An Intelligent Aid to Augment Performance and Training of Excavator Operators

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***Abstract*— We propose a 3D excavator simulator to evaluate and train operator's skills. This simulator consists of a diverse set of virtual environments, which were custom-built based on actual construction sites and contain different kinds of tasks with different difficulty levels to train and evaluate naïve operators. Our simulator mimics the motion dynamics of the excavator, in particular the hydraulic system behavior and the excavator mass and inertia. To simulate the environmental dynamics in real time, we employed the Unity3D physics engine to interact with solids (e.g., when removing rocks) and modified shaders to simulate granular materials (e.g., when digging sand). We conducted a set of evaluations with novice and expert operators to identify different metrics to assess the operator as well as the impact of training. Results show that naive subjects could improve their performance after 7 days of training. Naïve subjects' post-training performance was comparable to experts for simple tasks as digging and dumping.**

I. Introduction

The aging of heavy equipment operators is accelerating in high-income countries. In Japan, the number of skilled workers over 60y.o. in construction is estimated to be 1.53 operation of a hydraulic excavator [2]. It takes several years to master complex operations: the dynamics of hydraulic system is highly non-linear, and the operator commands the excavator joint velocity and not the end-effector displacement. Experts build an internal mental model that allows them to map world space explicit goals into joint space velocity commands and to operate an excavator effortlessly. This internal model can be quickly adapted, allowing an expert to proficiently operate any kind of excavator.

To the best of our knowledge, Japan is the most stringent in terms of regulations of heavy machinery operators, who are required to obtain a license at an excavator driving school. Schools use the same training template lasting 6 days that includes classroom and practical learning. That said, learning is limited to the understanding of explicit rules on operation and safety followed by practical training of simple tasks on an actual excavator. This apprentice is typically restricted to digging and dumping. Here we will test a digital simulator to train simple tasks like digging and dumping.

II. Experimental Protocol

A. Experimental Setup

A1. Existing Simulators

There are some older excavator simulators using OpenGL [3-6]. Wang and colleagues developed the first simulator employing Unity3D (prior to the creation of its physics engine) [7]. So et al and Akyeampong et al were the first groups to evaluate "Simlog," one of the first commercial simulators to train operators [8-9]. Others developed a low visual quality simulator employing Matlab and Simulink [10-11]. After 2014, most of the simulators were developed with Unity3D and some were connected to an excavator cabin [12]. Others included Head-Mounted Display (HMD) to afford an immersive experience [9, 13]. Wallmyr et al. displayed, in a CAVE-like room, a richer set of construction elements (cones, barriers, barrels, etc) [14]. Of notice, there are alternatives to Unity3D: Hilfert used Unreal Engine 4 [13]. Presently the state of the art in commercial simulators are the AGX Dynamics and Terrain modules from Algoryx [15-16] and the Vortex Excavator Simulator from CM Labs [17]. They are very realistic simulators employing a simplified version of the discrete element model (DEM) approach to simulate soil. These commercial simulators have a limited variety of environments and do not afford a more varied set of tasks such as loading different sizes and shapes of rocks, debris, trunks, coal, etc. or breaking different types of stones, pushing pipes or rocks.

A2. 3D Simulator

Our 3D simulator is made up of three-dimensional textured models of an excavator and a truck in several realistic virtual environments; these include elements similar to those of real operational environments for excavators. To display realistic 3D virtual environments in great detail requires a high-performance computer, a high-end graphics card, and high-resolution monitors.

To implement our simulator, we required an efficient operating system and a 3D engine software. Our simulator has two types of user interfaces: (1) graphical user interfaces (GUI), such as menus or graphical information that highlight

Figure 1. Simulator with all its components.

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something in the 3D virtual environment (e.g., options, errors, time, etc.) and (2) physical interfaces that the operator can use to control the excavator such as joysticks and pedals. Figure 1 shows the final setup of the complete simulator.

A.3 Hardware

We employed an Alienware Aurora R8 with an i7-9700 CPU with 8 cores and 32 GB of RAM, an NVIDIA GeForce RTX 2070 graphics card, four 4K (3840x2160 pixels) Dell P4317Q monitors, 2 Logitech X52 H.O.T.A.S. levers and joysticks as well as the Logitech simulation rudder pedals.

