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Gamification Procedure Based on Real-Time Multibody Simulation

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Abstract – *Gamification aims to redirect the motivating power of game mechanics towards a non-entertainment field to encourage user engagement. In the field of mechanical engineering, the gamification concept can be combined with real-time multibody simulation. The objective of this paper is to demonstrate how gamification can be used to analyze user experiences of a mobile machine. As a case study, an excavator is modeled using a semi-recursive multibody formulation. The excavator model is customizable and offers different sizes for a bucket and dipper arm's hydraulic cylinder. In the excavator model, gamification introduces game elements: goals such as filling the industrial hopper, obstacles such as utility poles, challenges such as fuel gauge, time constraint such as a timer, and fantasy element such as visualization graphics. The effect of different product features, such as the hydraulic system parameters, on the users' performance are analyzed. A product development team can utilize this information to improve the product design.*
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***Keywords**: Gamification, Multibody System, Product Development, Real-time Simulation, Users*

Nomenclature

$\mathbf{A}_j$	Rotation matrix of j^{th} body
A_1	Area on the cylinder side
A_2	Area on the piston side
B_{e_i}	Effective bulk modulus of i^{th} section
B_j	j^{th} rigid body
C_v	Flow rate constant
$\mathbf{C}$	Quadratic velocity vector
$\mathbf{d}_{j-1,j}$	Relative displacement vector between j^{th} and $(j-1)^{th}$ body
F_S	Force by a hydraulic cylinder
F_μ	Total friction force
$\mathbf{F}_j$	External force vector acting on j^{th} body
$\mathbf{I}$	3×3 identity matrix
$\mathbf{J}_0$	Constant inertia tensor of j^{th} body
m_j	Mass of j^{th} body
$\mathbf{M}$	Mass matrix
n_c	Total number of hydraulic inlets and outlets
p_i	Pressure within i^{th} section
P	Point location of the joint
$\dot{\mathbf{q}}$	Generalized velocity vector
Q	Point location of the joint
Q_{ij}	Ingoing or outgoing flow rate of i^{th} section
Q_v	Flow rate through valve
$\mathbf{Q}$	Generalized external force vector
$\mathbf{r}_j$	Global position vector of a point on j^{th} body
$\mathbf{R}$	Velocity transformation matrix
$\mathbf{R}_{j-1}^{cm}$	Global position vector of the origin of $(j-1)^{th}$ body
t	Time
$\mathbf{T}_j$	External torque acting on j^{th} body
$\bar{\mathbf{u}}_{j-1}$	Position vector of a point on $(j-1)^{th}$ body within its body reference coordinate system
U_{ref}	Reference voltage signal
V_i	Volume of i^{th} section
$\bar{x}_{\mathrm{B}_{j-1}}$	Coordinate of body reference coordinate system
X	X-axis of global coordinate system
X_0	Relative spool position
$\bar{y}_{\mathrm{B}_{j-1}}$	Coordinate of body reference coordinate system
Y	Y-axis of global coordinate system
$\bar{z}_{\mathrm{B}_{j-1}}$	Coordinate of body reference coordinate system
$\dot{\mathbf{z}}$	Relative joint velocity vector
Z	Z-axis of global coordinate system
δ	Virtual parameter
τ	Time constant
$\boldsymbol{\omega}_j$	Global angular velocity vector of j^{th} body

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$\boldsymbol{\omega}_{j-1,j}$	Relative angular velocity vector between j^{th} and $(j-1)^{th}$ body
$\sim$	Skew-symmetric matrix of the parameter

I. Introduction

Society's interest in games can change the traditional thinking of product design, product development, and consumer markets. The gamification concept aims to redirect the motivating power of game mechanics towards a non-entertainment field to encourage user engagement [1]. Gamification helps in monitoring the user's behavior by applying game-like criteria to strategic motives. Providing a game-like environment can help to improve productivity and end-user creativity.

