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Task Analysis of Human-in-the-Loop Tele-Operated Maintenance: What can ITER Learn from JET?

ABSTRACT
Remote maintenance will determine the available uptime of future fusion plants such as ITER. Experience at JET showed that a human-in-the-loop tele-operated approach is crucial, although this approach entails drawbacks such as the required extensive operator training and relatively long execution times. These drawbacks are common knowledge, but little quantitative research is available to guide improvements (such as improved training methods, or active operator support systems). The aim of this paper is to identify the key areas for further improvement of tele-operated maintenance for ITER. This is achieved by a detailed task analysis based on recent maintenance at JET, using task logbooks and video data as well as interviews with experienced master-slave operators. The resulting task analysis shows the (sub)tasks that were most time-consuming and shows a large variance in time performance within operators, but also substantial differences between qualified operators with different levels of experience. The operator interviews indicate that intuitive (virtual) visual feedback and artificial (guiding) forces are promising directions for improvement. The results found in this study will be used for future research and development activities focusing on haptic guiding strategies, with the aim to further design and optimize RH maintenance systems for ITER and beyond.

1. INTRODUCTION
Reliable and time efficient remote maintenance will be essential for future fusion plants such as ITER, since maintenance time will limit the uptime of the plant [1]. At JET, a fusion device with a fully operational Remote Handling (RH) system, the maintenance team has already built up an extensive body of experience with complex remote maintenance tasks. To be able to deal with the unpredictable nature of the maintenance required, a human-in-the-loop approach is found to be crucial [2]. The flexibility of this approach is however counterbalanced by the required extensive operator training, high operator workloads, human errors and relative long execution times. In the current situation, performance of the best skilled and most experienced operator (e.g. low execution times, less errors) is the benchmark. But can task performance go beyond this benchmark? Or can we reach this benchmark performance faster and with less requirements for operator skills (more effective training;; non-expert learns to operate as expert more quickly)? Performance improvements by improved tools (e.g. visualization, haptics, support systems) or by improved training could be possible [3,4,5]. However, little quantitative research about task execution is available to guide these improvements.

The goal of this paper is to identify and quantify opportunities for improvement of teleoperated task performance during ITER maintenance. A possible and insightful way to analyze expected RH task performance for specific ITER tasks is to execute RH tasks in a simulation (as done in e.g. [6]). To analyze real-world RH, the best comparable situation to ITER is the maintenance at JET. Although an extensive amount of descriptive information about JET RH experience is already available in literature, more detailed data analysis of tele-operated task execution (e.g. execution times and errors) would also be very insightful. Recently, data analysis of RH task execution was used to improve the RH planning [7], but besides that not much collated operational data is available. This paper analyzes the body of experience from recent shutdowns at JET, to investigate and quantify the main limitations and challenges of the current human-in-the-loop RH operations and to identify the key areas for further task execution improvement.

2. METHOD

2.1 STUDY DESIGN

The analysis of master-slave task performance is based on logged operational data and recorded camera views. Reliability and execution time are key issues in ITER maintenance. In this study we therefore tried to identify most time consuming (sub)tasks, investigate differences between operators (n=3) with different level of experience, and identify errors during task execution. To get more insight in the time variation, case studies of a long and a short execution were performed.

Because the execution time data has a (positive) skewed distribution, it is described with the median and the 1st/3rd quartiles. In addition, the sample mean is shown, since it is found to be the best estimate for the population median for small sample time studies [8]. The non-parametric Mann-Whitney U-test was used to investigate the differences in execution time between operators.

Besides the objective analyses, all official masterslave operators (n = 3) were asked to rate 8 potential directions for improvement using a 7-point Likert scale. The 8 potential directions for improvement are based on the current situation, operator input and literature: verbal instructions, camera views, Virtual Reality (VR) views [9], VR overlay [3], Natural Force Feedback (NFF), Forbidden Region Virtual Fixtures (FRVF), artificial guiding forces [4,5] and training.

