LUT University

GAMIFICATION OF AN INDUSTRIAL MACHINE USING THE REAL-TIME SIMULATION IN VIRTUAL REALITY ENVIRONMENT

Teollisuuskoneen reaaliaikaisen simulaation pelillistäminen virtuaaliympäristöön

Lappeenranta-Lahti Univeristy of Technology LUT

Bachelor's Programme in Mechanics, Bachelor's thesis

2023

Pauli Pöppönen

Examiner: Lauri Pyrhönen M.Sc.(Tech)

ABSTRACT

Lappeenranta-Lahti Univeristy of Technology LUT

LUT School of Energy Systems

Mechanical Engineering

Pauli Pöppönen

GAMIFICATION OF AN INDUSTRIAL MACHINE USING THE REAL-TIME SIMULATION IN VIRTUAL REALITY ENVIRONMENT

Bachelor's thesis

2023

41 pages, 21 figures, 12 tables and 6 appendices

Examiners: Lauri Pyrhönen M.Sc.(Tech)

Keywords: Gamification, Indrustial machine, Real-Time, Virtual reality, Patu 655, Log crane, Game

Gamification is used in many fields for various needs. However its benefits have not yet been utilized to a large extent for training in the use of work machines. This work investigates of making a gamified simulation and further using that simulation as a training tool.

The real-time implementation of the simulation was done using a simulation program capable of handling both multibody dynamics and hydraulics. The hydraulic components work as the power transmission system of the selected industrial machine. The simulation was gamified with a separate game engine that also created an audiovisual environment. Those who used the gamified simulation were asked to fill out a survey.

From the survey of the study, it was noticed that the use of the gamified simulation increased the people's assessment of their own ability to use an industrial machine. Many users felt that the gamified simulation was realistic.

The gamified simulation of the industrial machine was found to be successful, with a verification of its real-time capability. From the survey, observations were made that could thus improve the simulation or the industrial machine itself.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Konetekniikka

Pauli Pöppönen

TEOLLISUUSKONEEN REAALIAIKAISEN SIMULAATION PELILLISTÄMINEN VIRTUAALIYMPÄRISTÖÖN

Kandidaatin työ

2023

41 sivua, 21 kuvaa, 12 taulukkoa ja 6 liitettä

Tarkastaja: Lauri Pyrhönen M.Sc.(Tech)

Avainsanat: Pelillistäminen, Teollisuus kone, Patu 655, Tukkinosturi, Peli, Realiaikainen, Virtuaali todellisuus

Pelistämistä käytetään monella alalla erilaisiin tarpeisiin. Pelillistämisen hyötyjä ei kuitenkaan vielä kaikilta osin ole hyödynnetty työkoneiden käytön koulutukseen. Tutkimuksessa perehdytään pelillistetyn simulaation tekemiseen ja pelillistetyn simulaaion käytöön työkoneen koulutuksen apuna.

Simulaation reaaliaikainen toteutus käyttäen simulaatio-ohjelmaa, joka kykenee simuloimaan sekä monikappaledynamiikkaa että hydrauliikkaa. Simulaatio pelillistettiin erillisellä pelimoottorilla, johon tehtiin myös audiovisuaalinen ympäristö lisäämään realistisuutta. Pelillistettyä simulaatiota käyttäneitä pyydettiin täyttämään kysely.

Tutkimuksen kyselystä huomattiin pelillistetyn simulaation nostavan henkilöiden arviota omasta osaamisestaan käyttää teollisuus konetta. Monet käyttäjät kokivat pelillistetyn simulaation olevan realistinen.

Teollisuus koneen pelillistetty simulaatio todettiin onnistuneeksi reaaliaikaisuuden todentamisen myötä. Kyselystä saatiin huomioita, joilla voitaisiin täten parantaa simulaatiota tai itse teollisuuskonetta.

Table of contents

Abstract

Tiivistelmä

Table of contents

Symbols and abbreviations

1 Introduction 8
- 1.1 Background 9
- 1.2 Aim and objectives 10

2 Multibody system dynamics combined with hydraulics 12

3 Simulation 14
- 3.1 Models 15
  - 3.1.1 Hydraulics 18
- 3.2 Mevea and Unity 19
- 3.3 Gamification 21
- 3.4 Realtime simulation 22

4 Results 24

5 Conclusions 27

References 29

Appendices

Appendix 1 Part properties

Appendix 2 Parts joint locations from body origin

Appendix 3 Joints locations on figures

Appendix 4 Hydraulics properties

Appendix 5 Gamification questionare

Appendix 6 Data from questionare

Figures

1 Picture from game 10

2 Open and closed loop structure in the coordinate system. The bodies are connected to each other by revolute joints in their system. (a) Open loop structure, structure remains open. (b) Closed loop structure, parts form a closed loop. 12

3 Hydraulics cylinder as an element of power transfer of an open-loop structure 13

4 Programs used in this thesis 15

5 (a) Incorrect surface orientation at Unity, (b) Pillar surface orientation visualisation turned on at Blender 17

6 Different purpose models: MeVEA model left (blue) Solidworks model center (green) Unity model right (red) 18

7 Hydraulic circuit 19

8 Meavea Solver motion data to Unity Mevea 2021 21

9 Game object (purple) as boundary box for logs box (green outlines) 22

10 Lift boom hydraulic cylinder pressures 23

11 Computation time without Unity 24

12 Computation time with Unity 25

13 Results of questionare 26

14 Pillar coordinate system orientation, origin point & COM

15 Lift boom coordinate system orientation, body coordinate system origin & COM

16 Tilt boom coordinate system orientation, body coordinate system origin & COM
17 Bracket 1 coordinate system orientation, body coordinate system origin & COM
18 Bracket 2 coordinate system orientation, body coordinate system origin & COM

19 Patu logcrane joint locations
20 Patu logcrane joint locations detail

21 Gamification questionare

Tables

1 Degrees of freedom 16
2 Accuracy comparison of models with Pillar model 18

3 Pillar joint locations from body origin (mm)
4 Lift boom joint locations from body origin (mm)
5 Tilt boom joint locations from body origin (mm)
6 Bracket 1 joint locations from body origin (mm)
7 Bracket 2 joint locations from body origin (mm)

8 Lift Hydraulic cylder (mm)
9 Tilt Hydraulic cylder (mm)
10 Claw Hydraulic cylder (mm)

11 Data from questionare
12 Legend for Table 11

SYMBOLS AND ABBREVIATIONS

Greek characters

ρ	density	[kg/m^3]

Abbreviations

3D	Three-dimensional
API	Application programming interface
CAD	Computer-aided desing
COM	Center of mass
Dll	Dynamic-link library
DOF	Degree of freedom
VR	Virtual reality

1 Introduction

Many different types of heavy machinery exist for different needs at different fields. However, what many machines have in common is the challenge of train personell. The challenge may be in the availability or cost of using the machine, which is why it is not worth running the machine at a low capacity. On the other hand, the available space may limit the training of several personnel at the same time. Training for heavy machinery can also be a risk to occupational safety. (Muth 2019; Cat 2022; Yadav et al. 2020, p. 133-145.)

The aviation industry has long used simulators to train pilots and maintain their skills. With the help of simulators, pilots are able to practice their skills in any kind of weather conditions while being able to repeatedly train challenging scenarios. The costs are minimal, as the simulation can be started at any point of ones choice. For example, pilots can specifically train the take-off from a challenging airport and once the air plane is in the air start the simulation again. Simulation also provides a safe environment where one can practice both standard situations and situations where something has gone terribly wrong. (Smith-Kohls 2020.)

The gamification of the simulation of industrial machines for training purposes has not been utilized on a large scale. A few simulation solutions for training exist, but they are not currently in use in many fields. At least one company is making real-time simulators for different companies (Mevea 2022). Large companies may have made simulations particularly for their own machines that are used to present products at various events or possibly to train their staff.

With gamificated simulation, the real machine would not have to be out of its actual use for the duration of the training, and it would be easier for the trainee to gain experience in using the machine in a safe virtual environment. Although gamified simulation may not fully teach how to use the real machine, it provides a solid basis for the person on functionalities of the machine and it is easier for them to start using the real machine.

1.1 Background

The study focuses on the usability of gamification for the training of industrial machines in real-time virtual environment. It is easier for the person being trained to try out the machine in a virtual environment where there is no risk of breaking down the machine or the environment. Occupational safety increases in a training situation when a person gets to try out the machine in virtual environment where other people are not present.

Different applications are needed to make gamified simulations and for all of these exist different options according to the needs. Multibody dynamics can be simulated, for example, with Mevea software. Multibody dynamics simulation require knowledge of body masses, centers of mass and inertia moments (Mevea 2022). In some cases the machine manufacturer may provide this information, or it van be obtained from Computer-aided desing (CAD) software, such as SolidWorks and Autodesk Inventor(AutoCad 2022; SolidWorks 2022). Many different programs exist for making games, such as Unity, Unreal Engine, Godot (Godot 2022; Unity 2022; Unreal 2022). In order to make a gamified simulation graphically spectacular, one needs a Three-dimensional (3D) modeling program where models and materials can be easily made. Such programs include, for example, Blender and Maya (Blender 2022; Maya 2022).

Using game elements in contexts that are not perceived as a game is one definition of gamification. Gamification can be done by adding, for example, achievements, points and/or a progress bar to the simulation, which tells the user how much of the required task is left or until you reach the next level. (Goethe 2019, p. 13-24.)

Currently, gamification is used in almost all fields, both in education and marketing. The purpose of gamification is to increase the user’s motivation and commitment to the task being taught. (Seaborn and Fels 2015.)