Remi-Omosowon et al. [2] have applied gamification to engage users in a loading system of a warehouse environment. They introduced an interactive simulation interface to manage loading patterns, helping to check loading feasibility, share knowledge, and improve user learning. Gasca-Hurtado et al. [3] have noticed that a lack of user motivation is a prime reason for defects in a software development process. Therefore, they utilized gamification to enhance users' engagement and communication within the team. Leclercq et al. [4] have explained the role of cooperation and competition gamification mechanics in engaging users in a co-creation platform. This helped to capture the dynamics and iterative nature of user engagement. Poncin et al. [5] have explained the positive impact of challenge and fantasy game mechanics on the user's experience. They concluded that a gamified interface for a product provides a compelling playful experience leading to stronger support intensions. Komeijani et al. [6] have pointed out that designing a user-centric product helps in eliminating redundant or missing functions from the product. Therefore, Signoretti et al. [7] have proposed a modular and reusable card game helping to design user-centric services or products. They considered the user's needs, emotions, and personality, creating a highly communicative environment based on game design. Abi Akle and Lizarralde [8] have also used a card game as a pervasive and persuasive tool to identify real design needs from users' feedback, helping in (re)designing products for sustainable outcomes. Furthermore, to combine gamification with a virtual environment, Holth and Schnabel [9] have utilized an immersive virtual environment creating a direct link between the user's perceptions and the created virtual environment. Their study showed a way of creating, testing, and experiencing a virtual environment that can incorporate the strengths of various disciplines into a common platform. As can be concluded from the literature overview, there are a number of studies on gamification encouraging user engagement [2]-[4], user experience [5], user-centric products [6]-[7], designing for sustainable outcomes [8], and the collaboration of various disciplines [9]. However, studies where gamification is utilized to identify the design needs for a complex mobile machine has been overlooked. In this study, this gap can be covered by using gamification in the framework of detailed physics-based real-time multibody dynamic simulation. As demonstrated in this study, users' experience and feedback can be captured using the gamified simulation model. This information, in turn, can help the product development team in the design of the machine details. Today's real-time simulation models that are based on multibody dynamics can accurately describe systems that consist of large numbers of bodies, actuators, and contact models. The objective of this paper is to demonstrate the gamification concept in the framework of a mobile machine. To this end, an excavator will be described by employing a real-time multibody approach. In the real-time multibody model, the role of gamification is to introduce the game elements, such as goals, obstacles, challenges, time constraints, and fantasy. Users can directly test-run the virtual prototype of the initial excavator model through this gamified user interface. User feedback (user experiences) can be processed and analyzed to provide the product development team with information to improve the design of the excavator, its subsystems, or user-interface further.

II. Multibody System Dynamics

The equations of motion for a constrained mechanical system can be described using a multibody approach. Embedded technique, augmented Lagrangian formulation, penalty formulation, recursive formulation, and semi-recursive formulation are examples of formulations that can used in this approach. The semi-recursive formulation is used in this research because it leads to a computationally efficient procedure when a large number of bodies with open kinematic chains, such as an excavator, are under investigation. In this study, the semi-recursive formulation is combined with hydraulics and contact subsystem models.

II.1. Semi-Recursive Multibody Formulation

The semi-recursive formulation describes kinematics using a relative coordinate system. Consider two rigid bodies B_{j-1} and B_j connected by a joint, as Fig. 1 shows. Here, the X, Y, and Z axes represent the global coordinate system, whereas the $\bar{x}_{\mathrm{B}_{j-1}}$, $\bar{y}_{\mathrm{B}_{j-1}}$, and $\bar{z}_{\mathrm{B}_{j-1}}$ axes represent the body reference coordinate system of body B_{j-1} and are located at its center of mass. Points P and Q are the locations of the joint on body B_j and body B_{j-1}, respectively, and $\mathbf{d}_{j-1,j}$ is the relative displacement vector between points P and Q.

Following the relative coordinate system, the global position vector $\mathbf{r}_j$, the global velocity vector $\dot{\mathbf{r}}_j$, and the global acceleration vector $\ddot{\mathbf{r}}_j$ of point P can, respectively, be written as [10]:

$$\mathbf{r}_j = \mathbf{R}_{j-1}^{cm} + \mathbf{A}_{j-1}\bar{\mathbf{u}}_{j-1} + \mathbf{d}_{j-1,j} \tag{1}$$

$$\dot{\mathbf{r}}_j = \dot{\mathbf{R}}_{j-1}^{cm} + \tilde{\boldsymbol{\omega}}_{j-1}\mathbf{u}_{j-1} + \dot{\mathbf{d}}_{j-1,j} \tag{2}$$

$$\ddot{\mathbf{r}}_j = \ddot{\mathbf{R}}_{j-1}^{cm} + \dot{\tilde{\boldsymbol{\omega}}}_{j-1}\mathbf{u}_{j-1} + \tilde{\boldsymbol{\omega}}_{j-1}\tilde{\boldsymbol{\omega}}_{j-1}\mathbf{u}_{j-1} + \ddot{\mathbf{d}}_{j-1,j} \tag{3}$$