2.2 MASTER-SLAVE OPERATORS

Becoming a good master-slave operator requires a specific scarcely available set of skills (e.g. good visualspatial ability and eye-hand coordination), which complicates the finding of good operators. At JET the operators are put through an extensive selection and trainings procedure before they become qualified masterslave operators. During the last maintenance shutdowns there where only three or four official master-slave operators at JET. The analyzed tasks were executed by three qualified operator with the following experience levels (months of shutdown operations, up to January 2011): A-33 months, B-12 months, C-2 months.

At the time of the questionnaire, the operator experience was as follows (months of shutdown operations, up to January 2013): A-40 months, B-19 months, D-8 months.

2.3 TASK DESCRIPTION

The primary JET maintenance task that is analyzed is the installation of the ITER Like Wall (ILW) Poloidal Limiter (PL) tile carriers. The JET vessel contains 10 Poloidal Limiter beams with each 25 ILW PL tile carriers (see Fig.1). The tile carriers use a hidden bolt design and need to be installed from bottom to top.

To do so, first a tile tool is mounted to the tile carrier, which is removed directly after installation of the tile carrier to the PL beam. A complete list of (master-slave) subtasks of the tile carrier installation is shown in Fig.2. Such tile carrier placement tasks are not foreseen in ITER. Nevertheless, the subtasks are highly relevant for ITER maintenance: placement of components (multi- point/complex contact tasks), bolting, inspecting, etc.

Remote Handling includes not only the execution of the master-slave tasks itself, but comprises a broad range of supportive tasks as slave robot positioning, adjusting cameras to obtain appropriate visual feedback, task planning and logistics of tools and components [10]. The RH process should be designed in such a way that the lead time is mainly determined by the master-slave tasks, and not by the supportive tasks. This paper will focus on the human-in-the-loop master-slave tasks only.

In this paper the data of two PL beams, in total 50 tile carriers, is analyzed: PL4D (start date 25-01-2011) and PL4B (start date 22-03-2011).

Tile 38 (w12 PL4B) is a diagnostic tile which required slightly different subtasks, and was therefore excluded in analyses involving the complete tile installation.

2.4 DATA DESCRIPTION

The JET RH team works with an extensive Operation Documentation System (ODS) which is based on a relational database [9,10]. All performed RH tasks of the last 10 year are systematically logged in this system;; the Responsible Officer in charge logs all subtasks when going through the task procedures and process flow diagrams. The system is not primarily designed for task time analysis, but could be used for our analysis by taking into account the following limiting characteristics. First of all, the time data contains some noise as the logging was not necessarily perfect in time, especially short tasks (<2min) were often logged as a couple at a time. Secondly lunch/diner times were sometimes included in the data without notification. The filtering and correction of this effect is carried out, but could introduce uncertainty or even systematic effects in the data. To deal adequate with these limitations of the data, 50 repetitions of the same tasks were included in the analysis and only longer tasks were assessed.

Besides the data from the ODS system, video recordings from the tasks have been analyzed. The 4 available camera views allowed to follow the task execution in detail.

3. OPERATIONAL DATA

3.1 RESULTS FROM LOGGED ODS DATA

The results are shown per subtask, per tile and per operator.

3.1.1 Subtasks of total task

Figure 2 shows a pie chart containing all master-slave subtasks for the complete installation of the 50 ILW PL tile carriers to beams D4 and B4. The total task duration was 21 hour and 16 minutes. The subtasks which required most time: 'install tile to beam'; 328 minutes (30% of total time) and 'torque bolts'; 223 minutes (17% of total time). The task sequences of these two most time consuming subtasks will be analyzed in more detail in section 3.2.

3.1.2 Execution time per tile

The execution time per tile is shown in Fig.3. The median installation time per tile is 21 minutes (mean = 25.5 minutes). The variation in execution time is quite large (interquartile range = 13 minutes).

