FORM 6

TEACHING-SCIENTIFIC COUNCIL

Teaching-scientific council of Faculty of Engineering, Kragujevac

and

COUNCIL FOR TECHNICAL-TECHNOLOGICAL SCIENCES

UNIVERSITY OF KRAGUJEVAC

At the meeting of the Council **TECHNICAL-TECHNOLOGICAL SCIENCES** of the University of Kragujevac held on 10.7.2024. године (decision number: IV-04-559/15) we have been appointed as members of the Committee for the evaluation and defence of the doctoral dissertation entitled: **"Neuroergonomic Assessment of Mental Workload in Adaptive Industrial Human-Robot Collaboration"**, of the candidate **Carlo Caiazzo**, student of doctoral academic studies Industrial engineering and Engineering management, for which a mentor has been appointed **dr Marko Djapan, associated professor**.

Based on the data at our disposal, we submit the following:

EVALUATION REPORT

OF THE FINISHED DOCTORAL DISSERTATION

1. Doctoral dissertation data
1.1. Doctoral dissertation title:
Neuroergonomic Assessment of Mental Workload in Adaptive Industrial Human-Robot Collaboration
1.2. Description of the doctoral dissertation (provide a short content with the page number indication, chapters, figures, graphs, equations and references) (up to 500 characters):
The doctoral dissertation contains 118 pages divided in 8 chapters, Introductions; Literature review; Design of experiments; Neuroergonomic assessment and EEG pre-processing; Subjective and observational measurements; Discussion and implication of the work; Conclusion; Literature; Annex 1 and 2. The doctoral dissertation contains 50 figures, 17 tables, 3 equations, and 264 references.
1.3. Description of the research subject (up to 500 characters):
The PhD work shows a comparative neuroergonomic analysis to assess the mental workload of participants in a manufacturing assembly task in collaboration with the robot. The mental workload was calculated using a formula that correlated the most intense waves from the scalp during the analysis. Further questionnaires and observational data were evaluated on the effectiveness of the task completed by the participant in three different scenarios, as well as the impact of the cobot on the workforce.
1.4. Analysis of initial hypothesis fulfilment:
Regarding the proof of hypotheses defines at the beginning of this PhD dissertation:

H1 - The implementation of collaborative robot solutions can reduce the level of mental workload (MWL) during work activities.

H2 - Reducing the level of mental workload improves the efficiency, effectiveness, and quality of work activities.

H3 - It is possible to define mental workload through objective sensorial devices and measurement.

H4 - The use and implementation of collaborative robots have a subjective positive impact on workers during work activities.

For the H1, it has been empirically shown that the implementation of cobots in the workplace, considering ergonomic and technical aspects to ensure a proper collaboration alongside the operator, has brought a significant reduction of MWL, proven with ANOVA statistical analysis, through the combination of objective (EEG) and subjective measurements (NASA-TLX). The proof of this hypothesis still presents some limitations. Firstly, the analysis was carried out for a sample of participants ($N = 10$). The chosen sample, though it was proper for the analysis under certain conditions, is still poor to define a thorough understanding of MWL trend in a HRC task. Further analysis should be addressed for a larger sample of participants.

Secondly, to adhere to the stipulated comparative evaluation, the same participants completed the task in all three scenarios over a minimum of four months. Whereas research investigations in the field of Neuroergonomics demonstrated that this timeframe was suitable for not having a memory bias of an activity performed by humans, the studies were only empirically shown. To the greatest extent of our knowledge, this is the first study to compare human performance and MWL in a comparative analysis with the same number of participants and the sole discriminant being the robot engaging with them in the workplace for an industrial HRC task.

For the H2, it has been shown that the reduction of MWL improves the level of efficiency, effectivity, and overall, quality of the task. The number of components accomplished by the participants over the time task, thus the productivity of the task, was shown to be higher when participants worked alongside the cobot. Specifically, in the third scenario, the level of productivity highly soared than in the standard scenario without the cobot.

Regarding the H3, it has been shown that through objective sensorial devices, it was possible to evaluate MWL. The deployment of EEG paved the way for a real-time, efficient, non-invasive neuroergonomic analysis of MWL. Different parameters could be extracted to evaluate MWL.