where $\mathbf{R}_{j-1}^{cm}$, $\dot{\mathbf{R}}_{j-1}^{cm}$, and $\ddot{\mathbf{R}}_{j-1}^{cm}$ are, respectively, the global position, global velocity, and global acceleration vector of the origin of the body reference coordinate system of body B_{j-1}, $\mathbf{A}_{j-1}$ is the rotation matrix of body B_{j-1}, $\tilde{\boldsymbol{\omega}}_{j-1}$ and $\dot{\tilde{\boldsymbol{\omega}}}_{j-1}$ are, respectively, the skew-symmetric matrix of angular velocity of body B_{j-1} and its derivative, $\bar{\mathbf{u}}_{j-1}$ is the position vector of point Q within the body reference coordinate system of body B_{j-1}, and $\dot{\mathbf{d}}_{j-1,j}$ and $\ddot{\mathbf{d}}_{j-1,j}$ are, respectively, the relative velocity and relative acceleration vector between bodies B_{j-1} and B_j. It can also be noted that $\mathbf{u}_{j-1} = \mathbf{A}_{j-1}\bar{\mathbf{u}}_{j-1}$.

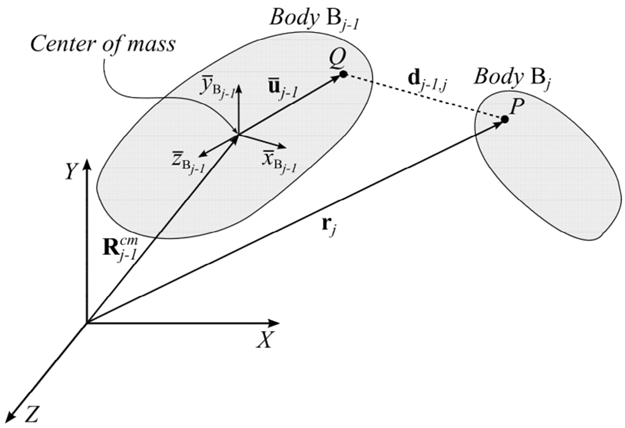

Fig. 1. Description of multibody system

The global angular velocity vector $\boldsymbol{\omega}_j$ and the global angular acceleration vector $\dot{\boldsymbol{\omega}}_j$ of body B_j can, respectively, be written in terms of the global angular velocity vector $\boldsymbol{\omega}_{j-1}$ and the global angular acceleration vector $\dot{\boldsymbol{\omega}}_{j-1}$ of body B_{j-1} as [10]:

$$\boldsymbol{\omega}_j = \boldsymbol{\omega}_{j-1} + \boldsymbol{\omega}_{j-1,j} \tag{4}$$

$$\dot{\boldsymbol{\omega}}_j = \dot{\boldsymbol{\omega}}_{j-1} + \dot{\boldsymbol{\omega}}_{j-1,j} \tag{5}$$

where $\boldsymbol{\omega}_{j-1,j}$ and $\dot{\boldsymbol{\omega}}_{j-1,j}$ are, respectively, the angular velocity and angular acceleration vector of body B_j with respect to body B_{j-1}. Using the kinematics above, the equations of motion for body B_j can be developed from the principle of virtual power in matrix form as [11]:

$$\begin{aligned}\left\{\delta\dot{\mathbf{r}}_j^{\mathrm{T}}\,\delta\boldsymbol{\omega}_j^{\mathrm{T}}\right\}&\left(\begin{bmatrix} m_j\mathbf{I} & 0 \\ 0 & \mathbf{A}_j\mathbf{J}_0\left(\mathbf{A}_j\right)^{\mathrm{T}}\end{bmatrix}\begin{bmatrix}\ddot{\mathbf{R}}_j^{cm} \\ \dot{\boldsymbol{\omega}}_j\end{bmatrix}\right. \\ &\left. + \begin{bmatrix} 0 \\ \tilde{\boldsymbol{\omega}}_j\mathbf{A}_j\mathbf{J}_0\left(\mathbf{A}_j\right)^{\mathrm{T}}\boldsymbol{\omega}_j\end{bmatrix} - \begin{bmatrix}\mathbf{F}_j \\ \mathbf{T}_j\end{bmatrix}\right) = 0\end{aligned} \tag{6}$$