3.1.3 Time performance per operator

The large variation in Fig. 3 is partly caused by variance within operators, but also an interesting difference in task performance between operators was found (see also Table 1).

The difference between operators is visualized in a cumulative distribution plot (see Fig.4). Between operator A and B no significant difference was found ($p = 0.54$, Mann-Whitney U-test), but between operator A and C ($p = 0.004$) and operator B and C ($p = 0.006$) a significant difference was found. The found difference is, as expected, related to operator experience.

The same differences between operators were found for the two most time consuming subtasks 'Install to beam' and 'Torque bolts'.

3.2 TWO CASE STUDIES BASED ON VIDEO DATA

In order to understand the large variation in taskcompletion times, video data was analyzed for the subtasks 'Install to beam' and 'Torque bolts'. This was done for a fast and a slow executed tile installation: tile 11 (total duration 11 minutes) and tile 4 (total duration 63 minutes), see also Fig.3. The results of the time analyses is shown in Table 2 and Table 3. In general it could be noted that the movements for the fast installation (tile 11) where smoother and more dexterous than for the more time consuming installation (tile 4). The largest differences in time performance between operators are described:

a) Collect bolt runner. In both cases the operators struggled to obtain the right slave gripper orientation to pick up the bolt runner. Tile 4: The operator slightly misaligned the bolt runner which caused wedging in the holder and resulted in extra delay.
b) Run in both tile bolts. Tile 4: Obtaining the right position and orientation of the bolt runner took a long time.
c) Torque tighten bolt 2. Tile 4: Positioning of the torque wrench during placement and the removal took a long time.

Furthermore tool pick-up from tool tray or floor could take up to 3 minutes. Operators often had to dig out the right tool and because the tools are not fixed, they slipped and rotated away during gripping.

3.3 ANOMALIES

Besides the skill based causes as discussed above, also errors within the tasks itself caused variations in duration. Examples are:

- Wrongly prepared tile carrier;; two dowels were placed in the wrong order, which caused a clash during placement of the tile carrier. It took 1 hour for the operator to find out what was wrong and to correct it.

- Torque wrench with wrong key. It took 15 minutes to find out why the bolt was not turning.
- Clash during placement;; after inspection with a handheld camera it appeared that outside the line of view a piece of weld remnant attached to the vessel wall was causing the clash. It did take 1 hour and 6 minutes to find this out.

4. OPERATOR INTERVIEWS

To complement the objective analysis, a questionnaire was presented to all official operators (n = 3) to identify opportunities to improve task performance, and identify needs for improvement. The results are shown in Fig.5. In the current situation, visual feedback to the operator was mentioned as one of the most important factors related to task performance (average rating: 2.3). At JET the quality of the camera views is quite high (up to HD quality), but intuitive views are often not possible and/or take quite some time to acquire, which results in a degraded task performance. Improvement of visual feedback, including the improvement of Virtual Reality, Virtual Overlays and view management is believed to be an effective way to improve task performance.

In general, the current natural force feedback via the master-slave system is perceived as sufficient (average rating: 0.3). However, artificial assistive forces to protect certain components or haptic shared control during task execution deemed promising (average ratings: 2 and 1.3 respectively).

Training is currently already an important part of the preparation, but is limited by hardware availability (RH system and components/tools). More and more specific training is expected to improve task performance (average rating: 1.3).

5. DISCUSSION

Analysis of the installation of the ILW PL tile carriers showed a large variation in master-slave task performance within operators and between operators. Part of this variation is inherent to the nature and unpredictability of the maintenance tasks;; non-standard tasks will take extra time. Another part of the variation in execution time is related to operator skills. Decreasing the time variance between repetition could increase time performance up to 57%. The video analysis for the two case studies showed that the less experienced operator moved less intuitive and dexterous: an improvement up to 25.9% is possible if all operators would work in the experienced level. Both situations shows room for improvement: better training or the use of operator support tools might get less experienced operators (in a faster way) to the more experienced level of task performance.

