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What to improve in Human-in-the-loop Tele-operated Maintenance? Analysis of executed Remote Maintenance at JET

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***Abstract*—The planned maintenance of the experimental fusion plant ITER requires telemanipulation techniques to allow human intervention in inaccessible places. The achieved performance with such systems is however expected to be sub-optimal and is characterized by long execution times compared to similar tasks performed manually. There is little quantitative research on task performance of real world telemanipulation tasks available to give insight in underlying causes for task execution difficulty.**

In this paper a detailed analysis of real world remote maintenance at fusion plant JET was performed with the aim to: i) identify key areas that are difficult for operators and require further improvement and ii) quantify the room for potential benefits.

Video recordings of the installation of 50 tiles executed by three official master-slave operators were analyzed. The task execution was characterized by a large variation in time performance, between but also within operators. Reduction of this variation could theoretically result in time reduction up to 41%. Recurring tasks like 'rough/fine approach' and 'retreat' covered more than 50% of the total task completion time and were identified as most promising for further improvement.

The results will be the base for further research on operator assistance with augmented visual or haptic guidance.

***Index Terms*—Remote maintenance, Tele-operation, human factors, task performance, task analysis.**

I. INTRODUCTION

THE planned experimental fusion plant ITER [1] is a worldwide project with the aim to prove the feasibility of fusion power as a future energy source. It is envisioned to require human in the loop remote maintenance techniques [2] due to the presence of high radiation levels and toxic materials and the complexity and unpredictable nature of maintenance tasks.

Besides satisfying high quality and safety requirements, it is a critical challenge to perform the tele-operated maintenance in the smallest possible timeframe to keep the substantial down-time of the plant within reasonable limits [3]. This is especially a challenge because tele-operated task execution is often characterized by low situational awareness, high operator workloads, human error and relative long execution times [4], [5]. What are promising directions to improve tele-operated task execution for ITER maintenance?

Most research in the tele-manipulation domain strongly focuses on the performance and stability of the telemanipulation device. Although significant improvements have been achieved in terms of device performance (e.g. control algorithms [6]–[9], hardware design [4], [10], [11]) and visual feedback (e.g. stereoscopic viewing, augmented visual feedback [12], [13]) it is widely recognized that tele-operated task performance is still sub-optimal.

To improve task performance in operational practice, several practical approaches have been applied such as stringent operator selection and training [14] as well as design upgrades in the environment to make it more robust for robot assembly (e.g. applying Design for Assembly principles [15], [16]: captive bolts, mechanical alignment features, grip features, etc.).

There is however limited insight in how to further improve tele-operated task performance. Which tasks or aspects are difficult and what makes them difficult? To be able to investigate solutions in a structured way, more quantitative research about difficulties in tele-operated task execution is required.

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* *See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

A unique and extensive body of experience with human-in-the-loop tele-operated maintenance tasks can be found at the Joint European Torus (JET) [2], ITER's predecessor and currently the largest tokamak with a fully operational remote maintenance system. Performed maintenance tasks range from component handling (0.5 – 250kg), mechanical cleaning, TIG/MIG welding and thread tapping to visual inspection and diagnostic system installation and calibration [17]. A considerable amount of descriptive literature about the remote maintenance at JET has been published, covering the maintenance philosophy [17], the RH system development [2],[18], planning of operations [5] and the required strict operator selection procedures and extensive operator training periods [14]. However, detailed quantitative analyses of task performance (e.g. execution times and errors) are hardly available.

A recent study made a first start to identify and quantify room for improvement based on performed maintenance at JET. To identify the most time consuming subtasks of a generic installation task, an analysis of the task execution was performed using logbooks, two video fragments and operator interviews [19]. The subtasks 'install to beam' and 'torque bolts' required most time and would be most effective to improve. Furthermore large variation in time performance, between qualified operators with different levels of experience, but also within operators was found. Bringing the average duration closer to the fastest trial, could substantially decrease overall maintenance time.

To be able to draw more detailed conclusions on smaller specific tasks, time data with a smaller resolution (seconds instead of minutes) and less noise would be required. Furthermore, beside the high level results (execution time data), also insights in underlying (skill-based) causes of variability would be required.

In literature from the industrial and medical domain, time motion or time-action studies are described as powerful quantitative methods which can be used to objectively analyze task executions [20], [21]. By measuring the number and duration of the actions needed for the operator to achieve his goal, the course and the efficiency of the execution can be assessed. For example in surgery [22], time-action analysis appeared a useful approach to identify and quantify possible improvement of skill based tasks and procedures.

To obtain more quantitative data about potential improvements of tele-operated task execution, two approaches have been followed to apply these time-action studies. First a detailed analysis based on a human factors experiment in a VR environment was performed [23]. A task analysis in three phases: on task, subtask and within subtask level, showed for a placement task that the final approach state requires most time. Although the capturing of skill based behavior in the measured time traces appeared challenging, the data showed that subjects had difficulties to correct errors in tool orientation during placement.

The second approach is presented in this paper and comprises of a detailed time-action analysis performed on video data of real executed remote maintenance at JET performed by qualified operators.

The main objective of this paper is to identify key areas for further improvement of human-in-the-loop tele-operated task execution and to quantify potential time reduction, based on in-depth analysis of performed maintenance at JET. Secondly, the analysis can serve as benchmark to validate preceding research done in VR.

Since (re)placement of components is one of the most fundamental and most recurring actions during maintenance, a placement and fixation task during JET remote maintenance [19] was chosen for a detailed time-action analysis on task, subtask and within subtask levels. The metrics *absolute time duration* and *variability in time duration* are used as triggers to analyze in more detail. The reason is because the most time consuming (sub)task are most effective to improve. Furthermore, a large variation in time performance indicates that some aspects of the task execution are not controlled well: either the task itself (e.g. manufacturing tolerances, small deviations of the environment), or the task execution by the human (e.g. situational and/or spatial awareness, accuracy, training). For the latter option, variability in performance can therefore be seen as a measure of skill, but could also be used to assess design parameters of a tele-operator device [24] or to identify task difficulty. Reduction of variability in time performance saves overall execution time. In this study, the amount of variation is addressed as an indication for potential room for time reduction. More specifically, for which subtasks can we

i) reduce *between subject* variation, with the ultimate goal to enable less experienced operators to perform like experts, and
ii) reduce *within subject* variation with the ultimate goal to enable all subjects to perform on average like their fastest trial.