where $\delta\dot{\mathbf{r}}_j$ and $\delta\boldsymbol{\omega}_j$ are, respectively, the virtual translational and virtual angular velocities of body B_j, m_j and $\mathbf{A}_j$ are, respectively, the mass and rotation matrix of body B_j, $\mathbf{I}$ is the 3×3 identity matrix, $\mathbf{J}_0$ is the constant inertia tensor of body B_j, $\ddot{\mathbf{R}}_j^{cm}$ is the global acceleration vector of the center of mass of body B_j, $\tilde{\boldsymbol{\omega}}_j$ is the skew-symmetric matrix of $\boldsymbol{\omega}_j$, and $\mathbf{F}_j$ and $\mathbf{T}_j$ are the external forces and torques acting on body B_j, respectively. The equations of motion for the entire system can be expressed as [11]:

$$\delta\dot{\mathbf{q}}^{\mathrm{T}}(\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C} - \mathbf{Q}) = 0 \tag{7}$$

where $\delta\dot{\mathbf{q}}$ is the dependent virtual velocity, $\mathbf{M}$ is the mass matrix, $\ddot{\mathbf{q}}$ is the generalized acceleration vector, $\mathbf{C}$ is the quadratic velocity vector, and $\mathbf{Q}$ is the generalized external force vector. To reduce the size of the system, equations of motion can be expressed using relative joint coordinates. To this end, the velocity transformation matrix $\mathbf{R}$ that relates global coordinates and relative joint coordinates is introduced as follows [11]:

$$\dot{\mathbf{q}} = \mathbf{R}\dot{\mathbf{z}} \tag{8}$$

where $\dot{\mathbf{q}}$ is the generalized velocity vector and $\dot{\mathbf{z}}$ is the relative joint velocity vector. By differentiating Equation (8) with respect to time, $\ddot{\mathbf{q}}$ can be obtained as follows:

$$\ddot{\mathbf{q}} = \mathbf{R}\ddot{\mathbf{z}} + \dot{\mathbf{R}}\dot{\mathbf{z}} \tag{9}$$

where $\ddot{\mathbf{z}}$ is the relative joint acceleration vector and $\dot{\mathbf{R}}$ is the time derivative of $\mathbf{R}$. Now, by substituting Equations (8) and (9) into Equation (7), the original form of the equations of motion can be expressed as:

$$\delta\dot{\mathbf{z}}^{\mathrm{T}}(\mathbf{R}^{\mathrm{T}}\mathbf{M}\mathbf{R}\ddot{\mathbf{z}} + \mathbf{R}^{\mathrm{T}}\mathbf{M}\dot{\mathbf{R}}\dot{\mathbf{z}} + \mathbf{R}^{\mathrm{T}}\mathbf{C} - \mathbf{R}^{\mathrm{T}}\mathbf{Q}) = 0 \tag{10}$$

Since Equation (10) is valid for any arbitrary vector of independent virtual velocities, $\delta\dot{\mathbf{z}}$ can be eliminated and

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the equations of motion can be expressed in a simple form:

$$\mathbf{R}^{\mathrm{T}}\mathbf{M}\mathbf{R}\ddot{\mathbf{z}} = \mathbf{R}^{\mathrm{T}}(\mathbf{Q}-\mathbf{C}) - \mathbf{R}^{\mathrm{T}}\mathbf{M}\dot{\mathbf{R}}\dot{\mathbf{z}} \quad (11)$$

II.2. Hydraulic System Modeling

This study models a hydraulic subsystem to describe the forces provided by hydraulic actuators. In practice, pressures in a hydraulic volume can be modeled by employing lumped fluid theory, which assumes that the effect of acoustic waves is insignificant [12]. The differential equation for pressure p_i in each hydraulic section i of volume V_i can be expressed as [12]:

$$\frac{dp_i}{dt} = \frac{B_{e_i}}{V_i}\sum_{j=1}^{n_c} Q_{ij} \quad (12)$$

where B_{e_i} is the effective bulk modulus of hydraulic section i defining the compressibility, Q_{ij} is the ingoing or outgoing flow rate, and n_c is the total number of hydraulic inlets and outlets. Valves control the flow rate, pressure difference, and direction of the flow. The valves are modeled using a semi-empirical approach in which the parameters for many cases can be obtained from manufacturer catalogues. In the semi-empirical approach, the flow rate through the valve is calculated as follows [12]:

