Simulating Ingress Motion for Heavy Earthmoving Equipment

HyunJung Kwon, Mahdiar Hariri, Rajan Bhatt,
Jasbir Arora*, and Karim Abdel-Malek

Center for Computer Aided Design, The University of Iowa, 116 Engineering
Research Facility 330 S. Madison Street Iowa City, IA 52246, USA
4110 Seamans Center for the Engineering Arts and Sciences,
The University of Iowa, Iowa City, IA 52242-1527
`jasbir-arora@uiowa.edu`

Abstract. Design of heavy earth moving equipment is based primarily on feedback from the driver. Most design studies on ingress focus on the motion itself and rely heavily on experimental data. This process requires physical construction of an expensive mockup before any feedback can be obtained. Moreover, most research and development on subject of ingress are limited to studies on passenger vehicles. Although the design of heavy vehicles requires more consideration to human safety and comfort, very little attention has been given to simulating ingress movement on those vehicles. This paper describes the development of a model to perform ingress motion for heavy equipment and its applications to study the response of the operator for different cab designs using SantosTM, the digital human model developed at Virtual Soldier Research at the University of Iowa.

Keywords: Human Modeling, Ingress, Predictive Dynamics, Heavy Equipment.

1 Introduction

Collecting feedback from customers is an important consideration while designing the layout of fixtures inside a heavy vehicle. However, it is time consuming and expensive to conduct experiments with multiple human subjects. Moreover, experiments can be performed only if the actual physical model of the cab, also known as a mock-up, exists. Building different vehicle mock-ups for experiments is also expensive and time consuming. It is even more difficult to rearrange the layout in a physical model in order to test various conceptual designs. Virtual tools that allow the designer to visualize how an operator is able to see the cab and surrounding environment once a physical prototype is build, could be very helpful to the designer to surmount these difficulties. In addition, if the virtual tools also allow the user to receive feedback in terms of physics based data that correspond to how the operator feels during cab ingress, it would allow designers to try different layout designs and perform a comparative study without having to build prototype mock-ups. Hence, this study

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* Corresponding author.

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focuses on the simulating ingress motion for a virtual human, especially on the virtual model of the heavy equipment. By generating different motions on different models, the designers can integrate the results of virtual human simulation tools into heavy vehicle cab design.

In the current field of study, most studies have focused on safety aspect due to the nature of the heavy equipment and its hazardous environment. Falls from equipment injuries in U.S mining were studied [1] and the impact on industry of those injuries was investigated [2]. Injury databases were utilized for this study by utilizing the injury narrative, nature of injury, body part injured, mine type, age at injuries. Impact forces during different ingress and egress methods are compared [3] [4]. This approach emphasizes the point that optimal design of entry and exit aids will minimize injuries. Ingress and egress motions were studied for injury aspects before the late 2000s. However, those investigations were concentrated on ingress/egress motion outside of the vehicle such as on the ladder or steps for going up or down. Moreover the studies just analyzed motions of certain subjects, but did not suggest or study improvements for design. Recently, the attention of studies has shifted to the ingress/egress motion itself. Reed [5] presented an approach to suggest guidelines for locating steps relative to door openings and seating positions. Ingress/egress motion for a truck cabin is usually measured by motion capture system [6]. Two different methods for evaluating joint loads were presented; force and moment methods and a force only method. Two different stepping motions were analyzed and validated. However, that study [6] is focused on stepping up and down motion, and on one specific truck cabin.

Although numerous studies on ingress and egress have been performed recently, greater part of the studies are focused on exterior of the heavy vehicle (the ladder or on the steps). None of the studies have reported what the proper locations of the components. Therefore the present study will predict ingress/egress motion of heavy vehicle using digital human modeling. The motion either within different vehicle geometry environment or with different personal characteristics can be predicted. Ingress motion will be tested in the environment of different components such as controller, handle, seat affected by driver's safety, health and efficiency.