A.4 3D-Engine

The software used to develop all the functionalities of the simulator was Unity3D. We created 19 environments using 3D assets. Each 3D simulator environment shared the same excavator model and camera angles. There are 15 training environments replicating five different construction sites, five highway and road work in the mountains and outskirts of a city, four debris cleanups in forest and rocky hills, and one mining operation, as well as 4 evaluation environments. The 15 training and 4 evaluation environments are totally distinct to assess generalization of the acquired skills. Our simulator incorporates the dynamics of the hydraulic system to replicate simple and realistic excavator behavior. We assumed that 2^{nd} order dynamics would suffice. We estimated the inertia and center of mass of the cab, boom, stick, and bucket from the manufacturer drawings and collected the step response of each segment of a "real" excavator. We then fitted a 1^{st} and a 2^{nd} order models to approximate this response. We assumed that when the bucket is loaded, its load is a point mass and transferred the added inertia to the different segments. Similarly, we transfer the inertia of the more distal segment to the more proximal segment. As an example, Figure 2 shows this simplistic approach: we took the actual excavator bucket step response and fitted the 1^{st} and 2^{nd} order responses. We used Unity Physics Engine to deal with the dynamics of solid debris, trunks, pipes, coal, rocks or stones and we used a Unity asset, originally used to destroy elements in games, to simulate the cracking and breaking of these stones or granite slabs (e.g., using a hydraulic jack hammer). For sand, dirt, gravel or mud, we employed two Unity assets. For the digging task, we modified a Unity asset to simulate snow through deformable grounds using shaders. When digging with the virtual excavator, the corresponding amount of sand, gravel or mud was removed, as a visual effect, from the 3D area defined. For the dumping task, we modified another Unity asset to simulate fluids using shaders and particles to generate the visual effect of dumping material from the bucket. We also used in some environments a more sophisticated asset (based on voxels and Marching Cubes). This means that we are modifying the mesh to decrease its height when the volume of soil is removed, and to increase its height above another area where we are dumping it. We have not yet compared the quantitative performance of expert operators in our simulator with their performance in a real excavator. However, qualitative feedback from 9 expert operators indicated that the simulator strongly resembles a real excavator and felt quite realistic.

B.B. Training and Evaluation Protocol

B.1 Experimental Subjects

The subjects were healthy males: 6 novices and 8 experts. Table.1 shows experimental subject demographics.

Table.1 Subject data

	Subjects number	Age	Operating years
Naive	6	25-34(Avg.29)	0
Expert	8	34-68(Avg.46)	6-40(Avg.18)

B.2 Experimental Protocol

Our protocol attempts to replicate the weeklong excavator driving school discussed in the Introduction section and it is summarized in Table 2. Experts and Novices were tested at baseline on the simulator following instruction and 1-hour of practice. Naïve subjects were then trained for approximately 7 hours (~1hr per day for 7 days) followed by a post-training assessment. This daily 1-hour long training was selected for convenience, and it is significantly shorter than the training at the driving school. We compared naïve subject pre-to-post training performance at baseline and completion evaluation.

Acclimatization Practice employed the same training environment as a "warm-up" prior to the evaluations. Each training session consisted of approximately 30 minutes in each environment (14 different training environments in total not used during Practice 1 or 2) performing different tasks. Training sessions preceded and succeeded lunch to minimize fatigue as well as human motor interference and consolidation. A written description of the task was displayed on the screen. We employed the same evaluation set pre- and post-training.

Table.2 Test flow

Subjects	**Phase**	**Test duration [hours]**	
		Experts	**Novices**
8 Experts 6 Naives	Acclimatization Practice	1	1
	Baseline Evaluation	2.5	3.5
	training	-	7
	Acclimatization Practice	-	1
	Completion Evaluation	-	2.5

B.3 Evaluation Environments

To determine the operator's skill level, we developed a set of four evaluation environments with a different difficulty level. Eval Environment 1 consisted of repeatedly digging soil close to the excavator and dumping it into surrounding pipes. The pipes change from large to small in diameter. Eval 2 consisted of digging soil at far from the excavator and dumping it into diagonal trenches at an angle to the right, followed by flattening the surface. Eval 3 and 4 consisted of sculpting a slope upward or downward (see Figure 3 and 4).

B.4 Evaluation Metrics

In this paper, we show 6 metrics extracted from Eval 1 which involved simple digging and dumping: 1) cycle time, 2) position error when dumping, 3) number of joints which are operated simultaneously, 4) task speed, 5) ratio of the idle time, 6) performance in Fitts's law.