$$Q_v = C_v X_0 \sqrt{dp} \quad (13)$$

where Q_v is the flow rate through the valve, C_v is the flow rate constant defining the size of the valve, dp is the pressure difference between the volumes, and X_0 is the relative spool position that can be expressed as [12]:

$$\frac{dX_0}{dt} = \frac{U_{ref} - X_0}{\tau} \quad (14)$$

where U_{ref} is the reference voltage signal for the reference spool position, and τ is the time constant describing the valve spool dynamics. The hydraulic cylinder helps in converting hydraulic pressure into mechanical work. The force F_S produced by a hydraulic cylinder as shown in Fig. 2 can be expressed using its dimensions and pressure in each chamber as follows [12]:

$$F_S = p_1 A_1 - p_2 A_2 - F_\mu \quad (15)$$

where p_1 and p_2 are the pressure on the cylinder and piston side, respectively, A_1 and A_2 are the areas on the cylinder and piston side, respectively, and F_μ is the total friction force resulting from the contact of the seal material with the cylinder and piston wall.

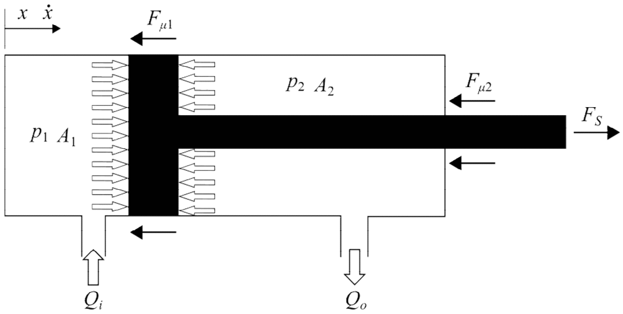

Fig. 2. Free body diagram of a hydraulic cylinder

II.3. Contact Formulation

During construction of a real-time mobile machine using multibody system dynamics, a contact subsystem also needs to be modeled. Moore and Wilhelms [13] have explained that there are two steps in contact formulation: collision detection and collision response. Collision detection determines the location and time of the collision, whereas collision response determines the contact force between the bodies involved. This research employs the object-oriented bounding box method [14] for collision detection and the penalty method [15] for collision response.

III. Gamification

The important advantage of gamification is increasing the engagement and involvement of users. This helps to create communities to improve collaboration [16]. Gamification creates challenges and new insights into regular life using the human instincts to engage in competition to learn, overcome barriers, and eventually win. Digital interaction through gamification makes the business environment more interactive and social. User-centric gamification design can increase customer satisfaction and productivity by minimizing errors to meet business goals [17]. In product development, the main aim is to introduce the experiences that people value most. The process can be done by motivating the people to reach their goal, and engaging them in product development is an excellent way of motivating them.

Leading users to have fun, explore, and use the product, developers can make their product more customer-oriented.

III.1. Elements of a Game

The role of gamification in a gamified application is to incorporate game elements. Reeves and Read [18] have identified the key game elements for a gamified experience. The key elements include goals and obstacles in the form of narrative contexts and rules that are explicit and enforced, challenges in the form of limited

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resources, fantasy in the form of self-representation with avatars and three-dimensional environments, and time constraints in the form of time pressure. Other examples of game elements include badges, leaderboards, and difficulty index in the form of reputations, ranks, and levels, team play in the form of teams, playfulness in the form of feedback, and play-centric design in the form of parallel communication systems that can be easily configured. In this study, a customizable simulation model provides options for bucket and hydraulic cylinder selection. The game elements incorporated in the customized simulation model are goals, obstacles, challenges, time constraints, and fantasy. Fig. 3 represents the flowchart of the gamification procedure adopted in this study.

