efficient model-based reinforcement learning for the assistive strategies to alleviate a large number of interactions that put a burden on the users. I applied the proposed method to an elbow joint exoskeleton robot. The experimental result showed that my method could learn the proper assistive strategies.

Next, I consider the model identification problem. In this thesis, I focus on model identification of soft actuators with the exoskeleton robots. To obtain the accurate models, the various external forces are required in the model identification process. However, previous identification approaches do not necessarily take actual situations in which the user wears the robot into account and obtain the accurate models. In this study, I propose a novel approach for obtaining accurate soft actuator models through the physical user-robot interactions for wearable robots, in which the user applies external forces to the robot.
I leverage an active learning framework based on Gaussian Process (GP) regression for the efficient identification. I conducted experiments using a two-DoF upper-limb exoskeleton robot with four pneumatic artificial muscles (PAMs). Experimental results showed that physical interactions between the exoskeleton robot and the user were successfully designed to identify PAM models.

Finally, I tackle the scalability problem of assistive strategies. The generalization for multiple tasks and extension to multiple DoF systems can improve the scalability. I propose learning task-parametrized assistive strategies for the exoskeleton robots that can adapt to unseen tasks. This method learns the assistive strategies from multiple sets of human-robot interaction data through different tasks. They can be generalized even for unseen tasks, given the task parameters without additional learning.
Furthermore, I exploit the synergies both of the human muscles and artificial muscles of the exoskeleton robots to reduce the number of control parameters of the assistive strategies so that they can be learned even with Multi-DoF systems.
I show that I can extract the synergies not only from the user's muscle activities but from PAMs contractions of the exoskeleton robot by using the learned PAM models. Then, I adopt a Bayesian optimization method to acquire the parameters for assisting human movements by iteratively identifying the user's preferences of the assistive strategies. I conducted

experiments to evaluate my proposed method with a PAMs-driven upper-limb exoskeleton robot. My method successfully learned assistive strategies with a practicable number of interactions.

From the results, many people could enjoy safe and comfortable assistance from the exoskeleton robots whose controllers adapt to the individual users and could be learned without experts' knowledge.
The proposed method would be applied to both of the augmentations on and rehabilitation.
Finally, the method would help to understand human behaviors during human-human collaboration or human-robot collaboration.

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論文審査の結果の要旨及び担当者

氏　名　（　　　濵屋　政志　　　）	
論文審査担当者	（職）　　　　　　氏　名 主 査　特任教授　柳田　敏雄 副 査　教授　大澤　五住 副 査　教授　北澤　茂 副査　招へい教授　鈴木　隆文 副査　招へい准教授　森本　淳

論文審査の結果の要旨

申請者は、外骨格ロボットの運動支援制御とモデル化を、ユーザとロボットの物理的相互作用から設計する手法を提案した。従来はユーザのモデルの複雑さから効果的な制御器の設計が困難であった。その結果、効果的な運動支援が得られず、制御器の調整に多大な時間を必要とした。本研究では、物理的相互作用からユーザやロボットの状態を評価して、ユーザに適応的な制御器や実用的なモデル同定手法を提案した。まず、物理的相互作用データから、ユーザの筋負荷を軽減させる運動支援をデータ効率の良い強化学習で設計した。次に、ロボットに搭載された空圧人工筋のモデル同定のために、相互作用戦略の設計手法を提案した。さらに、学習されたモデルを用いて、ユーザとロボットの筋シナジー抽出を行い、制御パラメータの次元を削減し、運動支援の多自由度拡張を行った。実験の結果、従来の手法と比較してユーザの筋負荷を減少させる運動支援を実用的な範囲で学習できた。これらの結果から、実用的な外骨格ロボット運動支援制御とモデル化の新たな枠組みを構築できたと考えられる。以上の理由より、学位授与に値すると認める。