Among the power ratios presented in the literature review, the MWL parameter (β/α) was the most significant in determining the cognitive burden of participants in three situations. In other research, other brainwaves, such as theta waves, were used to analyze the MWL. However, today, the selection of a stress indicator is disputed. Furthermore, setting up and installing the EEG neuroergonomic hat took time during the test preparation period. Due to the gel on the electrodes, participants had to wait 20 to 30 minutes to mount the EEG cap. Indeed, setting up EEG devices remains a time-consuming operation.

For the H4, subjective evaluations such as the NASA-TLX and surveys revealed that the deployment of cobots had a favourable impact on participants during the assembly activity. According to the participants' responses, the assembly activity with the robot made it safer and more pleasant to take up the plate from the gripper. Furthermore, the encounter was deemed more educational and pleasurable. In terms of motion, the participants did not feel terrified when the robot moved, and its response when they seized the pieces from the gripper was not aggressive.

1.5. Analysis of applied research methods:

The tests were conducted in a modular industrial assembly workstation built for neuroergonomic research and located at the Faculty of Engineering laboratory at the University of Kragujevac in Serbia. The assessment included successive manual assembly activities. Three case studies were prepared for the experiments: in the first scenario, the participant achieved the work without any interference in the assembly area; in the second scenario, the robot takes the components sequentially to the assembly and

provides them to the operator; and in the third scenario, robot carries sequentially the components completely prepared to the assembly providing them to the operator. The goal was to conduct a comparative analysis of the mental workload by the EEG real-time acquisition in these three different scenarios. The three experimental scenarios were set in different periods of the year with a period of a minimum of 4 months each to reduce the error-bias in the comparative neuroergonomic analysis. Moreover, to reduce the noise due to internal factors that might influence the workload, experiments started in the morning hours of the day, conducted in an isolated environment and at room temperature. The mental workload was evaluated for three consecutive halves of each scenario. Regarding the number of participants, the G*Power software tool was employed to define the minimum sample size, enough to carry out the experiments through the analysis of variance with repeated measures (ANOVA RM). For the scenarios with the cobot, a matrix risk assessment was deployed to evaluate the safety of the machine implements in the collaborative workplace, collaborating with the participants. Nonetheless, technical parameters were chosen regarding the cobot's speed, position, and force gripper from guidelines to guarantee a proper and safe collaboration with the participants. Moreover, at the end of the test, NASA-TLX questionnaire were provided to the participants to evaluate subjective metrics such as mental, physical, and temporal demand, fluency, performance, and stress. Finally, observational measurements like checklists and timer were deployed to evaluate further metrics like productivity, efficiency, and quality of the tasks for each scenario.

1.6. Analysis of research objective fulfilment:

For the comparative analysis, the participants accomplished three different types of experiments, which include standard scenario, in which the participant performed the task without any intervention and support; collaborative scenario, in which the participant performed the task interacting with the robot (supporting activity) in the workplace; collaborative guided scenario, where the participants performed the task in collaboration with the robot and guided by Poka-Yoke aspects taken into account.

The mental workload parameter, defined through EEG measurement as the power ratio between Beta Waves (stress/engagement index) and Alpha Waves (relaxation index), provides for the evaluation of the participants' mental effort in three scenarios. Furthermore, NASA TLX is an established multidimensional subjective questionnaire that assesses the cognitive effort of participants completing a task. For this study, it is used to correlate the objective analysis from the EEG neuroergonomic assessment to further analyse mental workload. A combination of objective and subjective metrics is required to assess the cognitive response of the operator doing the task in the three circumstances. Finally, observational measures using a checklist are used to analyse the level of efficiency, effectiveness, and quality of the tasks in the three situations.

The realization of the set goals within this doctoral dissertation is expected to develop a method to design HRC activities through the real-time acquisition of EEG data. In this sense, the following results are expected, which represent the contribution of this work:

- Efficient Real-time acquisition of physiological data such as EEG.
- Development of an extended stage Best-Worst model for determining the relative importance of RFs' impact on each denoted KPI
- Analysis of cognitive workload of the operator while performing assembly tasks in HRC scenarios.
- Evaluation of productivity in a HRC activity.
- Lower level of mental workload in the collaborative scenarios

The Commission is of the opinion that the research objectives were successfully met.