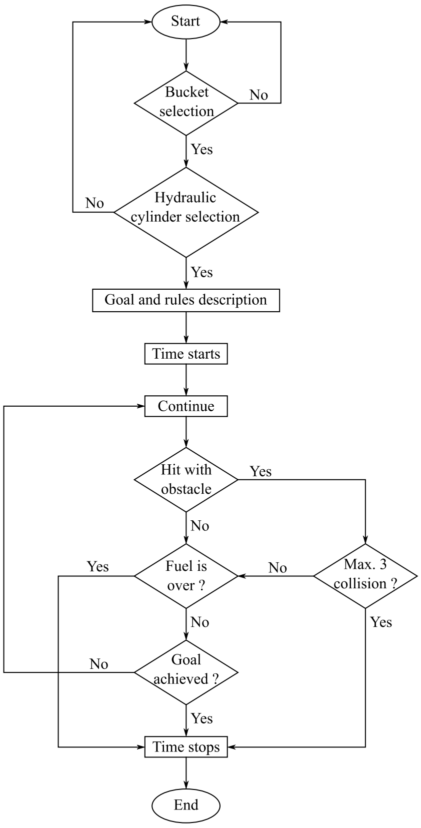

Fig. 3. Gamification procedure adopted in the study

III.2. Quantitative and Qualitative Methods of Extracting Data

The quantitative method starts with the data collection and analysis to support decisions on a particular phenomenon [19]. Game data is extracted to provide quantitative data for the study. Interviewing is one of the simplest and most practical qualitative methods of data collection [20].

There are different types of interview methods, such as narrative interviews, factual interviews, focus group interviews, and confrontational interviews [21]. This study employs semi-structured face-to-face interviews to obtain users' feedback.

III.3. Utilizing Virtual Prototype through Gamification

Dynamics deals with the forces, torque and effects of relative motions [22]. Thus, virtual prototyping with multibody system dynamics is crucial to replicate the real entity of a particular product.

To prepare a virtual prototype of a crawler type excavator, it is important to analyze the forces and motions of different parts of the excavator. This study includes different parameters to make the tasks more challenging, and system dynamics is needed in the virtual prototype of the excavator to make the model perform as intended.

IV. Case Study of an Excavator Model

Fig. 4 depicts the excavator that this study uses as a case example. The excavator is modeled using a semi-recursive approach as explained in section 2.

As Fig. 4 depicts, the model has nine bodies, 10 joints, two closed loop constraint equations, and 11 degrees of freedom. In addition, the driver controls six hydraulic cylinders to move the main boom, dipper arm, and bucket. Crawlers are modeled using particles and constraints, whereas the ground is modeled using a granular particle system.

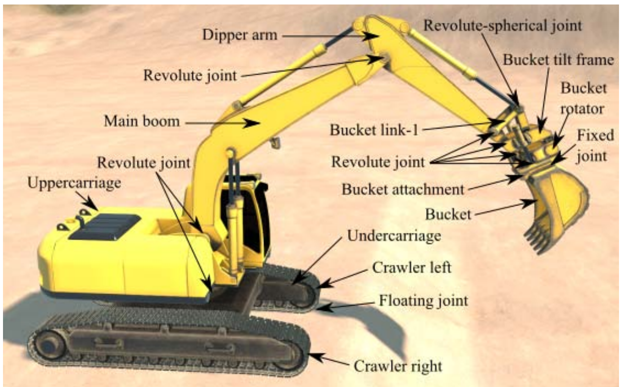

Fig. 4. Excavator model utilized in this case

IV.1. Customized Excavator Model

The excavator model under consideration can be modified. The size of the bucket and the hydraulic cylinder responsible for the movement of the dipper arm are the two customizable features. Different bucket sizes affect the amounts of particles dug, the working cycles, and fuel consumption [23].

Different hydraulic cylinder sizes affect the generated force, the torque generated by the hydro-motor, the lifting speed of the dipper arm, and fuel consumption [23]. It should be noted that the velocity and the reaction of the dipper arm have a significant effect on the working cycle time and total operation time.

Table I and Table II represent, respectively, three different sizes of buckets and hydraulic cylinders available for users.

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TABLE I
DIFFERENT SIZES OF BUCKETS [23]

Size	Volume (m^3)	Mass (kg)
Small	0.318	315
Medium	0.512	450
Large	22.55	750

TABLE II
DIFFERENT SIZES OF DIPPER ARM'S HYDRAULIC CYLINDERS [23]

Size	Cylinder diameter (mm)	Piston-rod length (mm)	Mass (kg)
Small	120	1630	8
Medium	140	1650	10
Large	160	1670	12

IV.2. Task Utilized in Gamification

The excavator model described above is gamified by introducing game elements, such as goals, obstacles, challenges, time constraints, and fantasy, as section 3 explains. The game mechanics that this excavator model employs define the settings, rules, interactions, and boundary conditions of the game. However, the dynamics of this game depends on the users' behavior and their interaction with the gamified excavator model.

The goal of this gamified excavator model is to load two tons of gravel (represented as a percentage in the material indicator) into an industrial hopper. Users are free to collect gravel from anywhere on the ground.