An promising research direction to improve operator task performance is the use of artificial guiding forces or haptic shared control. Preliminary research showed promising results for a simplified 3 DOF case [4], and for a 6 DOF case with a virtual slave [5], but is it promising for real tasks as maintenance at ITER? The analyses of the two case studies at JET, showed time consuming positioning and orientation phases which might benefit from artificial guiding forces. Tasks which are expected to benefit from guiding forces include: picking up of tools and components, free air movements especially during difficult conditions (e.g. no intuitive visual feedback, difficult robot/task orientations) and contact tasks involving motion.

The JET operators rate visual feedback as one of the most important factors related to task performance. The quality of available visual feedback during ITER RH will probably be less than currently at JET (choice of camera is limited by the amount of radiation), which makes development in VR and augmented visuals even more important for ITER. A promising research direction is synthetic viewing, which combines data from 3D models with real-time sensory information into a real-time up to date model. Such a calibrated model allows for a wide range of assistive functions, e.g. 'see through' obstacles that are blocking the camera and highlights in a virtual overlay [3], and even haptic assistance [4,5].

Additional training of master-slave tasks is another potential approach to improve task performance. The apparent learning effect during the shift of the least experienced operator (see Fig.3) should be investigated for a larger data set, but suggests that offline training of specific tasks just before the real execution would improve performance. To make training more flexible and less dependent on availability of hardware, a promising approach is training in Virtual Reality with a physics engine to simulate dynamic effects and contact forces (e.g. used in [4,5]).

Note that given the small amount of available trained operators (n = 3) future research into real-life task execution cannot include more relevant subject, but could and should focus on understanding more and different tasks.

CONCLUSION

A detailed analysis of master-slave tasks during remote maintenance at JET identified the most promising tasks and directions for performance improvement of RH at future fusion plants. Analysis of log files and video data of the placement of 50 ILW Poloidal Limiter Tiles showed:

- Subtasks 'Install on beam' and 'Torque bolts' required most time, resp. 30% and 17 % of the total time. Time improvements for those subtasks would be most effective to improve total execution time.
- There is a large variation in execution time between task repetitions (between and within operators): ranging from 11 to 63 minutes. For this case, the total task duration would improve with 57% if all task repetitions would take 11 minutes.
- The difference in time performance between operators is related to the amount of experience: the average task execution time for the most and less experienced operator are resp. 18.9 and 38.7 minutes. For this case, the total task duration would improve with 25.9% if all operators worked at the experienced level.

Potential ways to improve task performance include instruction, (artificial) force and visual feedback and training. The natural force feedback is perceived as good enough by the operators, so improvement of haptic transparency seems not very important. Additional artificial forces to protect the environment and to guide during tasks were indicated to be promising to improve master-slave task performance. Furthermore it was indicated by the operators that the quality of visual feedback (intuitive views, time needed to obtain views) is strongly related to task performance. Improvements in VR, virtual overlay and view management are expected to be beneficial.

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	Total	*Op. A*	*Op. B*	*Op. C*	*Op. A+n.*
Median (mean) [min]	*21.0 (25.5)*	*19.0 (18.9)*	*17.0 (21.0)*	*37.5 (38.7)*	*23.5 (27.3)*
q1/q3 [min]	*16/29*	*14/22*	*16/25*	*26/47*	*16/35*

Table 1: Median, mean and 1st / 3rd quartile of total execution time (master-slave tasks) per tile shown per operator.

"Install to beam"	*Duration (s)*	
	Tile 4 (slow)	*Tile 11 (fast)*
Position on beam 100mm above previous tile	*19*	*26*
Lower to final position	*35*	*38*
Release Lower (Gold) Tool Grip on	*20*	*7*
Collect in Fastening (SILVER)	*45*[a]	*25*[a]
Run in both Tile bolts (2 Nm max)	*116*[b]	*41*[b]
Fasten both Dowel Bolts fully	*76*	*55*
Fasten Tile Bolt 1 (8Nm)	*15*	*20*
Fasten Tile Bolt 2 (8Nm)	*19*	*15*
Inspect Installation	*0*	*0*
Total time:	*345*	*227*

Table 2: Break-down of execution time for subtask "Install to beam', based on video data.

