Lappeenranta
University of Technology

Lauri Luostarinen

NOVEL VIRTUAL ENVIRONMENT AND REAL-TIME SIMULATION BASED METHODS FOR IMPROVING LIFE-CYCLE EFFICIENCY OF NON-ROAD MOBILE MACHINERY

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1381 at Lappeenranta University of Technology, Lappeenranta, Finland on the 1st of April, 2015, at noon.

Acta Universitatis
Lappeenrantaensis 630

Supervisor	Professor Heikki Handroos Laboratory of Intelligent Machines Department of Mechanical Engineering Lappeenranta University of Technology Finland
Reviewers	Research Professor Timo Määttä Smart Industry and Energy Systems Systems Engineering Remote Operation and Virtual Reality (ROViR) VTT Technical Research Centre of Finland Ltd Finland
	Professor Andrzej Sobczyk Division of Hydraulic Drives and Transportation Equipment Institute of Machine Design Faculty of Mechanical Engineering Cracow University of Technology Poland
Opponents	Research Professor Timo Määttä Smart Industry and Energy Systems Systems Engineering Remote Operation and Virtual Reality (ROViR) VTT Technical Research Centre of Finland Ltd Finland
	Professor Andrzej Sobczyk Division of Hydraulic Drives and Transportation Equipment Institute of Machine Design Faculty of Mechanical Engineering Cracow University of Technology Poland

ISBN 978-952-265-762-6
ISBN 978-952-265-763-3 (PDF)
ISSN-L 1456-4491
ISSN 1456-4491

Lappeenrannan teknillinen yliopisto
LUT Yliopistopaino 2015

Preface

The research for this dissertation was carried out during the years 2011 - 2014 in the Laboratory of Intelligent Machines, Department of Mechanical Engineering, Lappeenranta University of Technology (LUT). The research was carried out in a project which was financially supported by Finnish Metals and Engineering Competence Cluster (FIMECC). The main target of the project was to take a significant step towards user centred research and development of mobile machines by developing virtual environments and real-time simulators. Demand for the research topic originated from two non-road mobile machinery manufacturers participating the project.

A spin-off company of LUT specialized in developing real-time simulation systems for mobile machinery participated the project. In this work, the experimental simulations are carried out using simulation software of this company because many methods and solutions are based on the work carried out in LUT. In addition, the research team had prior knowledge about the models and methods used.

I would like to express my gratitude to my supervisor Professor Heikki Handroos for encouraging me in research work.

I gratefully appreciate the valuable work that my reviewers Research Professor Timo Määttä and Professor Andrzej Sobczyk have done in reviewing my thesis and also the response they provided to me to improve this thesis.

I would like to express my gratitude to my colleagues at the Laboratory of Intelligent Machines and also in other laboratories of Department of Mechanical Engineering. The good spirit has supported me during the years.

In addition, word of thank to my family and friends who have supported me in preparing this thesis.

Last but very certainly not least I would like to thank my beloved Iina for understanding and patience she has shown during this work.

Lappeenranta, April 2015

Lauri Luostarinen

Abstract

Lauri Luostarinen

Novel virtual environment and real-time simulation based methods for improving life-cycle efficiency of non-road mobile machinery

Lappeenranta 2015
80 p.
Acta Universitatis Lappeenrantaensis 630
Diss. Lappeenranta University of Technology
ISBN 978-952-265-762-6
ISBN 978-952-265-763-3 (PDF)
ISSN-L 1456-4491
ISSN 1456-4491

Virtual environments and real-time simulators (VERS) are becoming more and more important tools in research and development (R&D) process of non-road mobile machinery (NRMM). The virtual prototyping techniques enable faster and more cost-efficient development of machines compared to use of real life prototypes. High energy efficiency has become an important topic in the world of NRMM because of environmental and economic demands. The objective of this thesis is to develop VERS based methods for research and development of NRMM.

A process using VERS for assessing effects of human operators on the life-cycle efficiency of NRMM was developed. Human in the loop simulations are ran using an underground mining loader to study the developed process. The simulations were ran in the virtual environment of the Laboratory of Intelligent Machines of Lappeenranta University of Technology. A physically adequate real-time simulation model of NRMM was shown to be reliable and cost effective in testing of hardware components by the means of hardware-in-the-loop (HIL) simulations. A control interface connecting integrated electro-hydraulic energy converter (IEHEC) with virtual simulation model of log crane was developed. IEHEC consists of a hydraulic pump-motor and an integrated electrical permanent magnet synchronous motor-generator.

The results show that state of the art real-time NRMM simulators are capable to solve factors related to energy consumption and productivity of the NRMM. A significant variation between the test drivers is found. The results show that VERS can be used for assessing human effects on the life-cycle efficiency of NRMM. HIL simulation responses compared to that achieved with conventional simulation method demonstrate the advances and drawbacks of various possible interfaces between the simulator and hardware part of the system under study. Novel ideas for arranging the interface are successfully tested and compared with the more traditional one.

The proposed process for assessing the effects of operators on the life-cycle efficiency will be applied for wider group of operators in the future. Driving styles of the operators can be analysed statistically from sufficient large result data. The statistical analysis can find the most life-cycle efficient driving style for the specific environment and machinery. The proposed control interface for HIL simulation need to be further studied. The robustness and the adaptation of the interface in different situations must be verified. The future work will also include studying the suitability of the IEHEC for different working machines using the proposed HIL simulation method.

Keywords: virtual environment, real-time simulator, simulation, non-road mobile machinery, off-highway, working vehicle, log crane, mining loader, human effect, human factor, energy consumption, fuel consumption, productivity, efficiency, HIL, hardware in the loop, HITL, human in the loop

Contents

List of publications

The thesis consists of following scientific journal and conference articles.

1. L. O. Luostarinen and H. Handroos, "Using Simulation in Virtual Reality Environment to find effects of human operators on the life-cycle efficiency of off-highway working vehicles", *International Review on Modelling and Simulations (IREMOS)*, vol. 6, no. 5, pp. 1629-1636, 2013.

2. L. O. Luostarinen, R. Åman, H. Handroos, “Tool for studying effects of human operators on energy consumption of working hydraulics of off-highway working vehicle”, *8th FPNI Ph.D Symposium on Fluid Power*, 2014, Lappeenranta, Finland.

3. R. Åman, P. Ponomarev, L. O. Luostarinen, H. Handroos, J. Pyrhönen, L. Laurila, “Experimental Analysis of Electro-Hydraulic Hybrid Actuator Systems in Off-Highway Working Vehicles”, *8th FPNI Ph.D Symposium on Fluid Power*, 2014, Lappeenranta, Finland.

4. L. O. Luostarinen, R. Åman, H. Handroos, “Development of Control Interface for HIL Simulation of Electro-Hydraulic Energy Converter”, *International Review on Modelling and Simulations (IREMOS)*, vol. 7, no. 4, pp. 653-660, 2014.

