Proceedings of the 33rd European Safety and Reliability Conference (ESREL 2023)
Edited by Mário P. Brito, Terje Aven, Piero Baraldi, Marko Čepin and Enrico Zio

Published by Research Publishing, Singapore.
doi: 10.3850/978-981-18-8071-1_P295-cd

User-centered Evaluation Framework for Telerobot Interface and Interaction factors – a case study on medical device manufacturing

Inês F. Ramos[1], Keerthi Sagar[2], Philip Long[3], Ernesto Damiani[1], Maria Chiara Leva[4], Gabriele Gianini[1]

[1] Università degli Studi di Milano, Italy. E-mails: ines.fernandes@unimi.it, ernesto.damiani@unimi.it and gabriele.gianini@unimi.it

[2] Irish Manufacturing Research Centre (IMR), Ireland. E-mail: keerthi.sagar@imr.ie

[3] Atlantic Technological University, Ireland. E-mail: philip.long@atu.ie

[4] Technological University Dublin, Ireland. E-mail: mariachiara.leva@tudublin.ie

The use of telerobots for surgery, military missions or rescue activities are increasingly commonplace, and so are guidelines to achieve an ergonomic design and optimal system-operator performance. However, in medical device manufacturing, in particular for fine-manipulation and highly precise operations, the existing human-machine interface and interaction (HMII) design standards to date are insufficient to ensure a cost-effective ergonomic teleoperation solution, that complies with the learnability, usability, dependability and efficiency required for this case-study. We analyze the most relevant human-system interface and interaction requirements for telerobotic systems applied to medical device manufacturing, and expand on the current standards with knowledge from recent research results in this field. We further our contribution by proposing a use-case-based telerobotic system architecture and experimental setup for human-centered evaluation of the telerobotic system HMII design.

Keywords: Telerobotics, Human-in-the-loop, Medical Device Manufacturing, Standards, EEG, Eye-tracking

1. Introduction

In the medical device manufacturing industry, precise assembly tasks and manipulation of complex materials and objects are common challenges, including precise cutting on miniature pieces made of deformable material. Adaptable automation solutions are urgently needed to maintain competitiveness in today's high-cost society. A human-in-the-loop teleoperation system provides a solution for these automation needs, combining the benefits of the robotic system (motion scaling for highly precise movements, speed, accuracy, repeatability) with the expertise of the operators, reducing automation costs, lowering safety requirements (compared to the use of cobots or manual operations), and reducing the costs of maintaining a clean room, a common requirement for the manufacturing of medical devices. Teleoperation is still a difficult task for non-expert users Rea and Seo (2022), and more focus should be put in user-centered interface and interaction solutions to solve the outstanding challenge of operator performance. User-centered problems revolve around either awareness and understanding of the remote environment (remote perception), or the control of the robot Chen et al. (2007) Rea and Seo (2022). These problems should be primarily considered when designing a teleoperated system and the interactions between the operator and the robot.

2. Human-in-the-loop telerobotic system for medical device manufacturing

In our telerobotic system we implement a novel combination of mixed-reality-based interface and haptic shared-control interaction that has not been yet applied to human-in-the-loop medical manufacturing applications, aiming to increase remote situational awareness, reduce operator workload and reduce training time.

The system is designed and developed taking into consideration the manufacturing tasks that have to be carried out. It consists of a remote station with a KUKA KR4-Agilus 6-DoF robotic arm with different end-effector tools options, such as a hot-wire and a gripper, force-torque sensors, and three 2D cameras (two fixed on the workspace and one attached to the end-effector). The operator controls the robot with a Phantom Omni controller with six DoF, that provides haptic feedback to the operator representative of the forces received by the robotic arm in the remote environment.

A mixed-reality interface is developed to provide a higher sense of immersion and virtual functionalities, such as an interactive camera and a 3D workspace-robot representation. Haptic feedback is used as a complementary information channel for the operator to sense the environment and the interaction of the robot with other elements. Additionally, the control schema was simplified so the user can control directly the end-effector of the robot, and shared-control options were developed to assist with complex precise operations (using haptic virtual fixtures).

3. HMII design guidelines considerations

Human-robot interaction via teleoperation has commonalities with human-computer interaction field (HCI), however existing GUI-based usability design and evaluation methods lack the integration of the new interaction technology currently being used to improve teleoperation systems, and the consideration of the new challenges it creates. A document is created compiling and integrating heuristic design guidelines from multiple fields, including the human-computer interaction, virtual reality, robotics and haptic interaction field, for the user-centered design and compliance evaluation of the developed teleoperation system. The developing document contains several guidelines retrieved from current standards and recent research results, and provides practical evaluation questions and methods.

4. User-centered evaluation

Since cost-effective solutions for low-volume manufacturing scenarios are required, the design efforts are focused on achieving an ergonomic and intuitive system for skilled manual operators. The evaluation of the developed system is done from the point of view of the user, focusing on the user experience, and assuming the technical and functional properties of the system are appropriate for the requirements of the intended use. The following evaluation data will be collected to assess the system for compliance with the key guidelines identified:

- Task performance data, such as task completion time KPI's related to the specific tasks carried out.
- Operator state data: objective metrics estimated from physiological sensor data, including a consumer-grade mobile EEG-cap and eye-tracker mounted on a monitor, and subjective metrics gathered from user questionnaires.
- Human-system interaction data, to assess interaction efficiency and effectiveness.

5. Conclusion

Our work aims to provide other researchers and practitioners with a better understanding of the potential of human-in-the-loop robotic solutions, with insights into the applicable standards, recommendations drawn from recent research and a user-centered evaluation framework that can be used to access compliance and improve human-robot interactions.

Acknowledgement

This work was supported by the European Union's Horizon 2020 Research and Innovation Programme under the CISC project (Marie Skłodowska-Curie grant agreement no. 955901), the FineTETHER project (Marie Skłodowska-Curie grant agreement no. 847402), and national capital grant funding program Enterprise Ireland (CE-2020-0221). The work was partially supported by the project MUSA (CUP G43C22001370007, Code ECS00000037), and by the project SERICS (PE00000014) under the NRRP MUR program, both funded by the EU - NextGenerationEU.

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