Section II describes the methods for the performed time-action analysis, with section III, IV and V describing the results, discussion and conclusions.

II. METHODS

A. Remote Handling system configuration

The remote maintenance at JET is performed using a dexterous two-armed master-slave telemanipulator called Mascot [2]. The Mascot slave is situated on the end of a multi-jointed boom, which allows relocation throughout the JET vessel (see Fig. 1, right). A second boom carries task modules, providing tools and components close to the working area. Master and slave are kinematic identical and bilateral control is implemented via joint-based position-error control. Additionally, the operator can use several assistive features: (partial) weight compensation, force multiplication (1:15/1:3/1:6) and simple constraints (locking of degrees of freedom). The Mascot operator gets visual feedback from multiple (adjustable) camera views. Two cameras are mounted on the two slave-arm and a top-, front- and overview camera are available. The camera views of the remote environment are complemented with a virtual reality (VR) view.

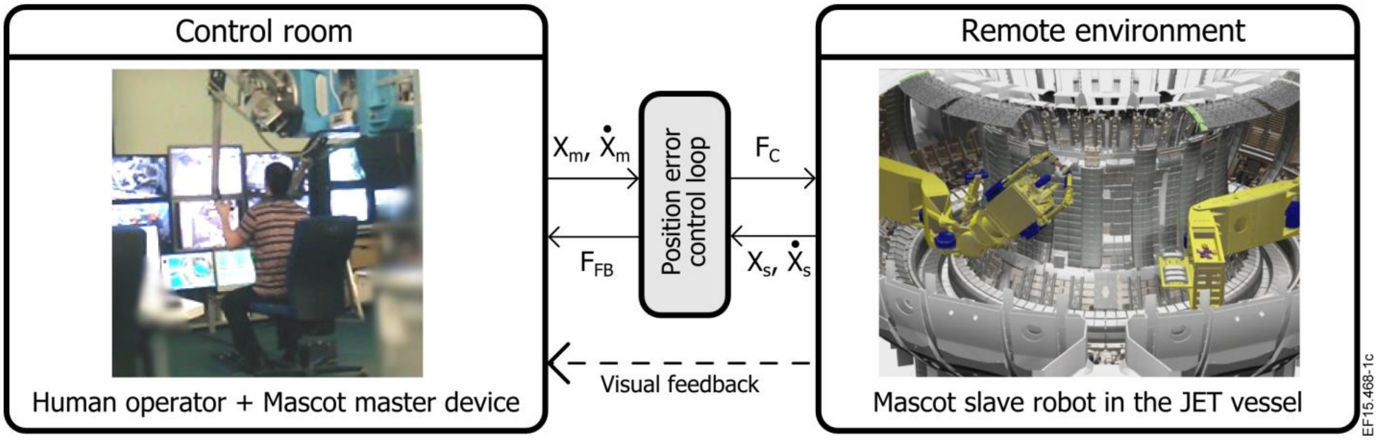

Fig. 1. Schematic representation of the Mascot tele-manipulation system at JET. The human operator controls the two arms of the Mascot slave robot (right) by manipulating the two Mascot master arms (left). The master and slave robot are kinematic identical (2x 6DOF + gripper). The human operator gets visual and haptic feedback (F_{FB}) from the environment.

B. *Remote Maintenance task*

The JET maintenance task that was selected for the time-action analysis is part of the installation of the ITER Like Wall (ILW) Poloidal Limiter (PL) tile carriers. These tile carriers function as protection of the inner vessel wall and are placed on 10 vertical beams. Based on analysis of rough logbook data a preceding study showed that substep ‘Install tile to beam’ required most time; up to 30% of the total task-completion-time [19]. The current study will analyze this substep ‘Install tile to beam’ in more detail (see Fig. 2). Per vertical beam 25 tiles (+/-10 kg) have to be installed in a sequence from bottom to top. The tile placement is performed with two-handed, and is facilitated by a central alignment pin on the tile. After placement one of the (robot)hands is used to grasp the bolt runner, which is used to subsequently run in and fasten the two location dowels and the two fixing bolts.

Fig. 3 shows the nominal actions or subtasks of the task ‘Install tile to beam’ (a more detailed task breakdown can be found in section D). Although the overall task itself is application specific and does not exist in other telemanipulation domains, the subtasks are highly representative and relevant for other (hard contact) domains: placement of components (multi-point and complex contact tasks), grasping, bolting, etc..

This study focusses on the task performance of the master-slave operator and the analysis will therefore only include the skill-based master-slave tasks, the time required for general robot positioning, task planning and logistics of tools and components are not included.

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

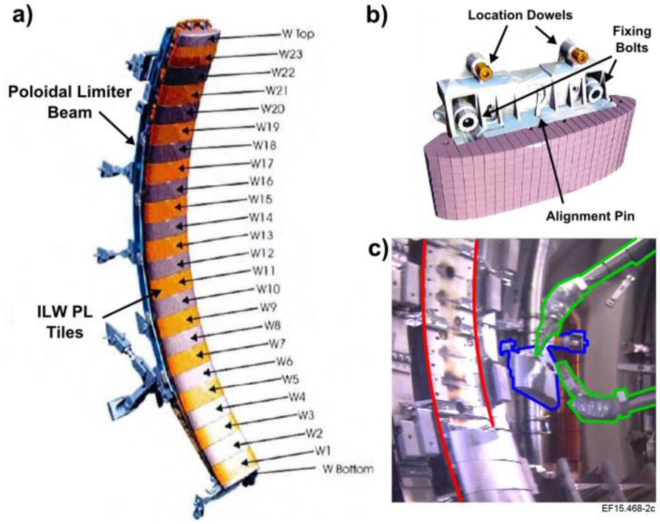

Fig. 2. Analyzed maintenance task: ‘Install tile to beam’ during ‘Installation of ITER Like Wall (ILW) Poloidal Limiter (PL) tile carriers’. a) 1 of the 10 Poloidal Limiter Beams in the JET vessel, consisting of 25 tiles. b) ILW PL tile (+/-10 kg). c) An tool interface with two grip features is connected to the tile (highlighted in blue) to allow the two handed placement (see two slave arms highlighted in green). The boltrunner tool is also transported via this tool interface. The target location (PL beam) is highlighted in red.