Obstacles, such as utility poles, are placed near the industrial hopper. Users will be penalized if the bucket, dipper arm, or main boom hits the utility poles or the industrial hopper's edge, and the collision sensor reading will indicate this. Players are allowed to hit the obstacles a maximum of three times. A fuel gauge indicates the amount of fuel left. A timer measures the total time taken by the users to achieve the goal. Users have three attempts to achieve the goal. Fig. 5 illustrates the graphical user interface used to invoke the gamified experience, including all of the game elements introduced above.

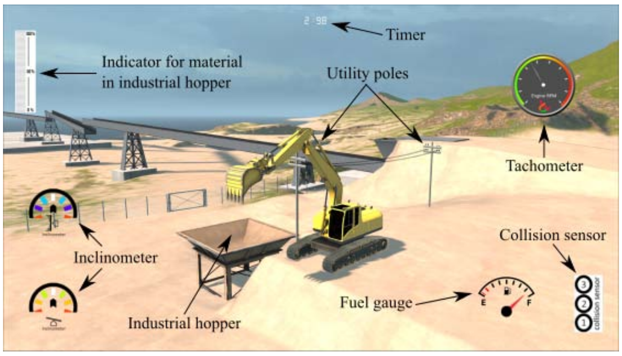

Fig. 5. Gamified graphical user interface for the excavator model

IV.3. Data Collection

This study presents data concerning the average time required to achieve the goal, the maximum number of hits with an obstacle, the average fuel consumption, the dipper arm's movement, and the selection of bucket and cylinder-piston options. A sample size of 16 users comprising of both experienced and inexperienced excavator users performed the task. In addition, semi-structured interviews were conducted to record user experiences on the trail run. The users received the questionnaires beforehand. As users' gamified experience is difficult to predict in the questionnaire, face-to-face interviews were conducted to obtain positive and negative feedback on the game.

V. Results and Discussion

This research explores the possibility of improving the excavator design through user experience. From the three successful attempts made by the users, a leaderboard was created based on the average weighted score of the time required, fuel consumption, and number of hits with obstacles. Based on the leaderboard, a comparison analysis was carried out for the arm movement, which is the distance between the center of the upper carriage and the center of the bucket. As an example, Fig. 6 compares the arm movements of the winner, the second-to-last, and the last person with respect to time in their first attempt.

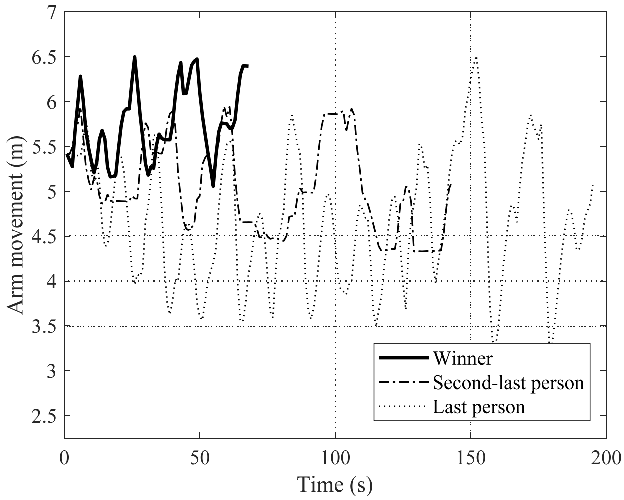

Fig. 6. Arm movement comparison between the winner, the second-to-last person, and the last person

Fig. 6 shows that the range of arm movement is 5 to 6.5 m for the winner, 4.2 to 6 m for the penultimate person, and 3.2 to 6.5 m for the last person. The winner's arm movement fluctuates rapidly but deviates relatively less compared to the second-to-last and last person. Based on the trend of the users, the more the arm movement fluctuates and the less it deviates, the less time the user consumes.

Therefore, the designer may consider this source of information for modifying the arm length, producing a more efficient design for performing a regular job. In addition, changing product features such as the size of the bucket or the size of the dipper arm's hydraulic cylinder affects users' performance. Out of all possible combinations of different sizes of buckets and hydraulic cylinders, Fig. 7 shows the percentage distribution of

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these possible combinations selected by the users. It is apparent that users most frequently chose a large bucket with a large or medium hydraulic cylinder. None of the users selected a small bucket and its combinations, and they even ignored medium bucket and small hydraulic cylinder.