1.7. Analysis of the obtained research results and the list of candidate's published scientific papers from the doctoral dissertation (authors, paper title, journal title, volume, year of publication, pages from-to, DOI number, category):

A part of the candidate's research results from the doctoral dissertation was presented to an international scientific audience by publishing the work in international journals of category M22 and international conferences (M33).

International journals (M22):

1. **Caiazzo, C.**, Savković, M., Pusica, M., Milojevic, D., Leva, M.C., & Djapan, M. (2023). Development of a Neuroergonomic Assessment for the Evaluation of Mental Workload in an Industrial Human–Robot Interaction Assembly Task: A Comparative Case Study. Machines. https://doi.org/10.3390/machines11110995
2. Petrovic, M., Vukicevic, A.M., Djapan, M., Peulic, A., Jovicic, M., Mijailovic, N., Milovanovic, P., Grajic, M., Savkovic, M., **Caiazzo, C.**, Isailovic, V., Macuzic, I., Jovanovic, K. (2022) Experimental Analysis of Handcart Pushing and Pulling Safety in an Industrial Environment by Using IoT Force and EMG Sensors: Relationship with Operators' Psychological Status and Pain Syndromes. Sensors, 22, 7467. https://doi.org/10.3390/s22197467
3. Savkovic, M., **Caiazzo, C.**, Djapan, M., Vukicevic, A.M., Pušica, M., Macuzic, I. (2022) Development of Modular and Adaptive Laboratory Set-Up for Neuroergonomic and Human-Robot Interaction. Research Frontiers in Neurorobotics, Vol. 16, https://doi.org/10.3389/fnbot.2022.863637

International conferences (M33):

1. **Caiazzo, C.**, Nestić, S., Savković, M. (2022). A Systematic Classification of Key Performance Indicators in Human-Robot Collaboration. In: Mihić, M., Jednak, S., Savić, G. (eds) Sustainable Business Management and Digital Transformation: Challenges and Opportunities in the Post-COVID Era. SymOrg 2022. Lecture Notes in Networks and Systems, vol 562. Springer, Cham. https://doi.org/10.1007/978-3-031-18645-5_30
2. **Caiazzo, C.**, Savković, M., Djapan, M., Macuzic, I. (2022). Framework of modular industrial workstations for neuroergonomics experiments in a collaborative environment. Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022), Edited by Maria Chiara Leva, Edoardo Patelli, Luca Podofillini, and Simon Wilson https://doi.org/10.3850/978-981-18-5183-4_J01-07-285-cd
3. **Caiazzo, C.**, Djordjevic, A., Savković, M., Djapan, M., Vukicevic, A. Architecture of human-robot collaboration in manufacturing industries. The 19th International Conference "Man and Working Environment" Occupational and Environmental Safety engineering and Management, pp. 307-314, November 24-25th 2022, Niš, Serbia. https://scidar.kg.ac.rs/handle/123456789/18387
4. Savković, M., Mijailović, N., **Caiazzo, C.**, Djapan, M. Advanced physical ergonomics and neuroergonomics research on an assembly workstation. The 19th International Conference "Man and Working Environment" Occupational and Environmental Safety engineering and Management, pp. 351-358, November 24-25th, 2022, Niš, Serbia. https://scidar.kg.ac.rs/handle/123456789/18500
5. **Caiazzo, C.**, Savkovic, M., Pusica, M., Nikolic, N., Milojevic, Dj., Djapan, M. Framework of a Neuroergonomic Assessment in Human-Robot Collaboration. 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, pp. 2814-2820, doi: 10.3850/978-981-18-8071-1_P214-cd
6. Pusica, M., **Caiazzo, C.**, Djapan, M., Savkovic, M., Leva, M.C. Visual Mental Workload Assessment from EEG in Manual Assembly Task. 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, pp. 2999-3005, doi: 10.3850/978-981-18-8071-1_P667-cd
7. **Caiazzo, C.**, Savkovic, M., Komatina, N., Mijovic, N., Macuzic, I., Djapan, M. A comparative analysis for the evaluation of productivity in human-robot collaboration, International Symposium on Occupational Safety and Hygiene – SHO'23, pp. 206-211, 20-21 July, 2023, Porto, Portugal, https://doi.org/10.24840/978-989-54863-4-2_0206-0211 (the best paper award)

1.8. Assessment of the completed doctoral dissertation as the candidate's original scientific work in the appropriate scientific field and analysis of the plagiarism report (up to 1000 characters):

The Committee considers that the doctoral dissertation "Neuroergonomic Assessment of Mental Workload in Adaptive Industrial Human-Robot Collaboration" is the result of the candidate's original scientific work in the field of Industrial engineering.