1.2 Aim and objectives

The machine chosen was the log crane Patu 655, which can be found at the LUT university. The log crane is relatively simple considering the multibody system. The actuation of the log crane is based on hydraulics, as tilting and lifting is performed by hydraulic cylinders and turning by a hydraulic motor. This study uses motor for turning as shown in Mevea tutorial 1 (Mevea 2020, p. 24-25).

The goal of this study is to create a gamified simulation in a virtual environment that can be used to teach a person to use the Patu 655 log crane. The study uses scoring to teach the user to place logs correctly in the cart so they can transported in a safe way. Figure 1 shows the scoring in the upper left corner.

Figure 1: Picture from game

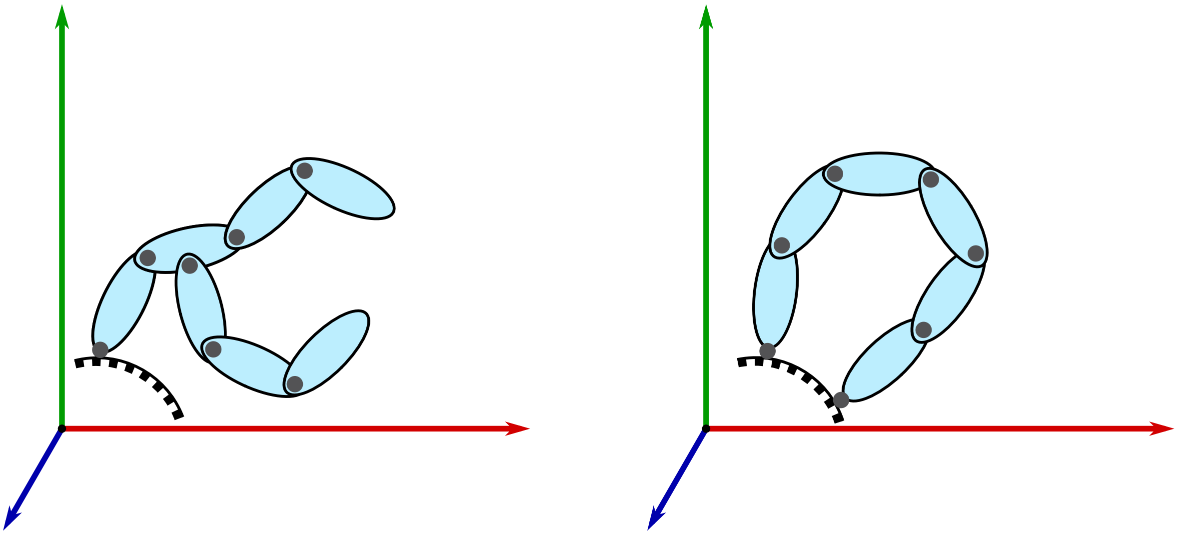
The gamification process is presented, including:

- Modeling the geometry of parts using CAD software and based on technical drawings
- Building a simulation model in simulation environment
- Visualizing the game with 3D software
- Building the actual gamificaion with game-engine

The resulted gamified simulation was tested by a group of users with various backgrounds and their feedback was collected in a form of a questionnaire to asses the success of the game. For the success of testing, it is important to receive information even from more experienced users than from completely new ones.

2 Multibody system dynamics combined with hydraulics

Multibody models consist of several rigid or flexible bodies connected together with joints. The parts are subject to potentially large rotations. These parts can be divided in different categories, which may partly overlap. These categories include subsystem, body, part and substructure. (Huston 1990, p. 1-33; Wittenburg 2008, p. 1-20.) The parts can be arranged either in an open loop structure or in a closed loop structure as shown in Figure 2.



(a) Open loop

(b) Closed loop

Figure 2: Open and closed loop structure in the coordinate system. The bodies are connected to each other by revolute joints in their system. (a) Open loop structure, structure remains open. (b) Closed loop structure, parts form a closed loop.

The joints connecting bodies together create kinematic constraints to the system. Possible joints include, for example, a revolute joint and a spherical joint. The revolute joint only allows rotation around one axis and prevents translational movement in all three directions, giving the joint one Degree of freedom (DOF). The spherical joint allows rotation around all axes, but similarly prevents translational movement, giving the joint three degrees of freedom. (Huston 1990, p. 88-89.)

Multibody systems can also have various force-transferring elements that are connected to the system. Power-transferring systems include, for example, an internal combustion engine, an electric motor, pneumatic and hydraulic components. Multibody dynamics examines the dynamic behavior of multibody systems. Figure 3 shows a hydraulic cylinder as a power-transferring element.

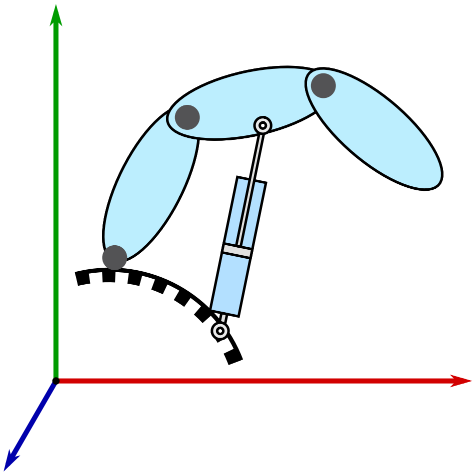


Figure 3: Hydraulics cylinder as an element of power transfer of an open-loop structure

The power transfer system of the study is the hydraulic system. The hydraulic system makes it easy to transfer the desired power to the desired location. Hydraulic systems are used in a wide variety of devices, such as precision control systems such as robots and aircraft. On the other hand, hydraulics is also used in systems that require great amount of power, such as various machines in the metal industry. Also, many mobile systems use hydraulic systems due to their high force-to-weight ratio. With electronic control, hydraulic systems are highly effective and accurate systems. (Watton 2014, p. 1-8.)

Single-cylinder hydraulic systems usually have a pump, two valves, a cylinder and a tank. The pump moves the liquid, and the valves control the direction of movement of the cylinder.

3 Simulation

Simulation is a very useful research tool to obtain information about the system under study without a physical prototype. The simulation model must be sufficiently accurate and appropriate to achieve useful results. A fundamental requirement of real-time simulation is that the evaluation time of the simulation needs to be less than the actual time that would be needed to realize the real physical action. When this is realized, the simulation can be presented visually in real-time.(de Jalon and Bayo 2012, p. 266.)

The complexity of the simulated object poses a challenge to the real-time nature of the simulation. Possible sources for complexity can be, for example, by the number of parts, the number of joints, the number of degrees of freedom and/or the accuracy of the graphics if it is necessary to visually represent the model. It is therefore necessary to carefully decide the physical phenomena to be studied to obtain the relevant information of the system, while maintaining the real-time capability. (Banks et al. 2004, p. 1-30.)

The game is based on a real-time simulation model of the industrial machine. Mevea was chosen to simulate multibody dynamics. The program was chosen because of its tutorials and documentation, in addition to which the author was already familiar with the program. (Mevea 2022.)

Unity was chosen as the game engine because people around the world have used the program to make games for computers, consoles and phones alike. Thanks to this, there are a lot of tutorials for the program as well as tips on how different things can be done, making it easy to gamify the simulation. (Unity 2022.)

The Blender program was chosen because it is an open-source 3D graphics creation program that can be used to create animations, surface materials and even videos in addition to models. Blender makes it easy to change models to other file formats needed in MeVea and Unity. Making materials is a remarkable feature that was used because it brings a sense of finish to the work. (Blender 2022.)

The Solidworks program was a natural choice for modeling objects as the values of body masses, centers of masses and inertia tensors were topics of interest. Because the author was already familiar with the program, there was no need to learn new user interfaces. Thanks to this, accurate models could be made quickly, as no time was spent practicing the program. (SolidWorks 2022.)

The programs were used to support each other and their connections are described in Figure 4. The picture also introduces the modified gamification workflow that was applied in this work. First, the models were made and information about the parts was defined, which were then added to the programs that were used to make the gamified simulation.

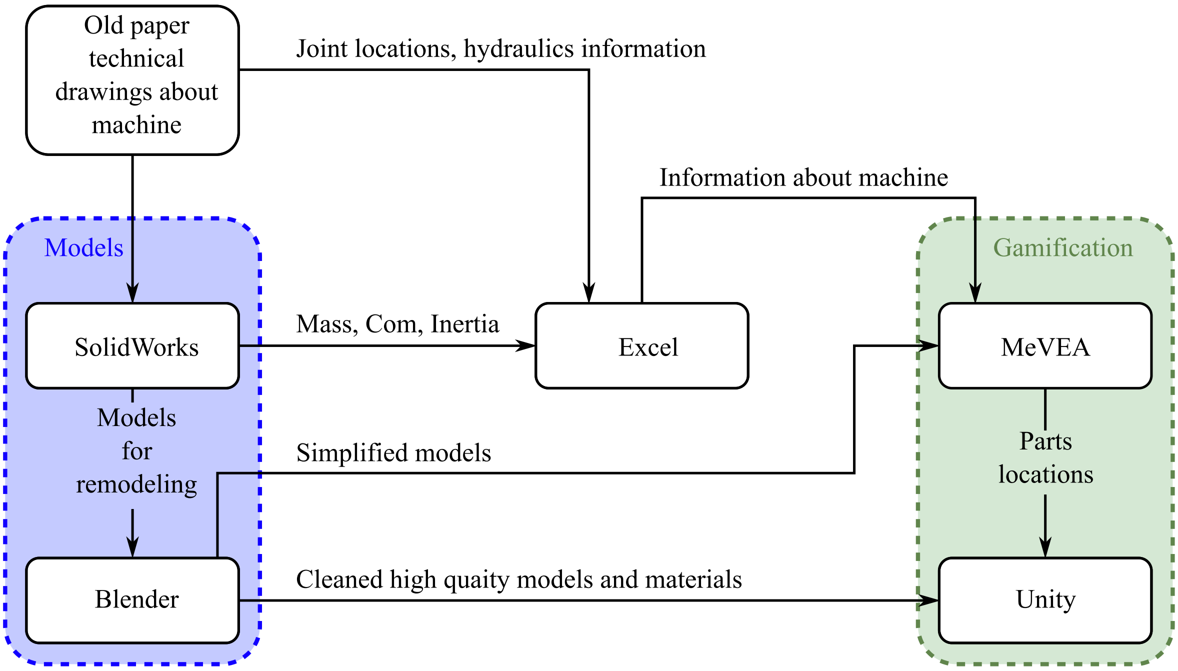


Figure 4: Programs used in this thesis

3.1 Models

The CAD models were prepared with Solidworks software from old technical drawings of the prototype. Simplification was made for the models material, assuming the bodies to be made of plain carbon steel with the most significant property being the mass density $\rho = 7800$ kg/m^3. The variation in the density characteristics between different steel grades is typically minimal and therefore this simplification can be considered acceptable. By using this density property, mass, Center of mass (COM) and inertias of the bodies are calculated.

