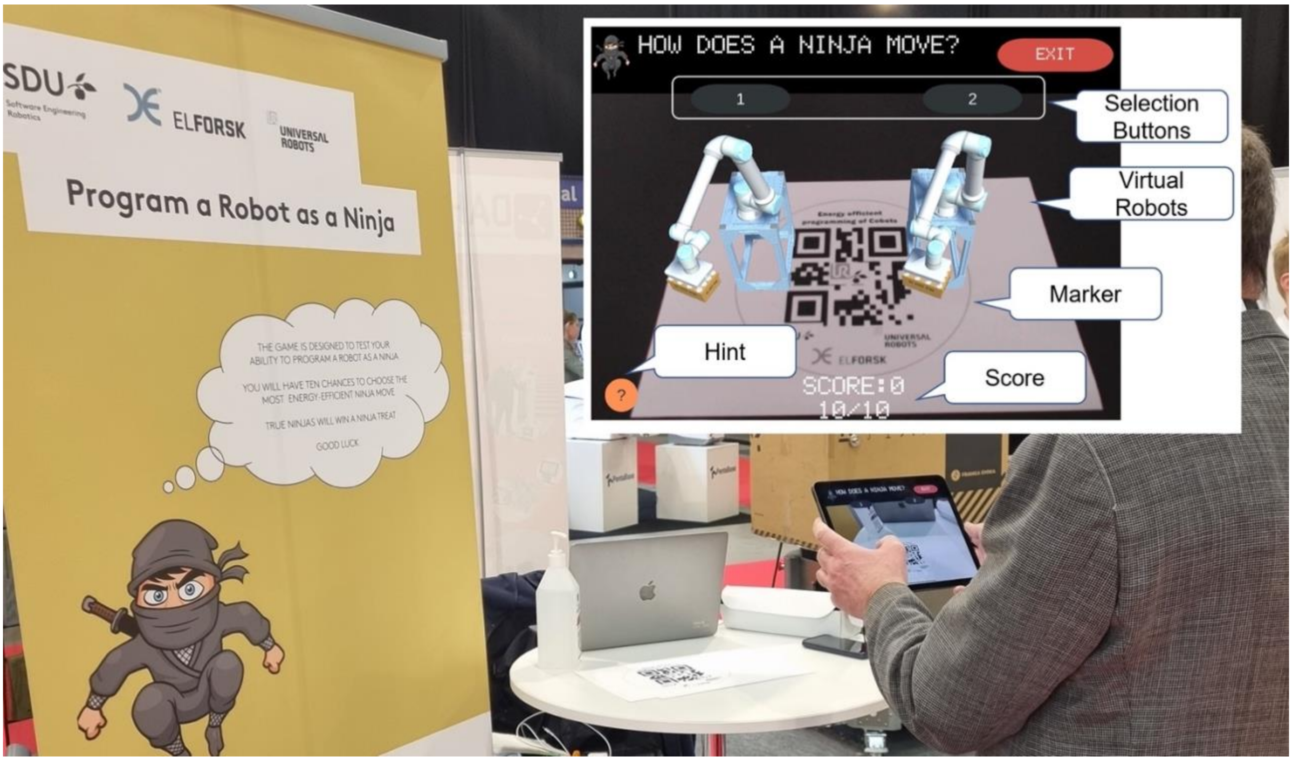
Project Title: Energy-effective Programming of Collaborative Robots