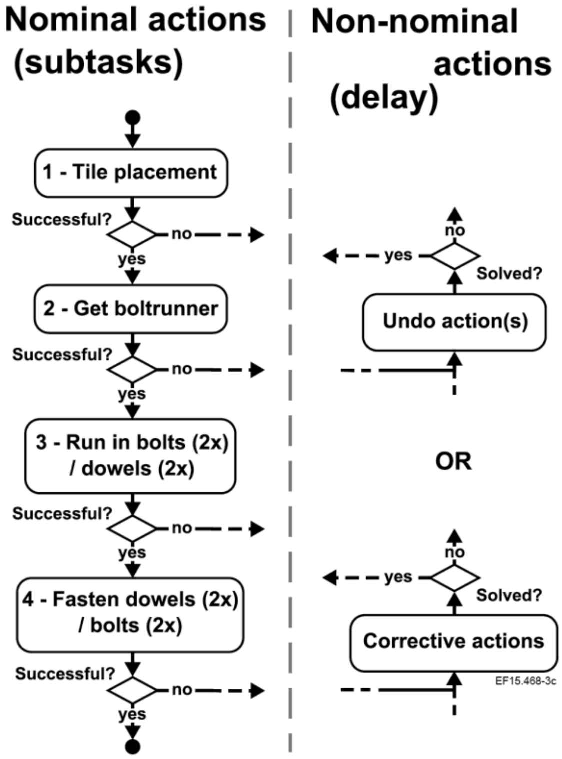

Fig. 3. The nominal task execution of the task ‘Install tile to beam’ consists of four subtasks’. Non-nominal situations require additional corrective actions and/or repetitions and will cause delay.

C. *Master-slave operators*

Working with a master-slave system is a highly demanding task, for which only a limited amount of people possess the required skills (e.g. good visual-spatial ability and eye-hand coordination) to become a master-slave operator on expert level. The master-slave operators at JET are therefore put through an extensive selection and training procedure before they become a qualified Mascot operator [14]. During the last shutdowns only three or four qualified Mascot operators were available at JET.

The analyzed tasks were executed in January and March 2011 by three qualified operators with the following experience levels (months of shutdown operations, up to January 2011): A-33 months, B-12 months, C-2 months. For some part of the tile installation a novice operator was being trained by operator A. This data was excluded from the analyses since it is not clear who was controlling the master–slave system.

D. *Time-action analysis*

The time-action analysis was executed based on available CCTV video recordings of the selected maintenance task executions. The (unedited) video logs provided four synchronized camera views, showing the four main views of the task environment, varying between the two slave arm cameras and top-, front and overview cameras.

To get detailed information on different task levels, the time-action analysis was performed following the Three Phased Task Analysis approach [23]. A Hierarchal Task Analysis [20], [23], was used to break down the nominal maintenance task ‘Install tile to beam’ into subtasks (phase II of the Three Phased Task Analysis) and states (phase III of the Three Phased Task Analysis), see Table I and Fig. 4. The states are defined based on task relevant stages and environmental constraints. The motion-centric task taxonomy as defined in [25] was used to classify the states in a generalized set of actions: 'Rough approach’, ‘fine approach’, ‘fine push/pull’, ‘rough follow path’, ‘apply pressure’ and ‘retreat’ (table I, bold terms in right column).

TABLE I

SUBTASKS AND STATES DURING ‘INSTALL TILE TO BEAM’

No.	Subtask (Analysis phase II)	No.	State (Analysis phase III)	State characteristics
1	Tile placement (2-handed)	1.1	Move tile to beam	**Rough approach** (>2cm)
		1.2	Align tile	**Fine approach** and make contact (<2cm)
		1.3	Final position tile	Fine movement in contact (**fine push/pull**)
2	Get bolt runner	2.1	Move gripper to boltrunner.	**Rough approach** (>2cm)
		2.2	Grasp boltrunner	**Fine approach**, align and close gripper (<2cm)
		2.3	Extract boltrunner from stand	Unlock boltrunner by 30 degree rotation (bayonet), **retreat** boltrunner carefully (no wedging)
3	Run in bolts/dowels (4x)	3.1	Move boltrunner to bolt.	**Rough approach** (>2cm)
		3.2	Align/insert boltrunner	**Fine approach** and make contact (<2cm)
		3.3	Rotate bolt	Rough rotational movement (**rough follow path**)
		3.4	Retreat boltrunner from bolt	Fine movement / **retreat** (no wedging)
4	Fasten dowels/bolts (4x)	4.1	Move boltrunner to bolt	**Rough approach** (>2cm)
		4.2	Align/insert boltrunner	**Fine approach** and make contact (<2cm)
		4.3	Apply torque to fasten bolt	Increase torque until 8Nm threshold (**apply pressure**)
		4.4	Retreat boltrunner from bolt	Fine movement / **retreat** (no wedging)

Bold terms are based on the motion-centric task taxonomy defined in [25].