Appendix 1 contains the properties of the bodies. The moments of inertia in the appendix, which values are calculated relative to the COM was selected for use. The COM is measured relative to the origin of the body, which is also one of the joints in the body. The origin and COM of the body are also visually illustrated in Appendix 1.

Based on the technical drawings and the manufacturer documentation of spare parts, the joints on the parts were verified, as well as the types of joints. In the models, the origin given to the parts serves as the one joint from which the other joints were dimensioned (see Appendix 2). The machine has a closed loop in which the parts are joined together in the shape of a loop in Appendix 3.

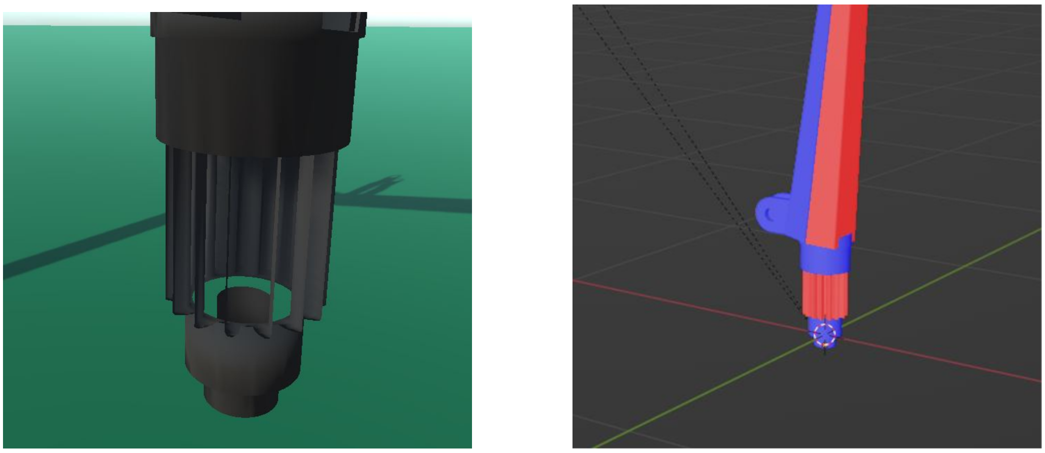
A table was made of the number of joints and the number of parts, which allows to calculate the DOF for the machine Table 1. From the table we note that the DOF would be zero in the machine. The reason for this calculation is that revolute joints in the same direction constraining the same direction of movement. The phenomenon is similar to the two hinges on the door, both introducing 5 constraints to a multibody system with only 6 coordinates however, producing a system with one DOF. In this case, the constraints are parallel.

Table 1: Degrees of freedom

Name	Number
Bodies	5
Revolute joints (open loop)	5
Revolute joints (closed loop)	1
Degrees of freedom (DoF)	0

The models prepared with Solidworks include highly complex geometries and were therefore modified in Blender to suit Mevea and Unity. Mevea's models were made extremely simple in order to use the same model as a collision box. Unity's models were made slightly more accurate but aimed at significantly reduced model resolution.

When making models, it is important to consider the orientation of surfaces. Especially in the Unity program, the surface orientation has a significant effect on the graphics. In Figure 5a, taken from Unity, it is noticed that the orientation of the surface is wrong and the part is visible through. This can be easily fixed in the Blender program by changing the surface. All surfaces have two sides: the opaque side and the transparent side. In Figure 5b, the Blender program has an activated feature , which visualizes the orientation of surfaces in models. In the picture, blue represents a surface through which one cannot see and a red surface is visible through.



(a) (b)

Figure 5: (a) Incorrect surface orientation at Unity, (b) Pillar surface orientation visualisation turned on at Blender

The models made for Unity can be lightened by removing surfaces irrelevant to visualization. Figure 6 graphically shows the differences between the models. Table 2 shows the differences between the models in terms of the number of points that make up the surface, number of edges that form between the points and number of surface elements. Of these differences, we note that solidworks models have significantly the most points from which the parts are formed.

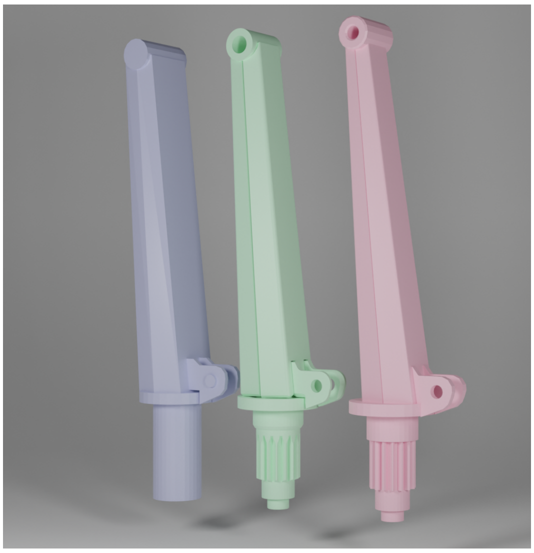


Figure 6: Different purpose models: MeVEA model left (blue) Solidworks model center (green) Unity model right (red)

Table 2: Accuracy comparison of models with Pillar model

Software	Verts	Edges	Faces
Mevea	348	676	336
SolidWorks	9052	27042	17980
Unity	3393	6610	3218

3.1.1 Hydraulics

The dimensions of the hydraulic cylinders were changed in relation to the technical drawings when modeling the cylinders in the Mevea software. The reason for this was the excessively large trajectories allowed by the cylinders, which would have broken the simulation. Errors in trajectories may be due to the dimensions of the prototype drawings that had not yet been fully verified or due to end dampers missing in the cylinder drawings. Appendix 4 shows the dimensions used in the work. The hydraulic circuit of the crane has three cylinders, three solenoid valves, a pump and a tank, as well as hoses that connect the hydraulic components to each other (Figure 7).

In the present system under study, each cylinder is controlled by one hydraulic valve. The valves are double-acting, that is, they can be used to control the cylinders in both directions. With the help of these cylinders, the crane is moved and a grapple is used to grab the logs.

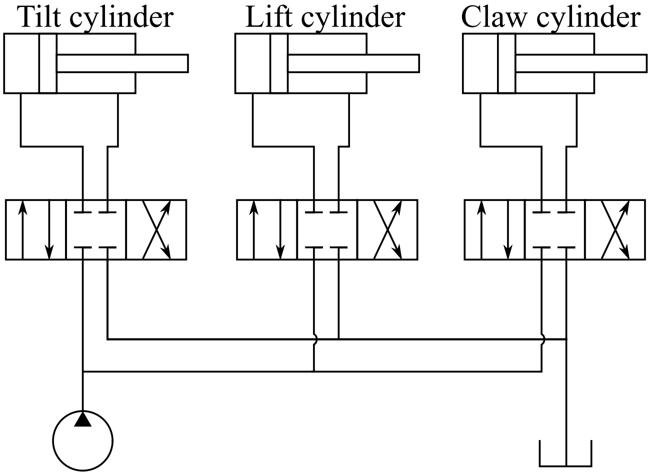


Figure 7: Hydraulic circuit

3.2 Mevea and Unity

MeVEA software is a real-time program developed for the simulation of dynamic systems. Using this software, it is easy to make a simulation of an industrial machine using multibody systems and multibody systems dynamics. It is easy to add graphics models to the software to illustrate the operation of the machine. (Mevea 2022.)

In the MeVEA Modeller program, the desired machine can be introduced by fixing it in coordinate system. Alternatively in the program, the machine can also be given an environment in which the machine can move. The movement of the machine in the environment is enabled by different joints and interaction forces, which are given in the form of various parameters. MeVEA Solver simulates a built entity.(Mevea 2020.)

In the software, one can also enter a collision parameter. In this case two parts are given either a new coarser model (so-called hit box) or the original model if it is not too complex which would slow down the calculation. Thanks to this feature, it is possible to model the contact behavior between parts.(Mevea 2020.)

The software can be used to define various external forces affecting to certain points of the multibody system. These forces can be defined as constant forces and torques in certain direction or to be generated. For example, by hydraulic cylinders or motors. All these features allow to accurately simulate the operation and behavior of the machines.(Mevea 2020.)

Since the gamification of this study is to be implemented in Virtual reality (VR), VR glasses are needed for it. This was easily implemented in Uniy by choosing a ready-made template, which already included the controls needed for the VR glasses, and to which the necessary game elements were added. The VR glasses worked flawlessly in Unity when the sensors that come with the VR glasses were placed near the workstation. With the help of these, the position and rotation of the glasses can be determined. In this case, the user of the simulation is able to move slightly in their surroundings, as well as look around.