Symbols and abbreviations

A	Area
A_{cyl}	Piston area
A_{or}	Area of orifice
B_c	Bulk modulus of a cylinder
B_e	Effective bulk modulus
B_h	Bulk modulus of a hose
B_p	Bulk modulus of a pipe
C_d	Discharge coefficient
$Coll$	Number of collisions
E	Energy
E_{hydr}	Hydraulic energy
E_{mec}	Mechanical energy
ELF	Engine load factor
F_{cyl}	Cylinder force
F_{RMS}	Root mean square value of a cylinder force
F_{μ}	Friction force of a cylinder
FC	Fuel consumption
$\mathbf{M}$	Mass matrix
p	Pressure
p_{LS}	Pressure in load sensing line
p_p	Pressure at pump outlet
p_{tank}	Tank pressure

Δp	Pressure difference
P	Power
P_{hydr}	Hydraulic power
P_{mec}	Mechanical power
$Prod$	Working productivity
Q	Volume flow
$\ddot{q}$	Vector of accelerations of n generalized coordinates
$\mathbf{Q^c}$	Vector of generalized constraint forces
Q_{cyl}	Cylinder volume flow
$\mathbf{Q^e}$	Vector of generalized forces
Q_{in}	Volume flow into a volume
Q_{out}	Volume flow out of a volume
Q_p	Pump volume flow
$\mathbf{Q^v}$	Quadratic velocity vector incl. velocity-dependent inertia forces
T	Torque
t	Time
Δt	Simulation time step length
V	Volume
v	Piston velocity
V_c	Volume of a cylinder
V_h	Volume of a hose
$V_{p\ rad}$	Radian volume of a pump
V_p	Volume of a pipe

V_{tot}	Total volume
x	Piston position
η	Efficiency
η_{vol}	Volumetric efficiency of a pump
ρ	Fluid mass density
ω	Angular velocity

3D	Three Dimensional
DOF	Degree Of Freedom
FIMECC	Finnish Metals and Engineering Competence Cluster
HIL	Hardware-in-the-Loop
HITL	Human-in-the-Loop
HMI	Human Machine Interface
ID	Inverse Dynamics
IEHEC	Integrated Electro-Hydraulic Energy Converter
LHD	Load-Haul-Dump vehicle
LUT	Lappeenranta University of Technology
MBS	Multibody System Dynamics
NRMM	Non-Road Mobile Machinery
PID	Proportional-Integral-Derivative
R&D	Research and Development
RMS	Root Mean Square
UX	User Experience

VE	Virtual Environment
VERS	Virtual Environment and Real-time Simulator
VR	Virtual Reality

PART 1: OVERVIEW OF THE DISSERTATION

1. Introduction

1.1 Background and motivations

This research was conducted in the Energy and Life Cycle Cost Efficient Machines (EFFIMA) research program, project New Generation Human-Centred Design Simulators for Life Cycle Efficient Mobile Machines (LEFA), managed by the Finnish Metals and Engineering Competence Cluster (FIMECC), with the aim of developing and designing a virtual environment (VE) based tools for the purpose of mobile machine design, testing and operator training.

Non-road mobile machinery (NRMM) is used for ore extraction, road and site construction, freight handling as well as for several other industrial sectors. They are essential for modern civilization. NRMM developed for different tasks have much structural similarities. Typically they consist of steel body, rubber tires, hydraulic actuators and mechanical power transmissions. Typically NRMM is operated by a human operator. Because of the similarity of the machines, the research methods developed and tested for one type of NRMM can be often applied also for other type of machines. In the case studies of this work an underground mining loader and a log crane are taken as examples (Figure 1).

Life-cycle efficiency of mining machines is an important issue because the production of primary metals can be expected to increase in the future due to the increasing global demand for end products. Like other industrial sectors, the mining industry is facing pressure to reduce environmental impact. It has been found that the loading and hauling stage has the most significant contribution to CO_2 emissions for iron ore and bauxite production [1]. In addition, a company manufacturing mining loaders was a participant in the project, in which the research cases are carried out. Thus, an underground mining loader was used in two case studies.

Forest industry has a significant role for economics of Finland. A several log crane and forest machine manufacturers are located in Finland. Because of previous projects, a log crane was available in the Laboratory of Intelligent Machines in Lappeenranta University of Technology (LUT). Thus, it was natural to carry out the hardware-in-the-loop (HIL) simulation case studies using the log crane (Figure 1b).

(a) (b)

Figure 1. Non-road mobile machinery: (a) mining loader, (b) log crane

High energy efficiency ensures the competitiveness of NRMM manufacturers under environmental and economic pressure. Design processes have traditionally placed emphasis on technical performance rather than human effect. Though, the human operator has a key role in operation of NRMM.

It has been found that by changing the driving style in traffic, human operator can reduce the energy consumption of the vehicle over 30 percent [2]. Effects of operating style and human machine interface (HMI) on the energy efficiency of small unmanned ground vehicle has been also studied. When operating the vehicle below the optimal velocity, the energy consumption can increase by up to 100 percent [3]. However, the nature and extent of the human effect on the life-cycle efficiency of NRMM has not been well determined. Articles discussing the energy efficiency of NRMM exist, but they are not describing the effects of human operators on NRMM in details [4], [5], [6], [7].

Understanding the human effect can contribute significantly the development of more efficient machinery. The development of virtual environments and real-time simulators (VERS) has created new possibilities for studying the human effect on NRMM and for studying benefits of novel energy efficient technology. The acronym VERS is not yet well established. Interest in electro-hydraulic hybrid power transmissions has recently been remarkable among researchers and manufacturers. Ensuring the suitability of new components for different machines requires extensive testing. Initial testing can be carried out completely in virtual environment (VE). After manufacturing the first prototype of a new component, further tests can be carried out using HIL simulation where the new prototype is run as part of a virtual working machine.

1.2 Scope of the work

The aim of this doctoral thesis is to show that life-cycle efficiency aspects and especially the effects of human operators on life-cycle efficiency can be considered in research and development (R&D) of NRMM significantly more detailed than with traditional R&D methods. State of the art VERS enable immersive simulation of physically adequate models of NRMM. The work concentrates on developing a method to study effects of human operators on life-cycle efficiency of NRMM. The effects of human operators are studied on the overall energy consumption and productivity of a mining loader. The effects of human operators on the energy consumption of working hydraulics of the mining loader are also studied. A comprehensive study of efficient operating styles is not carried out but the suitability of VERS for comparing life-cycle efficiency of different operating styles is shown. The work also concentrates on developing a control interface connecting integrated electro-hydraulic energy converter (IEHEC) with virtual simulation model of log crane. The control interface is developed for testing the physical IEHEC prototype in operation of hydraulic cylinders for different NRMM in the future. The work only gives samples of possibilities of presented technology and methods. Due to increasing computing capacity and more realistic virtual technology a number of new ideas and applications can be proposed in the future. Investment costs into such technology is becoming quite reasonable.

1.3 Scientific contribution of thesis

The main contributions of the work lies in the research of methods for R&D of NRMM to take advantage of VERS technology.

1. Studying the suitability of VERS to find effects of human operators on the life-cycle efficiency of NRMM. Developing a process for R&D of NRMM which is taking the effects of human operators into account in early phase of development. Such a study with a virtual environment of this extend has not been proposed in the reference articles. The present study clearly indicates the importance of driving skills in many factors affecting the life-cycle. The results demonstrate significant variations in life-cycle related factors.

2. Experimental studying and development of novel control interfaces for HIL Simulation of Electro-Hydraulic Energy Converter as a part of power transmission of NRMM. Novel ideas in selecting the quantities transmitted through the interface back and forth are presented. In particular using virtual closed loops to approximate variables typically obtained by using inverse dynamic model is rarely used in literature.

1.4 Author's contribution

Four scientific articles have been published regarding to research introduced in this dissertation. The author was the first writer in three articles. In addition, he co-authored one article.

Author has worked as a member of team responsible for the design and realization of the VERS in the Laboratory of Intelligent Machines at LUT.

Author was responsible for designing and organizing user tests. Sequent, the suitability of VERS to find effects of human operators on the life-cycle efficiency of NRMM was studied. Author has analysed the results of user tests and proposed a process which is taking the effect of human operators into account in R&D of NRMM. Following titles of articles are related to this part of the research.