Project Number: 352-035

Project Period: 01.03.2020 to 31.05.2022



Partners

SDU

UNIVERSAL ROBOTS

Supported by

ELFORSK

Table of Contents

Purpose of the project

Collaborative robots make it possible to complete more and more tasks with unprotected robots in close collaboration with humans. Collaborative robots are programmed by users by physically demonstrating what the robots should do. However, when users do programming, they do not intuitively think about energy efficiency. Therefore, robots can end up using more power than they need to. Examples of actions that results in wasted energy includes unnecessary high lifts, long movement trajectories, wait time between operations, repetitions of movements or inefficient use of robot mounted tools. When a robot uses more than it needs to in comparison with an energy-efficient programming it introduces an increased electricity consumption. SDU and UR will address this research challenge by developing new methods for programming robots that can make it easy and natural for users to energy optimize the programming of robots. The project's hypothesis is that Augmented Reality (AR) and digital models can enable energy optimizing algorithms to be included in the users programming by demonstration. Here the user in AR will be guided by concrete proposals for how the robot's movements can be energy optimized. UR is the world leading company within light weight collaborative robots and SDU is internationally leading within robotics. The project partners envisage that the next research step within robot programming is the use of AR for programming by demonstration. The project's research results will not only benefit the company UR but also all other companies within robots collaborating with SDU.

Summary of the project process, method used and results obtained

The project followed a constructive methodology across the work packages of the project based on the following process steps and research questions:

1. Obtain general and comprehensive understanding:
    a. RQ1: What is the energy consumption model of a collaborative robot?
    b. RQ2: What are the uses of Augmented Reality in collaborative robot technology?
    c. RQ3: How do the operational parameters (manufacturer command, velocity limit, acceleration limit, operational time, payload) affect the energy consumption of collaborative robots?
2. Innovation: develop a solution idea:
    a. RQ4: What techniques should be used to reduce the energy consumption of collaborative robots?
3. Demonstrate the solution:
    a. RQ5: How to optimize the task of palletizing?

The section will summarize the method used and results obtained for each of these research questions.

RQ1: What is the energy consumption model of a collaborative robot?

Many models are available in the literature and simulation tools for motors current, torque, energy consumption, etc. However, the errors are evident when the model results are compared to real measurements. M. Gafaleta et al. [1] point out that current robot simulation tools or mathematical models do not offer reliable features for accurate energy estimation. Additionally, M. Gafaleta et al. highlight that the errors for energy consumption models are hidden in the academic literature and become evident whenever energy measures are compared to simulation results. We consider that using hybrid models (data and process-driven) is necessary to obtain accurate results. Our modeling methodology possesses three steps: motion planning, dynamic model, and EC model. Using cobots of different sizes (UR3e and UR10e) and loading, we collected over 55,000 samples per case and trained the model to identify the model's unknown parameters. The model estimated the power consumption of a testing dataset with a maximum RMS error of 6 [W] - 3.85%. In the final experiment, the complete system was tested using a user-defined program composed of six instructions. The results showed an accurate estimation of the power profile with an RMS error of 2.39 [W] and 4.23 [W] for UR3e and UR10e. [2]

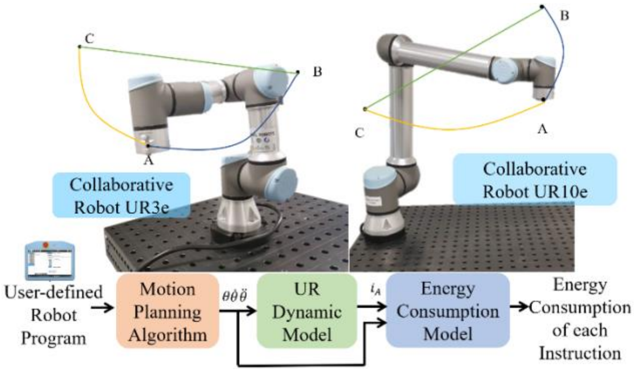


Fig. 1. The model estimates the energy consumption of user-defined robot programs for cobots. The model was trained and tested using UR3e and UR10e.Energy Consumption Model for Lightweight Robots.

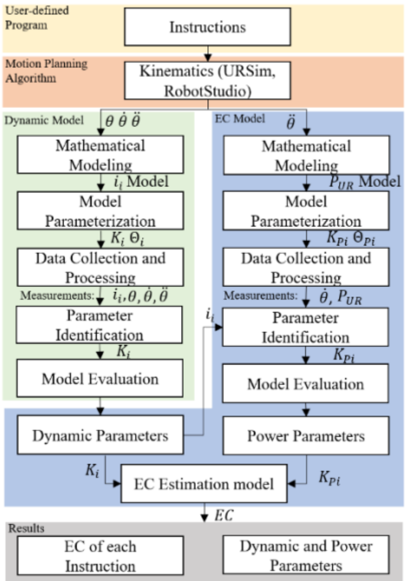


Fig. 2. Methodology overview for EC estimation

RQ2: What are the uses of Augmented Reality in collaborative robot technology?

