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Virtual Operator Models for Off-highway Machine Virtual Prototyping

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ABSTRACT. ***Increasing demands on the world's resources require the design of off-highway machines that provide greater functionality and productivity along with greater efficiency. Model-based or virtual design provides a means for achieving these design improvements with reduced time and costs. However, virtual design is often limited by the fidelity with which human operators are modeled. A greater understanding of how highly skilled operators obtain high machine performance and productivity can inform machine development and advance agricultural and construction machine automation technology. This research investigated how machine operator expertise, strategies, and decision-making can be integrated into operator models that simulate authentic human behavior in construction machine operations. The initial effort of this work was to develop a virtual operator model (VOM) through a combination of human factors and physical system modeling techniques. Operator interviews were conducted to build a framework of tasks, strategies, and cues commonly used while controlling an excavator through repeated work cycles. A closed loop simulation demonstrated that a VOM could simulate the trenching work cycle and enable closed-loop virtual equipment operation simulation. Advancing the state of the art in operator modeling requires models that can adapt. Approaches to enable a generic virtual operator model to adapt to changes in the environment based on the operator's actions were investigated. The closed loop simulation performed successfully when using the VOM, the vehicle model, and an environment model which represented how the VOM adapted during a complete trenching operation.***

Keywords. Adaptation, Closed Loop Simulation, Model-based design, Operator Model, Off-highway machinery design

Introduction

Increasing demands on off-highway machines with greater functionality and productivity along with greater efficiency, can only be met by improved design processes. Virtual design, the process by which new features are modeled and tested in a simulation environment, is applied intensively in the modern product design. Model-based or virtual design provides a mean for achieving machine design improvements with reduced time and costs. In the product development process, virtual design is often used for feature or system validation. Virtual design is typically conducted early in the design process when it is less expensive to make changes. However, virtual design is often limited by the model fidelity of the human operators when used for validation and assessment compared to traditional validation and assessment methods, which utilize physical machine prototypes, human operators, and real-world testing in a controlled environment (Filla, Ericsson, & Palmberg, 2005).

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 off-road vehicle dynamics, combined with strong human-in-the-loop control, dynamic simulation of the complete vehicle system must include the operator, environment, and tasks. To 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.

An excavator is a common piece of equipment used on construction sites, and trenching operations were selected for this study. In a trenching operation, the dimensions of trench and pile change after each work cycle. Human operators can adapt to the changes in the environment and adjust how they control the vehicle. It typically takes multiple work cycles to complete the trenching operation.

Virtual closed-loop, simulation-based design requires models of the vehicle, the operator, and the environment. A VOM represents the human operator and aims to replicate how human operators operate machines. To inform the design of a VOM, human factors methods can be helpful to study the behavior of human operators, including decision making, perception, and strategies. The existing VOMs starts with mimic vehicle control inputs through trajectory tracing (Filla, 2005; Elezaby, 2011). The current work of this paper creates a VOM independent of the vehicle model that generates the vehicle model control inputs based on a model of human decision making rather than tracing pre-defined trajectories.

Current VOMs (Filla, 2005; Elezaby, 2011; Du, Dorneich & Steward, 2016) are developed under fixed environment conditions for particular machine models, and use finite state machine to model each of the tasks in the operation. This is a limitation of the current state of the art. In this work, preliminary work that developed a fixed environment VOM (Du, Dorneich & Steward, 2016) has been extended to simulate a complete trenching operation where the work cycles adapted to changes in the work site environment.

Virtual Operator Model Description

A virtual operator model was developed to represent excavator operators' decision making processes and behaviors. The VOM is a simulated operator, which controls the vehicle model to perform certain tasks. The VOM will be used to form a closed-loop simulation to test machine design similar to a human-machine system.

Development Process

The development of the VOM started with operator interviews and task analysis, which helped the researchers to understand the behavior and decision-making processes of operators and derive operator model requirements. Interviews were guided by an interview protocol and collected information about operators' operating experience, behavior, strategies, and possible problems during operation (Du, Dorneich, & Steward, 2014). Throughout the interviews, open-ended questions queried operators about their background (experience, types of operations, equipment) and about what they do before, during, and after operations. Audio recording and written notes were used to document the interviews. Five participants with different backgrounds, skill levels and experiences participated in the interviews.

During an excavator trenching operation, machine operation data were collected by using video cameras inside and outside the cab and sensors mounted on the machine. These data were analyzed to understand the machine operation and operator behavior. The data collected from operator interviews and machine operation were used to represent the behavior and strategies of operators. With these behavior and strategies, the virtual operator model was developed to represent human operators to control the machine. The virtual operator model was formulated to include perception, decision making, and action modules to produce the control inputs for a vehicle simulation (Du, Dorneich & Steward, 2016).