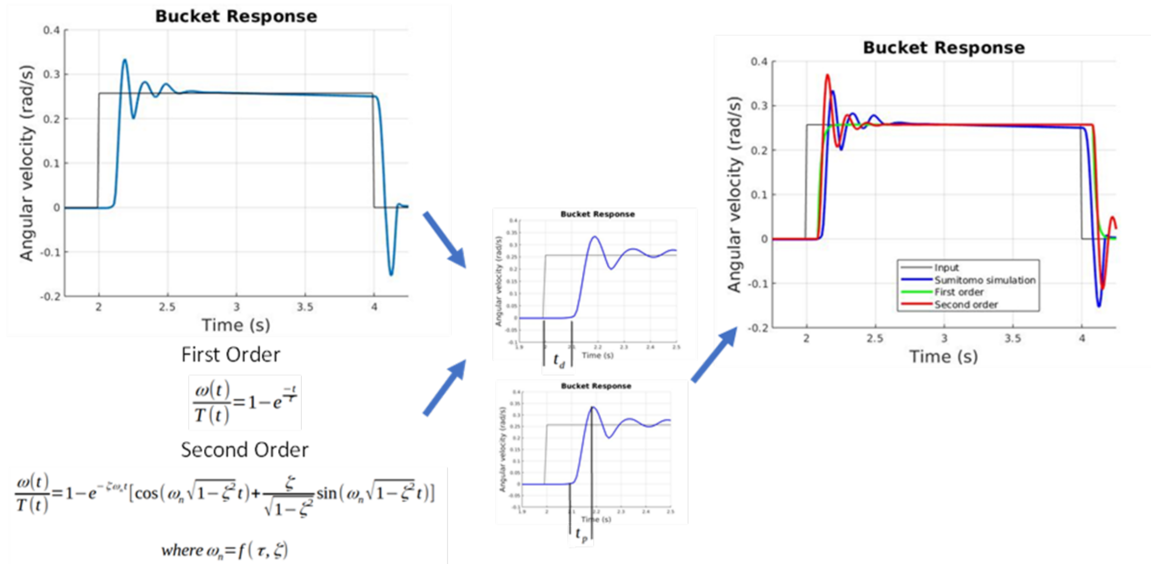

Figure 2. Bucket Step Response. The real bucket step response is shown on the left. After estimating the inertia, we tuned the remaining model parameters of a 1st and 2nd order systems from the time delay and peak time (see mid-panel). On the right panel we compare the 1st and 2nd order models with the real bucket step response.

Cycle time is defined as time duration from the beginning of the digging to the completion of the dumping excluding mis-operation. Tip distance error at dumping is the horizontal distance between the bucket tip and the center of each pipe. The idle time ratio is a percentage of the cycle time that the speed is less than 10% of maximum achievable joint speed. The task speed indicates how fast the sand height in the pipe changes. The number of joints indicates the average number of excavator joints which are operated simultaneously. The performance index b is the learning rate in Fitts' law; $T = a + b\log_2(1 + D/W)$; where D is the distance from the center of the digging to the center of the pipe (3.263[m]) and W is diameter of the pipes (0.8, 0.9. 1.0, 1.2[m]), t is time to carry sand from the digging area to the pipes. Failures, i.e., hitting obstacles, were eliminated prior to any analysis.

