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A task analysis approach to quantify bottlenecks in task completion time of telemanipulated maintenance

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ABSTRACT

Telemanipulation techniques allow for human-in-the-loop assembly and maintenance tasks in otherwise inaccessible environments. Although it comes with limitations in achieved performance – required strict operator selection and extensive training are widely encountered – there is very little quantitative insight in the exact problems operators encounter during task execution. This paper provides a novel hierarchical task analysis approach to identify the most time-consuming subtask elements and to quantify the potential room for performance improvement during telemanipulated maintenance tasks. The approach is illustrated with a human factors case study in which 5 subjects performed six generic maintenance tasks, using a six degree of freedom master device connected to a simulated task environment. Overall it can be concluded that the proposed three phased task analysis is a useful tool to guide improvements since it is able to relate high-level problems (e.g. large variability) to behaviour on lower task-levels. For the case study, the largest potential for improvement was found for specific subtasks characterized by complex contact transitions and precise control of tool orientation, and in the reduction of variation of the task execution.

1. Introduction

When human interventions are required in hostile environments, telemanipulation is needed. An example is the envisioned teleoperated maintenance for the experimental nuclear fusion plant ITER [1], which is foreseen to require challenging maintenance in an environment with high radiation levels and toxic materials. Efficient maintenance is one of the key factors to the success of ITER and other future fusion plants: maintenance limits the uptime of the plant and should be executed in the shortest possible time-frame [2]. In general, the performance of such remote task execution is limited (long execution time, limited accuracy, errors) and prone to high workloads [3,4][3,4], even though operators passed a very strict selection procedure and an extensive training period [3]. This illustrates how difficult and challenging execution of remote maintenance is.

While many efforts have been made to improve task execution by for example proper design of the telemanipulation device (improved transparency through hardware [4–6], and control [7–9]), improved visual feedback (e.g. stereoscopic viewing, augmented visual feedback [10,11]), and guidelines for the design of the task environment (e.g. the Design for Assembly approach [12,13]: captive bolts, mechanical alignment features, grip features, etc.), there is still limited insight about what exactly complicates task execution and how this is reflected in the task execution. For example, are the long execution times the result of slow motions, inefficient motion coordination or errors and restarts? Currently, most valuable contributions to understand complicating factors in remote maintenance tasks are high level and assumption-based [4]: an expected specific cause (e.g. limited transparency, 2D viewing, sense of presence) is manipulated, and subsequently task performance is experimentally evaluated with high-level metrics, usually execution time. Although such an approach can quantify overall improvements, it can't give insight into the underlying behaviour that causes these improvements, such as: timing, variability, repeatability, trajectories and exerted forces. Insight in the relation between high-level task execution and low-level kinematic and dynamic description of operator behaviour would be very useful to guide possible directions

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for further improvements. Furthermore, it enables to see 'high-level' research results in the context of achievable improvements on a skill-based level.

Task analysis can be a powerful tool to give insight in task execution and to identify potential improvements in human-machine interaction [14]. Although widely used in other fields (e.g. surgery [15,16]), it is, to the knowledge of the authors, hardly used for (non-medical) teleoperated task execution. In a previous study by the authors, a high-level task analysis was performed on logbook and video data of real executed remote maintenance tasks at the operational fusion facility JET (the closest comparison to the envisioned maintenance at ITER) [17]. The high-level results provide insight in the overall execution time of tasks and effects of the operator's level of experience on time performance. Detailed task analysis of subtasks was however not possible with the available logbook data and would require additional detailed video analysis. Although the available unique operational logbook and video data is a very valuable source for task analysis, it also has some limitations. Since the data does not origin from a measurement in a controlled laboratory environment, it contains inherent uncertainties (e.g. deviations from task protocol, unclear waiting times), complicating reliable analysis. Furthermore, besides task-completion-time, no objective data is available about the skill level execution like performed trajectories and exerted forces. To gain more insight in how to improve teleoperated maintenance, it is important to perform more detailed task analyses which study the relationship between high-level tasks performance and low-level kinematic and dynamic data.

The main objective of this paper is to determine and illustrate a task analysis approach to identify which aspects of teleoperated maintenance tasks are bottlenecks in terms of task completion time – and to quantify the potential for improvement. A case study with six fundamentally different tasks, selected to cover a wide spectrum of possible tasks, will be used to show that the proposed approach is a general approach to compare and assess task execution. A key element of a systematic approach in this study is the application of a controlled Virtual Reality task environment, ensuring repeatability and facilitating the detailed measurement of a large amount of task execution variables. Specifically, we will carry out six representative, complex tasks, and analyse in detail the duration of those tasks and the complications associated with. The task completion time, and the variety therein, are used as a proxy for the task complexity and potential room for improvement. The complex tasks will be broken down to well specified atomic tasks. The variation of the task completion time of these atomic tasks can then be associated with specific skill-based behaviour (e.g. trajectories, contact forces, etc.) measured with the VR system.

