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User-Centered Assistive Robotics for Production
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Human-Robot Interaction Concepts in the AssistMe project

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Abstract—**In this paper we present results of the AssistMe project which aims at enabling close human-robot cooperation in production processes. AssistMe develops and evaluates different means of interaction for programming and using a robot-based assistive system through a multistage user-centered design process. Together with two industrial companies human-robot cooperation scenarios are evaluated in two entirely different application areas. One field of application is the assembly of automotive combustion engines while the other one treats the machining (polishing) of casting moulds. In this paper we describe the overall project methodology, followed by a description of the selected use case and a detailed outline of the first two expansion stages. The paper closes with an overview on the results of the first two rounds of user trials and gives an outlook on the next expansion stage of the human-robot cooperation scenario.**

I. INTRODUCTION

Traditional robot systems are programmed mostly offline with text based programming languages or by complex CAD/CAM based simulation tools. That is suitable for traditional robot systems used in specialized situations such as optimized and fenced working environments, only applicable for high production volumes. Robots for smaller production volumes (applicable for SMEs) would require two main success factors. That's on the one hand safe applicability without expensive safety hardware like dedicated workspace or fences. On the other hand systems would benefit from applicability for smaller production volumes and lot sizes which requires frequent reprogramming – ideally without expensive software tools or robot and computer vision specialists. Robot manufacturers address both safety and ease of use and reprogramming with contemporary products. Limitation of system power and implementation of safety relevant control system structures as well as safety relevant functionality like safely limited speed or workspace are used to make systems safe enough for even collaboration, as it is defined in the DIN ISO 10218 standard. Improved user interfaces should make systems useable without special training. Main modalities implemented by the system used (a Universal Robot UR10 system) are touch based programming with graphical elements as well as manual interaction by hand-guidance during parameterization of the programs. Human workers and the robots could work as a team through more flexible human-robot interaction [1]. But how to develop a robot system that meets the needs of its users in an industry 4.0 environment? An answer has to take User Experience (UX) into account, which – according to Alben [2] – comes everywhere into play were humans interact with a system. This includes cooperation and usability but also factors such as perceived safety, stress, or emotions [3]. The work presented in this paper illustrates how a UX study helped improving a standard-software to a physical interaction interface for real-world usage. A multistage user-centric design approach was performed, involving representative factory works performing user studies in their actual working environment. Finally we want to introduce a proposal of the improved interface to be evaluated at the very end of the AssistMe project.

II. RELATED WORK

The Industry 4.0 paradigm of close human-robot cooperation makes fundamental research necessary, not only in robotics, but also in user-centered HRI. Little research has been performed so far concerning industrial robotics, associated UX, and how HRI impacts production performance. Existing research already showed potential application scenarios of physical HRI [4] and that the UX of robots changes over time [5]. A methodological approach how to evaluate the usability of teach pendants for teaching a robotic arm was demonstrated by [6]. Current research for example is the learning of motor skills by pHRI [7] and the industry-oriented application [8]. The focus of our research follows a similar interest as [6] especially on how to use UX to improve a newly introduced robotic arm without a safety fence in a factory environment.

III. ASSISTME SYSTEMS

In the AssistMe project two usecases in three expansion stages are evaluated. One of the usecases is the assembly of a combustion engine. That includes the installation of a cylinder head cover. The installation is carried out manually by stacking the cover with pre-inserted screws onto the motor block and tightening the screws with a manual power tool.

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The electronic screwdriver of the manual workplace is fitted with a push start mechanism, electronic control unit and a shut-off clutch and therefore starts rotating when pushed onto the screw and stops motion when retracted respectively when a predefined torque is reached. The working instruction of the workstation includes several additional process steps. An automatic screw tightening system is expected to provide assistance and to reduce the workload at the workstation for the human worker. A state-of-the-art collaborative robot system is equipped with the power tool (Fig. 1) and programmed to perform screw tightening operations in the required order and accuracy to meet a defined process quality (screw-in depth, torque,…).

Fig. 1 - Usecase Combustion Engine Assembly – screw positions to be parameterized by the user.

A. *Robot A*

Robot A is a standard Universal Robot UR10 system with its teach pendant and the integrated programming and parameterization infrastructure. A basic script for the movement contains the pre-screwing process and can be called by the teach pendant program. The teach pendant program manages position variables (that have to be parameterized by the worker) and the execution of the global program to process the screws in the correct order.

Fig. 2 - www.zacobria.com - UR10 programming

B. *Robot B*

To be able to provide smooth and precise one hand-guidability a FT-sensor was integrated in robot B. Shortkey buttons trigger alignment shortcuts (Fig. 3). Preconfigured TCP alignments can be triggered and cause the tool to rotate around the TCP to move the tool intuitively to an (e.g. perpendicular) orientation to maximize process stability and robustness towards inaccurate teach-in of process points.