According to the procedure of the University of Kragujevac, the plagiarism detection procedure of this doctoral dissertation was carried out. In the Report on the verification of the originality of the doctoral dissertation no. IV-04-436/5 dated May 31st, 2024, and taking into account that the doctoral dissertation was written in English, a match was established with six sources. The majority of the matches are exclusively about the work on which the candidate is the first author and the work represents the result of the completed doctoral dissertation (published in scientific journals and international conferences). One small part is related to document Report on the assessment of the scientific basis of the topic and the fulfilment of the requirements of the candidate and the proposed mentor. Therefore, the report on the originality check of the doctoral dissertation (plagiarism check) and the mentor's assessment on the originality check report of the doctoral dissertation "Neuroergonomic Assessment of Mental Workload in Adaptive Industrial Human-Robot Collaboration" of candidate Carlo Caiazzo unequivocally indicate the originality of the doctoral dissertation.

1.9. The significance and impact of the doctoral dissertation in the current state of a specific scientific field:

Manual assembly operations, such as wire harnessing, remain an obstacle in industrial processes. This has prompted the investigation and study of HRC systems that enable operators to work alongside robots. Thus, understanding the MWL in HRC is crucial. However, the method of using wireless, real-time, objective metrics like EEG in industrial HRC tasks to define the MWL in terms of brainwave activity is still in its early phases. The rising deployment of these technologies in fenceless industrial areas has motivated researchers to investigate the operator's mental workload correlated with productivity and efficiency indexes. The methodology implemented in this study indicates the feasibility and validity of blending EEG data with subjective measurements (NASA TLX) and observational measures (checklist) in HRC tasks. The use of EEG is growing rapidly due to its suitability, effectiveness, and practicability in many circumstances.

1.10. Evaluation of the fulfilment of the requirements for the doctoral dissertation defence according to the study programme, faculty's general act, and university's general act (up to 1000 characters):

Candidate Carlo Caiazzo passed all the exams for the doctoral academic studies in Industrial Engineering and Engineering Management (according to the issued certificate of passed exams of the Service for Student affairs No. 1631 dated 03.10.2023), which satisfied the first of the requirements for the defense of the doctoral dissertation.

The doctoral dissertation of the candidate Carlo Caiazzo was written according to the instructions of the Regulations on application, preparation and defense of doctoral dissertations of the University of Kragujevac and in terms of content corresponds to the topic accepted by the Teaching and Scientific Council of the Faculty of Engineering, University of Kragujevac and the Council for Technical and Technological Sciences of the University of Kragujevac. Student Carlo Caiazzo showed a complete understanding of the field of industrial engineering and fully mastered all the principles of scientific and research work, from reviewing the literature, setting up hypotheses, designing and conducting experiments, analyzing and explaining the results, which is best demonstrated by published papers in scientific journals and international conferences as first or co-author. Candidate Carlo Caiazzo published a paper as the first author entitled "Development of a Neuroergonomic Assessment for the Evaluation of Mental Workload in an Industrial Human-Robot Interaction Assembly Task: A Comparative Case Study" which satisfied another requirement for the defence of the doctoral dissertation.

Bearing in mind the mentioned facts, we believe that the research objectives have been met and that all the scientific, professional and administrative requirements for the defence of the doctoral dissertation of the candidate Carlo Caiazzo have been met.

2. CONCLUSION

Based on the analysis of the doctoral dissertation and the submitted documentation, the Committee for the evaluation and defence of the doctoral dissertation, entitled **"Neuroergonomic Assessment of Mental Workload in Adaptive Industrial Human-Robot Collaboration"**, by the candidate **Carlo Caiazzo**, recommends the competent authorities to accept the doctoral dissertation and approve its defence.

Committee members:

Ivan Mačužić, full professor

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