VOM Structure

Based on the Human Information Processing model (Newell & Simon, 1972), a VOM was systematically structured to represent the internal processes of a human operator (Figure 1). This structure included a Human Perception model, a Human Decision Model, an Action Model, an Initialization Module, and an Environment Model. The VOM was designed to act as a separate module which could be used with different vehicle models to form a closed-loop simulation.

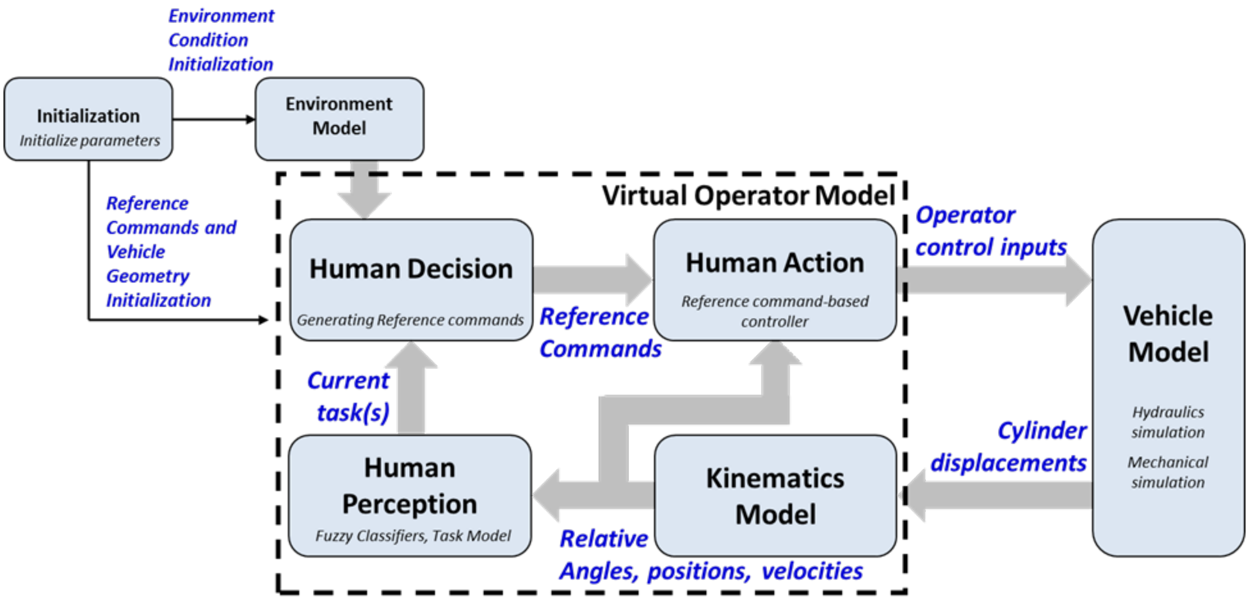


Figure 1. Virtual operator model structure consists of several models representing human information processing.

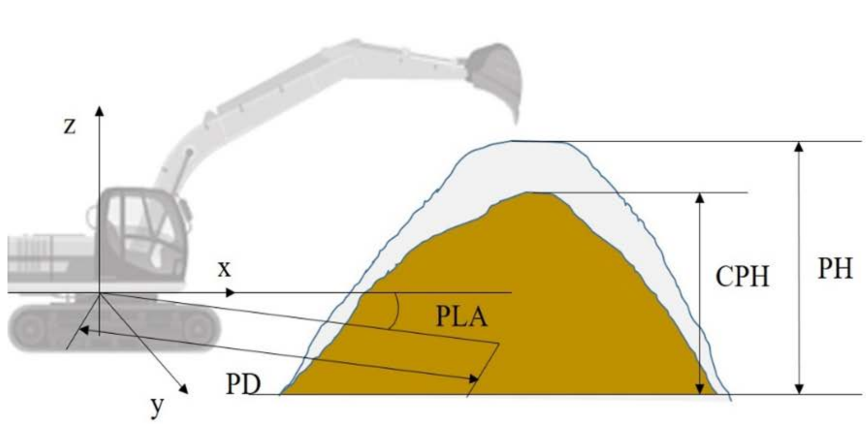
In general, the VOM generates the control inputs with which human operators control physical machines through joysticks. The kinematics model receives kinematic information from vehicle models, which are prepared and sent to the human perception, human decision, and human action models. The human perception model receives information about environment conditions and machine components conditions, which are observable by human operators. For example, human operators can perceive the height of the bucket relative to the ground, but not the pressure in a cylinder. Fuzzy classifiers then classify the human-perceived information to trigger task transitions between different sub-tasks of the trenching work cycle. The outputs of the classifiers are the inputs to the state machine in the human perception model, which determines the current task state. The human decision model determines the reference commands by considering environment information, machine geometrics and the current state. The reference commands are target positions of vehicle components, which are sent to the human action model. In the human action model, reference commands are compared to the current position of vehicle components, and the differences are used to generate control inputs for vehicle model through PID controllers. The initialization module reads in vehicle information, environment conditions, and strategy information, which are paired to correct variables or used to calculate reference commands. With the initialization module, vehicle information can be updated easily when simulating other vehicle models. The environment model describes the condition of environment, and updates any changes needed after each work cycle.