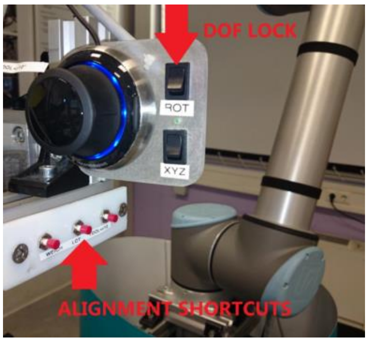

Fig. 3 - FT-sensor, shortcuts and DOF locks

The GUI of the robot controller interface was replaced by XROB, a PC-based robot programming system, that covers both robotics and sensors and algorithms to assess sensor data. Benefits are on the one hand simplification of the interplay between robotics and machine vision and on the other hand simplification of the programming experience for the robot (that was perceived as confusing with robot A).

XROB (Fig. 4) is capable to manage several sensors and evaluation algorithms. Program templates can be used to compose basic functionality to advanced and reusable subprograms. Prior to evaluation of robot B templates for a combined rough 3D position deviation compensation and a 2D position fine compensation were prepared for reuse by the workers.

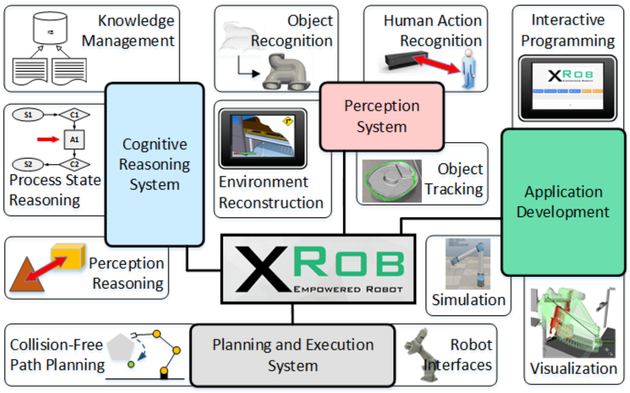

Fig. 4 - XROB framework

IV. USER EVALUATION

The goal was to explore if there is a difference in the UX between a robot with remote-HRI (robot A) and a technical revised version of this robot with physical-HRI (robot B). Both robots offered two control modes: remote control via touch-panel and direct-manual control via physical guidance. The touch-panel for remote control featured a graphical user interface consists of buttons to steer the robot and to save the taught movement trajectories. The physical-HRI mode enabled the operators to control the robotic arm directly, manually and without an additional intermediate layer. Robot A was optimized for remote control, whereas the improvement of robot B consisted of an extended physical HRI. Five participant were recruited to participate in the two studies. This small participant number can be sufficient to identify the most severe usability problems and was already discussed by [9].

The current study was conducted one year after the previous one. Within this time, robot A was upgraded to robot B, so robot B could only be examined after robot A. However, both studies had the same structure: (1) Introduction of the robot: Each participant was introduced to the robot and its control mechanisms. The participants were assigned the task to parameterize the process points in a predefined robot program. That means they had to bring the robot's tool to a precise position above the screw and that they had to adopt the position parameters to a program in the UR-teach pendant (for robot A) or to the XROB-user interface. Fig. 1 shows the screw positions as process points. For process quality precision of the parameterization is crucial. As Fig. 5 points out especially lateral or orientation deviances are critical for process effectivity while vertical positioning could be effectively observed visually during teach in process.

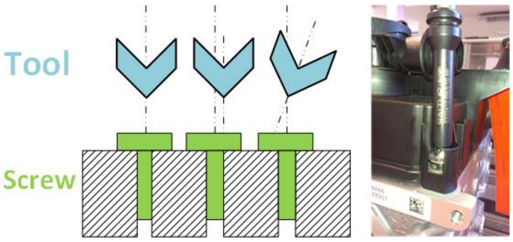

Fig. 5 - screwing process - error sources & real view

In order to relief stress and increase compliance, the participants were assured that the focus of investigation was only the robot's performance and there were no negative implications for them. (2) Conducting the user study: Each participant was audio- and videotaped with two cameras in order to generate a holistic perspective. This included a head mounted camera (first-person view - Fig. 6) and a hand camera (context oriented view). (3) Post-study questionnaires, including NASATLX, SUS, and self-developed items. The aim of the analysis was to compare the temporal demand, and the UX (including usability and performance expectancy) of the first and second version of the robot prototype. The findings are used for a the third (and last last) technical revision (design of the user interfaces of robot C, D and E) before the robot is deployed in the normal factory environment. The analysis of the video data (comments, reactions and feedbacks) consisted of (1) a rough clustering of all relevant issues, (2) a detailed description of their key features, and (3) overlapping topics were merged to categories or differentiated from each other.