The environment created in Mevea needs to be replicated in Unity, where the names of different bodies are required to be the same as the ones used in Mevea (Mevea 2021). In Unity, separate elements can then be added to the environment, such as a grass and trees that bring life and a sense of reality to the simulation. Each game element that appears to the user was given a material made with Blender.

In order to make the Unity model to follow the multibody simulation implemented with Mevea, the Unity package included with Mevea is added there, which offers a way to connect the programs with each other. The package works based on Mevea's Application programming interface (API) and Microsoft's Dynamic-link library (Dll). (Mevea 2021.)

In Unity, the package is added to the hierarchy. MeveaInterface is a prefabricated game object that includes code based on the C# programming language. This code uses the Dll interface to read Mevea's API. In this way, the location of the parts can be read from Mevea. In order to move parts in Unity, the parts of Mevea and Unity must be named in the same way. Figure 8 shows the data transfer principle between Mevea and Unity. (Mevea 2021.)

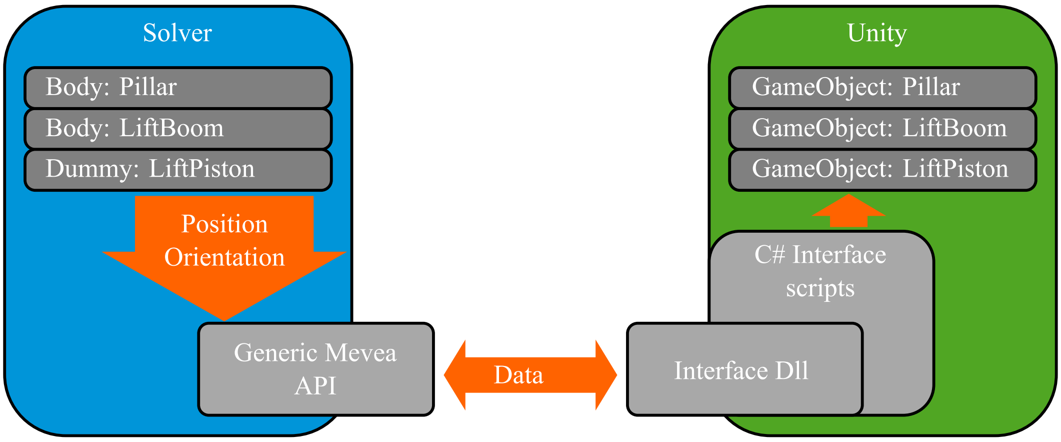


Figure 8: Meavea Solver motion data to Unity Mevea 2021

3.3 Gamification

Gamification of simulation requires some game elements to be added to it. For this purpose, rewarding with points was chosen as a game element. Calculating points is one of the simplest ways of implementing gamification (Reiners and Wood 2015, p. 1-3). The idea of the game is to lift a log into the trailer and place it in the cart in a suitable place to make it safe to transport the logs.

This has been accomplished in Unity by placing an invisible hit box on the trailer depicted in the Figure 9 with purple, which serves as a inspection area. Another hit box has been added inside each log to act as a viewing object that is depicted in the figure as a green border line within the black cylinder (representing the log). The game is designed to reward users on base of green hit boxes inside inspection area.

Each time a logs is being placed into the trailer area correctly, meaning the green box is fully inside the purple area, the user is rewarded by a point. When all the logs that were on the ground have been lifted into the cart correctly, the game beeps. This teaches users how to properly put the logs in the trailer, while teaching good working practice. If the logs are being placed poorly into the trailer, it will be more difficult to put the next logs.

Figure 9: Game object (purple) as boundary box for logs box (green outlines)

3.4 Realtime simulation

The inherent need of real-time capability of gamified simulation sets specific computational requirements for the simulation. In order to the simulation of the study to remain in real-time, the computation of each time step must be performed within 1.5 ms, which is the simulation time-step. This relatively short time step, in turn, is due to hydraulics being used as a source of force, which often has really fast vibrations during operation.(Mevea 2020.)

Figure 10 shows the pressure of the lifting boom on each side of the piston during work cycle. This figure sows that when the simulation is turned on, the hydraulics have a considerable vibration in the pressure.

During operation, pressure levels oscillate significantly. Therefore, to ensure the stability of the simulation, the simulation time-step is chosen to be 1.5 ms, which is also the maximum time-step hydraulics recommended by Mevea for hydraulics simulations.(Mevea 2020.)

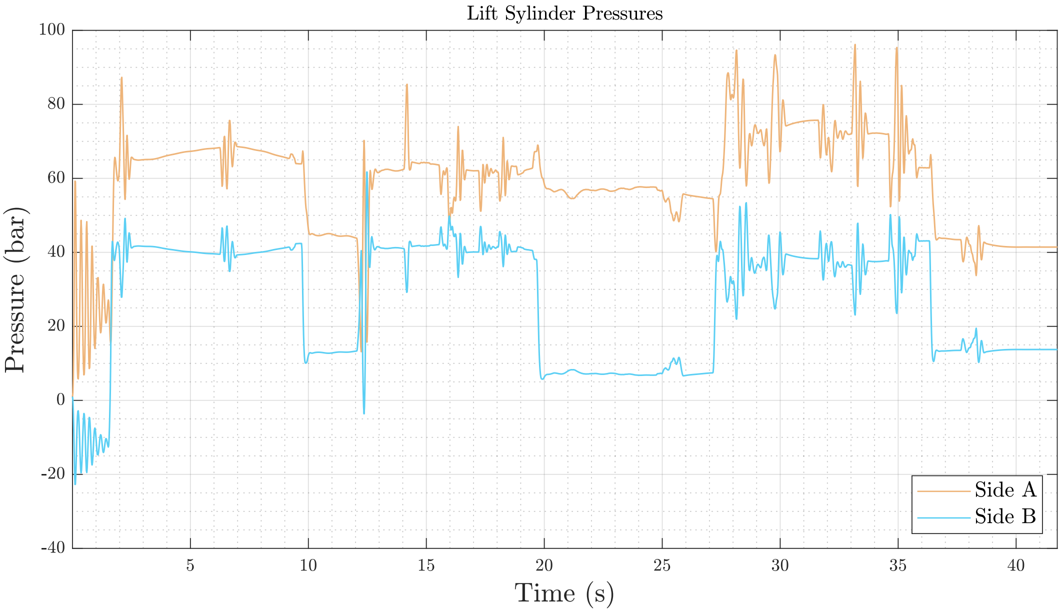


Figure 10: Lift boom hydraulic cylinder pressures

4 Results

The real-time capability was verified with the help of Mevea Solver, where the length of the computational time per simulation time-step time can be measured when the simulation is on. The real-time capability of the simulation was experimented in two ways: 1. when both Mevea and Unity are operating and 2. when only Mevea is operating. The computational times for both scenarios 1 and 2 are depicted in Figures 11 and 12, respectively. In both figures, the graph labeled as time step represents the limit under which the simulation is real-time, while computation time is the actual time used for calculation of one time step of simulation. In both experiments, the crane was operated as similarly as possible for fair comparison. A simulation was started, the first log was lifted into the trailer and the measurement was stopped.

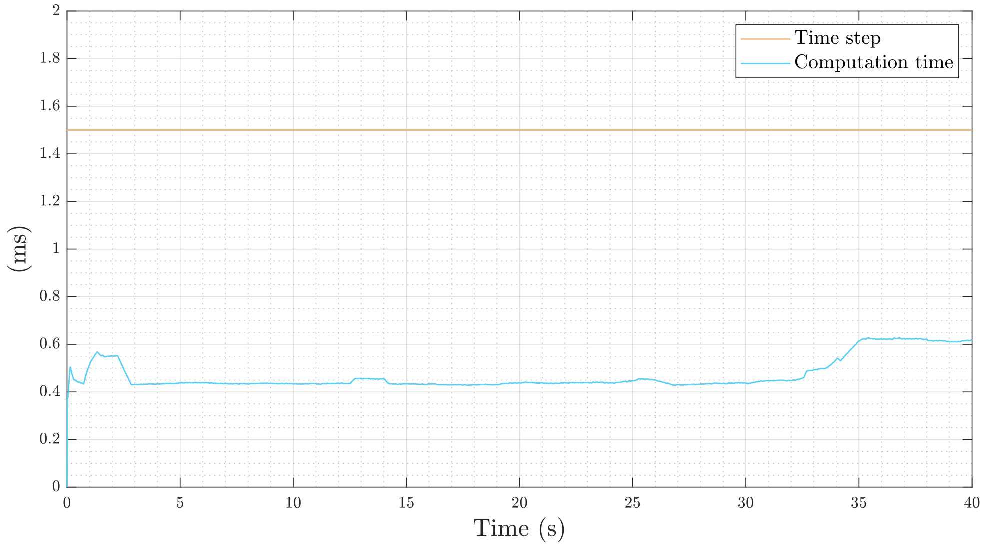


Figure 11: Computation time without Unity

The users were asked to fill a brief survey (Appendix 5) after they had used the gamified simulation and the data of the survey was collected for analysis. Users who had used heavy machinery or log cranes in the past was considered as a group of experienced operators in the analysis. The simulation was tested by four experienced users and six inexperienced users. The feedback from both these user groups were analyzed separately as well as the feedback of all the users.