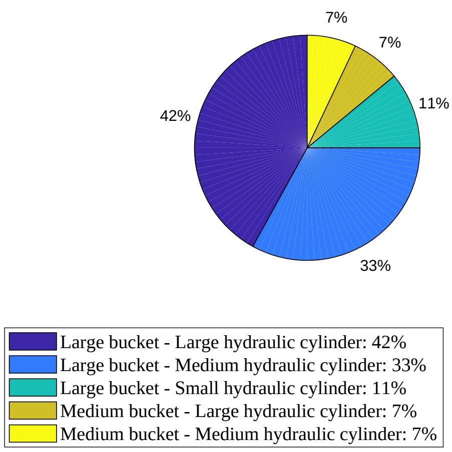

Fig. 7. Distribution of bucket and hydraulic cylinder size combinations selected by the users

As an example, Fig. 8 shows the performance of a user who chose different sizes of hydraulic cylinders in all three attempts but used a large bucket every time. For this user, the outcome was that when a medium hydraulic cylinder is chosen along with a large bucket, the time and fuel consumption was lower than when a large or small hydraulic cylinder is chosen.

A similar trend is observed for all of the other users as well. Whenever a large bucket and a medium hydraulic cylinder configuration were selected from any other configuration, the user's performance improved considerably.

Therefore, this study suggests that a large bucket and medium hydraulic cylinder may be the right combination for carrying out the regular task in hand. Similar studies can be carried out to benefit the product development team with such source of information.

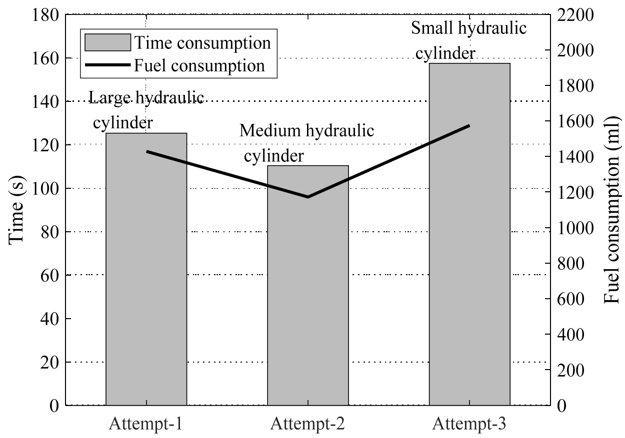

Fig. 8. Example of a user's performance with a large bucket and different hydraulic cylinder sizes

Along with the game data, this study also analyzes and discusses users' feedback from the interview process. It is noteworthy that 62% of the users found the goal to be challenging, whereas 38% found it easy. In addition, 94% of users identified the fantasy element and enjoyed the gamified experience, whereas 6% did not. The users also suggested that additional features such as a small screen inside the compartment, improved balancing system, and monitoring devices for temperature and humidity needs to be introduced.

VI. Conclusion

This study introduced a design approach in which the gamification concept is combined with a multibody dynamic system. The objective of this paper was to demonstrate how gamification can be used to analyze user experiences of a mobile machine. As a case study, an excavator was modeled using a semi-recursive formulation.

The excavator model introduced game elements such as filling the industrial hopper as the goal, utility poles as obstacles, fuel gauge as a challenge, a timer as a time constraint, and visualization graphics as the fantasy element. The excavator model offers different sizes for the bucket and the dipper arm's hydraulic cylinder. A leaderboard for the users was created based on the average weighted score of time required, fuel consumption, and the number of hits with obstacles.

Based on the leaderboard, the arm movements of the winner, the penultimate person, and the last person were compared. As a result, the more the arm movement fluctuated and the less it deviated, the less time the user consumed. In addition, changing product features such as the size of the bucket or the dipper arm's hydraulic cylinder affected user performance. A product development team can utilize this information in improving the product.

Along with the bucket or dipper arm's hydraulic cylinder, the product development team could customize numerous product features, and accordingly, select the best set of parameters. The results of this study function as a proof of concept. However, due to the limited sample size, conclusions regarding the excavator's design may be unreliable. The results from such procedures could be debatable if selection of the appropriate users for the study is not made with care. The set of users should be a combination of new, medium-experienced, and skilled users. Selecting new or medium-experienced users for the study might not provide reliable solutions.

By using a small set of users as in this study, no firm conclusion can be drawn from the users' feedback. In addition, the literature in this paper provides no information about the misuse of gamification in the context of this research work. For future research, it would be interesting to determine why different users experience/perform differently despite using exactly the same artifact under similar conditions.

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