1. Using Simulation in Virtual Reality Environment to find effects of human operators on the life-cycle efficiency of off-highway working vehicles

2. Tool for studying effects of human operators on energy consumption of working hydraulics of off-highway working vehicle

The author was responsible for developing a control system of the test rig used for HIL simulations of integrated electro-hydraulic energy converter (IEHEC). In addition, the author has worked as a team member responsible for carrying out the experimental testing. Furthermore, the author was responsible for modelling multibody model of the log crane, developing a novel interface connecting test rig and multibody model. After preparations experimental tests were run and results analyzed. Following titles of articles are related to this part of the research.

3. Experimental Analysis of Electro-Hydraulic Hybrid Actuator Systems in Off-Highway Working Vehicles

4. Development of Control Interface for HIL Simulation of Electro-Hydraulic Energy Converter

1.5 Outline of the thesis

In Chapter 2, a state of the art review of virtual environments and real-time simulation is given and the simulation software used for the research of this thesis is introduced.

Chapter 3 introduces the simulation laboratory and proposes a process for using VERS to find effects of human operators on the life-cycle efficiency of NRMM.

Chapter 4 presents the development of HIL simulation system for studying suitability of integrated electro-hydraulic energy converter for different working machines.

In Chapter 5 the results of this work are discussed and recommendations for future research are presented.

In Chapter 6 the conclusions are presented.

2. State of the art - Theoretical background

2.1 Virtual environments and real-time simulators in research and development of non-road mobile machinery

The terms virtual reality (VR) and virtual environment (VE) have been widely used by researchers and nowadays also by industry. The terms have slight interpretation differences in literature. In addition, the meanings of VR and VE are very close to each other. Commonly the terms VR and VE are describing a computer synthesized, three dimensional environment in which human participants have a sense of presence and they can navigate around the environment. Realistic effects and interaction with physical objects are essential for the sense of presence in VR and VE. [8], [9], [10]

Simulation is the imitation of the significant parts of operation of a real-world system or process over time. [11], [12], [13] Simulation can be carried out using computers [14], [15], [16], [17].

Real-time simulation can be seen as a special case of conventional simulation. Typically, the conventional simulation methods used in the product development processes are free from solution time restrictions. As a consequence, the simulation of a few seconds is allowed to take several minutes or even hours of real time. This is called off-line simulation. In the case of real-time simulation, the calculation must be processed according to predetermined time requirements on real time. In the case of NRMM simulation, the predetermined simulation time step is typically around one millisecond. A time synchronous connection between the virtual real-time simulation and the real world enable human-in-the-loop (HITL) and hardware-in-the-loop simulations. [18], [19], [20], [21], [22] , [23]

The following definition of simulator is used in this work. A real-time simulator is a device which simulates a physical system and is responding to external stimuli as fast as the real system. The simulator is required to sense operator’s actions and respond so fast that the operator cannot distinguish between simulator response and true system response. [11], [12], [17], [19]

The development of VERS has enabled detailed review of machine design and assessing the effects of human operators on the machinery in early phase of R&D process. VERS have a potential to decrease the time-to-market and to improve the understanding of customer needs, which are important factors in product success of NRMM nowadays. [6], [24], [25], [26], [27], [28], [29] Constructing of such VERS has been discussed in [30], [31], [32], [33] and [34]. The level of immersion of VERS has a significant effect on the usefulness of the results [35]. Figure 2 illustrates two examples of VERS.

Simulations carried out in virtual environment have significant advantages over field tests on a real vehicle. Typically, manufacturing, testing and modifying of real machines is more expensive compared to virtual implementation. In addition, the conditions of experimental tests can be set equal for all participants and uncommon and dangerous conditions can be studied safely. Furthermore, data acquisition is relatively easy in VERS because real sensors are not required. [36], [37], [38]

A disadvantage of simulators is that the accuracy of the results is not absolute because as a rule the accuracy of the simulation model is limited. Thus, simulators are most suitable for comparing technical solution or human performances and for operator training. [36], [37] A weak immersion can cause inaccuracy in results [35]. Some get symptoms of simulator sickness in VERS. Thus, they cannot perform tasks in the VERS in the same level of performance as in real working environment. [39], [40]

Figure 2. Virtual environments [41]

2.2 Studying human related factors

Three possible methods can be employed in research of human effect on NRMM: 1) Field tests on a real vehicle, 2) Human-in-the-Loop simulation, 3) completely virtual simulation including models for machinery and operator performance.

2.2.1 Completely Virtual implementation

Completely virtual simulations of human operated NRMM require modelling of the performance of human operators. Accurate human operator models would enable studying of human related factors also in off-line simulations. Driver models that take the fundamental human factors (i.e. gender, age and driving experience) into account have been developed for relatively simple car driving tasks [42]. Human-performance models has been studied also to assess operator performance during excavation processes but integrating all aspects of human performance and behaviour into simulation model remains still a challenge [43]. NRMM are operated in varying and harsh environments which requires the operators to adapt in new situations often. Studying of human effects requires detailed performance models to achieve reliable results but the development of such models has not succeeded, so far. Thus, a real-time simulation and virtual environment with a real human operator are required for studying effects of human operators.

2.2.2 Human-in-the-Loop Simulation

In HITL simulation, the human operator is part of the real-time simulation loop. Control signals given by the operator are sent to the real-time simulation. The virtual machine reacts to the signals as a real machine would react. Figure 3 illustrates a HITL simulation situation.

Figure 3. Human-in-the-Loop Simulation [44]

Human centred R&D of NRMM can be made more effective by using HITL simulation because the user experience of the operator can be tested already in early phase of product development. With an accurate simulation model, vehicle ride vibrations, which have a great effect on human comfort and health, can be studied [45]. When developing a novel user interface for NRMM, the user experience (UX) tests can be carried out any time during the development [46], [47]. The human effect on the loading cycles of NRMM can be taken into account when developing energy efficient hybrid power transmissions for NRMM [25]. HITL simulation facilitates cultural differences to be taken into account because equal virtual environment tests can easily be set-up in several countries [48]. Driver errors and behaviour can be analysed in critical driving situations using VERS [49]. The usefulness of new vehicular assistance features and their effect on human behaviour has been studied using HITL simulation [50], [51].

2.3 Hardware-in-the-Loop Simulation

HIL simulation setups are widely used for R&D of machinery to reduce development time and to ensure reliability and safety of complex components and systems [52]. In HIL simulation, which is also called hybrid simulation, external hardware is connected to run as a part of the virtual simulation. The external hardware can send control signals to simulation or external hardware can be controlled by a signal from the simulator. In HIL simulation real constraints (e.g. sensor accuracy, signal noise, sampling period of an embedded controller, modulation frequency and fault operations) of the hardware can be taken into account. An adequate dynamic real-time simulation of a working machine provides realistic loading cycles for the real prototype under test [21], [53], [54].