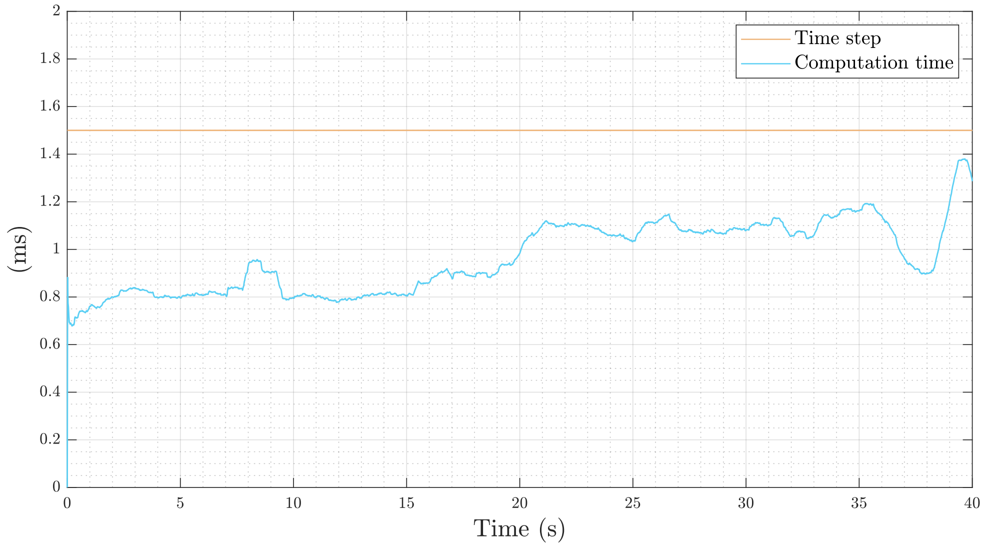


Figure 12: Computation time with Unity

The analyzed feedback from both experienced user group and inexperienced user group is depicted in Figure 13. The figure shows the average time users used the gamified simulation, and their average assessment for their competence to use the device before and after the training and their assessment on the realism of the simulation (points 0-5).

From the data obtained from the survey, it was found that the majority of those who tried the simulation stated that the simulation was realistic. Moreover, majority of users assessed their ability to use the simulation was enhanced even after only 15 minutes of experimentation. Two of those who tried the simulation felt that the device was more challenging in comparison with their initial assessment. However, these two users tried the simulation for less than 15 minutes. One experienced user estimated that the skill level remained the same. The survey also included two open questions that some of the individuals answered. In these questions, the users were asked for feedback how gamification or logcrane could be improved. These proposals highlighted:

- The correspondence of the joystick controls with the real machine
- Add collision boxes to parts
- Add visual aids to the user
- Stiffening the movement of the grapple

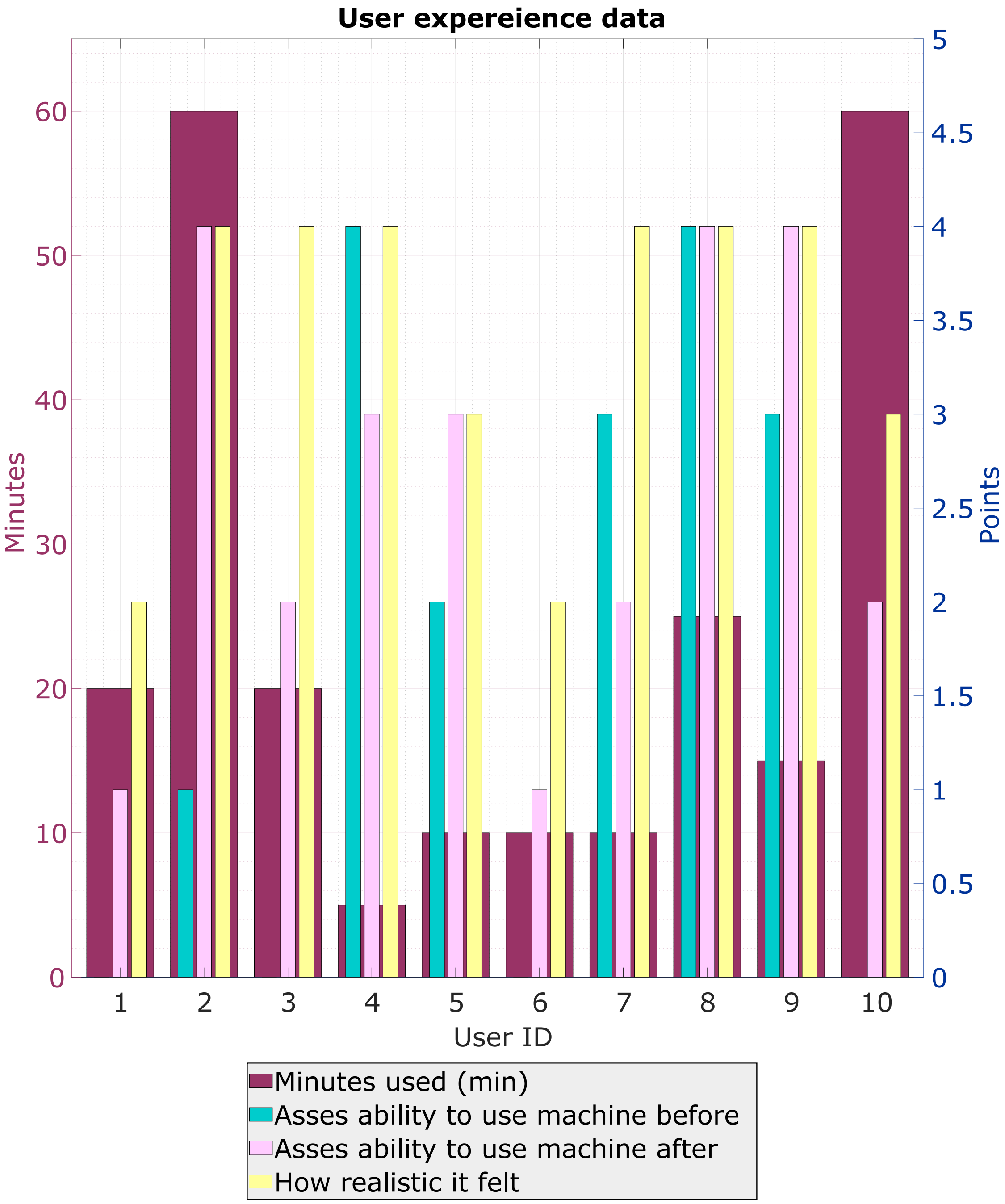


Figure 13: Results of questionare

5 Conclusions

The goal of the study was to gamify a real-time simulation of the Patu 655 log crane. Moreover, the successfulness of the gamified simulation was assessed by collecting feedback from the users in a form of a survey. The gamified simulation realized all the goals set for the work. The simulation achieved the real-time capability and the gamification was successfully implemented by adding a scoring feature into it. Moreover, survey provided the valuable feedback on the operation of the gamified simulation from the users' point of view.

Although the amount of data collected by the survey was relatively limited through both the number of questions and the number of users. However, answers clearly indicate that even with a relatively short training period, the users felt that even within a short period of time they felt that they had better control over the use of the device. All users in the group of experienced users (four in total) found that the gamified simulation corresponds well to a real device. The median time to use the simulation was 17.5 min among all the users. This can be considered relatively short period of time for actual training and in the further studies it could be further investigated how the users ability to use the simulation enhances after a longer period of time used for training. The users' willingness to use the simulation only a short period of time may be due to the simplicity of the game. Two people who only briefly tested the gamified simulation replied in the survey that the simulation was more difficult than they initially thought and that this could have changed if they had continued the experiment.

The answers to open questions revealed that some users would have liked the joystick controls to better correspond the controls of the real log crane. Another thing that users suggested was including the collision boxes for all parts of the device. In this work, some of collision phenomena present in the actual system were neglected in the simulation for the simplicity, and adding these would raise the sense of reality in the simulation.

In the open questions, the users also gave proposals how to develop the product itself. Some of the users felt difficulty in lifting the logs. They reported specifically difficulties in finding a correct lifting point (center of gravity) of the log, which made the log to swing in an uncontrolled manner. The users proposed assistance for finding the center of gravity of the log by a visual indicator. On the other hand, they also proposed that stiffening the movement of the grapple would diminish the swinging behavior and thus ease the operation of the crane. This visual proposition could also be implemented for the device itself with the help of various sensors and, for example, a laser pointer.

For a gamified simulation, it would be good to have a possibility to adapt the level of graphics complexity to the computing power of different hardwares, which could reduce certain elements on the screen. For example, reducing the amount of grass significantly reduces the computational loading of visualization, which allows more fluent use of gamified simulation also with lower end or older computers.

The simulation could also include more game elements, such as a leader board, which would help to increase the competitive spirit. The leader board could be based on, for example, time used to accomplish the loading of logs on trailer. In order to keep the training interesting and get more out of it, new levels could be made for the game, where the logs would be in different places and in different positions. The scoring system should check logs orientation related to trailer too. This would help users to understand better how to place logs on trailer correctly.

Gamification is a laborious process in which the target and scope of gaimification need to be carefully specified. The process of building the gamified simulation from scratch requires a great amount of time due to number of steps and programs needed. Gamification requires a range of skills and possibly also different experts, such as a screenwriter whose ideas are implemented by 3D modelers and coders. The realism of the game can be also increased by a realistic audio environment, which can be created by sound designers.

References

AutoCad 2022, ‘Inventor’, [AutoCad Website]. [Referenced 16-12-2022] Available at: `https://www.autodesk.fi/products/inventor/overview?us_oa=dotcom-us&us_si=a468d76d-6775-4837-a172-b46744e29b68&us_st=inventor&us_pt=Inventor&term=1-YEAR&tab=subscription&plc=INVPROSA`.