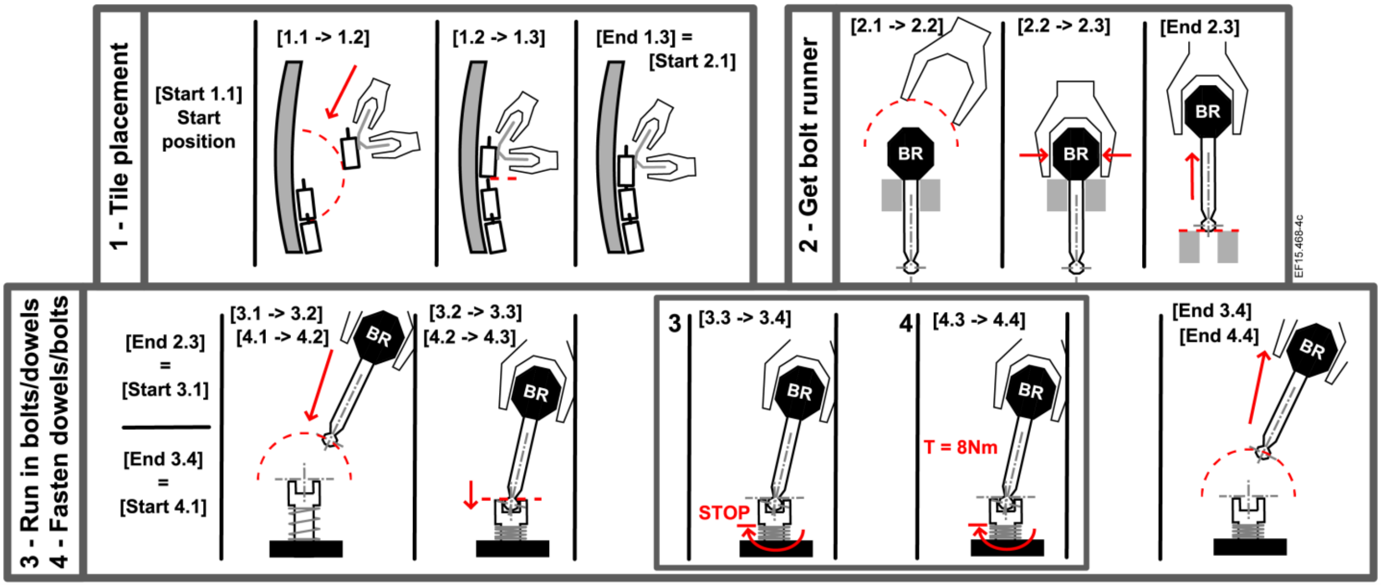

Fig. 4. Schematic representation of the Mascot slave in the remote environment showing the defined state transitions for subtasks ‘**1-Tile placement**’ (top left), ‘**2-Get boltunner (BR)**’ (top right), and ‘**3-Run in bolts**’ (bottom) and ‘**4-Fasten bolts**’ (bottom). The states are described in more detail in table I.

The task breakdown is based on the nominal task execution; only actions that directly contribute to the advancement of the task (so called 'Goal Oriented Actions', as shown in Fig. 3) are included. Non-nominal actions (e.g. extra visual inspection, unsuccessful trials, repetitions) are a separate category.

The task analysis started when the slave robot was in the right position and the slave arms started moving, and stopped when the bolt runner was retreated after fixing the last bolt. The duration of all states was measured for the 50 task executions. Non-nominal actions were logged separately.

The Three-phased Task Analysis was used to systematically quantify the distributions in task completion time for different task levels, using metrics in the following groups:

- Absolute time duration and variation in time duration (indication for magnitude of potential time improvement)
  Metrics: Median and 1st / 3rd quartiles of task completion time, group mean of task completion time.
- Comparison to fastest trial (indication for ease to achieve potential time improvement)
  Metrics: Difference in average task completion time and the fastest trial, group mean of task completion time normalized to fastest trial.

The complete task (phase I) was further analyzed at the level of abstract subtasks (phase II). Subtasks with the largest variation were then selected to be further analyzed at state level (phase III).

Because the execution time data has a (positive) skewed distribution, it is described with the median and the 1st/3rd quartiles. The data was compared using a non-parametric Mann–Whitney U-test. The significance level was corrected for 3 tests per dataset using the Bonferroni correction: $p = 0.05/3 = 0.017$.

III. RESULTS

Figure 5 shows the task completion time for the installation of each of the 50 tile carriers. Non-nominal actions (grey) resulted in substantial peaks in task completion times; all together responsible for 30% of the total task completion time.

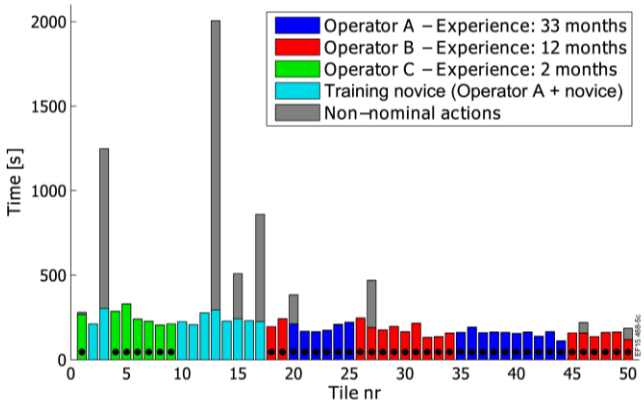

Fig. 5. Task completion time for the installation of 50 tile carriers. The bar color shows which master-slave operator was on shift. Grey peaks show non-nominal actions. Marked tile installations (●) are performed by fully trained qualified operators and are used for further analysis.

Table II lists the non-nominal actions and gives a short description explaining the causes for the peak in completion time. The two longest delays were 28 and 13 minutes (1711s and 786s) and occurred during the final positioning state of the tile placement. In both cases the installation location needed only a small adjustment, but identifying this required a lot of time. Furthermore the placement itself was not executed in a smooth way and required a second attempt. The other 11 delays ranged from 12s to 635s and occurred during the 'Rotate BR' state of the 'run in bolts/dowels' subtask. Most of them were caused by a small misalignment in the positioning of the tile carrier.

The results of the time action analysis for the nominal execution are presented in three phases: Section A covers the whole task, section B and C provide more detailed results for the subtasks and states respectively.

A. *Analysis Phase I – Complete task*

Table III and Fig. 6 show the same data as Fig. 5 but without the non-nominal actions and only for the task executions performed by fully trained qualified operators. The least experienced operator (C) required substantially more time, namely 240s as a median, compared to operator A and B, which required 163s and 164s respectively ($p_{AC}<0.001$, $p_{BC}=0.002$,

TABLE II

NON-NOMINAL ACTIONS.

Tile #	Subtask	State	Time [s]	Description
1	3 - Run in bolts	3.1 - Move to bolts	12	Initiated wrong task; movement to wrong bolt
3	1 - Tile placement	1.3 - Final positioning	786	Tile location required some adjustment; tile was removed again to adjust a bolt
3	3 - Run in dowels	3.3 - Rotate to run in dowels	160	Location dowel got stuck; loosen other bolts slightly again and shift tile slightly
13	1 - Tile placement & 3 - Run in dowels	1.3 - Final positioning & 3.3 - rotate to run dowels	1711	Final positioning did not succeed; loosen bolt on location side slightly and retry (528s). Secondly the location dowel got stuck; complete tile was removed for visual inspection, no error was found and the retrial succeed (1183s).
15	3 - Run in bolts	3.3 - Rotate to run in bolts	267	Visual check with camera zoom; the tile was not placed properly. Loosen bolts, shift slightly, and refasten bolts to solve it.
17	3 - Run in dowel	3.3 - Rotate to run in dowel	635	Location dowel got stuck; loosen other bolts slightly again and shift tile slightly
20	3 - Run in bolts	3.3 - Rotate to run in bolts	20	Change of procedure: Started with running in a location dowel, but in between first a bolt was run in.
20	3 - Run in dowels	3.3 - Rotate to run in dowels	152	Location dowel got stuck; loosen other bolts slightly again and shift tile slightly
27	3 - Run in bolts	3.3 - Rotate to run in bolts	148	Bolt got stuck; re-insert BR and retry, than loosen bolt again and retry
27	3 - Run in dowels	3.3 - Rotate to run in dowels	131	Location dowel got stuck; loosen other bolts slightly again and shift tile slightly
46	3 - Run in dowels	3.3 - Rotate to run in dowels	63	Location dowel got stuck; loosen other bolts slightly again and shift tile slightly
50	3 - Run in bolts	3.3 - Rotate to run in bolts	20	First bolt got stuck; loosen again and first do the position dowels
50	3 - Run in bolts	3.3 - Rotate to run in bolts	46	Second bolt got stuck; loosen again and retry.