2 Problem Definition

2.1 Heavy Equipment Environment

Unlike passenger cars, heavy equipment vehicles have complex component connections, transmit loads and have attachment points for implements. In addition the heavy equipment vehicle is designed to travel over rough terrain. The operating room of the vehicle is located high off the ground level and is accessible through a ladder. This high position of the operating room is to protect the operator from the harsh construction environment as well as provide wider view of the construction area. While the driver's seat is located proximally to an entrance door for a passenger car, in heavy equipment vehicles the operator's seat is located in the center of the room. The operating room of a heavy vehicle has more space for the driver to move in and out. In addition, the operating room ceiling is placed at a higher level making it easy for the operator to walk upright and reach to the operator's seat. The machine's frame, articulation (control panel), and steering for wheeled equipment are the major components of the heavy equipment operating cab. Once the operator steps off the access ladder, the operator has to avoid these components to get in or get out. Since it is off the ground and is a restricted space, the locations of those components become important. The location and placement of these components should also guarantee the operators' safety.

2.2 Safety Factors (Regulations)

Heavy equipment operators are prone to fall frequently both on and off the work zone premises, and for many different reasons [7]. Use of foot and handholds, as well as non-skid coating on the deck, can help prevent falls. In addition, drivers are expected to maintain a "three-point stance" during truck ingress and egress. That is, they are expected to have two feet on the steps and one hand on the handhold at all times. This stance should also be used when climbing up and down or between the cab and trailer to connect brake and light lines. Furthermore, the driver must be aware that jumping from cabs, trailer is dangerous.

3 Video Analysis

Ingress and egress movements are complex, as almost the whole body is involved in the motion within a highly constrained environment. These motions are affected by not only the physical capability of the operator, but also dimensions and anthropometry of the operator's body. The size, layout, width and shape of the door influence the motion as well. A detailed motion analysis must be carried out in order to be able to generate different movements for predicting motion. The motion is defined based on the structure of the object (vehicle). Stepping up or climbing up a ladder is included in ingress motion for the heavy equipment vehicle. But, for some larger vehicles such as the wheel loader, which have large operating rooms, entering the operating room and sitting could be also a part of ingress.

3.1 Motion Analysis

Experienced drivers were asked to get in and out normally of a wheel loader. The open door motion strategy is studied as a pilot study in this paper. The observation is mostly focused how to move from or to the interior of the cab avoiding obstacles. Key components are determined as obstacles to avoid. The movement of the body and direction of the foot was tracked in the cab geometry. Ingress motion is analyzed in chronological phases. Ingress consists of three distinct motion phases called subtasks: walking forward (to approach the cab), ladder climbing, and the ingress maneuver. The ingress maneuver is again divided into two subtasks: entering the cab and sitting. For the continuity of the motion for ingress, the end position of each subtask should be identical with next starting position. The key frames for each subtask are summarized as below;

Subtask 1 – Entering inside. Since climbing the ladder and opening the door will not be considered in this subtask, the starting position should be standing posture. Therefore, Subtask 1 starts from a standing posture and ends in a sit-ready position in the cab.

Subtask 2 – Sitting. This is the position in which a person fits their body in a narrow area between the dashboard and seat. Then the hip should be located in the proper area of the seat.

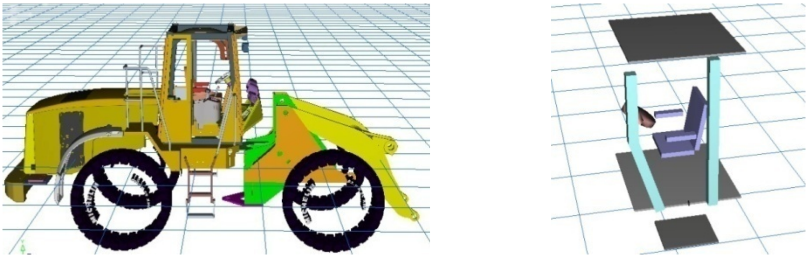
Fig. 1. Motion Analysis

3.2 Key Components

In order to improve computational efficiency not all components of the cab are included. Key components are determined by video analysis. When the operator gets in through the door frame, it becomes a key component to avoid. Both arms cannot penetrate the frames and foot cannot go through a step; the operator has to bend to avoid hitting his head on the top side of the frame. While moving in and out of the narrow seat area, the lower body should avoid seat. Therefore seat is defined as another key component. The key components are provided to the ingress model in the form of simple primitives that represent the complicated cab geometry.