Banks, J., Carson, J., Nelson, B. L. and Nicol, D. 2004, *Discrete-Event System Simulation (4th Edition)*, Prentice Hall.

Blender 2022, ‘About’, [Blender website]. [Referenced 16-12-2022]. Available at: `https://www.blender.org/about/`.

Cat, W. S. 2022, ‘Recognizing heavy equipment hazards’, [Western States Cat Website]. [Referenced 13-12-2022]Available at: `https://www.westernstatescat.com/about-us/resources/heavy-equipment-hazards/`.

de Jalon, J. and Bayo, E. 2012, *Kinematic and Dynamic Simulation of Multibody Systems: The Real-Time Challenge*, Mechanical Engineering Series, Springer New York.

Godot 2022, ‘Godot’, [Godot Website]. [Referenced 16-12-2022]. Available at: `https://docs.godotengine.org/en/stable/`.

Goethe, O. 2019, *Gamification Mindset*, Human–Computer Interaction Series, Springer International Publishing, Cham.

Huston, R. L. 1990, *Multibody dynamics*, Butterworth-Heinmann.

Maya 2022, ‘Maya’, [AutoCad Website]. [Referenced 16-12-2022]. Available at: `https://www.autodesk.fi/products/maya/overview?us_oa=dotcom-us&us_si=152ffa7c-1438-4516-9394-6e2de61b2502&us_st=maya&us_pt=Maya&term=1-YEAR&tab=subscription&plc=MAYA`.

Mevea 2020, *Mevea Modeller Beginner Tutorials*, Mevea ltd., Lappeenranta, Finland.

Mevea 2021, *Mevea API documentation*, Mevea ltd., Lappeenranta, Finland.

Mevea 2022, 'Mevea', [Mevea Website]. [Referenced 16-12-2022]. Available at: `https://mevea.com/`.

Muth, R. 2019, 'Heavy equipment operator safety tips: 8 ways to prevent jobsite injury', [Heavy Metal Equipment & Rentals Website]. January 17, 2019 [Referenced 13-12-2022]. Available at: `https://www.heavyequipmentrentals.com/about/news/heavy-equipment-operator-safety-tips`.

Reiners, T. and Wood, L. C., eds 2015, *Gamification in Education and Business*, Springer International Publishing.

Seaborn, K. and Fels, D. I. 2015, 'Gamification in theory and action: A survey', *International Journal of Human-Computer Studies* pp. 14–31.

Smith-Kohls, T. 2020, '4 benefits of flight simulator training when learning to fly', [California Aeronautical University Website]. August 12, 2020 [Referenced 9-12-2022]. Available at: `https://calaero.edu/benefits-flight-simulator-training/`.

SolidWorks 2022, 'Solidworks', [SolidWorks Website]. [Referenced 16-12-2022]. Available at: `https://www.solidworks.com/`.

Unity 2022, 'Unity', [Unity Website]. [Referenced 16-12-2022]. Available at: `https://unity.com/`.

Unreal 2022, 'Unreal', [Unreal Website]. [Referenced 16-12-2022]. Available at: `https://www.unrealengine.com/en-US`.

Watton, J. 2014, *Fundamentals of Fluid Power Control*, Cambridge University Press, USA.

Wittenburg, J. 2008, *Dynamics of multibody systems*, 2nd ed. edn, Springer, Berlin.

Yadav, A., Arora, B., Varadharajan, S. and Yadav, B. P. 2020, State of the art review of accidents due to moving parts of the machinery in industries, *in* F. I. Khan, N. A. Siddiqui, S. M. Tauseef and B. P. Yadav, eds, 'Advances in Industrial Safety', Springer Singapore, Singapore, pp. 133–145.

Appendix 1. Part properties

In Figures 14 to 18:

- coordinate system orientation is depicted with red, blue and green arrows
- body coordinate system origin is depicted with full blue arrows
- COM is depicted with black and white mark

Pillar

```
Mass properties of PillarV4
Configuration: Default
Coordinate system: – default –

Mass = 88.418100 kilograms
Total weld mass = 4.839520 kilograms
Volume = 11308465.662433 cubic millimeters
Surface area = 1.675435 square meters

Center of mass: ( meters )
X = -0.017403
Y = 0.577291
Z = -0.000002

Principal axes of inertia and principal moments of inertia:
( kilograms * square meters )
Taken at the center of mass.
Ix = (-0.080378, 0.996764, -0.000004) Px = 0.509489
Iy = (-0.996764, -0.080378, -0.000162) Py = 16.461907
Iz = (-0.000162, -0.000009, 1.000000) Pz = 16.534255

Moments of inertia: ( kilograms * square meters )
Taken at the center of mass and aligned with the output
coordinate system. (Using positive tensor notation.)
Lxx = 16.358844 Lxy = -1.278080 Lxz = 0.000017
Lyx = -1.278080 Lyy = 0.612552 Lyz = -0.000059
Lzx = 0.000017 Lzy = -0.000059 Lzz = 16.534255

Moments of inertia: ( kilograms * square meters )
Taken at the output coordinate system.
(Using positive tensor notation.)
Ixx = 45.825490 Ixy = -2.166376 Ixz = 0.000019
Iyx = -2.166376 Iyy = 0.639331 Iyz = -0.000155
Izx = 0.000019 Izy = -0.000155 Izz = 46.027680
```

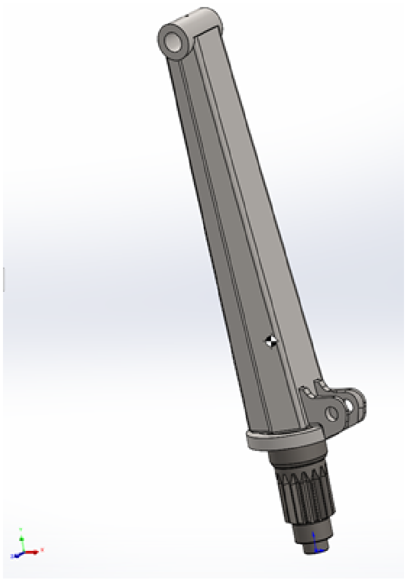


Figure 14: Pillar coordinate system orientation, origin point & COM

Lift boom

Mass properties of LiftBoomV4
Configuration: Default
Coordinate system: – default –

Mass = 129.945672 kilograms
Total weld mass = 13.717360 kilograms
Volume = 16659701.503127 cubic millimeters
Surface area = 4.291605 square meters

Center of mass: (meters)
X = 1.229248
Y = 0.055596
Z = 0.000000

Principal axes of inertia and principal moments of inertia: (kilograms * square meters)
Taken at the center of mass.
Ix = (0.999677, 0.025410, 0.000000) Px = 1.225049
Iy = (0.000000, 0.000000, -1.000000) Py = 110.452812
Iz = (-0.025410, 0.999677, 0.000000) Pz = 110.514230

Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system. (Using positive tensor notation.)
Lxx = 1.295612 Lxy = 2.776103 Lxz = 0.000000
Lyx = 2.776103 Lyy = 110.443667 Lyz = 0.000000
Lzx = 0.000000 Lzy = 0.000000 Lzz = 110.452812

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system. (Using positive tensor notation.)
Ixx = 1.697261 Ixy = 11.656735 Ixz = 0.000000
Iyx = 11.656735 Iyy = 306.798065 Iyz = 0.000000
Izx = 0.000000 Izy = 0.000000 Izz = 307.208859

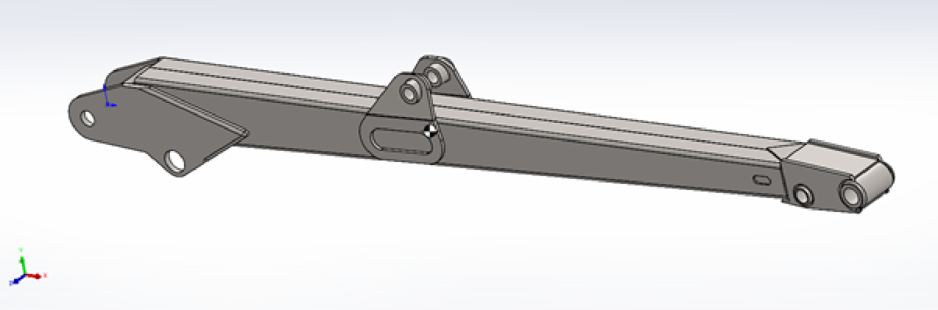


Figure 15: Lift boom coordinate system orientation, body coordinate system origin & COM

Tilt boom

```
Mass properties of TiltExtensionBoom
Configuration: Default
Coordinate system: – default –

Mass = 141.942729 kilograms
Total weld mass = 15.928340 kilograms
Volume = 18197785.722500 cubic millimeters
Surface area = 5.671741 square meters

Center of mass: ( meters )
X = 0.659935
Y = 0.251085
Z = 0.000000

Principal axes of inertia and principal moments of inertia: ( kilograms * square meters )
Taken at the center of mass.
Ix = ( 0.999758, 0.021999, 0.000000) Px = 1.023694
Iy = (-0.021999, 0.999758, 0.000000) Py = 66.608744
Iz = ( 0.000000, 0.000000, 1.000000) Pz = 67.053707

Moments of inertia: ( kilograms * square meters )
Taken at the center of mass and aligned with the output coordinate system. (Using positive tensor notation.)
Lxx = 1.055433 Lxy = 1.442440 Lxz = -0.000003
Lyx = 1.442440 Lyy = 66.577004 Lyz = 0.000000
Lzx = -0.000003 Lzy = 0.000000 Lzz = 67.053707

Moments of inertia: ( kilograms * square meters )
Taken at the output coordinate system. (Using positive tensor notation.)
Ixx = 10.004029 Ixy = 24.962320 Ixz = 0.000000
Iyx = 24.962320 Iyy = 128.395055 Iyz = 0.000001
Izx = 0.000000 Izy = 0.000001 Izz = 137.820354
```