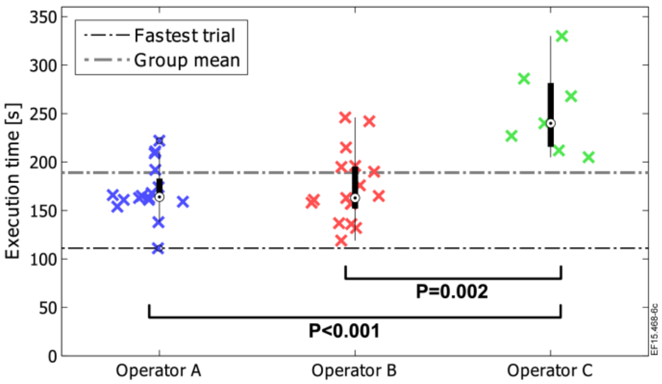

Fig. 6. Analysis phase I. Task completion time for the nominal tile carrier installations per operator. Large variation can be seen for all subjects. The least experienced operator (C) needs on average substantial more time. Even the more experienced operators (A,B) can potentially improve their completion time with a factor 1.5 (median -> fastest trial). Only the 40 executions performed by qualified operators (marked (●) in Fig. 5) are included, and the non-nominal actions are excluded.

TABLE III
RESULTS – PHASE I; TASK COMPLETION TIME OF THE TILE INSTALLATION

	Task completion time per operator [s]		
	A	B	C
Median (1st q / 3rd q)	**164** **(160/183)**	**163** **(152/195)**	**240** (216/282)
Group mean		189	
Fastest trial		111	
Comparison to fastest trial			
Norm. m.* (norm. 1/3q*)	1.48 (1.44/1.65)	1.47 (1.37/1.76)	2.16 (1.94/2.54)
Diff. median & fastest trial	53s (32%)	52s 32%	129s 54%
Norm. group mean		1.70	

m. = median / norm. = normalized
Normalized with respect to fastest trial. / **Bold = mentioned in text*

Mann-Whitney U-test). Between operator A and B no difference was found (p_{AB} = 0.86). The variance within operators is also quite high, shown in a interquartile range of 23, 43 and 66 for operator A to C respectively (Table III). Even the two most experienced operators (A and B) show a difference between median and fastest trial of 32 %.

B. Analysis Phase II – Subtasks

Can we pin-point these found variations in time performance to (one of) the subtasks? Fig. 7 shows the task completion time of the four subtasks. All subtasks show a substantial variation in task-completion-time. The largest absolute variation was found for the subtasks '3 - Run in bolts' and '1 - Tile placement' (interquartile range: 31s and 28s respectively, Table IV). This variation was also reflected in a large difference between group average and the fastest trial: 53.2s and 21s respectively, which comes down to a relative difference of 58.3% and 63.6% with respect to the group mean (Table IV).

The largest relative difference between group mean and the fastest trial was found for subtask '2 - Get boltrunner', with a factor 2.9 between the fastest trial and group mean (Table IV).

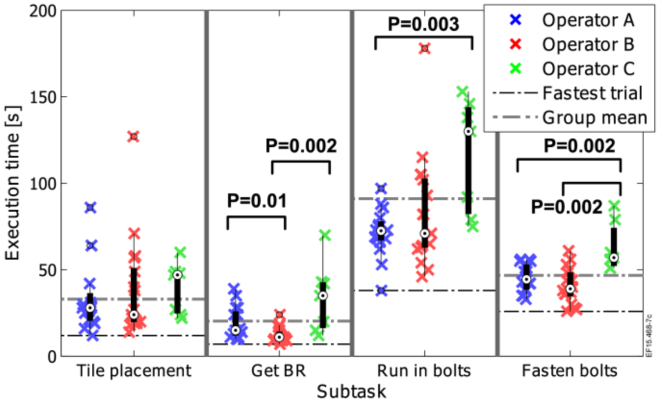

Fig. 7. Analysis phase II. Completion time per subtask. Large variation for all subjects. Largest absolute variation for '3 - Run bolts', highest relative variation for '1 - Tile placement'. Subjects C has highest average time. Only the 40 executions performed by a single operator (marked (●) in Fig. 5) are included.

TABLE IV
RESULTS – PHASE II;
TASK COMPLETION TIME – SUBTASKS 'TILE INSTALLATION'

	Task completion time per subtask [s]			
	Tile placement	Get BR	Run bolts / dowels	Fasten dowels / bolts
Group median (1st q / 3rd q)	27.5 **(20.5/48.5)**	14 (11/24)	75 **(64/95)**	45 (37/55)
Group mean (over sub. med.)	33.0	20.3	91.2	46.8
Fastest trial	12	7	38	26
Comparison to fastest trial				
Norm. gr. mean*	2.75	**2.90**	2.40	1.80
Diff. gr. mean & fastest trial	**21s** (63.6%)	13.3s (65.6%)	**53.2s** (58.3%)	20.8s (44.5%)

med. = median / norm. = normalized / sub. = subject / gr. = group
Normalized with respect to fastest trial. / **Bold = mentioned in text*

As found for the whole tasks, operator C showed a larger median task completion time for all the four subtasks when compared to operators A and B. This effect was significant for subtasks '2 - Get BR' (p_{BC}=0.002), '3 - Run in bolts' (p_{AC}=0.003) and '4 - Fasten bolts'(p_{AC}=0.002, p_{BC}=0.002).