"Torque Bolts"	*Duration (s)*	
	Tile 4 (slow)	*Tile 11 (fast)*
Torque Tighten Bolt 1 (25Nm)	*95*	*74*
Torque Tighten Bolt 2 (25Nm)	*112*[c]	*52*[c]
Inspect Installation	*-*	*18*
Total:	*207*	*144*

Table 3: Break-down of execution time for subtask "Torque Bolts', based on video data.

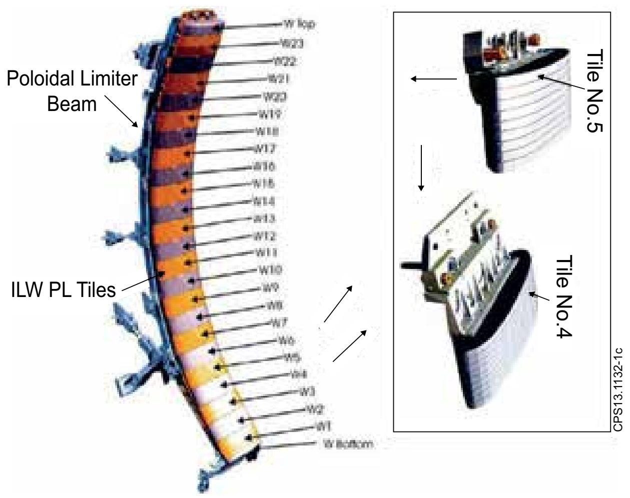

Figure 1: Left: 1 of the 10 Poloidal Limiter Beams in the JET vessel. Right: ITER Like Wall (ILW) Poloidal Limiter tile carriers - 25 per beam - have to be installed from bottom to top.

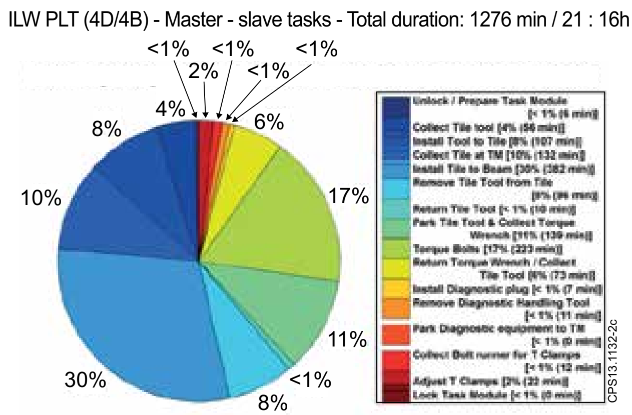

Figure 2: Execution time of master-slave subtasks for installation of the 50 ILW Poloidal Limiter Tile carriers on beam 4D/4B.