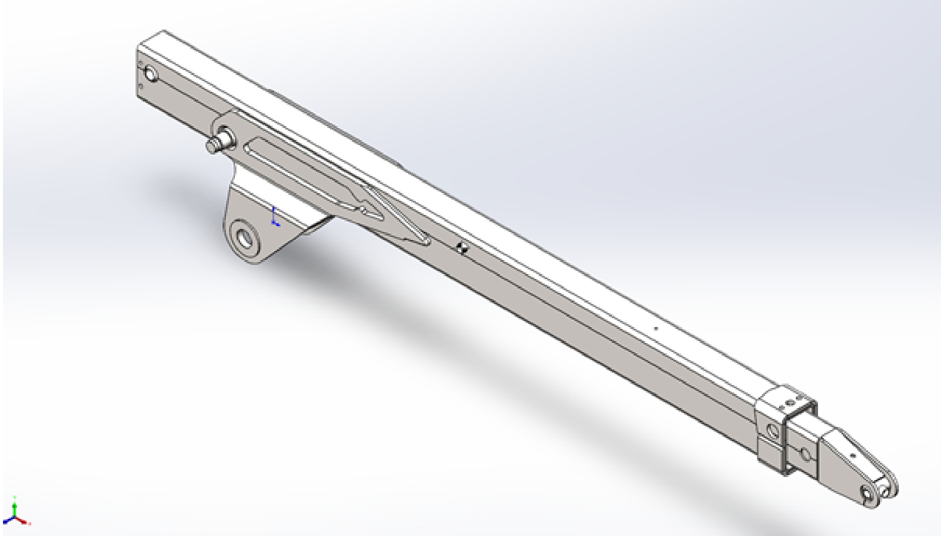


Figure 16: Tilt boom coordinate system orientation, body coordinate system origin & COM

Bracket 1

Mass properties of Bracket1
Configuration: Default
Coordinate system: – default –

Mass = 11.524039 kilograms
Total weld mass = 1.207660 kilograms
Volume = 1477440.890506 cubic millimeters
Surface area = 0.265682 square meters

Center of mass: (meters)
X = 0.004000
Y = 0.257068
Z = 0.000000

Principal axes of inertia and principal moments of inertia: (kilograms * square meters)
Taken at the center of mass.
Ix = (0.068597, 0.997644, 0.000000) Px = 0.080655
Iy = (0.000000, 0.000000, 1.000000) Py = 0.268644
Iz = (0.997644, -0.068597, 0.000000) Pz = 0.334259

Moments of inertia: (kilograms * square meters)
Taken at the center of mass and aligned with the output coordinate system. (Using positive tensor notation.)
Lxx = 0.333066 Lxy = 0.017355 Lxz = 0.000000
Lyx = 0.017355 Lyy = 0.081849 Lyz = 0.000000
Lzx = 0.000000 Lzy = 0.000000 Lzz = 0.268644

Moments of inertia: (kilograms * square meters)
Taken at the output coordinate system. (Using positive tensor notation.)
Ixx = 1.094621 Ixy = 0.029205 Ixz = 0.000000
Iyx = 0.029205 Iyy = 0.082033 Iyz = 0.000000
Izx = 0.000000 Izy = 0.000000 Izz = 1.030384

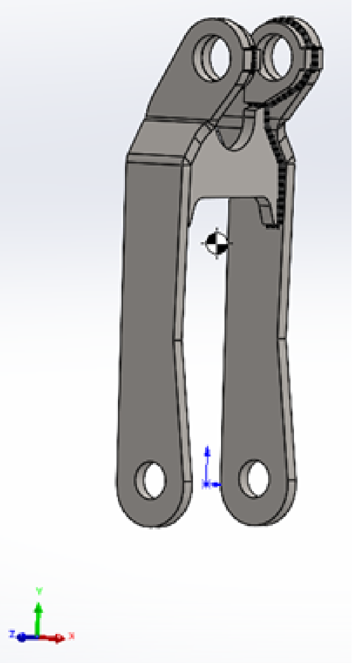


Figure 17: Bracket 1 coordinate system orientation, body coordinate system origin & COM

Bracket 2

```
Mass properties of Bracket2
Configuration: Default
Coordinate system: – default –

Mass = 7.900191 kilograms
Volume = 1012845.048931 cubic millimeters
Surface area = 0.206653 square meters

Center of mass: ( meters )
X = 0.212792
Y = 0.000000
Z = 0.000000

Principal axes of inertia and principal moments of inertia: ( kilograms * square meters )
Taken at the center of mass.
Ix = ( 1.000000, 0.000000, 0.000000) Px = 0.052095
Iy = ( 0.000000, 0.000000, -1.000000) Py = 0.216772
Iz = ( 0.000000, 1.000000, 0.000000) Pz = 0.260808

Moments of inertia: ( kilograms * square meters )
Taken at the center of mass and aligned with the output coordinate system. (Using positive tensor notation.)
Lxx = 0.052095 Lxy = 0.000000 Lxz = 0.000000
Lyx = 0.000000 Lyy = 0.260808 Lyz = 0.000000
Lzx = 0.000000 Lzy = 0.000000 Lzz = 0.216772

Moments of inertia: ( kilograms * square meters )
Taken at the output coordinate system. (Using positive tensor notation.)
Ixx = 0.052095 Ixy = 0.000000 Ixz = 0.000000
Iyx = 0.000000 Iyy = 0.618533 Iyz = 0.000000
Izx = 0.000000 Izy = 0.000000 Izz = 0.574497
```

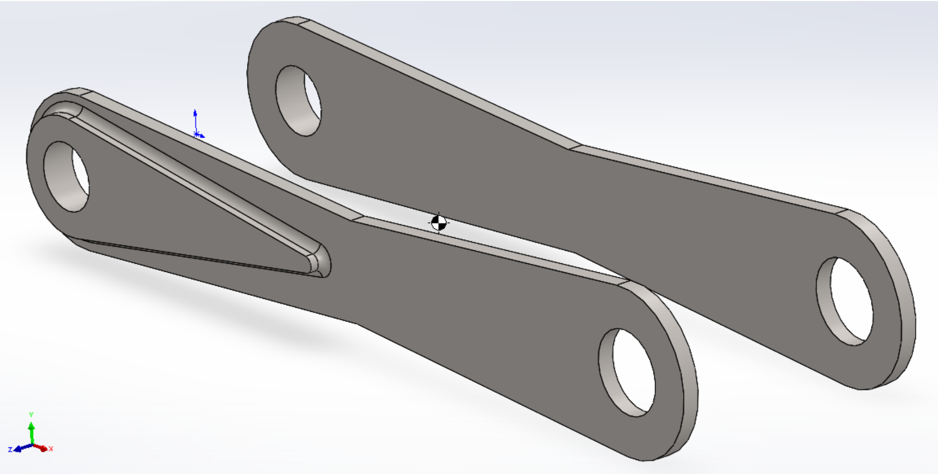


Figure 18: Bracket 2 coordinate system orientation, body coordinate system origin & COM

Appendix 2. Parts joint locations from body origin

Table 3: Pillar joint locations from body origin (mm)

Part	Mount	Lift boom	HyLiftC
X	0	-90	170
Y	0	1426.11	386.1132
Z	0	0	0

Table 4: Lift boom joint locations from body origin (mm)

Part	Pillar	HyLiftP	HyBracketsC	Bracket 1	Tilt boom
X	0	302.5	1263	2690	2880.081
Y	0	-105	206.7022	6.592554	21.59255
Z	0	0	0	0	0

Table 5: Tilt boom joint locations from body origin (mm)

Part	Lift boom	Bracket 2	Load
X	0	95	2208.057
Y	0	-240.432	10.56546
Z	0	0	0

Table 6: Bracket 1 joint locations from body origin (mm)

Part	Lift boom	HyBracketsP
X	0	42.5
Y	0	457.2274
Z	0	0

Table 7: Bracket 2 joint locations from body origin (mm)