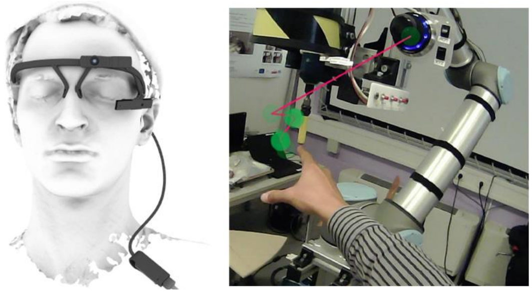
Fig. 6 – Head Mounted Device for gaze tracking - gaze tracking results

V. RESULTS

A total of five male assembly workers were recruited to participate in both studies (a representative sample for the factory with which we collaborated). The sample might be rather small but even for companies with several 1000+ employees it was difficult to find workers who work at a special part of the assembly line, predictively for the whole project duration (2 years+) who fulfill requirements (left- / right-handedness, age, robot training,…). Each participant was interviewed for 30 minutes and filled in demographic questionnaires afterwards. The mean age of the study participants was 45.4 (SD=5.7) and they had no prior experience with robotic systems. Four out of five participants had experience with computers and automated systems previous to the studies.

The teaching using robot A yielded requirements regarding robot hand guidance. Gear friction yields stacking and imprecise movement. Locking of certain degrees of freedom (e.g. rotation or translation,…) is asked for by the users as well as semiautomatic tool alignment and expected to improve both programming time and process quality.

A state of the art force torque sensor was integrated (in robot B) as well as buttons to call perpendicular realignment or locking of rotational or translational degrees of freedom. That should make the robots more effective. Additionally a RGB-D sensor as well as a 2D sensor for position deviation correction were added (see Fig. 7). Robot B was evaluated with exactly the same assignment of parameterization of the process points. The teaching duration using remote (robot A) and physical (robot B) control mode was extracted from the video recordings. Table I shows a decrease in average duration by 23.11%, and a strong shift from software- to manually controlled usage. This shift towards the direct manual guidance of the robot was also measurable in two dimensions of UX: Usability and Performance Expectancy. The first was investigated using the System Usability Scale (SUS). The second describes one's belief that using the system will help him or her to attain gains in job performance, and was measured using two items which were derived from [4]. Table II shows the increase in the dimensions Usability, Learnability and Performance Expectancy.

TABLE I
AVERAGE DURATIONS OF THE TEACHING PROCESS IN STUDY I AND II INCLUDING THE PERCENTAGE OF BOTH CONTROL MODES

Duration (m:s)	Robot A	Robot B
Average Total [SD]	6:25 [2:27]	3:36 [1:03]
Remote Control [%]	6:25 [100.00]	1:01 [28.43]
Physical [%]	0:00 [0.00]	2:35 [71.57]

TABLE III
USER EXPERIENCE IN STUDY I AND II INCLUDING PERFORMANCE EXPECTANCY (PE), SYSTEM USABILITY SCALE (SUS), AND ITS SUBSCALES USABILITY (SUS-U) AND LEARNABILITY (SUS-L)

Duration (m:s)	Robot A	Robot B	Diff. [%]
PE [0-5]	2.40 [1.08]	3.40 [0.89]	1.0 [20.0]
SUS-U [0-4]	2.00 [0.73]	2.53 [0.27]	0.5 [12.5]
SUS-L [0-4]	1.70 [0.76]	2.60 [0.65]	0.9 [22.5]
SUS [0-100]	48.50 [13.99]	63.50 [3.79]	15.0 [15.0]

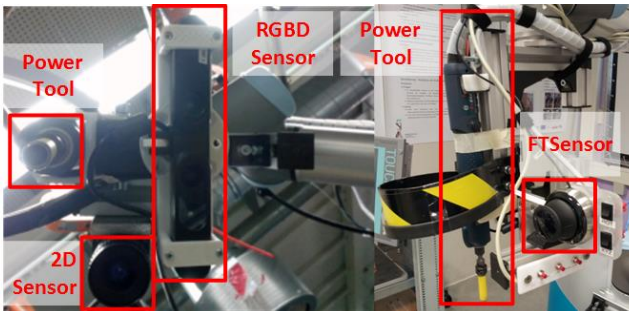

Fig. 7 - Robot B - Tool

During expansion stage 1 experiments (with robot A) the user had to use the Touch Panel 95.4% of the time while manual guidance mode was used only 4.6% of the time. This was due to cumbersome navigation in menus and submenus on the robot teach pendant during the parameterization process. As a consequence a more linear programming approach is proposed for expansion stage 2 which led to the integration of the XROB programming system.