3.3 Model

A CAD model of the cab is redefined and reduced to a primitive model. The prop model consists of key components giving users the ability to test and interact with between these components easily and study the resulting motion. It also simplifies the model, it allowing the user easily define the necessary parameters for a given task. This model takes on the size and shape of a generic model representing the model the operator is performing the task on. The user can then scale this prop model to size, orientatation, and position the model as required for the task. The properties defined by the model are then passed to the digital human modeling evaluator and task analysis can be performed. It is imperative that the user has the ability to easily define the parameters. It is also important for the user to be able to expand the ingress models to different cab models. For these reasons, it has been determined that the best way to give user both ease of use and flexibility is to use a more simplistic prop model than Fig 2(a).



(a) Actual Model (b) Simplified Prop Model

Fig. 2. Digital Models

3.4 Inputs

Obstacles. The first type of input needed from the user is information on the particular cab model. This is provided to the ingress motion in the form of simple primitives that represent the complex cab geometry that Santos^{TM} will encounter while entering the cab. This task accepts two types of primitives, cylinders and planes. The cylinders and planes can be defined as either finite or infinite. For finite cases, the cylinder is defined by two end points and a radius; while, a plane is defined by three points and a thickness. These primitives can then be used to approximate geometry where santos will come in contact with during ingress.

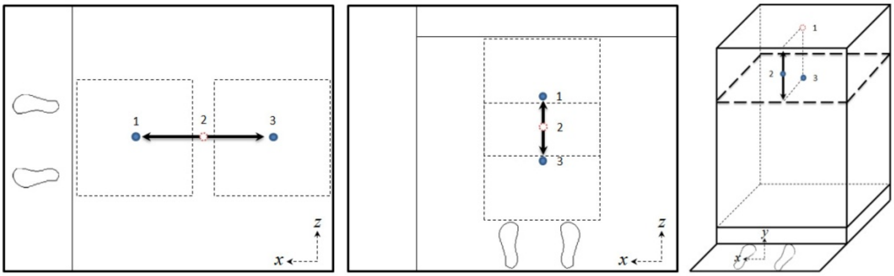
Foot Position. Foot position is defined by the combination of the size of the seat cushion, which shape is assumed to be a square, location of the door, used as a criterion to recognize the door location from the Santos so that he can detect the entry point. Foot position is also defined by available room area that Santos can walk in. As available area in the room gets larger, bigger step sizes are needed. Once user makes changes to the cab geometry, the step will be automatically adjusted.

Hand Positions. To adhere to the three points of contact safety regulations in section 2.2, the operator must grab something for their safety while moving into the cab. In order to satisfy this condition, the user has to specify hand location as an input. Hand position is measured in Cartesian coordinate space from global axis of digital human. The user can choose either right hand or left hand.

Assumptions. For this study, in its preliminary stage, there are several assumptions. Walking to the ladder and ladder climbing are not considered. Instead of connected motion between ladder climbing and entering, it assumed that Santos is standing on the deck area; as his starting position. The door of the operating room is open such that driver doesn't need to open and close during the motion. The operator's movable range is limited to a minimum of 3 steps at the very least .The adjustable area for the objects should not interrupt those limited steps. Other assumptions in this study include the exclusion of vision effects, lack of reaction forces and friction is made during this study.

4 Simulation Concepts

First, assuming operating room area does not change, seat position is selected in three different locations along each x (case1) and z (case2) axis in Fig 3.



Case 1 Case 2 Case 3

Fig. 3. Simulation cases

Maximum movable points are marked as points 1and 3 in Fig. 3; Point 2 is the midpoint of the line joining points 1 and 3. Movable seat area is measured excluding the foot rest area (case 1) and control penal area (case 2). Ceiling height is a variable in case 3. Point 3 is sitting height of the digital human and point 1 is standing height in case 3. Default locations of the actual model are Point 2 for the case 1 and case 2, point 1 for the case 3 are. Therefore, a total 9 different cases will be simulated to investigate the effects of location of key components with regard to the movement of digital human.