Part	Lift boom	HyBracketsP
X	0	480
Y	0	0
Z	0	0

Appendix 3. Joints locations on figures

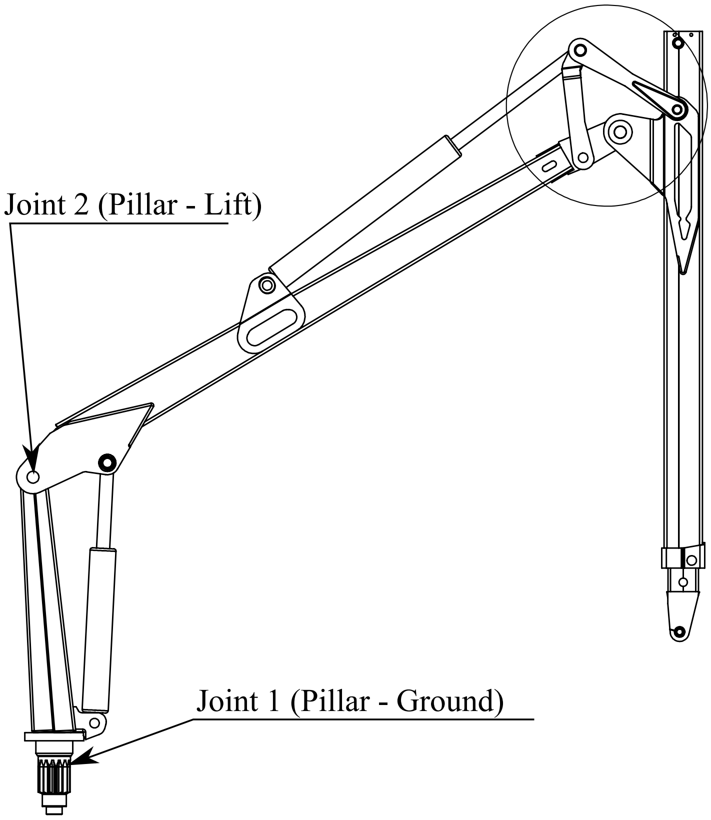
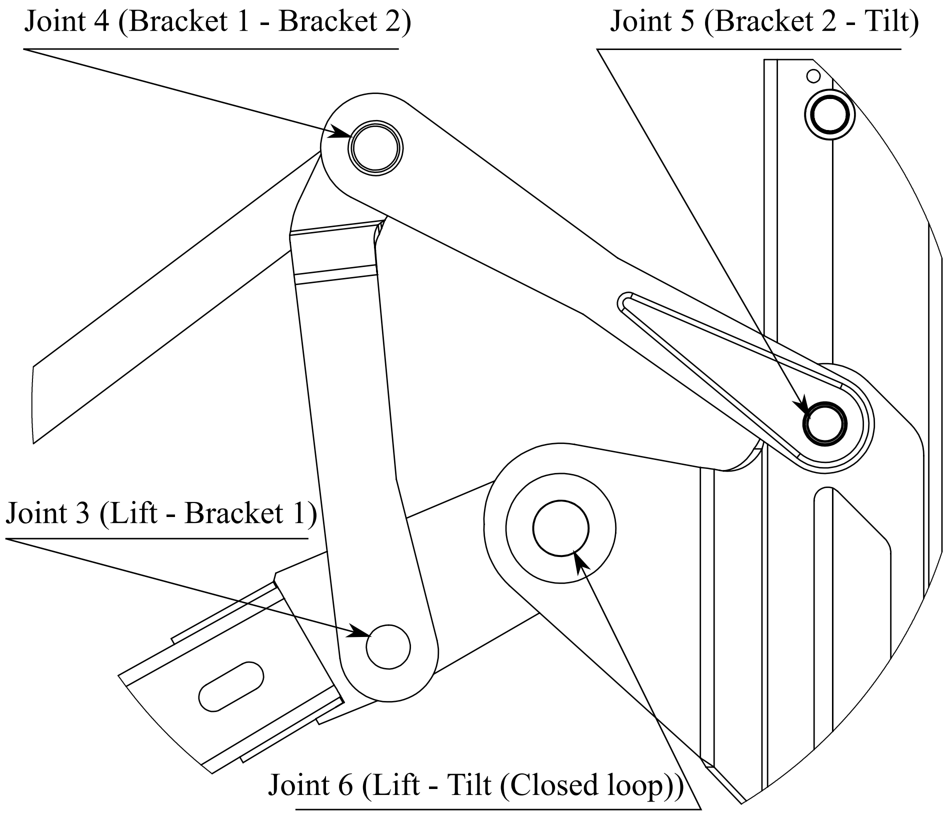


Figure 19: Patu logcrane joint locations



DETAIL

Figure 20: Patu logcrane joint locations detail

Appendix 4. Hydraulics properties

Table 8: Lift Hydraulic cylder (mm)

Piston Rod length	650
Cylinder Chamber length	590
Piston length	55
Cylinder attachement length	95
Min stroke	115
Max stroke	650

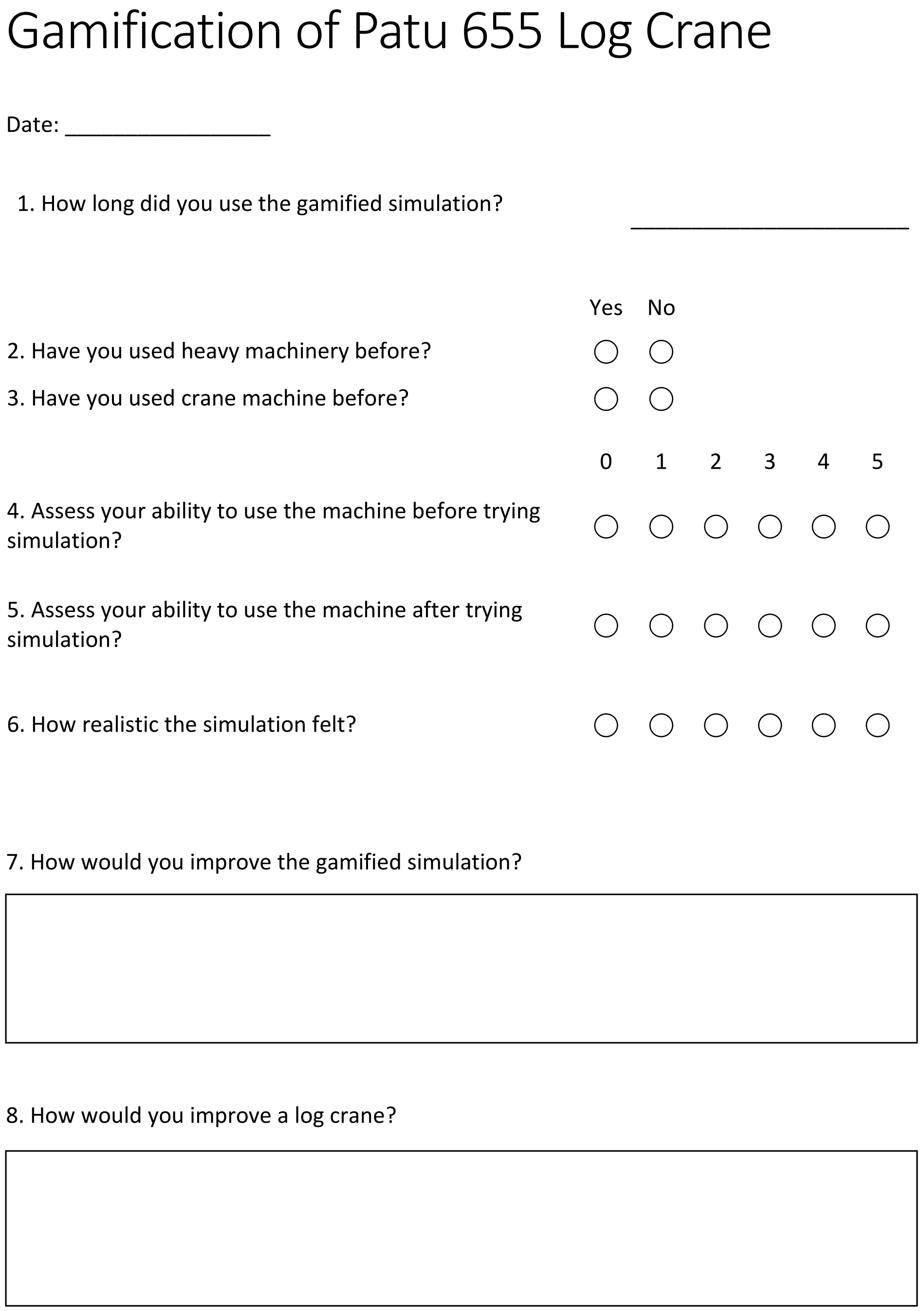
Table 9: Tilt Hydraulic cylder (mm)

Piston Rod length	905
Cylinder Chamber length	825
Piston length	45
Cylinder attachement length	100
Min stroke	125
Max stroke	905

Table 10: Claw Hydraulic cylder (mm)

Piston Rod length	343
Cylinder Chamber length	320
Piston length	35
Cylinder attachement length	92
Min stroke	58
Max stroke	343

Appendix 5. Gamification questionare



Gamification of Patu 655 Log Crane

Date: ________________

1. How long did you use the gamified simulation? ______________________

	Yes	No				
2. Have you used heavy machinery before?	○	○				
3. Have you used crane machine before?	○	○				
	0	1	2	3	4	5
4. Assess your ability to use the machine before trying simulation?	○	○	○	○	○	○
5. Assess your ability to use the machine after trying simulation?	○	○	○	○	○	○
6. How realistic the simulation felt?	○	○	○	○	○	○

7. How would you improve the gamified simulation?

8. How would you improve a log crane?

Figure 21: Gamification questionare

Appendix 6. Data from questionare

ID	min	Ex	AB	AA	Re	QT	Better	Same	Worse
1	20	0	0	1	2	0	1	0	0
2	60	0	1	4	4	0	1	0	0
3	20	0	0	2	4	0	1	0	0
4	5	1	4	3	4	1	0	0	1
5	10	1	2	3	3	1	1	0	0
6	10	0	0	1	2	1	1	0	0
7	10	0	3	2	4	1	0	0	1
8	25	1	4	4	4	0	0	1	0
9	15	1	3	4	4	1	1	0	0
10	60	0	0	2	3	0	1	0	0
	min	**Ex**	**AB**	**AA**	**Re**	**QT**	**Better**	**Same**	**Worse**
Users		4/10				5/10	7/10	1/10	2/10
Median	17.5		1.5	2.5	4				
Average	23.5		1.7	2.6	3.4				

Table 11: Data from questionare

User = **ID**
Time used simulation (min) = **min**
Asses ability to use before = **AB**
Asses ability to use after = **AA**
Realism = **Re**
Experienced user = **Ex**
Quickly tried = **QT**
Assessed ability to be better = **Better**
Assessed ability to be same = **Same**
Assessed ability to be worse = **Worse**

Table 12: Legend for Table 11