HIL simulation can be carried out in three different levels which are: signal level HIL simulation, power level HIL simulation and mechanical level HIL simulation. In signal level HIL simulation, only the embedded controller of the machine is under test. All the other parts (power electronics, actuators, mechanical power transmission and mechanical load) are simulated virtually. The embedded controller is working just as it were connected into a real machine. The signal level HIL simulation has been often employed in aerospace and automotive applications for assessment of controller boards [55]. In the power level HIL simulation, also power electronics are tested, in addition to the embedded controller. The other parts are simulated. Control signals and power variables are transferred between the hardware and the virtual model. A second power electronics set must be connected to the virtual simulation to provide the load for the power electronics under test. In the mechanical level HIL simulation, the whole drive (control, power electronics and actuator) is evaluated. The mechanical construction of the working machine is simulated. The subsystems of the drive under test are connected normally as in a real machine. Another actuator is often used to provide mechanical load for the actuator under test. [54]

A significant benefit of using HIL simulation is that changing the test setup is relatively easy compared to testing with a real machine. For instance, when the performance of a prototype of new power transmission component needs to be tested in different machinery, the physical connections of the prototype are not necessary to change. Only necessary action is to change the virtual model of the NRMM to describe another machine. Also testing of software components has the same flexibility. [54], [56], [57]

Appropriate control interface of the HIL simulation depends on the system in question. For the mechanical level HIL simulation the suitable physical parameters for the control interface can be e.g. position, velocity, acceleration or force. The physical actuator repeating the simulated mechanical load for the actuator under test has typically force or velocity servo control (torque or rotational speed servo control for rotational systems). In some cases, the selection of the control interface depends on the operation mode of the system. [56], [58], [59], [60].

A reliable study of working machines using mechanical level HIL simulation requires running of an accurate simulation model of the machine on real-time. Multibody dynamics approach has been applied to generate real-time models for HIL-simulations [61], [62]. Versatile real-time simulation software with user-friendly graphical modelling features is an important tool in rapid development of mechanical level HIL simulation setups.

Inverse dynamics (ID) is a classical method to solve the input force of a model if the desired motion is known [63], [64], [65]. Thus, a mechanical level HIL simulation setup can be built by solving ID of a NRMM model. A real-time ID solution of a complex multibody system is a problematic task and requires a lot of computing power [66]. Also, the availability of versatile real-time multibody modelling and simulation software with ID solver is limited on the market.

Multiple different HIL simulation setups have been developed for studying dynamic phenomena of fluid power systems. Commonly, nonlinear behaviour of fluid power systems and sensor noise cause problems in hydraulic HIL setups. [67], [68], [69], [70]

HIL method has been used for studying mechanical power transmissions, as well. In [71] a system has been developed, in which an automotive transmission is driven by a dynamometer emulating the engine. In transmission output, another dynamometer is emulating the response of vehicle. According to the authors, this arrangement allows rapid and accurate testing under realistic conditions and offers consistent repeatability scenarios as engine/vehicle changes.

2.4 Simulation environment used in this work

In this work, the experimental simulations are carried out using commercial software from Mevea Ltd. Mevea is a spin-off company of LUT. Many methods and solutions are based on the work carried out in LUT. Mevea software was chosen because the research team had prior knowledge about the models and methods used. The software is especially developed for real-time modelling and simulation of NRMM. The software is a general purpose tool which is implemented in a real-time simulation environment with a three dimensional visualization system and an audio system. The software includes also a versatile real-time interface to connect external hardware, e.g. control devices of different machines and a motion platform. The modelling of complex NRMM is effective due to the graphical user interface.

The software uses Multibody System Dynamics (MBS) to solve responses of mechanisms. MBS is a common method for creating dynamic three dimensional (3D) simulation environments. A MBS can consist of rigid and flexible bodies and joint constraints connecting the bodies. The multibody simulation approach uses numerical methods to solve nonlinear equations of motion with respect to time. Modern computer technology enables simulation of large mechanisms using the MBS approach. Additional components such as actuators, external forces and collisions can be connected to the MBS simulation to enable simulation of typical functions of NRMM. A good review of multibody system dynamics is presented by Shiehlen [72], Shabana [73] and Yoo [74]. Also several books have been written considering MBS [75], [76], [77]. The description of the dynamics of mechanical parts is based on the Newton-Euler equation (1).

$$M\ddot{q} + Q^c = Q^e + Q^v \tag{1}$$

,where q is the vector of n generalized coordinates which define the position and orientation of each body in the system, M is the mass matrix, Q^e is the vector of generalized forces, Q^v is the quadratic velocity vector that includes velocity-dependent inertia forces, and Q^c is the vector of constraint forces related to a chosen set of generalized coordinates [30], [21].

Collisions are important feature when simulating machinery in their working environments. A general collision modelling method working in wide variety of cases is necessary in efficient modelling of NRMM. [22] In the research related to this work the dynamic tyre simulation of the mobile machinery is based on LuGre tyre model. LuGre model is well known and efficient method for real-time simulation of interactions between tyre and road [78].

Double-acting cylinders (Figure 5) are commonly used to actuate mechanisms of NRMM. A fluid power circuit is necessary to power hydraulic cylinders. Typically, a fluid power circuit consist of oil tank, pump, valves and pipelines. In the simulation software in question, the modelling of the fluid power systems is based on the assumption that the pressure is evenly distributed in control volumes [79]. The method is called lumped parameter modelling method and it is introduced in [80].

Figure 4 illustrates how a simple fluid power circuit with a valve-controlled double-acting cylinder is modelled.

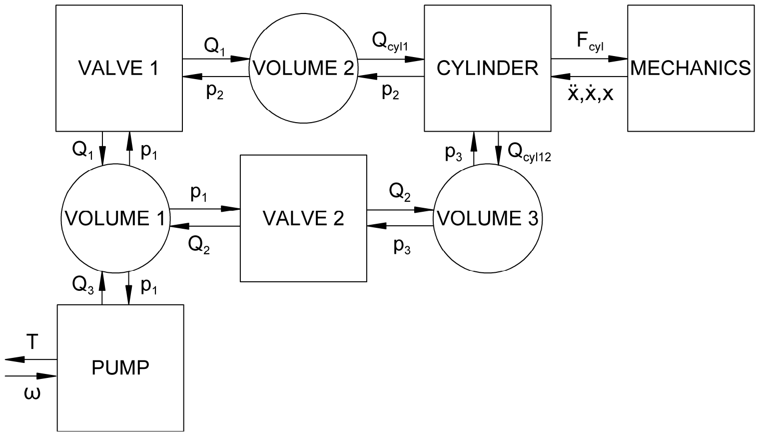


Figure 4. Simple fluid power circuit divided in control volumes [81], [82]

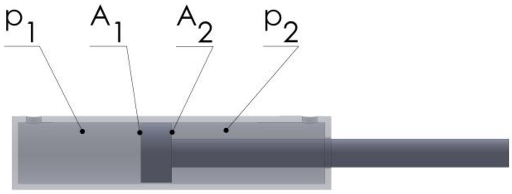


Figure 5. A simplified presentation of a double-acting cylinder

The force produced by hydraulic cylinder can be calculated by equation (2):

$$F_{cyl} = p_1 A_1 - p_2 A_2 - F_\mu \tag{2}$$

, where p is the pressure in cylinder chamber and A is the piston area, respectively. F_μ is the total friction force of the cylinder. The friction force occurs between seals of the piston and the surfaces of cylinder. The friction force has a significant role in damping of the hydro-mechanical systems. The friction force is depending on the chamber pressures, efficiency of the cylinder and on the piston velocity. [83] The cylinder volume flow is:

$$Q_{cyl} = \dot{x} \cdot A_{cyl} \tag{3}$$

, where $\dot{x}$ is the piston velocity and A_{cyl} is the piston area. In practice, different types of hydraulic valves consist of multiple different flow orifices. The volume flows in and out of the each volume through the orifices can be described by the conventional equation of the volume flow in turbulent orifice by Merritt [79]:

$$Q = C_d A_{or} \sqrt{\frac{2 \cdot \Delta p}{\rho}} \tag{4}$$

, where C_d is a discharge coefficient, A_{or} is area of orifice, ρ is the fluid mass density and Δp describes pressure difference over the orifice. Hydraulic pumps convert mechanical power into hydraulic power. The pump volume flow is calculated using equation (5):

$$Q_p = \omega \cdot V_{p\,rad} \cdot \eta_{vol} \tag{5}$$

, where ω is pump angular velocity, $V_{p\,rad}$ is radian volume and η_{vol} is the volumetric efficiency of the pump. The pressure in a control volume can be integrated according to equation 6:

$$\dot{p} = \frac{B_e}{V}\left(\sum Q_{in} - \sum Q_{out} - \dot{V}\right) \tag{6}$$

