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Modeling expertise and adaptability in virtual operator models☆

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ABSTRACT

To advance construction machine design and testing, model-based design and virtual operator models (VOMs) can be used to explore machine designs virtually. However, current VOM efforts have been restricted to mimicking known trajectories, recorded from actual machine operations. Previous work developed a VOM to use in closed-loop simulation with an excavator model. To advance the utility of model-based machine testing, the fidelity of the VOM was enhanced along three lines: 1) representation of expert work cycle operation, 2) adaptation to changes in work site environment and 3) adaptation to changes when operating different machines. To represent expertise, work cycle task overlap was modeled – a hallmark of expert human operator performance. A mental model was developed to adapt to changes in the work site environment. Finally, the VOM was generalized to adapt to changes in excavator dimensions, eliminating the need for time intensive “tuning” typical of trajectory-dependent models. Three case studies demonstrated task overlap modeled productivity gains typical of expert operators, VOM control outputs adapted as trench depth and pile height increased, and the VOM adapted to different excavator models automatically. An additional case study compared VOM results to human-recorded data. This work advances the ability to integrate human expertise and adaptability in virtual operator modeling, resulting in a more realistic simulation of operations.

1. Introduction

Improved machine designs are needed to meet the increasing demands on construction machines for greater functionality, productivity, and efficiency. Yet in human-machine systems, human operators play a significant role and affect system performance. Typical product design processes measure performance of a new construction machine design using expert human operators driving physical prototypes in defined test environments [1]. While this method produces high fidelity data, it is time consuming, resource intensive, and necessarily requires that the physical prototype of the machine be built. To advance machine design and testing, model-based design and virtual operator models can be used to explore machine designs virtually. Increasing efforts in model-based design in industry has yielded high fidelity models to test new machine designs and new features. Fidelity in this context describes the degree to which a simulation reproduces accurate and reliable behaviors of real-world phenomenon [2].

Virtual design, the process by which new features are modeled and tested in a simulation environment, is applied iteratively in the modern product design. Model-based or virtual design provides a means for achieving machine design improvements with reduced time and costs [3]. In the product development process, virtual design is often used for feature or system validation [4]. Virtual design is typically conducted early in the design process when it is less expensive to make changes.

Closed-loop simulation-based virtual design uses simulations that include a representation of the machine and the operator, which has feedback loops or paths between its output and its input. However, virtual design of construction machines with operators-in-the-loop has often been limited by the fidelity of the model of human operators. This limitation is particularly an issue when virtual design is used for validation and assessment. Traditional validation and assessment methods, by way of comparison, utilize physical machine prototypes, human operators, and real-world testing in a controlled environment [1].

While machines have been modeled with a fidelity that enables robust testing, current operator models struggle to capture operator expertise and require time-intensive tuning to each new machine design. These limitations hamper engineers from making solid comparisons in the virtual prototyping stage between different design alternatives, and limits their ability to do virtual design. Given the tightly coupled, non-linear nature of construction machine dynamics, combined with human-in-the-loop control, dynamic simulation of the complete system must include the operator, environment, and tasks. To

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advance machine testing, a virtual operator model (VOM) needs to be developed to represent how human operators operate machines. The fidelity of VOMs needs to be increased by using a more human-centered basis for virtual operator modeling, and increasing the fidelity of operations modeling.

Current VOM efforts in construction have largely been restricted to developing models that mimic known trajectories, usually recorded from actual machine operations [5,6]. This implies that any change to the machine design would require a time-intensive process of "re-tuning" the VOM to mimic new machine trajectories. This limits their utility in fast-paced iteration in model-based design cycles. Furthermore, the work cycle of an operation has been modeled as discrete, sequential series of tasks, as the operator completes one task before moving to the next [5]. However, operating the machine in such a discrete manner is typical behavior of novice users [7]. Experts can overlap tasks, beginning a new task of the work cycle while still completing the previous task. This enables the operator to "push" the machine to increase efficiency and performance. The current state of the art VOMs [5–7] were developed under fixed environment conditions for particular machine models, and use finite state machine to model each of the tasks discretely in the operation.

In recent work, the authors developed a VOM based on the human information processing model to generate operator inputs based on an understanding of how humans process cues from the environment to make decisions on how to control the machine [7]. To inform the design of a VOM, human factors methods were used to study the behavior of human operators, including decision making, perception, and control strategies. The VOM represented the human operator decision-making process and aims to replicate how human operators operate machines. That effort simulated one work cycle, for one machine type, and assumed that each task in the work cycle was discrete. However, a robust virtual closed-loop, simulation-based design capability requires the interaction of high-fidelity models of the machine, the operator, and the environment.