The selection of suitable task analysis techniques will be presented in Section 2, along with a survey on task definition/selection. Section 3 describes the human factors case study in detail, with Sections 4–6 describing the results, discussion and conclusions.

2. Task analysis

2.1. Selection of task analysis techniques

Since the early 1900s, the field of ergonomics developed, enabling better description and analysis of human involvements in systems with the aim to discover more efficient ways to perform tasks. A main contribution to the field has been the development of task analysis approaches to help focus research and solutions (see Kirwan and Ainsworth [14] for a review). The most used and most generic approach is the hierarchical task analysis (HTA) [18], that decomposes high-level tasks (goals) into a hierarchy of subtasks (sub-goals), and relates these to the corresponding required conditions. One of the key features of HTA is that "the hierarchical structure enables the analyst to focus on crucial aspects of the task within the context of the overall task" [14], for example by focusing on the largest error variance [18]. Furthermore, HTA can serve as a framework which provides justification and boundaries for other specific task analyses approaches, like procedure analysis, workload assessment, task frequency analysis, time and motion studies, etc. A large amount of theoretical and procedural literature exists about HTA (e.g. [19,18][19,18]) and the method is applied to a wide range of applications, e.g.: interface design and evaluation, allocation of function, and supervisory control of complex systems. Examples of specific analysis of skill-based tasks can be found in the medical field to assess and evaluate surgeons technical skills [15] or to evaluate new techniques, protocols and instruments by assessing task performance [16]. For analysis on skill level, HTA can be combined with other more detailed analysis techniques like: activity sampling [14], time-line analysis [14], or time-action analysis [16]. Providing objective data about number and duration of performed actions, the proportion of time spent on different activities, and efficiency of actions. Additionally, observational techniques can be applied to obtain data about behaviour aspects of the task execution [14], preferably by using a checklist or a set of criteria, e.g. the 'global rating scale' [20], to make the assessment process more objective.

Although a variety of task analysis techniques exist, applied to a range of applications, no specific literature was found on analysis and performance improvement of (non-medical) teleoperated task execution.

Based on the summary above we selected a combination of existing task analysis techniques which could provide relevant insight in task execution during teleoperated maintenance. In this paper, the task analysis is performed in three phases, which are based on an HTA task decomposition with three levels of detail: task level, subtask level, within subtask level. To obtain objective information on the distributions of execution time, activity sampling/time-action analysis is used in each phase (task level). The amount of variance in (relative)time duration, which could indicate task difficulty, is used to focus the analysis for the next more detailed analysis phase. On the lowest task level also signal time traces, which capture skill-based behaviour, are analysed.

2.2. Selection of a general set of tasks

The specific focus of this study is maintenance in hard-contact environments. Which set of generalisable maintenance tasks to select for the case study? Based on literature three possible ways to define or categorise tasks have been identified, and are discussed below: a classification in terms of general function, a human-centred classification, and a task-centred classification.

Teleoperated maintenance tasks in terms of functional perspective cover the whole range of normal hands-on maintenance; mechanical cleaning, vacuum cleaning, MIG/TIG welding, visual inspection, sawing, filing, thread tapping, dust and flake sampling, wiring loom installation, etc. [21]. For robot planning, these tasks have been subdivided into more general manipulation primitives or elemental actions; e.g. move, approach, transport, place, push, slide, grasp, release [22,23]. A second way to describe tasks is from the human controller point of view. The human changes his control behaviour depending on the task. Well known (parts of) tasks can be performed mainly based on feed forward, unknown and untrained task rely more on feedback control.

Furthermore, humans can intuitively adapt their neuromuscular properties to enhance task performance: from very compliant during a force task to very stiff during a position tasks [25]. An example of a task classification considering different types of (sub)tasks can be found in [26], in which four fundamental motion types for a bolt and spanner task were defined; Free air movement, Contact transition, Constrained translational movement and Constrained rotational movement. Besides the discussed human control approaches, also higher level strategy plays an important role in how tasks are executed. An example is the use of special mechanical alignment features (see Fig. 1 and Table 1), which are often used in telemanipulation situations. These alignment