, where $\dot{p}$ is the first time derivative of pressure, B_e is the effective bulk modulus of the volume, V is the studied volume, Q_{in} and Q_{out} are volume flows in and out of the volume. $\dot{V}$ describes the alternation of the control volume, e.g. actuator movement. Effective bulk modulus is the sum of affecting components in volumes (7). It is used to describe the compressibility of volumes. [83]

$$B_e = \frac{1}{\frac{1}{B_{oil}} + \frac{V_h}{V_{tot}}\frac{1}{B_h} + \frac{V_c}{V_{tot}}\frac{1}{B_c} + \frac{V_p}{V_{tot}}\frac{1}{B_p}} \tag{7}$$

, where B_h , B_c and B_p are the bulk modulus of the hose, cylinder and pipe, respectively. V_h , V_c and V_p are the volumes respectively. B_{oil} is the bulk modulus of the oil and V_{tot} is the sum of the previously mentioned volumes. When the fluid power circuit is properly vented, the effect of the air dissolved into the hydraulic fluid can be neglected [84]. Thus, the elastic behaviour of the hoses has the greatest effect on the effective bulk modulus.

3. Virtual environment and real-time simulator in finding effects of driving performance of human operators on the life-cycle efficiency of NRMM

The development of VERS has offered numerous new possibilities for R&D of NRMM. In this chapter, a method for studying effects of human operators on the life-cycle efficiency of NRMM in VERS is described. Conventionally, assessing the user effect on the machine's efficiency has been superficial (see Chapter 1.1). Though, the operators are playing a key role in operation of machinery. A good understanding of the effect of human operators on the life-cycle efficiency of machinery can result in increased efficiency. VERS is a very suitable tool for assessment of operator's effect, because using a virtual prototype the assessment can be carried out in early phase of R&D project. In this phase, the necessary changes for the machine can be done with lower efforts and costs. In the virtual environment the factors related to efficiency are easier to acquire and the effect of changing environmental conditions can be eliminated.

3.1 Simulation Laboratory

Immersion level of VERS has an effect on the behaviour of human operators of virtual NRMM. With sufficient high immersion level the operators behave as they were operating a real NRMM. It has been shown that high resolution visualisation, head tracking system, realistic sound feedback and motion feedback are essential in creation of high immersion level in VERS. [35], [85], [86], [87], [88] Corresponding information has been received also from manufacturers of NRMM.

In this work the case studies which are related to effects of human operators are carried out in a simulation laboratory which has been developed to offer high immersion level for the operators' of virtual NRMM (Figure 6). The literature regarding the high immersion level of VERS was taken into account during development of the simulation laboratory. The simulation laboratory is described more detailed in [89]. The laboratory is equipped according to the following list. The list was presented earlier in [29].

1. Four ViewSonic PJD6381 3D projectors
2. Four NVIDIA 3D Vision Pro glasses and a transmitter (NVIDIA Corporation, 2013)
3. Three Da-Lite Ultra Wide Angle rear projection screens sized 2.67 x 2.10 m and floor projection surface
4. 12 OptiTrack FLEX:V100R2 motion tracking cameras, two Optihubs and Tracking Tools software
5. 6-DOF Gough-Stewart type motion platform with Omron SGDH-04AW-0Y Servopacks and 6 UBA2RNI linear actuators by Servomech
6. dSPACE real-time computer with ds1005 processor board
7. Dell Precision T7500 with two Intel Xeon X5560 CPUs, a soundcard by Creative Technology Ltd. and two NVIDIA Quadro FX5800 GPUs connected together with SLI bridge.
8. Dolby 5.1 Surround sound amplifier with speakers and a subwoofer
9. A vibration generator by The Guitammer Company

(a) (b)

Figure 6. Overview of the simulation laboratory: (a) with light, (b) during simulation

3.2 Mining Loader

The case studies are carried out using an underground mining loader, which is also called load-haul-dump (LHD) vehicle (Figure 7). The model of the loader consists of a rear-body and front-body that are connected to each other by an articulated joint. Steering of the loader is implemented by rotating the articulated joint using hydraulic cylinders. At the front end the LHD has a boom structure that is used to move and to actuate the bucket. The boom mechanism is actuated by hydraulic cylinders. The LHD includes a conventional mechanical driveline consisting of diesel engine, torque converter, gearbox, differentials and planetary gears. The model of the diesel engine is based on the engine with displacement of 7.2 litres and maximum output power of 220 kW. The simulated mining loader has a bucket with a volume of 4.6 m^3. The weight of the loader in operating condition is 26 000 kg. The hauling capacity is 10 000 kg. [82]

Figure 7. Virtual loader

The seat of the operator is oriented sideways. When driving forward or operating the bucket, the operator is watching left. With reverse direction, the operator looks right. Due to dimensional limitations and safety requirements of underground mines, the size of the windows of the operator’s cabin is constrained. Thus, the field of view is narrow. Especially, the forward view is very limited, due to the large bucket, which is blocking the line of sight.

Figure 8 is illustrating the view from the cabin. Figure 9 illustrates the loading situation seen from outside of the loader.

(a)

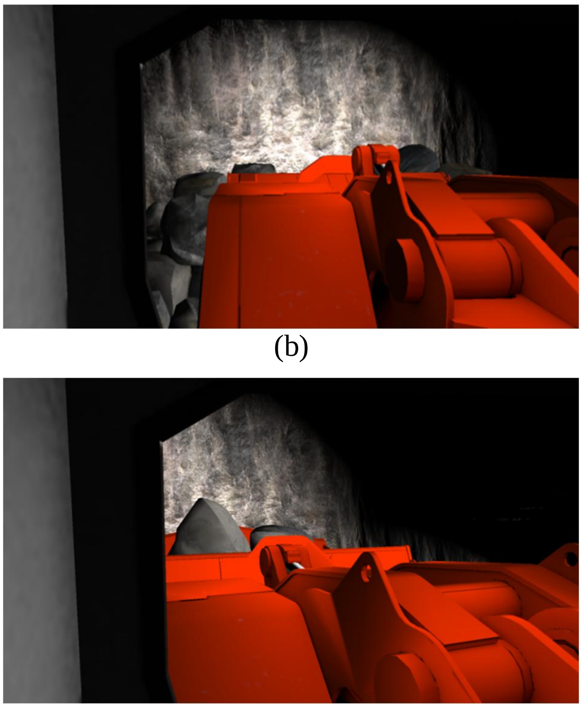


Figure 8. Operators view from the cabin of virtual loader:

(a) during loading, (b) driving in a corner of the tunnel

Figure 9. Loading situation

3.3 Assessing the effect of the operator on the efficiency of NRMM in of R&D process using VERS

A R&D process, in which the effect of the machine's operator on the life-cycle efficiency related factors is taken into account, is presented in [82]. Figure 10 presents a possible R&D process of working machine utilising VERS as the main testing tool. In practice, a wide variety of R&D processes are used by NRMM manufactures depending on the modernity and advancement of the R&D methods.