C. Analysis Phase III – States of subtasks

Can we find specific states which require most time and/or are the origin of found variations in completion time? What are promising states to improve? First the states of two subtasks with respectively the largest absolute and the largest relative variation are investigated.

The subtask analysis showed that the largest absolute variation was found for subtask '3 - Run in bolts'. Where does this variation originate from? Fig. 8 and Table V show the task completion time for the four states of subtask '3 - Run in bolts'. The largest absolute variation was found for the state '3.3 - Rotate bolt' (interquartile range: 6s, Table V), with a fastest trial of 7 seconds but also a peak up to 54 seconds.

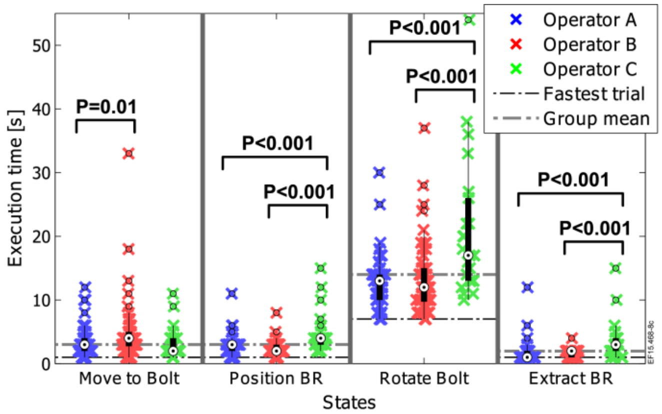

Fig. 8. Analysis phase IIIA. Task completion time per state of ‘3 - Run in bolts’, (4x per tile; 160 data points per state). Largest relative variation for ‘3.1 - Move’ and ‘3.2 - Position’, but absolute times are small. Largest absolute variation for ‘3.3 - Rotate bolt’. Only the 40 executions performed by a single operator (marked (●) in Fig. 5) are included.

TABLE V
RESULTS – PHASE IIIA;
TASK COMPLETION TIME – STATES ‘3 - RUN IN BOLTS’

	Task completion time per state [s]			
	Move BR to bolt	Position BR	Rotate bolt	Extract BR
Group median (1st q / 3rd q)	3 (2/4)	3 (2/3)	13 **(10/16)**	2 (1/2)
Group mean (over sub. med.)	3.0	3.0	14.0	2.0
Fastest trial	1	1	**7**	1
Comparison to fastest trial				
Norm. gr. mean*	**3.0**	**3.0**	2.0	2.0
Diff. gr. mean & fastest trial	2s (66.7%)	2s (66.7%)	7s (50.0%)	1s (50.0%)

med. = median / norm. = normalized / sub. = subject / gr. = group
Normalized with respect to fastest trial. / **Bold = mentioned in text*

The largest relative differences between group mean and fastest trial were found for states ‘3.1 - Move to bolt’ and ‘3.2 - Position boltrunner’, namely a factor 3 (Table V).
Except for state ‘3 - Move to bolt’, the time performance of operator C was significantly worse compared to operator A and B (p<0.001).

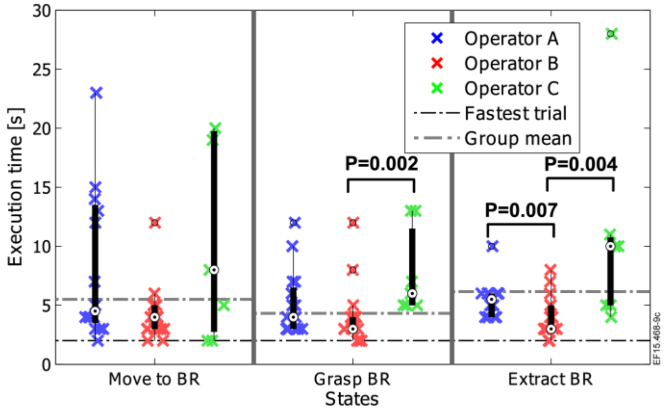

Fig. 9. Analysis phase IIIA. Task completion time per state of ‘2 - Get BR’. Largest absolute variation for ‘2.1 - Move to BR’, largest difference between group mean and the fastest trial for ‘2.3 - Extract BR’. Only the 40 executions performed by a single operator (marked (●) in Fig. 5) are included.

TABLE VI
RESULTS – PHASE IIIA;
TASK COMPLETION TIME – STATES OF SUBTASKS ‘2 - GET BOLT RUNNER’

	Task completion time per state [s]		
	Move to BR	Grasp BR	Extract BR
Group median (1st q / 3rd q)	4 **(3/10)**	4 (3/6)	5 (4/6)
Group mean (over sub. med.)	5.5	4.3	6.2
Fastest trial	2	2	2
Comparison to fastest trial			
Norm. gr. mean*	2.75	2.10	**3.1**
Diff. gr. mean & fastest trial	2.5s (63.6%)	2.3s (53.8%)	**4.2s** (67.6%)

med. = median / norm. = normalized / sub. = subject / gr. = group
Normalized with respect to fastest trial. / **Bold = mentioned in text*

The subtask with the largest relative difference between group mean and fastest trial was ‘2 – Get boltrunner’. Fig. 9 and Table VI show the task completion time of the three states of subtask ‘2 - Get boltrunner’. The largest absolute variation was found for the state ‘2.1 – Move to boltrunner’ (interquartile range: 7s, Table VI), with peaks to 23 seconds. The largest difference between group mean and the fastest trial, namely 4.2 seconds, was found for state ‘2.3 – Extract boltrunner’, which corresponds to a factor 3.1 between the fastest trial and group mean (Table VI).
The time performance of operator C compared to operator A and B was significantly worse for states ‘2.2 – Grasp BR’ (p_{BC}=0.002) and ‘2.3 – Extract BR’ (p_{BC}=0.004)

Besides the impact of the different states on a specific subtask, it is even more relevant to look to the impact of the different states on the whole task. Fig. 10 shows the task completion time for all states, grouped in elemental actions according a motion-centric task taxonomy [25]. Relative short states in a specific subtask, like ‘rough’ and ‘fine approach’, appear to require a substantial amount of time at task level. The more frequent