Human-Robot Interaction (HRI) for collaborative robots has not changed since the introduction of the first cobot. The main interface to communicate with the robot remains a wired display - teach pendant (TP). While attempts are made to make the programming experience better - more intuitive touch-screen displays, it generally remains the same. With the recent rapid development of Augmented Reality (AR), the HRI of the cobot could drastically change. In [3] we report results for exploring AR- based implementations in robotics and categorizes them based on the type of the used device, with the main focus on the least explored category - mobile AR. Furthermore, two experiments are conducted to determine the user's experience in robot programming using TP with a mobile-based AR interface. For this reason, an AR application prototype is developed as a co-interface to a TP. The results of the experiments are presented: the first examines the user needs that are missing in current solutions, while the second one analyses the user experience of using the robot with an AR interface. The obtained results suggest that users could benefit from mobile-based AR solutions in the commissioning and troubleshooting phase of the lifetime of the robot. However, at the same time, this solution is not advanced and accurate enough (yet) to encourage users to switch to the new platform and abandon the classical TP, while programming the robot.

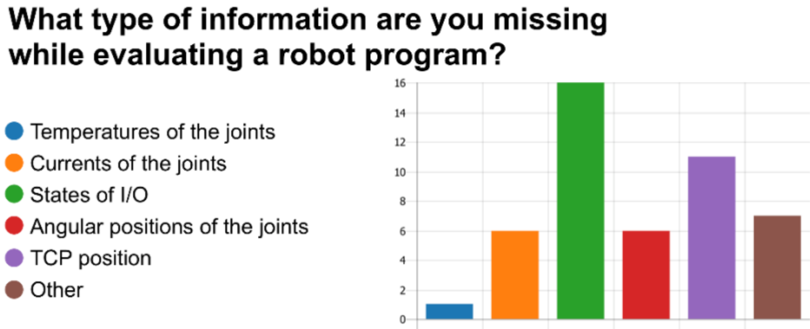


Fig. 3: Survey results regarding what type of data respondents are missing while robot programming

Knowing that AR interfaces are not yet mature to replace TP, we propose to use AR as a tool that allows to collect, visualize and simulate data. The user can visualize in real time the data from the robot and select the data streams to be collected. Then, we included the Energy Consumption model in the interface. This digital twin represented via augmented reality can estimate the power consumption at any time. In the project we developed a prototype with the following features:

- Data Visualization: Even though AR cannot replace TP, AR can help to improve the interaction to the users. AR allows to merge the real robot to the data. The user can see how the robot moves and the data that usually is in the TP. Besides, there are some robot changes that are not perceptible to the human senses. The user has additional capabilities when the data is shown in the interface.
- Data Collection: The visualization is used to observe and determine the data required to be stored. Using the same interface, the user can select the data.
- Data Simulation: Current simulators and models do not offer a precise power estimation. The model obtained in RQ1 can be used to create a better digital twin of the robot. The user interface allows to visualize the robot and its data and estimate its power consumption without a need of a real robot.

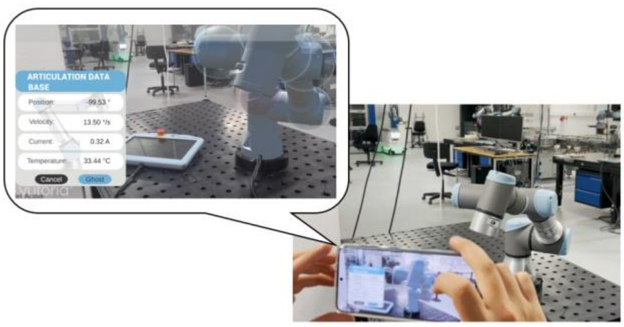


Fig. 4: Data visualization, collection and simulation using AR

RQ3: How do the operational parameters affect the energy consumption of collaborative robots?