Human Operator Model Adaptation

Increasing the adaptability of the VOM will result in closed-loop, computer-based simulation capability that will impact the development process through better efficiency, lower cost, and more flexibility compared to traditional vehicle testing in early design process. Current VOM efforts model a static work cycle. The VOM described above has been extended to model changes in the environment after every work cycle. For the trenching operation, the pile and trench models were developed to enable adaptation to different pile heights and locations as well as different trench depths.

Pile Model

The pile model describes the pile dimension and location including the dynamic pile height parameter which changes after each dump (Figure 2). The pile was described by using six parameters: 1) pile height (PHs) at the beginning of the trenching operation and thus is the initial pile height; 2) current pile height (CPH) at the current simulation step; 3) maximum pile height (PH) allowed; 4) increase in pile height (deltaPH) after each dump; 5) angle (PLA) that excavator needs to swing from trench to pile; and 6) distance (PD) between the pile and the excavator cab. These parameters were created as variables, which can be initialized at the beginning of simulation to create different environment information. After initialization these variables are available to the VOM, which can be used to calculate reference commands at each simulation step. The reference commands translated to control inputs of machine model to follow commands. CPH and deltaPH were updated after each simulation step.

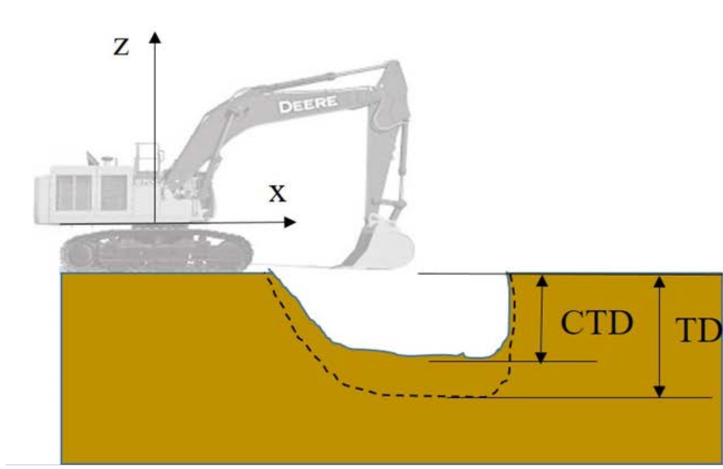


Environment Parameters	
PH	Max. Pile Height intended
CPH	Current Trench Depth
deltaPH	Depth Increase per Cut
PHs	Pile Height start
PLA	Pile Location Angle
PD	Pile Distance

Figure 2. Pile model to represent the increasing trench depths during the operation.

Trench Model

The trench model describes the dimension and location of the trench including the dynamic parameters of trench depth after each simulation step (Figure 3). The trench is defined with four parameters: 1) maximum trench depth (TD) planned ahead of time; 2) current trench depth (CTD) at current time step during simulation; 3) trench depth change (deltaTD) after each cut; and 4) trench depth (TDs) at the beginning of the simulation. Variables are used to represent these parameters in the model, which can be defined during initialization. Reference commands were updated after each time step by using these parameters.



Environment Parameters	
TD	Max Trench Depth
CTD	Current Trench Depth
deltaTD	Depth Increase per Cut
TDs	Trench Depth start

Figure 3. The trench model to represent the increasing trench depths during the operation.

Case Study

Two case studies were designed to test the adaptability of the VOM for different vehicle models and environment situations.

Test Case 1: Baseline Simulation with Vehicle Models

Test Case 1 was developed to test the VOM's ability to simulate a vehicle model. First, the vehicle model named E360 were simulated using the VOM. The VOM is demonstrated to simulate a vehicle models with dynamical environment changes, the trench depth and pile height increasing during the simulation. The results, which demonstrated in the following sections for machine responses, proved that VOM was able to form a closed loop simulation with a vehicle model.