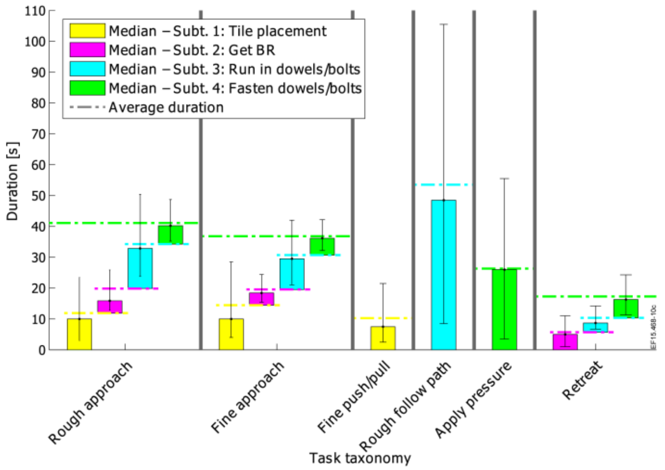

Fig. 10. Analysis phase IIIA. Task completion time shown for all states (complete task) grouped according a generalized set of actions (see table I and [25]). The bars show the median duration and are plotted cumulative per generalized action. Bar colors show the corresponding subtasks. The error bars represent the 1st and 3rd quartiles.

elemental actions 'rough approach', 'fine approach' and 'retreat' together take 51% of the total time.

IV. DISCUSSION

A time-action analysis of tele-operated maintenance at JET was performed with the goal to identify and quantify potential room for improvement. Although the main focus of the analysis was on nominal task execution, it must be noted that 30% of time was spent on non-nominal tasks. First non-nominal task execution is discussed, after which the analysis of nominal task execution is discussed per analysis phase.

Non-Nominal Execution

For the analyzed set of 50 tile placements, potentially up to 30% of overall task execution time could be saved if non e.
-nominal task executions could be prevented (Fig. 5). The two longest delays were observed in state '1.3 - Final positioning', and were caused by a small mismatch between tile interface and place location. The operators could have resolved this mismatch easily by slightly adjusting a bolt on the location side, and this action would not require much extra time (in the order of minutes). However, finding out this mismatch (by trial-and-error) showed to be difficult and very time consuming, which indicates that situation awareness of the operator was low.

The ten out of the eleven other delays were observed during state '3.3 - Rotate to run in bolts'. For this state, a small misalignment of the tile was the main cause leading to non-nominal action. State 3.3 itself is not very demanding for the operators, but the state appears to be a critical part of the task where inaccuracies or errors made in preceding subtasks show up. The placement accuracy in preceding subtasks is partly facilitated by mechanical (self)alignment features, which constrain and guide the tiles to the final location. Improvement of assistance during this (final) alignment could reduce the occurrence of non-nominal re-adjustment actions in later stages.

Operators sometimes deviated from procedures, enlarging the negative effect of small tile misalignments. Instead of 'first run in all bolts than fasten all bolts', operators sometimes chose to take a shortcut and fasten a bolt in one go. In ideal cases this shortcut results in small time savings, but in case of (small) misalignments it will result in non-nominal actions causing relative large delays. More strict adherence to the procedures could prevent the delays caused by this type of non-nominal executions.

Interestingly, the four longest delays all were observed when a trainee handled the device (Fig. 5), suggesting that these errors can (partly) be seen as beginners errors. The observed low situation awareness of the operator described earlier is likely also related to the training phase and could be a cause of the delays. Although the amount of errors and their impact is expected to be lower when a fully trained operator would have performed the same tasks, these trainee trials do show some fundamental difficulties of the tasks (e.g. final alignment/ procedure following/ situation awareness). Improving these aspects would not only be helpful for trainees, but would probably also make the task less demanding for fully trained operators.

Nominal Task Analysis Phase I – Task level

When looking to the nominal tasks executions of the three qualified operators (Fig. 6), it appears that the least experienced operator (C) required substantially more time for the same tasks. This trend was also observed in the logbook-based analysis of the overall task [19]. The difference in task completion time between least experienced operator C and operators A and B is likely to decrease with more training of operator C. Potentially, this could improve the median of the task completion time from 240s to 164s. Whether an expert performance level actually will be reached or not is however strongly dependent on operator skill and aptitude, and the required training time can take up to 2,5 year [14].

The observed large variation in time performance for the experienced operators A and B is remarkable (inter-quartile-range of 23s and 43s, Table III). Compared to the fastest trial, even the experienced operators could potentially improve 32% in time performance (Table III). Since it concerns strictly selected and very experienced operators, more training is not likely to reduce this variation. Are there specific parts of the task which are primarily responsible for this large between and within subject variation? And could these variations be reduced? These questions were addressed by the analysis of subtasks (phase II) and states (phase III) with the goal to give more insight in how the tasks are executed and where to focus for improvement.

Nominal Task Analysis Phase II – Subtask level

All subtasks show a large difference between group mean and the fastest trial (>44.5%). Although it is not known to what extent this variation originate from inconsistency in the task itself or from poorly controlled aspects in human execution, it is most promising to investigate tasks with the largest variation. Subtasks '3 - Run in bolts' and '1 - Tile placement' show the largest absolute variations (interquartile ranges of 31s and 28s) and potential reduction of variation in these subtasks could have largest effect on total task completion time.

The variation in execution time relative to the fastest trial is largest for subtasks '2 - Get bolt runner' and '1 - Tile placement'. The large factors between the fastest trial and group mean, respectively 2.9 and 2.75, give an indication that variation in task execution can be reduced easiest for these subtasks.

The difference in median execution time between the most and least experienced operators, as found for the overall task, is visible for all subtasks, however only partly significant. The subtasks with the largest absolute variation '3 – Run in bolts' and the subtask with the largest difference between group mean and fastest trial '2 – Get bolt runner' are analyzed on state level.

Nominal Task Analysis Phase III – Within subtask level

All subtasks show a large difference (>50%) between group mean and the fastest trial. Most of the time variation in subtask '3 - Run in Bolts' originates from state '3.3 - Rotate bolt', so reduction of time variation in this state is most effective for the total task completion time. Close observation of the video data shows however that the variation is not caused by the bolt rotation part of the task, but by small misalignments of the tile which resulted in jamming of the bolt and required some wiggling to be corrected. Although jamming and wiggling will be an inherent part of the 'run in bolt' state in the not-perfect real world, it should be avoided as much as possible. Better alignment in the preceding placement state could potentially be reached by better mechanical alignment features or visual/haptic operator assistance and so reducing the variation in the bolt running state.