Currently, there is no formal methodology for the energy assessment of anthropomorphic robots. A methodology for the energy consumption assessment of cobots is required. The methodology assesses through six experiments the following criteria: joint configurations, joint temperatures, payload, movement command, acceleration limit, velocity limit, and trajectory planning. Then the methodology is utilized in a case study using the robot UR3e. We analyzed the results of the experiments to describe the relationship between the energy consumption and the evaluation parameters, thus paving the way to optimization strategies. [4]

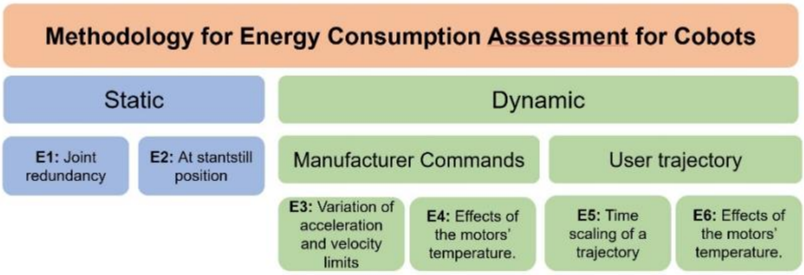


Fig. 5. Experiments for the energy assessment

From the experiments, the following patterns and characteristics were obtained:

- From the UR3e energy analysis, we observe that cobot joint configuration affects the EC. We could optimize the robot's home position to reduce the EC when the robot is on standby. However, the EC in the redundant joint configurations does not change significantly. Therefore, this option should not be considered in the optimization strategies.
- The criteria "time scaling" and "velocity and acceleration limits" demonstrated that the relationship between the EC and the task motion time is linear. The logical conclusion is that the robot should move as fast as possible to optimize the EC. However, including the waiting period in all cases, the cobot approximately consumes an equal amount of energy. Consequently, it does not make sense to consider these criteria in the optimization approaches.
- Experiment 4 (E4), which uses linear and PtP commands, shows that the EC increases when the temperature rises. Experiment 6 (E6), which uses continuous angular movements, indicates that the EC decreases when the temperature rises. Since the energy savings are not considerable, it is not reasonable to include cooling hardware to decrease the joint temperatures.

RQ4: What techniques should be used to reduce the energy consumption of collaborative robots?

Firstly, the energy consumption of the collaborative robot was assessed by a set of experiments based on the RQ3. We analyzed the results of the experiments to describe the relationship between the energy consumption and the evaluation parameters, thus paving the way to optimization strategies. Next, we propose three strategies to reduce energy consumption:

1) Optimal standby position: From the experiments, we observed that the energy consumption of the robot varies according to the stand-by position. We propose to use positions that have less gravitational torque.

2) Optimal robot instruction: We analyzed the energy consumption of predefined movement commands to move between two points. The results showed that the most efficient command is linear in joint space or point to point movement (PtP). In comparison to linear in cartesian space, linear in joint space movement reduces the mechanical losses due to friction.

3) Optimal motion time: We proposed to obtain the characteristic curve (EC vs. execution time) of a given path. Then, it is possible to get the optimal scale factor that minimizes the robot EC. The results show that the robot consumes 96.71% (without payload) and 97.33% (with payload) of the maximum experimental energy consumption.

4) Reduction of dissipative energy: We propose to include a dynamic power saturator that aims to use all the regenerated energy (potential energy or kinematic breaking energy). The proposed control scheme reduces the energy consumption by 5.27% in the proposed experiment. Besides, the temperature of the cabinet is reduced. Potentially, the energy for ventilation might be reduced.