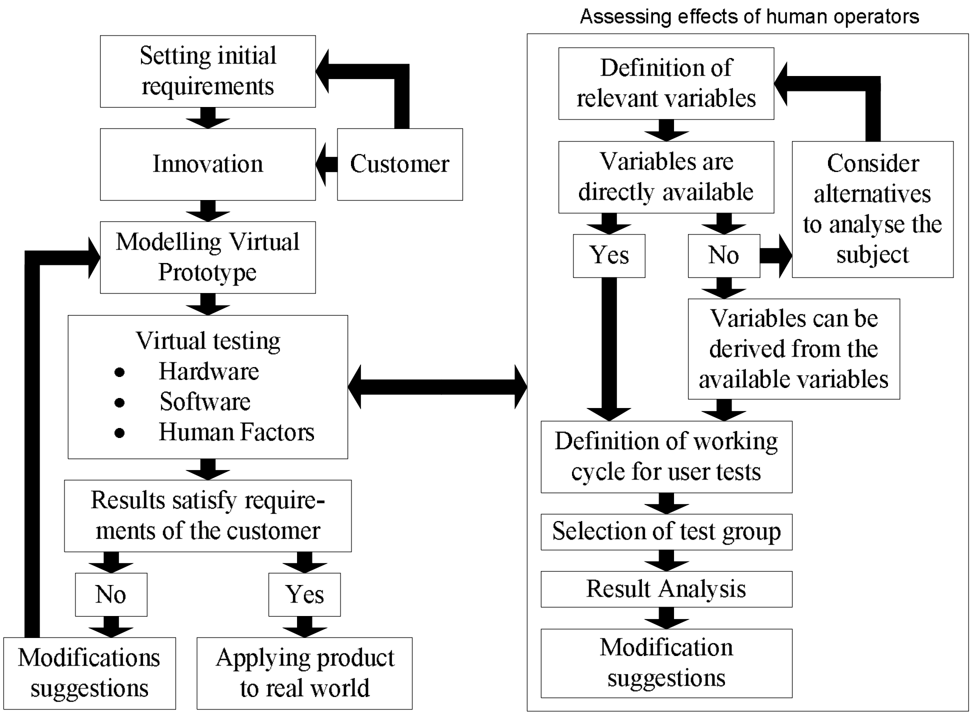


Figure 10. Possible VERS based R&D process of NRMM taking effects of human operators into account

3.4 Case studies

Two experimental studies were carried out using the proposed process. In the first experimental study the effect of an operator on the overall life-cycle efficiency of the loader was studied. A small test group performed tests in virtual underground mine using a mining loader and the results of the participants were compared later. [82] The first experimental study is referred below as a first case study. In the second experimental study the effect of the driving style on the efficiency of working hydraulics of the loader was studied in the same virtual underground [90]. The second experimental study is referred below as a second case study.

3.4.1 Selection of Variables to log

Depending on the complexity of the simulation model thousands or even millions of variables are available for acquisition. It is not possible or reasonable to log all the data available. Depending on the working cycle and the amount of test drivers the completion of user tests can take several hours. It is important to consider carefully that all the relevant variables are logged, in other case user tests need to be carried out again. The variables logged during simulation in the first case study were selected according to Table 1.

Table 1. Variables from simulation

Variable	Symbol	Unit
Simulation time	t	s
Diesel engine power output	P	W
Total Energy Consumption	E	kWh
Collisions against the mine walls	*Coll*	Pcs, m/s
Forces of lift and tilt cylinders	F_{cyl}	N

Some variables may not be directly available from the simulation. This is because the software used provides a limited number of variables as an output to the user. The data transfer and storage are limited to ensure the real-time performance of the simulator. In that case, the variables need to be derived after the real-time simulation from the available ones or an alternative method to assess the issue must be found. The derived variables of the first case study were defined according to Table 2.

Table 2. Variables derived from the simulation results

Variable	Symbol	Unit
Fuel consumption	FC	l / h
Engine Load Factor	ELF	-
RMS of Cylinder Forces	F_{RMS}	N
Working Productivity	*Prod*	m^3 / h, m^3 / l

The engine output power equals to the product of the angular velocity and the torque of the output shaft at the time step. The energy consumption is energy output from the diesel engine divided by the engine efficiency. The efficiency of a heavy-duty diesel engine varies typically between 25 and 45 percent depending on the operating point [91]. The efficiency of the engine was not taken into account in real-time simulation, but an average engine efficiency factor (34 percent) was used in data analysis. The energy content of diesel fuel varies around 10 kWh / litre [92]. The fuel consumption was calculated from the simulated energy consumption based on the average engine efficiency and energy content of diesel fuel. In future studies more detailed efficiency chart could be used. The productivity indicators are calculated based on the energy consumption, simulation time and amount of transported rocks.

The number of collisions evidently affects the durability and service costs of the machine. In addition, the speed of the collisions is an important factor as it determines the momentum of the machine during the collision. The higher the momentum, the greater the probability of the damage. Serious damage requires extra maintenance. This has a negative effect on the life-cycle costs and to the production while the machine is not working.

Selection of factors indicating energy consumption such as power and fuel consumption of the diesel engine is trivial. But selection of factors indicating service life e.g. durability and fault probability is more complex.

Stress in critical parts of the mechanical structure is in proportion to the forces to which the parts are subjected. The stress history determines the fatigue life time of the structure. A number of alternative approaches to determine stress histories from multibody simulation is provide in literature. The first approaches to determine structural stress histories from multibody simulation were proposed in 1996 [93], [94]. The latest articles show that determining the stresses of structural details during real-time multibody simulation is possible but challenging and the methods are still under development [95], [96].

At the current study the history of lifting and tilting cylinder forces were considered sufficiently accurate for relative comparison of test drivers. The root mean square (RMS) values of lifting and tilting cylinder forces are calculated after real-time simulations to create factors indicating durability of the boom. The boom is one of the critical mechanical structures of the loader. The RMS of the cylinder force is calculated by Eq. (8).

$$F_{RMS} = \sqrt{\frac{\sum_{i=0}^{n} F_i^2}{n}} \tag{8}$$

, where F_i is the cylinder force at each time step and n is number of time steps.

The second case study focuses on the efficiency of working hydraulics actuating the bucket of the mining loader. The fluid power system (Figure 11) consists of a variable displacement load-sensing (LS) hydraulic pump, a complex mobile directional control valve, asymmetrical cylinders and pressure relief safety valves. Pipes and hoses are used to connect the components to each other.

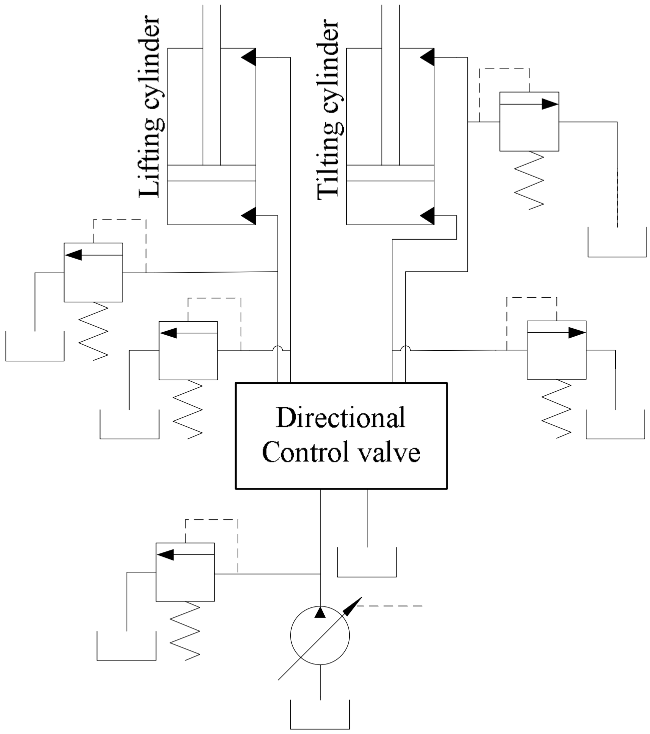


Figure 11. Schematic of the fluid power circuit

The variables logged during simulation in the second case study were selected according to Table 3.