To advance the utility of model-based machine testing in virtual environment, the fidelity of VOMs needs to be enhanced along the lines of representing human operator expertise in multiple ways: representation of expert human work cycle operation, and an expert's ability to adapt to changes in the work site environment and different machines. These three dimensions center on the theme of expertise and adaptability, and are the subject of this paper. There are many ways that expertise is manifested in construction machine operators, but the three focused on in this paper are the ones that emerged from our interaction with operators and engineers in industry [7]. Increasing the fidelity of the VOM will result in a more realistic simulation of operations. Enhanced closed-loop, computer-based simulation capabilities will affect the development process through better efficiency, lower cost, and more flexibility compared to traditional machine testing in the early design process.

For this project, the excavator trenching operation was selected as the target construction machine operation for virtual operator development. Excavator trenching is a common construction operation, which contains multiple tasks that are applied and adapted to multiple situations and conditions. Based on interviews and observation, the five *tasks* making up a complete trenching *work cycle* were identified: Bucket Fill, Bucket Lift, Swing-to-Dump, Dumping, and Swing-to-Trench [7]. An *operation* consists of multiple work cycles to dig a trench of a prespecified depth. During the operation, an operator needs to dig a trench at a predetermined location and orientation with defined dimensions, and dump the material either in a defined area or into a truck.

This work was motivated by trying to model the expert behavior found in the kinds of productivity tests done in industry during the design process, where expert test operators run pre-defined operations to evaluate the machine. These productivity tests are explicitly designed to push the operator and machine to maximum effort to understand the limits of the machine (e.g. [8]). Thus, industry test operators tend to work at their maximum ability to finish trenching as soon as possible. To enable closed-loop simulation of a trenching operation, the VOM must generate human operator behavior based on cues that are perceivable to the operator, account for changes in the environment affecting the operation as it progresses, and adapt to different situations or disturbances during the operation.

The VOM should simulate expert control of the machine. It takes an expert "pushing" the machine to its limits to test the capability of a new design to increase productivity. In interviews with construction machine operators [7], the concept of overlapping tasks emerged very quickly in those discussions as a key way that expertise is manifested in a repetitive task-based work cycle in construction machines like the case of the excavator being used to dig trenches. However, current VOMs are developed without consideration of how expertise is manifested by real operators. Expert human operators can start attending to the next task while the current task is nearing completion. A VOM that models overlaps in operator attention to multiple tasks is needed to generate more realistic control inputs.

Experts are able to adjust the machine operation based on changes in the work site. Simulation using current VOMs can only simulate and repeat a work cycle without adaptation to the changes in the environment. However, for the trenching operation, the dimensions of the trench and material dump pile change after each work cycle. Human operators adapt to the changes in the environment and adjust their control of the machine. It typically takes multiple work cycles to complete the operation. A model that tracks changes to the environment is needed, where the VOM adjusts operator control inputs as the work site environment is changed by the machine operations.

Finally, another aspect of expertise is an operator's ability to start using different machine makes and models and very quickly operate them at a high level of productivity. Different excavators can be used in the same construction site depending on the capability required. Different excavators share general control features, and so expert operators can apply their general knowledge of excavator operation when switching between different excavator models and capabilities. Human operators use their generalized knowledge of machine control to understand the differences between excavators and adjust their control behavior to operate different equipment without much effort. However, current VOMs based on trajectory mimicking are unable to adjust to changes in machine dimensions, power, and capabilities. Based on discussions with industry experts, significant effort is required to tune the current VOMs to simulate a different machine models. Current VOMs cannot adapt to differences in machine models [7]. However, the VOM architecture approach described in this paper generates control input by simulating operator processing of information (cues from the machine and the environment) to generate control inputs based on operational goals, not on a pre-defined, pre-learned trajectory. This method provides the possibility of the model automatically adapting to different machine models since the VOM reasoning is based on operator perceptible cues, and not machine geometric dimensions. The VOM must be generalized such that new machine characteristics are accounted for as the operation is simulated.

In this work, a fixed VOM [7] was extended to simulate expert behavior by enabling tasks to overlap in the work cycle. The VOM was also extended to simulate a complete trenching operation where the operator model adapted to changes in the work site environment. Finally, the VOM was generalized to be independent of the machine model, and generates the machine model control inputs based on a model of human decision making rather than tracing pre-defined trajectories.

The following section reviews the previous work related to operator modeling. The VOM approach is presented, and the methods to address the three areas limiting the fidelity of current VOMs. Four case studies are represented, with results demonstrating the approach. Finally, current and future work is discussed.