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# Virtual operator modeling method for excavator trenching☆

Yu Du [a], Michael C. Dorneich [a,*], Brian Steward [b]

[a] Industrial & Manufacturing Systems Engineering, Iowa State University, United States
[b] Agricultural & Biosystems Engineering, Iowa State University, United States

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ABSTRACT

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. Physical prototype tests of construction machines require significant time and cost. However, computer-based simulation is often limited by the fidelity in 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 construction automation technology. Operator interviews were conducted to build a framework of tasks, strategies, and cues commonly used while controlling an excavator through repeating work cycles. A closed loop simulation demonstrated that an operator model could simulate the trenching work cycle with multiple operator strategies, and adapt to different vehicle and work site settings. A virtual operator model that captures human expert behaviors can be used to assess vehicle characteristics and efficiency, and inform the design of automation systems.



## 1. Introduction

The human operator of off-road vehicles is an integral part of the human-machine system performance. High fidelity machine models are used in simulation to test new vehicle designs. However, the fidelity of human operator models is often a limiting factor in the overall ability to conduct closed-loop simulation testing. This research investigated how machine operator expertise, practices, and decision making can be integrated into an operator model for virtual simulation of closed-loop construction vehicle operation. The goal of the research was to capture the behavior and performance of a human operator and represent the operator in a virtual operator model that simulates authentic human behavior in a well-defined construction machine operation.

Considering the complexity and non-linear nature of off-road vehicle dynamics, and the fact that the operator is intimately enmeshed in the closed-loop control system of the vehicle operation, field testing with human operators is the most common method used to test designs with physical prototypes and human operators in real working environment [12]. Vehicle field testing requires significant cost and time compared to computer-based simulation. Virtual design or model-based design, the process by which new features are modeled and tested in a simulation environment, is typically conducted early in the design process where it is less expensive to make changes. While machines have been modeled with a fidelity that enables robust testing, operator models are still in early stages of development. Methods for closing the simulation loop around operator, vehicle, and environment models need to be investigated.

Human operator decision-making and behaviors are varied and complex. Because of this complexity, it is difficult to develop and validate human operator models. Currently, only a few studies [8,11] have documented virtual operator model development and validation. These limitations on virtual operator technology limit design engineers' ability to make reliable comparisons in the virtual prototyping stage between different design alternatives.

Additional challenges exist in the development of virtual operator models. Operator models are typically created by tuning control models to mimic trajectories. Often they are tuned to be specific to a particular vehicle operating under specific conditions. If the vehicle design is changed, or the operating conditions are varied, the model often has to be re-tuned to match the new operating profile. These models focus on trajectories, not on operator perception and decision making processes. Human operators, in contrast, can adapt to changes in the machine or changes in the environment. Standard methods to model operator behavior and ability to adapt have not been established in this domain. Most approaches are focused on the control of the vehicle, rather than the operator behavior that generates the control inputs. Cognitive modeling has been developed as computational representations of internal cognitive processes; however they are designed to be task-independent [4], and focus on modeling constructs such as working memory [2]. These computational cognitive models focus on how human operators interact with the environment and make decisions,

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* Corresponding author at: Iowa State University, 0068 Black Engineering Building, Ames, IA 50011-2164, United States.
*E-mail address:* dorneich@iastate.edu (M.C. Dorneich).

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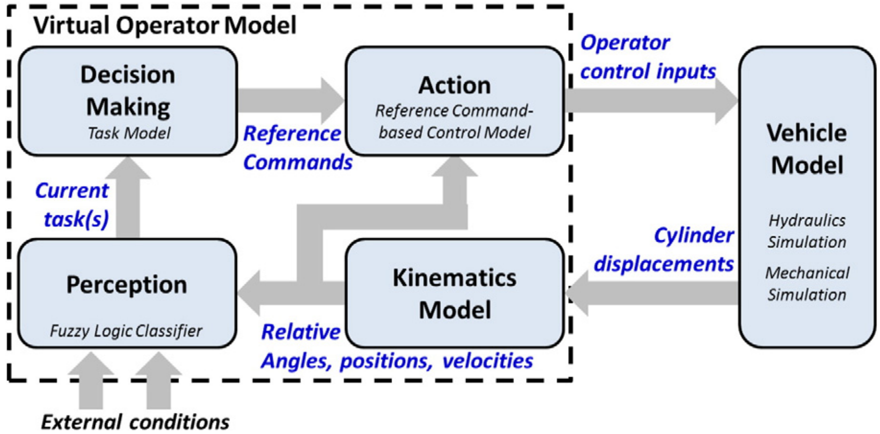


**Fig. 1.** Closed loop simulation of a virtual operator and a vehicle.

but are not designed to produce the control inputs of a human in vehicle operation. In the domain of off-road vehicle operations, the challenge is to summarize complicated cognitive processes in a model that is dynamical in nature, with the goal of creating an input/output model that faithfully represent operator expertise, sophistication, and adaptability.