Test Case Results

Figure 4 demonstrates how the machine responded to the simulation by showing the changes of Bucket Height, Bucket

Rotation Angle, Swing Angle, and Distance Ratio during simulation. The bucket height varies for different work cycles, which indicates the changing trench depth and pile height during the operation.

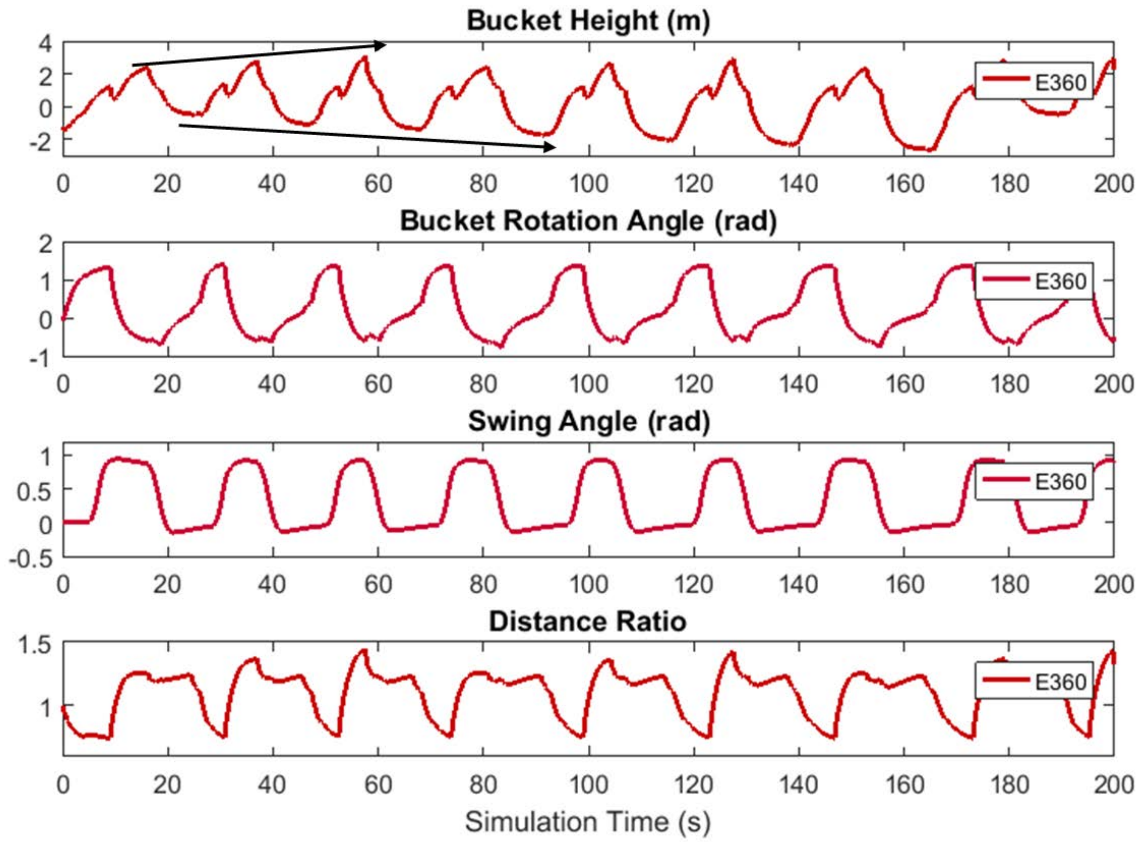


Figure 4. Machine response of the closed loop simulation by indicating increasing trench depth and pile height during simulation. Arrows on the Bucket Height graph demonstrate the increasing pile height and trench depth.

Test Case 2: Simulation with Different Environment Parameters

Secondly, different environment conditions were modeled, which could be realized by changing trench depth, pile location, and pile height. Adaptation to environment changes was demonstrated from the simulation results. Environment parameters, which define the conditions of environment, were modified to simulate how VOM response to different environment conditions. Table 1 shows the different environment settings, that pile location and pile height changes as well as the trench dimensions, but the increments for pile height and trench depth stay constant.