The results show that Cobots potentially reduce from 3% up to 37% of their energy consumption, depending on the optimization technique. [5]

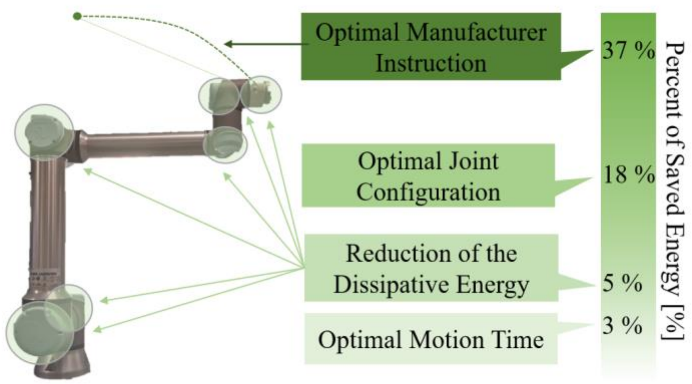


Fig. 6. Energy saved using the proposed optimization techniques

RQ5: How do palletizing task can be optimized?

Optimizing behavior in terms of electricity consumption can have an impact on system reliability. Our approach is demonstrated using a case study within a palletizing task for products distribution. The robot distributes different products from a conveyer layer to different pallets. The environment influences the system's behavior, and neglecting the environmental behavior has an indirect negative impact on optimizing the system's behavior. To increase the system's flexibility, the behavior of the environment is modeled dynamically to apply the disorderliness of its behavior. The resulting models are formally verified.

By examining the past environmental behavior and predicting its future behavior, electricity consumption optimization is done dynamically. The optimization is based on optimal joint configuration and the dynamical analysis of the environmental behavior. The system predicts when the robot should move to an efficient standby position. The verification results acquired using a UPPAAL-SMC show that the optimization of system behavior by predicting the environmental behavior has been successful [6].

Conclusion of the results of the project including the energy savings/energy efficiency achieved

We presented an EC model that estimates the electric power consumption using motor currents, motor speeds, and articulation positions. Knowing the robot's power profile, we find the EC by the integration of the power profile. The model performed accurately with a maximum RMS error of 6 [W] - 3.85%. One reason for the model error is the sensors' noise with a 1.7 [W] standard deviation. The model is reliable and can be used to estimate the energy consumption of instructions of a robot program.

The findings from AR exploratory study suggest that robot programming cannot be done using an AR application anytime soon. While some of the features were very helpful to the programmers, they are not useful for programming the robot. AR could help alongside the teach pendant to do the following: sales and marketing, commissioning, and troubleshooting.

Based on the exploratory study, an app for data collection, visualization and simulation was created. The data visualization and collection tools help to solve troubleshooting. If the robot data is stored and overlapped with the real robot, the operator has additional information to understand possible failures. Moreover, the AR digital twin of the robot help to determine the solution feasibility. Compared to current AR digital twins, our solution has the advantage of offering prediction of motor currents and energy consumption.

We conclude from the first method that it is recommendable to use linear movements in joint space (PtP) instead of cartesian linear movements, especially for fast moves. When the robot uses cartesian linear movements, the friction increases due to unnecessary movements. In our case of study, this method saves up to 37% (without payload) and 26% (with payload) of EC.

We proposed to obtain the characteristic curve (EC vs. execution time) of a given path. Then, it is possible to get the optimal scale factor that minimizes the robot EC. The results show that the robot consumes 96.71% (without payload) and 97.33% (with payload) of the maximum experimental energy consumption.

The dynamic power saturator transforms all the regenerated energy (potential energy or kinematic breaking energy) into kinematic energy. The proposed control scheme reduces the energy consumption by 5.27% in the proposed experiment. Besides, the temperature of the cabinet is reduced. Potentially, the energy for ventilation might be reduced.

We observed that the cobot joint configuration affects the EC. The experiments showed a correlation between the EC and the gravitational toque. The robot has a joint configuration that consumes less energy in the case of redundant positions. Additionally, for long waiting idles times, the robot should move to a comfortable position of minimal gravitational torque. This technique can reduce up to 18 % of the idle energy.