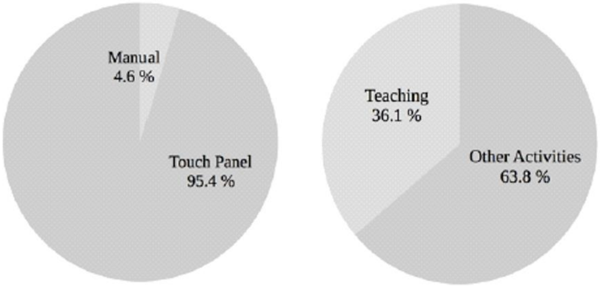

Fig. 8 - programming activities

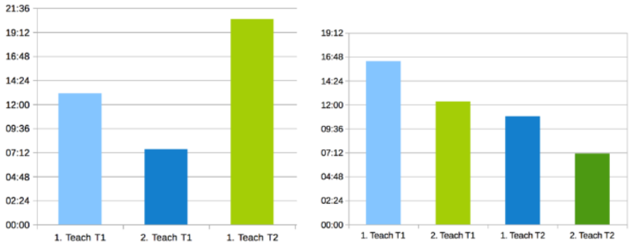

Fig. 9 - programming time with / without additional programming effort for parameterization of machine vision algorithms

Fig. **9** shows the programming time for robot A (T1) and robot B (T2). Total programming time including machine vision increased while training effect and additional input modalities (FT-sensor powered hand guidance,…) yield a net decrease of programming time.

Fig. **10** shows that the small acceptance of the manual guidance input modality in robot A can be increased dramatically if the implementation addresses user requirements and wishes.

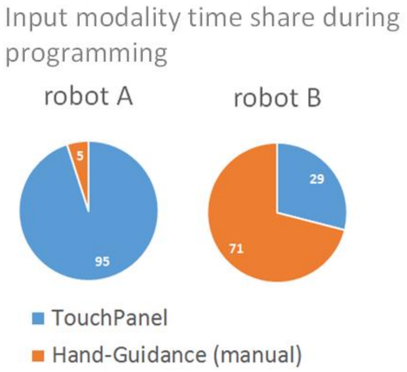

Fig. 10 - preferred input modalities for robot A and B

During the video analysis of robot B the expressed emotions and thoughts of the participants were clustered into several main categories. Qualitative feedback mainly focused on ergonomic details, such as the shape of the handholds on the robot, the positions and drag of the buttons/switches, and the fluency of the manual robot guidance. All of the volunteers pointed out that the robot should actively support them during the teaching process. Main feedback clusters were interpreted and conclusions drawn. Visual feedback during teach in was requested. If possible, information should be projected to the work piece surface. This would require additional projection technology as proposed by AssistMe.

VI. PROPOSAL FOR FINAL EVALUATION

An additional projection technology would enable spatial augmented reality methods.

A. Robot C

Spatial augmented reality interfaces are proposed and implemented as tangible user interface. Physical interaction with the product to process only might further minimize programming effort and be an easy to perceive means of interaction. A tangible marble is used for teach in of process points and the sequence of their processing. Therefore a 3D camera is integrated with a projector to detect marbles [21] positioned on top of screws to acquire spatial process points as well as taps onto projected buttons to confirm their order or other interactions with the programming system.

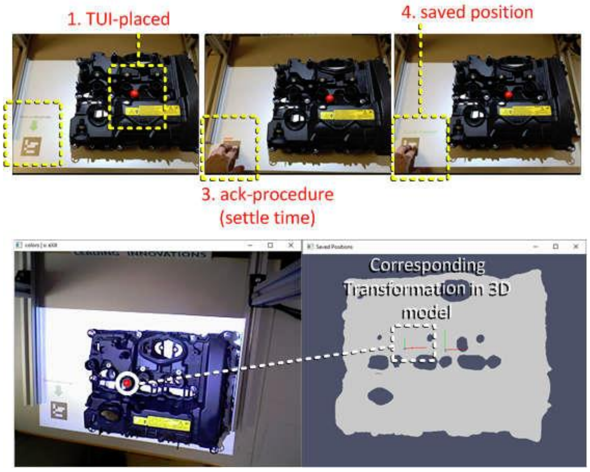

Fig. 11 - Tangible User Interface

B. Robot D

Robot D is controlled via a 2D interface as depicted in Fig. 13. Process points are entered by tapping onto a 2D representation of the processed object. A machine vision algorithm determines the spatial region of the tapped point and therefore determines both 3D process points and the sequence of the process points from the tapping order. Fig. 14 shows the technology applied to a bin-picking process where one of several objects in the 3D sensors field of view can be selected in a 2D representation of that data. The same technology is applied to the selection of regions and process-points on a single object in the sensor's field of view. Implicitly also the order of the process points can be entered.