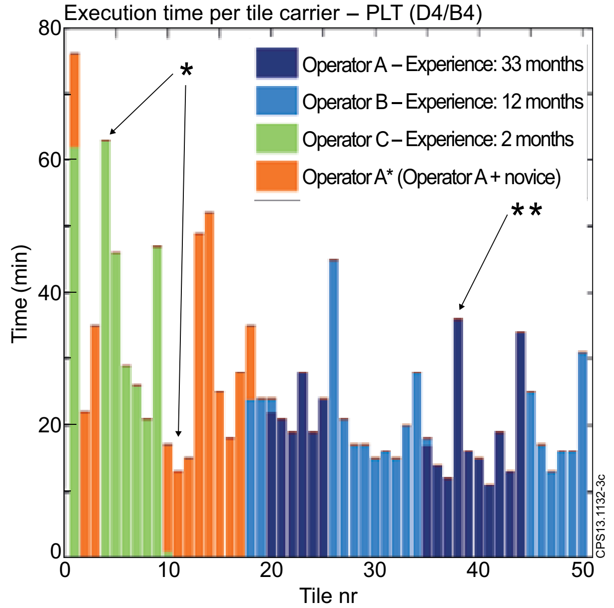

*Figure 3: The execution time of master-slave tasks per tile carrier for installation of the 50 ILW PL Tile carriers on beam 4D/4B. The bar color shows which operator was on shift. *Tile 4 and 11 are used for video analysis (section 3.2). **Tile 38 is a diagnostic tile with extra actions, and is not included in all analyses.*

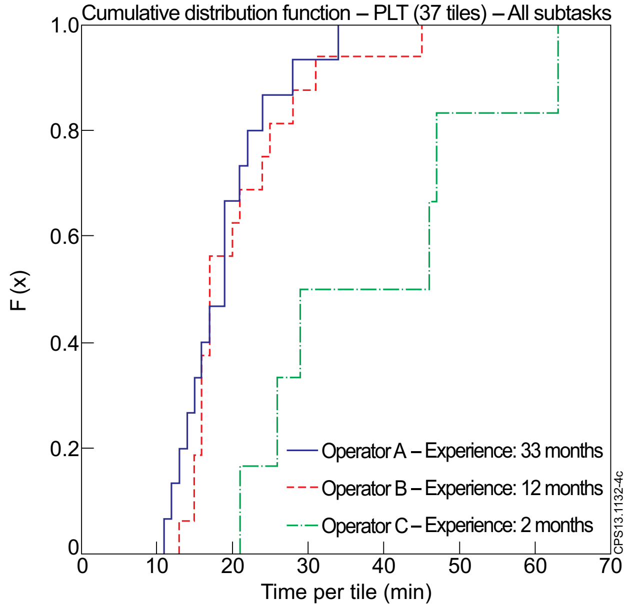

Figure 4: Cumulative distribution function of total execution time (Mascot tasks) per ILW Poloidal Limiter tile, shown per operator.

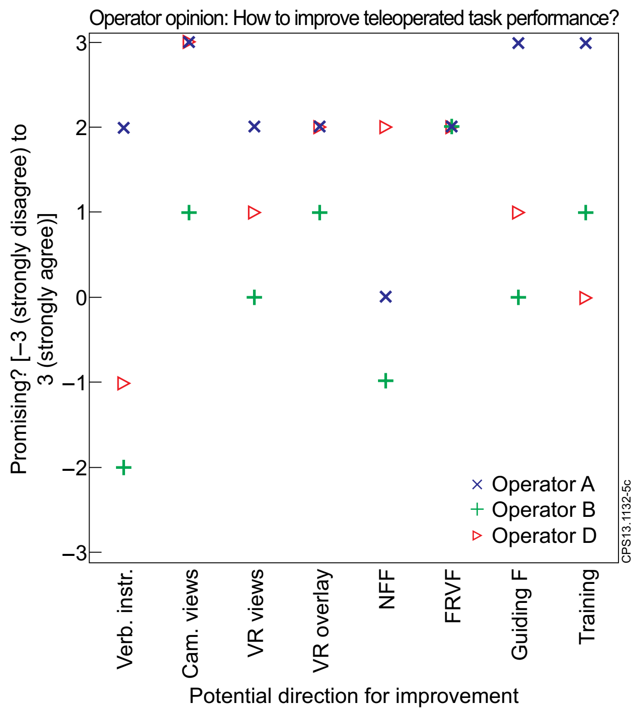

Figure 5: Mascot operator opinions about promising directions to improve teleoperated task performance. NFF = Natural Force Feedback / FRVF = Forbidden Region Virtual Fixtures. Operator experience: A-40 months, B-19 months, D- 8 months.