For subtask '2 – Get boltrunner', most variation originates from state '2.1 – Move to Boltrunner' and '2.3 – extract boltrunner'. The observed movement during the rough approach in state 2.1 looks relative slow and hesitant. This could be caused by the fact that the human operator needs to define the best approach trajectory while taking into account the robot kinematics in the small workspace available. During the extraction phase in state 2.3, the variation is mainly caused by misalignment of the boltrunner and the holder resulting in jamming. Making the operator more aware of appropriate trajectories and orientations by visual or haptic assistance could improve time performance and reduce variation.

The categorization in elemental actions shows the impact of the duration of certain type of task elements on the total task completion time. The quality of the rough/fine approach and final placement already showed to be important for duration of the following bolting state, but Fig. 10 shows that the rough/fine approach and retreat states all together also represent more than half of the total task completion time. This makes these approach and retreat tasks a promising focus for performance improvement.

Limitations

The main limitation of the unique data is the low number of subjects, even though it constitutes the entire population of active operators. The data is however the best data available for real executed tele-operated maintenance tasks. Furthermore, the potential bias caused by the small sample size is expected to be small and with little impact, since the populations consists of strict selected and highly trained operators.

The applied time-action analysis method gives a clear insight in the time distribution over subtasks and states, but only limited insight in the underlying reason of a certain time distribution. Besides time data, other measures for task performance (e.g. position, exerted forces) or operator workload would have been very useful, but where not available. Interaction with the operators and good knowledge of the task execution was therefore essential to be able to interpret the time results.

A factor that has large effect on the efficiency of the master-slave operator, but which was not obvious from the analyzed data, is the performance of the support team. Especially the operation of the viewing system, which is the responsibility of a second operator, is important. The speed and quality of positioning of cameras, tool tracking during an approach phase, and camera adjustments like zoom, focus, and roll do have large effect on the master-slave operator performance. The current study did not take this effects into account and assumed constant performance of the trained viewing system operators, but improvement and partly automation of the viewing system could definitely improve the efficiency of the master slave operator.

The task 'Install tile to beam' was selected as general and representative maintenance task, however besides installation of new components, maintenance also consists of the removal of old components. Although the required subtasks and states are similar, it is expected that removal operations encounter more unexpected situations, like components being stuck/damaged/deformed or more difficult to distinguish because of a changed color (heat) or a layer of dust. This will result in more non-nominal executions and larger variation in time performance during nominal executions. The proposed focus for improvements will still be beneficial, but the impact on total time will be somewhat lower than indicated for this installation task.

Important to note is that the found efficiency of the analyzed task executions is also affected by the component design. The design of the tile carriers at JET was compromised because it had to be retrofitted to already existing in-vessel components. If a complete new design could have been made, the design would have been much more remote handling 'friendly', allowing more repeatable and accurate handling. For other future applications which require efficient remote maintenance, it is therefore important that remote maintenance is already taken into account in the design phase [15], [16].

Other design improvements could be made in the tooling. In the analyzed situation, the bolt runner had to be parked to change its rotation direction. This amplified the time lost when there was a jammed bolt or misalignment. And it was made worse if the operator was slower at parking/collecting the bolt runner.

Since the analyzed task consists of elemental actions, the results do translate to other tele-robotic domains with hard contact environments like deep sea and nuclear industry.

The analysis in this paper focusses on the amount of variation in execution time as indication for potential time reduction. The amount of achievable improvement depends however on the ratio between inherent variation in the task and variation that could be decreased by an improved system, operator assistance, etc. Large variation in time performance is therefore no promise for possible time reduction, but should be seen as a promising direction.

Implication

The current state of the art tele-manipulated maintenance is characterized by large between and within subject variation. The between subject variation can be reduced by strict operator selection and training, however the large within subject variation seems inherent to telemanipulation, or at least to the current telemanipulation configuration. This corresponds with findings of Lumelsky [26], who related the source of difficulty of telemanipulated tasks to the limitations in human abilities for space orientation and interpretation of geometrical data. He concluded that further task performance improvement will require an 'effect of telepresence'.

As shown by this analysis, operator behavior and (time) performance differs per task, subtask or state. It would therefore be effective to focus performance improvement on specific tasks, enabling to solve specific task related difficulties encountered by the operator. Traditionally tele-presence aims to give virtual information to the user in such a way that he/she experiences “a sense of being there”. This could well be hindered by Lumelsky’s observation of human limitations [26], and is in fact not important for maintenance applications, since it is all about task performance. Instead, I aim to develop this concept to “a sense of feeling what to do”, to clearly and intuitively convey constraints in the environment and in the tools themselves [27]. This could potentially be reached by providing operators with intuitive task execution related guiding in the visual and haptic domain. Future research should focus on the applicability of support systems that aid the operator with augmented visual and haptic guidance.

V. CONCLUSION

This study provides detailed analysis of unique data concerning real world remote fusion maintenance, to identify key areas for further improvement and quantify potential time reduction. The novel data was gathered from video recordings at fusion plant JET, of the remote installation of 40 tile carriers performed by the (only) three qualified master-slave operators, and of 10 extra tile carriers performed during training of a new operator.

Based on a time-action analysis of the 50 tiles, it can be concluded that incidental non-nominal actions have large impact on absolute execution time of the entire tile placement; if these could be prevented it would result in a decrease of 30% in total execution time.

Also for nominal task execution of the 40 tiles, there is substantial room for improvement: the total tele-operated task execution is characterized by inherently large between- and within-subject variance:

- The median task completion time of the least experienced operator is 240 seconds for 40 tiles, which is 46% higher than the two most experienced operators (164s and 163s respectively).
- Compared to the fastest trial, even the two most experienced operators can reduce the task completion time with 32%.

Key subtasks, states and actions for further improvement in terms of time reduction were identified as:

- Subtask ‘Run in bolts’ and corresponding state ‘Rotate bolt’, which showed the highest absolute variance.
- Subtask ‘Get boltrunner’ and corresponding state ‘Move to boltrunner’ and ‘Extract Boltrunner’, which showed the highest relative variance.
- Recurring elemental actions like 'Rough approach’, ‘fine approach’, and ‘retreat’.

The data shows that reduction of variance in task completion time would substantially reduce required maintenance time. Enhancement of currently available approaches like extensive training and mechanical alignment features is not likely to decrease this variation in a substantial amount. Future research will focus on the applicability of support systems that aid the operator with augmented visual and haptic guidance.

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