2023 IEEE/ASME International Conference on
Advanced Intelligent Mechatronics (AIM)

Designing Comfortable Robotic System with Human Comfort Analysis and Modeling in Human-Robot Collaboration (HRC)

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Human-Robot Collaboration (HRC) is an interdisciplinary field that focuses on the collaboration of humans and robots as they achieve shared goals [1]. One of the limitations of the HRC studies is the lack of emphasis on human comfort, which is critical to the user acceptance of COBOTs and human experience during the HRC tasks.

In recent years, some researchers investigated how to evaluate and improve human comfort in HRC scenarios. Story et al. [2] assessed the impact of robot's speed and proximity setting on a person's workload and trust during an HRC task, finding that these factors greatly impact human's comfort. Dufour et al. [3] proposed a new approach to improve the comfort of a human standing or operating near a collaborative robot by considering visual–spatial attention. Figueredo et al. [4] proposed a method to improve human comfort by optimizing robot configuration and thus minimizing the muscular effort during HRC tasks. However, the research above limits their comfort evaluation methods by merely using subjective ratings or simple statistical comparison approaches. There is a lack of a mathematical modeling approach to evaluate human comfort in HRC tasks.

Therefore, the goal of this study is to build individual human comfort models with an analytical approach, and further conduct comfort factor analysis. The proposed comfort model can be used to predict human comfort feedback given a set of robot motion parameters; thus, it will contribute to designing a more comfortable robotic system which will adapt its working style in HRC in the future. The five factors have been adopted and sufficient number of their combinations provide a comprehensive coverage of the scenarios that a human subject will potentially encounter in HRC tasks. Also, the results yielded provide a satisfying overall prediction accuracy. Thus, the comfort prediction model has been proved to be universally appliable and extendable to a wide range of HRC scenarios. The model has already been applied in a new study which is used to compute comfort rewards for an MDP model in HRC.

In the experiment, different robot motion factors were taken into consideration during the design process: final delivery distance, robot moving speed, final delivery height, robot arm approaching trajectory and delivery pose. The entire experiment scenario pool is composed of 270 delivery tasks, while each task adopts a combination set of different factor levels as the robot motion control parameters. In this study, multiple factors are tuned at the same time for each task. In our study, a 5-point Likert Scale questionnaire is used to collect the subjective comfort level ratings from the subjects.

The analytical comfort model is built based on a set of primitive rewards determined by robot behavior factors. The process of building this comfort prediction model is to solve an optimization problem and obtain the optimal weight factor set and primitive comfort reward set. The overall average accuracy of analytical model among all participants is 81.33%. The factor analysis results indicate that robot behaviors do affect human comfort in HRC. Too long distance, too slow robot speed and too high robot pose yield high discomfort.

A physiological comfort model is developed to identify human comfort based on in-situ physiological signals A multi-class error-correcting output codes SVM (ECOC-SVM) approach is employed to classify the comfort levels. Three different techniques including Independent Component Analysis (ICA), Support Vector Machine Recursive Feature Elimination (SVMRFE) and Autoencoder were implemented independently for feature selection. The overall comfort level prediction accuracy of the ECOC-SVM multiclass classifier was 74.44%, 75.01% and 76.68% for the ICA, SVMRFE and Autoencoder feature selection methods respectively.

The comfort models can be used to guide the design of the robot behaviors during human-robot collaboration system to allow the robot to perform tasks in a comfortable way when collaborating with humans.

Acknowledgment

This work was supported by the National Science Foundation under Grant IIS-1845779.

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