An automated system can significantly improve consistency of repeated tasks in a stable, controlled environment which does not have much variation [3,28]. However, when the operating environment or conditions within which an automated system operates changes, higher-level machine intelligence technologies (beyond closed-loop control) must be in place for the autonomous system to adapt to these changes. Developing these types of behavioral responses for autonomous systems is challenging. A robust automation system with perception of external cues and use of internal goals may be able to exhibit adaptive behavior. For this behavior, expert human operator behavior and decision making processes may have great utility. A virtual operator model aims to capture key behaviors of human operators, enabling autonomous system to adapt to external environment changes.

Virtual operator modeling can enable human-in-the-loop dynamic evaluation in the virtual design stage, which results in cost and time reductions compared to the traditional product development [1]. This capability will enable simulation of model-based machine prototypes for performance analysis including fuel efficiency, productivity, and component loading. Virtual operator models enable closed-loop, whole system evaluations of the capability of new design features early in the design process.

The excavator trenching operation was selected as the modeling target. A virtual operator model was developed to simulate the human operator's perception, decision-making, and actions leading to control inputs for the trenching operation. Trenching using an excavator is a common operation in the construction environment, which requires multiple tasks within the work cycle. The operator needs to finish a trench with predefined dimensions, location and orientation within a certain time period and then must then deposit the material in a defined area or container. Operators judge their performance by time and quality of the trench, which means operators seek to finish the trench with maximum efficiency. A human-centered systems process was developed to capture and represent operators' tasks, strategies, cues, and constraints. The process included interviews and observation, and the analysis of machine data acquired from an excavator performing a trenching operation. A virtual operator model architecture was developed and implemented using various techniques to capture the fluid nature of tasks within an operation. The virtual operator model was tested by integrating it into a closed loop simulation with a vehicle model. The model was exercised by conducting tests using different digging strategies, varying vehicle hydraulic pump speeds , different pile locations, and different trench depths.

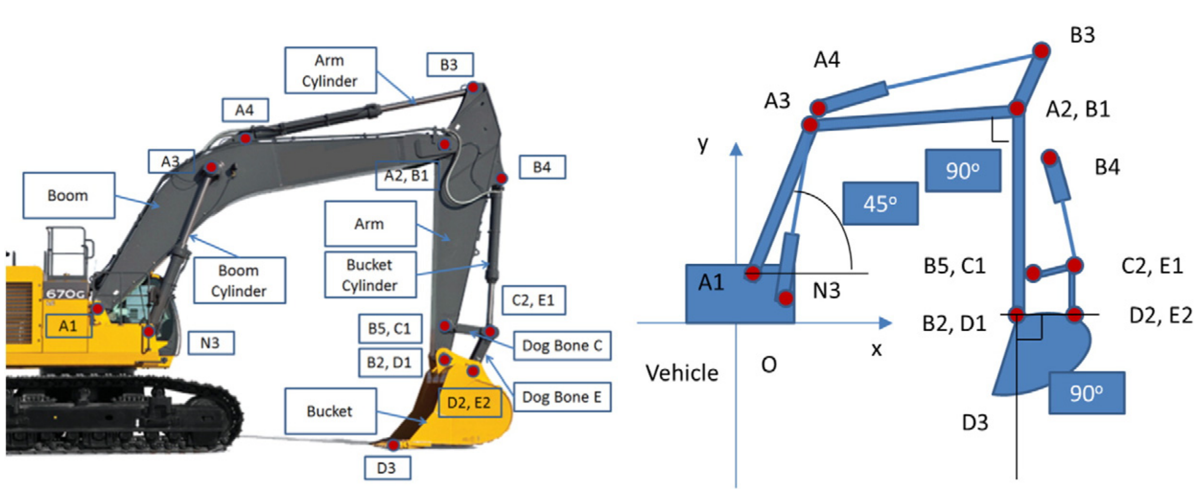


**Fig. 2.** Typical excavator mechanism with labeled rigid bodies and joint nomenclature (left) and simplified representation of the excavator mechanism with vehicle coordinate system defined and joint locations labeled (right), all used in the development of the kinematic model of the Boom, Arm, and Bucket.