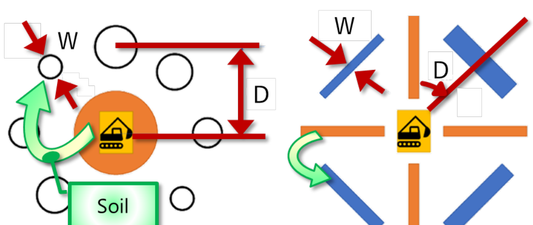

Figure 3. Evaluation Environment 1 and 2

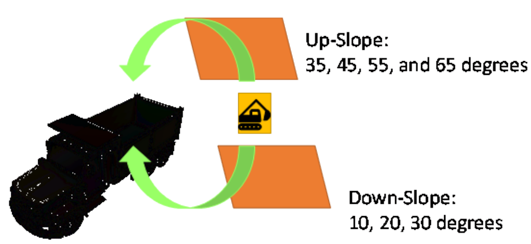

Figure 4. Evaluation Environment 3 and 4

III. Results

Like in the excavator driving school, training in a simulator for 7 days was efficacious and novices improved. Figure 5 shows the average cycle time of experts first time exposure to the simulator and naïve subjects pre-and-post training. The average cycle time of the experts was faster than novices time before and after training. In addition, the variance value for the experts is the lowest. The aggregated average cycle time for novices post-training was 40% shorter as compared to pre-training and the gap between experts and the naïve operators post-training dropped to ~9%. To assess the size of the change we used a t-test ($p < 0.05$) and the difference between pre-training novices and expert was statistically significant (p-value 0.015). Training was efficacious with the pre-to-post training showing significance (p-value = 0.016). There was no statistical significance on the cycle time between expert and post-training novices in this simple task.

The position error shows no statistical differences between naïve and experts. This result indicates that the position accuracy by the naïve operators at pre-training is close to the experts. Position accuracy is deemed the most important feature in line with many psychophysical studies in detriment to speed. The number of joints shows a statistical difference between experts and pre-trained naïve operators. There are no pre- to post-training differences for naïve operators, even though novices increase the post-training simultaneous use of multiple DOFs by 20%. This result may suggest that the skill of naïve operators tend to improve with our training, but perhaps the training period is not long enough. The other metrics, i.e., the task speed, the ratio of the idle time, and the performance index show statistical differences between experts and novice at pre-training and between naïve subjects pre- and post-training.

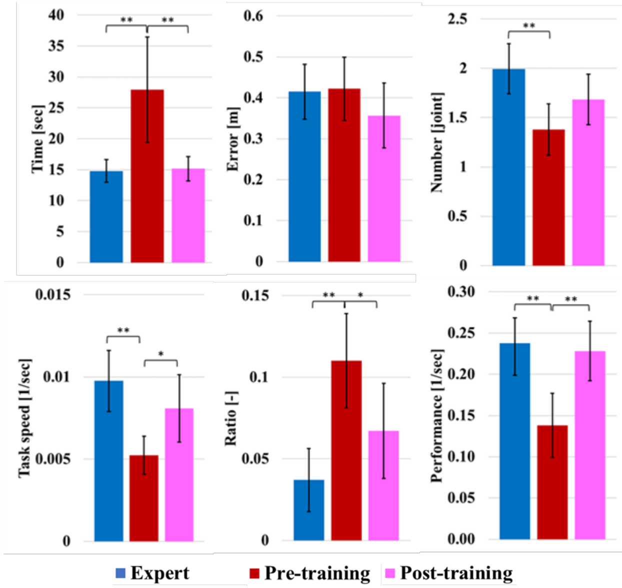

Figure 5. Comparison of each metric among 8 experts at baseline and 6 novices at pre-and-post training.

IV. Discussion

C.1 Training Effect

Results demonstrated that naïve operators were able to learn how to operate the excavator and improve their performance through the 7-day training in the simulator. The tasks performed in the training were purposefully different than tasks in the evaluation. Most metrics improved significantly and after training resemble or are closer to the expert's single exposure to the simulator. This result suggests that the subjects were able to learn in the simulator during training and generalize their experience to a different task during evaluation, which is a hallmark of the skilled operator (quickly adapt to different tasks and excavators). We ran a qualitative assessment among novice subjects and many highlighted that, until the second or third day of training, they had to explicitly remember the correspondence between the joystick and the excavator joint. Most of them claimed that they were able to operate the simulator effortlessly after the sixth session. Like in the excavator driving school, most of the naïve operators trained on our simulator could not simultaneously control two of the 4 excavator DOFs at completion of our protocol.

C.2 Gap between Naïve and Expert Operators

Our results suggest that 7 days of training suffice to reduce the gap between novices and experts. However, the level of difficulty in Environment 1 is low. Eval Environments 2 to 4 are more difficult. Initial indication is that novices will require a longer training period to learn how to simultaneous operate the bucket, arm, boom, and cab swing.

C.3. Transferable to real excavator?

It remains to be seen whether performance gains on the simulator are transferable to actual field operation.

V. Conclusion

We proposed a 3D excavator simulator to evaluate and train naïve operator's skills, and partially validated the effectiveness of this simulator. We speculate that the simulator might be safer and cheaper to train novices, and it appears at least for simple tasks that the simulator is an effective tool for training.

Acknowledgment

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