Table 1. Environment Information for Pile Location and Trench Dimension

Environment Information	Pile Location				Trench Dimension	
	Angle between Trench and Pile	Distance between Pile and Cab	Desired Pile Height	Pile Height Increment per Dump	Desired Trench Depth	Trench Depth Increment per Cut
Env1	0.8	6.5	1.5	0.3	1.5	0.3
Env2	1.0	7.0	2	0.3	2	0.3
Env3	1.3	7.5	2.5	0.3	2.5	0.3

Test Case Results

Three environment settings were used in simulation. The results represented how the vehicle model behaves during with different environment settings, which provides evidence of the adaptability of the VOM to different environment settings. Figure 5 represents the machine responses with different environment settings. The bucket height varies for different work cycles, which can indicate the changing trench depth and pile height during the operation with different environment situations.

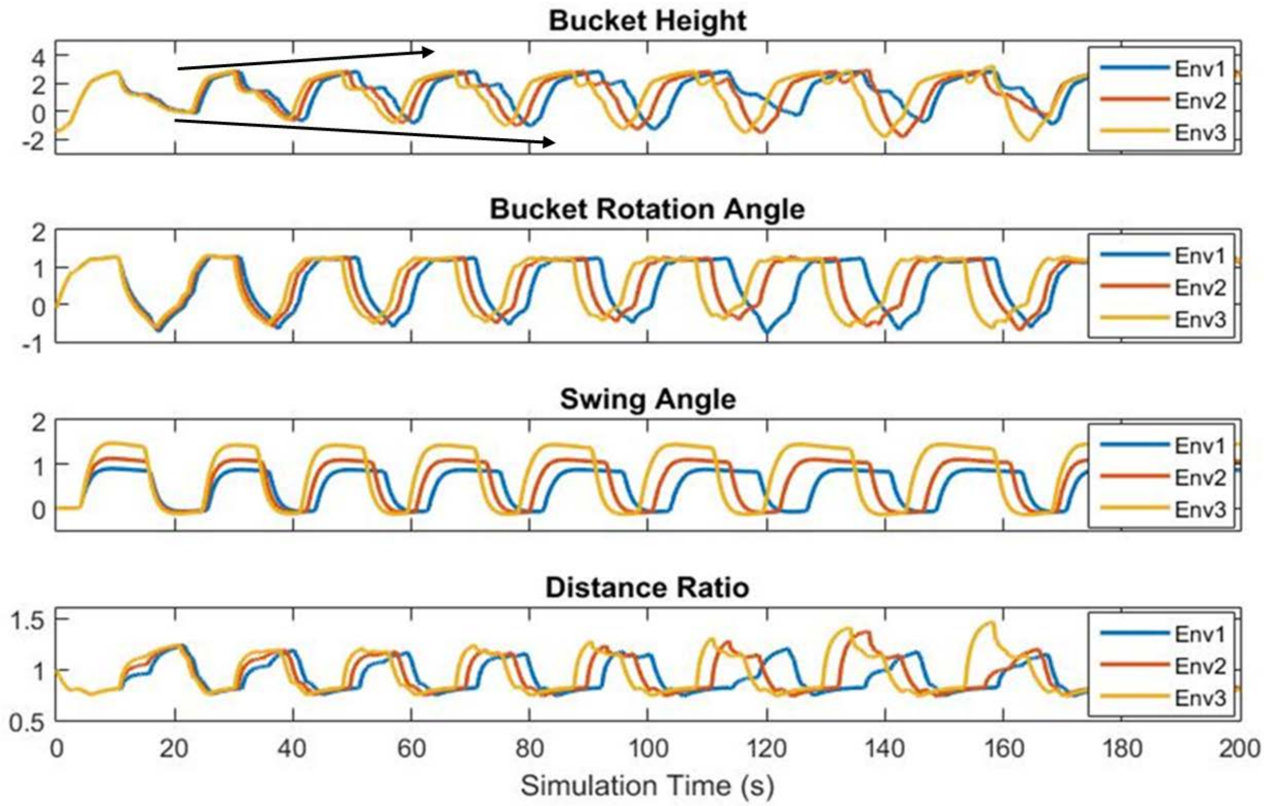


Figure 5. Machine Response of the Closed Loop Simulation using different Environment Situation Setting. Arrows on the Bucket Height graph demonstrate the increasing pile height and trench depth.

Conclusions

As the VOM is able to adapt simulate a complete trenching operation, where each work cycle effects a change in the environment. The learning capability of human operators can be integrated into the VOM for future work, which can optimize the way the VOM operates the vehicle model depending on the learning from environment, the vehicle model, and operator, which can be a way to model the VOM in a way that captures human operator learning. With the ability to adapt to different environment conditions, future work simulating how the VOM interacts with different soil types can be initiated, (which could include sophisticated soil models) and study of the mechanics of bucket interacting with soil.

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