5 Formulation

The entire simulation is governed by an optimization formulation. The design variables are the joint profiles $q_i(t)$ for ingress motion where i is the number of degrees of freedom. Besides the joint profiles, the initial posture is also optimized rather than specified from the experiment, while, the torque profiles are calculated from joint profiles using the recursive Lagrangian dynamics equations. The dynamic effort (the integral of the squares of all joint torques) is used as the objective function and is defined as:

$$\text{Minimize } f(\mathbf{q}) = \int_{t=0}^{\mathrm{T}} \left(\left(\frac{\tau(\mathbf{q},t)}{|\tau|_{\max}} \right)^{\mathrm{T}} \left(\frac{\tau(\mathbf{q},t)}{|\tau|_{\max}} \right) \right) \mathrm{d}t \qquad (1)$$

where T is the total time for the one step, $|\tau|_{\max}$ is the maximum absolute value of joint torque limit. Several constraints are proposed and implemented in this work to satisfy laws of physics and boundary conditions throughout the ingress process. These constraints include joint angle limits, ground penetration, and foot contacting positions, ZMP location [8], obstacle avoidance, continuity conditions.

5.1 Obstacle Avoidance

An avatar must avoid the collision of its body segments with other non-adjacent body segments as well as with the objects in the environment while performing a task. The avatar body segments and the obstacles in the environment are modeled using surrogate geometry. The body segments are represented by using one or more spheres rigidly attached to a local reference frame, such that these spheres move with the body segments.. The objects in the environment are modeled using one or more of the five primitive geometries: spheres, infinite cylinders, infinite planes, finite cylinders, and finite planes. A generic collision avoidance strategy is developed to avoid spheres with all the five primitive geometries used for representing obstacles.

As discussed in [9], the gradients of the collision avoidance constraint between 2 primitives should be continuous. For this purpose, the primitives used in collision avoidance need to have smooth surfaces (no edges). But finite cylinders and finite planes do not have smooth edges. Hence, as discussed in [9], we use additional spheres and cylinders to smooth out the edges of finite cylinders and planes and consider these modified elements instead, such that the constraint gradients are continuous. Note that collision avoidance includes both self (the avatar) avoidance and obstacle (the virtual environment) avoidance. As a result, the (modified) finite cylinders and planes used in the collision avoidance modules look as shown below:

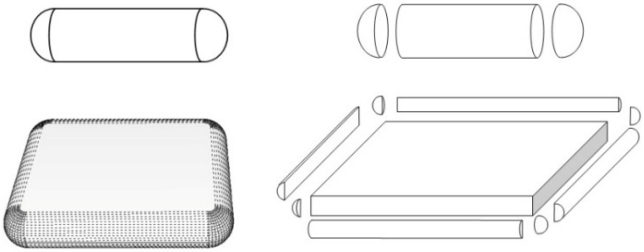


Fig. 4. Finite cylinders and planes

5.2 Continuity Conditions

The entire ingress tasks are divided to separate subtask for the convenience of calculation. To combine each subtask together, the continuity condition constraint is imposed. The basic idea is that the final posture of the previous subtask and initial postures of the subsequent subtask should be identical. These conditions are expressed as

$$\begin{gathered}\mathbf{q}_{\mathrm{pre}}(\mathrm{T}) = \mathbf{q}_{\mathrm{post}}(\mathrm{T}) \\ \dot{\mathbf{q}}_{\mathrm{pre}}(\mathrm{T}) = \ddot{\mathbf{q}}_{\mathrm{post}}(\mathrm{T}) \\ 0 \le \mathrm{t} \le \mathrm{T}\end{gathered} \tag{2}$$

where $\mathrm{q}_{\mathrm{pre}}$, $\mathrm{q}_{\mathrm{post}}$ are previous and following subtasks, $\mathbf{q}, \dot{\mathbf{q}}$ represents angle, velocity, of each DOF at the final (T) and initial time(0). The continuity condition is imposed on every subtask.

6 Results

The output results from the formulation are joint angle profiles and joint torque profiles. The predicted joint angle profiles and joint torque profiles are presented in Fig. 5 (case1), Fig. 6 (case2) and Fig. 7 (case3) respectively and plotted against time period. Ingress is a whole body motion; all the joint angles and torques would be plotted and compared. However, one specific joint – 1st spine is presented in this paper due to low back pain issues which is a pervasive disorder, affects 70% to 80% of adults at some time during their lives, and it costs at least $16 billion each year and disables 5.4 million Americans [10]. Therefore 1st spine is selected and plotted in each case. Entering motion for subtask1 arises from 0s to 3s followed by sitting motion for subtask2 from 3s to 4.5s. Since hand inputs have not changed, results of sitting motions are more sensitive than entering motions as changing geometry,. Most of the plots shaped similar in case 1 and 2 due to the foot position which is formulated to step around the seat area. In case 3, changing amount of 1st spine flexion/extension has been watched due to the height of the ceiling.