Table 3. Variables from simulation

Variable	Symbol	Unit
Pump volume flow	Q_p	m^3 / s
Pressure at pump outlet	p_p	Pa
Velocities of lifting and tilting cylinders	v	m / s
Output forces of cylinders	F	N
Volume flow through pressure relief valve	Q	m^3 / s
Simulation time	t	s
Time step length	Δt	s

Not all the variables of interest were directly available from the simulation. The variables derived from simulation results of the second case study were defined according to Table 4.

Table 4. Variables derived from the simulation results

Variable	Symbol	Unit
Hydraulic input power into the system	P_{hydr}	W
Hydraulic input energy into the system	E_{hydr}	kWh
Mechanical output power of cylinders	P_{mec}	W
Mechanical output energy of cylinders	E_{mec}	kWh
Overall efficiency	η	-

The hydraulic output power P_{hydr} of the pump is calculated by multiplying the volume flow Q by the pressure drop Δp over the pump at each time step, i (9).

$$P_{hydr\ i} = Q_i \cdot \Delta p_i \tag{9}$$

The mechanical output power P_{mec} is calculated by multiplying the velocity v of the cylinder by the mechanical output force F at each time step, i (10).

$$P_{mec\ i} = v_i \cdot F_i \tag{10}$$

The hydraulic and mechanical energies E_{hydr} and E_{mec} are calculated by multiplying the power by the time step length. The total energy consumption is the sum of the values of each time step (11, 12).

$$E_{hydr} = \sum_{i=1}^{n} P_{hydr\ i} \cdot \Delta t_i \tag{11}$$

$$E_{mec} = \sum_{i=1}^{n} P_{mec\ i} \cdot \Delta t_i \tag{12}$$

Energy efficiency is calculated based on the energy input E_{hydr} and the energy output E_{mec} of the system (13).

$$\eta = \frac{E_{mec}}{E_{hydr}} \tag{13}$$

3.4.2 Working cycle

To achieve comparable results for test drivers, the working cycle must be fixed. In designing of the test working cycle must be considered, which situations need to be studied and which results in each situation are available. For the case studies a work cycle that is typical for loaders is selected. The information is obtained from earlier project with a mining company. The test drivers are supposed to move a fixed-sized pile of rocks from loading point to the dumping point. The starting, loading, dumping and finishing points of the working cycle are marked in the Figure 12. The dumping point is located 14.5 m lower level than the loading point. Distance between the loading and dumping points is approximately 110 m. The volume of the rock pile was approximately 11 m^3, corresponding to 27 000 kg of rocks. After the whole rock pile has been hauled to the dumping point, the loader is parked next to the dumping point.

(a) (b)

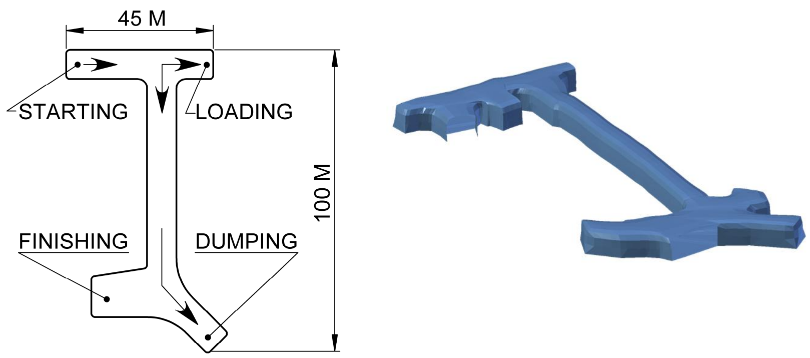


Figure 12. Virtual mining tunnel: (a) Route of the testing task, (b) 3D view of the tunnel

3.4.3 Test group

The selection of tests drivers has influence on the results of user tests. Size of the group and participants' experience levels should be considered carefully to achieve statistically valid results. The objective of the case studies of this work was to study the suitability of VERS for assessing effects of operators on the overall efficiency of NRMM and on the efficiency of working hydraulics of NRMM. Thus, small test group was considered to be sufficient for demonstrating the usability and the power of VERS. In the first case study, the test group consists of five operators with various experience levels, (Table 5).

Table 5. Experience levels of the test drivers in the first case study

Participant ID	VERS experience	NRMM experience
1	Novice	Competent
2	Expert	Novice
3	Competent	Expert
4	Novice	Competent
5	Novice	Expert
Experience levels	**Descriptions of the experience levels**	
Novice	Understand the basic concept and has operated in VERS / NRMM only few times or never.	
Competent	Has operated VERS / NRMM multiple times. The systems are familiar.	
Expert	Operates VERS / NRMM regularly. Are very familiar with the systems.	

Prior to the case study, the participants gained familiarity with the simulator in order to be able to perform the task fluently. In the second case study, one operator performed the task three times using different driving style in each performance. Due to lack of resources an experienced test operator group was not available for the second case study and one operator adapt himself to drive in three different driving styles. The driving styles were the fast (performance no. 1), slow (performance no. 2) and intermediate (performance no. 3).

3.5 Results of case studies related to studying human effects on life-cycle efficiency of NRMM

The variables logged from the real-time simulation and the variables derived from the logged data are illustrated by time domain curves and histograms in this chapter.

3.5.1 Results of the firsts case study

The total energy consumption and the average rate of fuel consumption are illustrated in Figure 13.

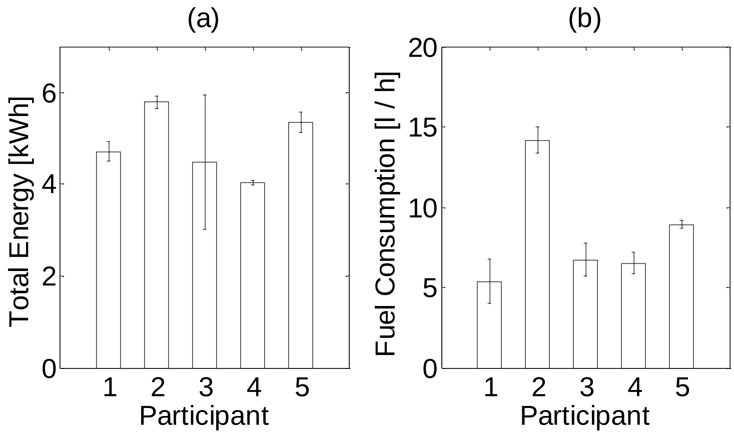


Figure 13. (a) Total energy consumption; (b) average rate of fuel consumption

Two indicators of productivity are calculated with respect to the amount of consumed energy and total time used for performing the task. Figure 14 (a) illustrates the average rates at which participants transported the rocks. Figure 14 (b) illustrates the average amounts of rocks in cubic meters that participants were able to transport with one litre of fuel.