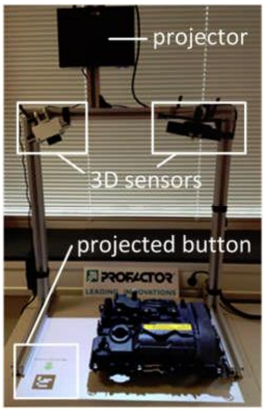

Fig. 12 - Tangible User interface system setup

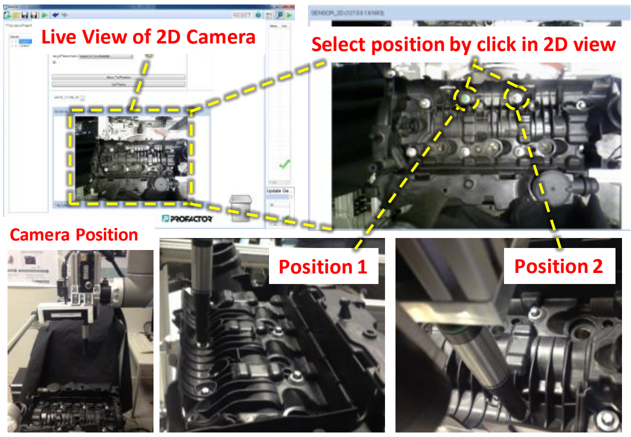

Fig. 13 – Define process points in 2D

C. Robot E

Robot E is programmed by positioning an externally tracked device (Fig. 15) or an extension like a stick to the process point. Once calibrated a precise position of a stick's tip mounted on an externally position tracked device can be calculated in real-time. Process points and their order are programmed by ordered tipping onto screws in question.

Fig. 14 - 2D tap based process point selection
(https://www.youtube.com/watch?v=nrhXEqG014o)

VII. CONCLUSION

The presented study demonstrated that the not-intermediated (direct manual) interaction with the robot can increase the experience of the robot's capabilities (usability, performance expectancy).

Fig. 15 – pointer with external tracking

The outcomes of a previous user study [22] led to a technical revision of the HRI mechanisms of the first robot prototype by incorporating the worker's feedback. In the current study the same workers tested the HRI mechanisms of the revised robot and the findings were compared with the previous version. Furthermore, it seems unlikely that the results can be explained by practice effects, due to the period of one year between the studies and the completely different interaction methods. However, the findings of the current study drove the last technical revision of the system (robot C, D, E) which will feature improvements in ergonomics and be evaluated in a final evaluation in 05/06 2017.

Collaboration can be improved by adding visual feedback on the robot and the work piece during the teaching (to reduce the burden of switching attention between the robot and touch panel). [15] [16] introduce the notion Spatial Augmented Reality (SAR) and describe it as enhancement or aggregation of several Augmented Reality (AR) technologies. One formulation [17] might be a depth camera projector based system to project (correctly distorted) information on three dimensional objects instead of flat screens (Figure 3) and may be used for projection of buttons. (Applied) robotics does not make use of SAR methods extensively. [18] introduces a projection based safeguard system for robotic workspaces especially for collaboratively used workspace. [19] gives an overview on Tangible User Interfaces (TUI) which denote interfaces that can be manipulated physically, and which have an equivalent in the digital world and represent a mean for interactive control. The project proposes a combination of TUI and SAR methods. Hand-guided positioning of the robot might be uncomfortable or time consuming due to inappropriate input modalities (friction afflicted robot drives, unintuitive touch screens,…). These were motivations for the implementations of technologies integrated in robot C,D and E and will be evaluated in the final evaluation in AssistMe.

The new HRI mechanisms of robot C, D and E will be based on the paradigm of joint/shared attention, which describes the shared focus of two individuals on an object. Joint/shared attention is realized when one individual alerts another to an object by verbal or non-verbal means such as eye-gazing or pointing (gestures). The application of this paradigm will result in gesture-based HRI mechanisms for robot C. This design decision will shift human-robot interaction towards the dynamics during human-human or human-animal interactions. Therefore, we expect that this approach will help to increase perceived safety, overall acceptance and to ease the transition of working with newly introduced robots.

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