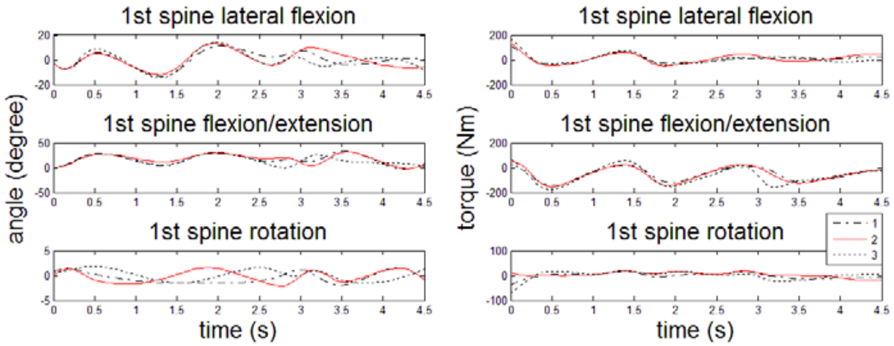


Fig. 5. Joint Angle and Torque for case 1

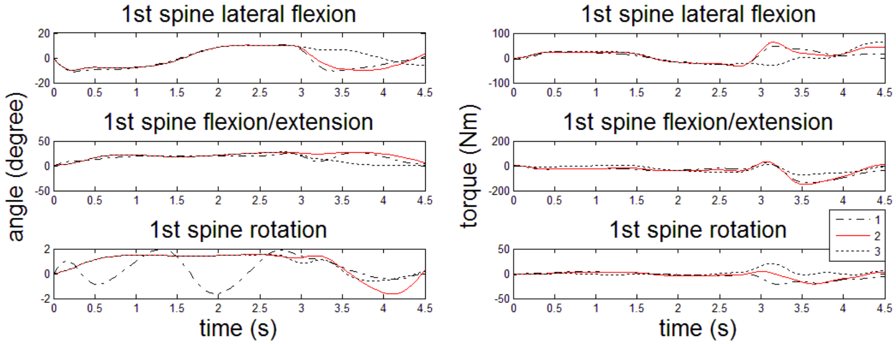


Fig. 6. Joint Angle and Torque for case 2

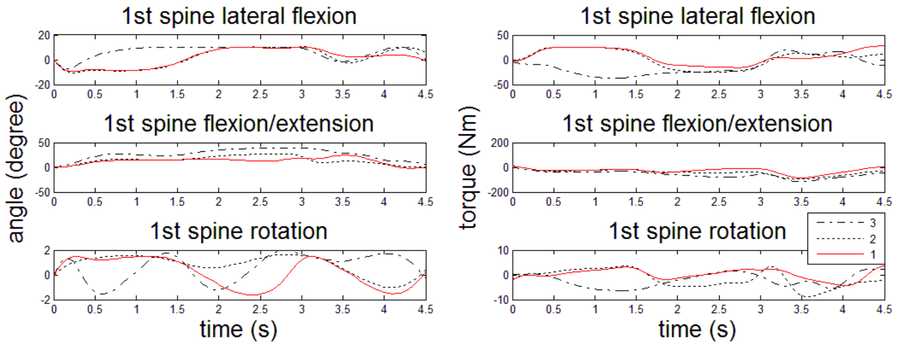


Fig. 7. Joint Angle and Torque for case 3

7 Conclusions

Initial results obtained from this study are promising and allow a user to perform comparative virtual studies of ingress motion for different geometry configurations and subsequently analyze the kinematic and kinetic results. This, in turn, helps with designing better cab interior for drivers to move without having to build expensive prototypes. This study is helpful in gathering information about critical effect of the joint actuation requirements under different loading conditions so that designers can prevent injuries to workers. By investigating changes in cab geometry for cab design process during ingress, working conditions for the operators can be improved. Such a capability will help in better design of in-cab environments of the heavy vehicles, and could be a useful tool in reducing the injury-related problems for the operators. The same process can also be applied for simulating egress motion.

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