In this work, we analyze the reduction of energy consumption by improving the behavior of the components without structural changes by using cost-optimal reachability analysis. Due to the dependence of system behavior on the environment, we examine the behavior of the environment from two aspects. First, the behavior of the environment may be quite irregular, so using fixed, predefined probabilities for incidents makes the existing system much simplified. For this purpose, to increase the system's flexibility against the disorderliness behavior of the environment, it is modeled dynamically. Second, the system can optimize its behavior by predicting the behavior that the environment may have in the future. The optimization performance was tested and verified using UPAAL-SMC, and the results showed that the energy consumption is reduced in 5 %. So, by examining the past environmental behavior, the system can dynamically adjust its behavior to optimize it in terms of energy consumption.

Perspectives and further application of the results

In particular, the results from this study could be used for optimizing tasks in conditions with limited energy availability. An example is a mobile manipulator with a battery to power the mobile robot and manipulator. Any smaller energy saving means longer battery autonomy. Therefore, the productivity of the robot would increase.

The EC model (RQ1) is standard and can be used to model other brands of robots. But it is required to collect more data from other robots to test the model. The final goal would be to create an open-source library to obtain the EC model of any anthropomorphic robotic arm.

A future perspective is that the techniques proposed in the RQ4 will be included as suggestions to the robot teaching pendant. The operator can get feedback on code of how to reduce the energy consumption of a given program.

One of the problems of using UR robots for high payloads is the heat generation. If the dynamic power saturator presented in RQ4 is applied to these applications, the energy burned is eliminated, and the heat will be reduced. Consequently, the robot would consume less energy.

To educate the robotic community about the outcomes of the project, we developed an AR game. The game is composed of ten scenes. In each scene, the user selects which is the robot that consumes less energy from two or three options. The scenes were designed using the optimization techniques proposed in RQ4, two scenes per technique and two additional for a palletizing application. This application disseminated our results to practitioners that attended to R22. We expect that our outcomes will be included in their future Cobot applications.

Fig. 7. AR Game presented in R22

Dansk sammendrag af formål, resultater og videre brug af resultater.

Kollaborative robotter gør det i dag muligt at udføre flere og flere opgaver med robotter uden afskærmning og i tæt samspil med mennesker. Kollaborative robotter bliver programmeret af brugerne ved at de rent fysisk demonstrerer hvad robotten skal gøre. Men da brugeren ikke intuitivt indtænker energioptimering i denne programmering, fører den til at robotterne kan bruge mere strøm end de behøver.

Programmering som leder til energispild kan f.eks. være unødvendigt høje løft, lange bevægelsesbaner, ventetid mellem operationer, gentagelse af bevægelser eller ineffektiv anvendelse af værktøjer monteret på robotarmen. Når en robot bruger mere strøm end den behøvede resulterer det i et øget elforbrug.

Projektet har via eksperimentelle data karakteriseret elektricitetsforbruget af en kollaborativ robot når den udfører en programlinje under forskellige forhold. På baggrund af data er der lavet en model som kan forudsige forbruget. Dernæst har projektet undersøgt hvordan augmented reality kan understøtte programmering af kollaborative robotter. Konklusionen er at for nuværende er teknologien ikke klar til at understøtte programmering generelt. Ud fra data er det undersøgt hvordan operationelle parametre påvirker strømforbruget som grundlag få at effektivisere forbruget.

Til at effektivisere forbruget er der udviklet en række strategier til at forbedre energieffektiviteten i forskellige situationer. 1. strategi er at bruge lineære bevægelser i leddenes rum i stedet for i det kartesiske rum, hvilket især har en effekt for hurtige bevægelser. 2. strategi er at optimere bevægelseshastigheden I forhold til den acceleration/hastighed der bruger mindst energi for den pågældende bevægelse. 3. strategi er at udnytte potentiel energi bedre ved nedadgående bevægelser. 4. strategi er at placere armen i stillinger med minimal påvirkning fra tyngdekraften når armen er I stilstand. Resultaterne viser at strategierne kan hjælpe med at reducere forbruget op til 37 procent ved at ændre på robottens instruktioner og reducere standby-tiden. For at bringe denne viden videre er der udviklet et AR baseret spil som lærer brugeren hvordan man kan energi-effektivisere programmeringen af en kollaborativ robot.

Overview of dissemination activities carried out during the project period.

Papers:

- J. Heredia, C. Schlette and M. B. Kjærgaard, "Data-Driven Energy Estimation of Individual Instructions in User-Defined Robot Programs for Collaborative Robots," in IEEE Robotics and Automation Letters, vol. 6, no. 4, pp. 6836-6843, Oct. 2021.
- J. Heredia, C. Schlette and M. B. Kjærgaard, " Energy Consumption Assessment for Lightweight Robots.," submitted for publication.
- J. Heredia, C. Schlette and M. B. Kjærgaard, " Energy Consumption Optimization for Lightweight Robots.," submitted for publication.
- Soltani, R., Kang, E. Y., and J. Heredia, “Towards Energy-aware Cyber-Physical Systems Verification and Optimization.”, Conference on Computer Science and Intelligence Systems, 2021.
- K. Zieliński, K. Walas, J. Heredia and M. B. Kjærgaard, "A Study of Cobot Practitioners Needs for Augmented Reality Interfaces in the Context of Current Technologies," 2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN), 2021, pp. 292-298.

Datasets

- J. Heredia, C. Schlette and M. B. Kjærgaard, Dataset for Energy Assessment of Collaborative Robots, 2021, DOI: 10.21227/xz5d-mg81

- J. Heredia, C. Schlette and M. B. Kjærgaard, Dataset of Collaborative Robotics for Energy Consumption Modeling, 2021 DOI: 10.21227/9wnt-8v86

Presentations

- 26.11.2020 Presentation “Grønne løsninger med softwareteknologier, der også sikrer privatlivets fred” at DigitalLead Digital Days, Online by Mikkel Baun Kjærgaard.
- 08.08.2021 Presentation: "A Study of Cobot Practitioners Needs for Augmented Reality Interfaces in the Context of Current Technologies," IEEE International Conference on Robot & Human Interactive Communication (RO-MAN) 2021 by K. Zieliński.
- 28.09.2021 Presentation: "Data-Driven Energy Estimation of Individual Instructions in User-Defined Robot Programs for Collaborative Robots,” IEEE/RSJ International Conference on Intelligent Robots and Systems IROS 2021 by Juan Heredia.
- 02.11.2021 Presentation “Software Technologies for Exploiting Production Data” at SDU, Odense at the event ““Curious today partners tomorrow” by Mikkel Baun Kjærgaard
- 23.05.2022 - Demonstration of project results in the form of AR game at R22, Odense
- 23.05.2022 - Presentation “Software and IoT for Robotic Applications at R22, Odense by Mikkel Baun Kjærgaard

Interviews

- Ing.dk interview: https://ing.dk/artikel/robotter-far-energivenlige-instrukser-251019

References

[1] M. Gadaleta, G. Berselli, M. Pellicciari, and F. Grassia, “Extensive experimental investigation for the optimization of the energy consumption of a high payload industrial robot with open research dataset,” Robotics and Computer-Integrated Manufacturing, vol. 68, no. July 2020, p. 102046, 2021.

[2] J. Heredia, C. Schlette and M. B. Kjærgaard, "Data-Driven Energy Estimation of Individual Instructions in User-Defined Robot Programs for Collaborative Robots," in IEEE Robotics and Automation Letters, vol. 6, no. 4, pp. 6836-6843, Oct. 2021.

[3] K. Zieliński, K. Walas, J. Heredia and M. B. Kjærgaard, "A Study of Cobot Practitioners Needs for Augmented Reality Interfaces in the Context of Current Technologies," 2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN), 2021, pp. 292-298.

[4] J. Heredia, C. Schlette and M. B. Kjærgaard, " Energy Consumption Assessment for Lightweight Robots.," submitted for publication.

[5] J. Heredia, C. Schlette and M. B. Kjærgaard, " Energy Consumption Optimization for Lightweight Robots.," submitted for publication.

[6] Soltani, R., Kang, E. Y., and J. Heredia, “Towards Energy-aware Cyber-Physical Systems Verification and Optimization.”, Conference on Computer Science and Intelligence Systems, 2021.