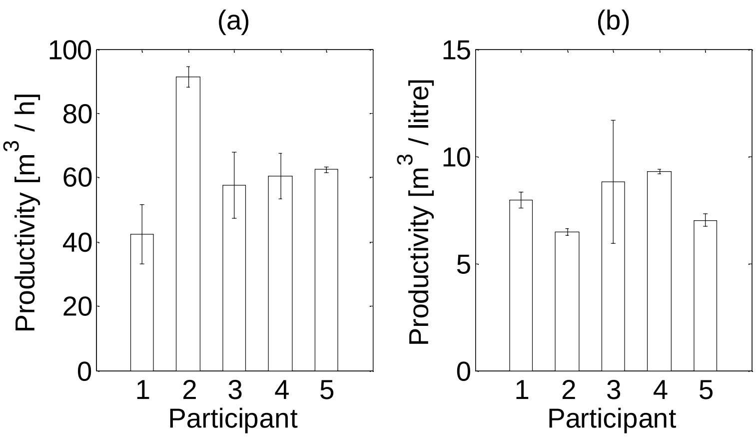


Figure 14. Productivity: (a) as function of time; (b) as function of fuel consumption

The mean values of RMS forces of lift and tilt cylinders are presented in Figure 15. The force sums are in relation to the stress history, need for maintenance and fatigue life time of the boom structure.

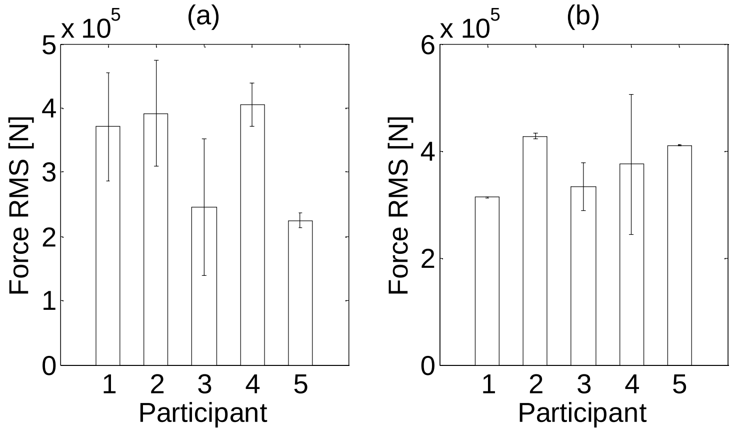


Figure 15. RMS force values: (a) lift cylinder; (b) tilt cylinder

The loading factors of the diesel engine are calculated by dividing the output power by maximum power of the engine. The analysis of loading factor data reveals that the engine loading was low during the task. It was observed that the participants were driving relatively carefully and slowly. Participant 2 had exceptional high engine loading compared to the other drivers. As an example of the engine loadings, the lowest and the highest loading curves are presented in Figure 16.

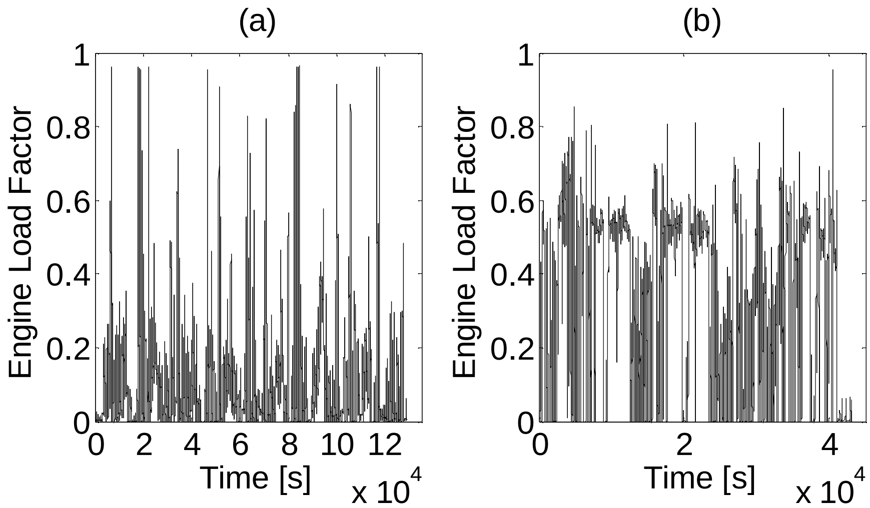


Figure 16. Diesel engine load factors: (a) the lowest loading; (b) the highest loading

3.5.2 Results of the second case study

The results of the second case study are presented below. The results are presented mainly for one driving performance (performance no. 2). Only the overall efficiency result is presenting all the three driving performances. The system input power of the working hydraulics actuating the bucket of the mining loader is defined by the hydraulic output power of the pump. The system output power is the sum of the mechanical output powers of the cylinders. Figure 17 illustrates the hydraulic output power of the pump and the mechanical output powers of the cylinders during a loading stage of the working cycle. Figure 18 illustrates the system powers during a dumping phase.

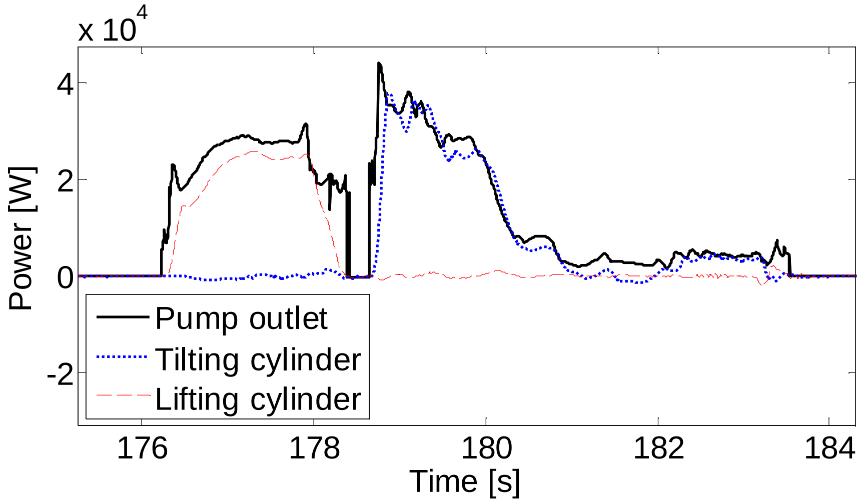


Figure 17. System input and output power during loading (performance no. 2) [90]

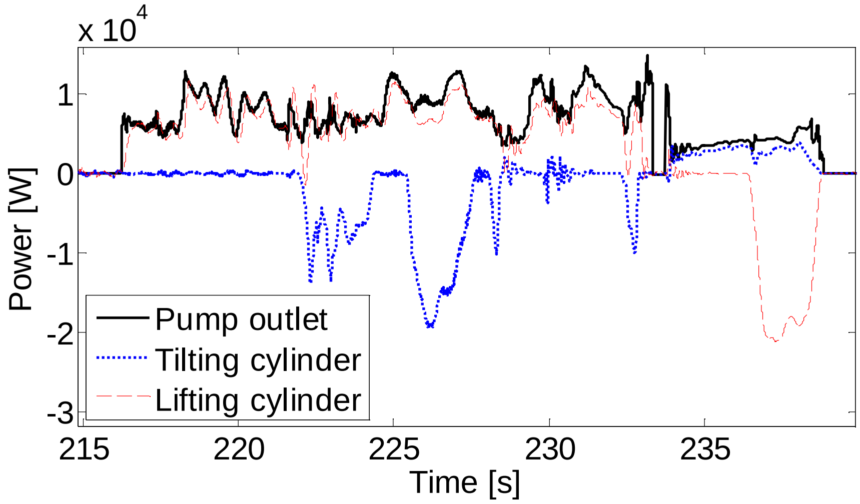


Figure 18. System input and output power during dumping (performance no. 2) [90]

Figure 19 illustrates the energy input and output of the working hydraulics. The “Tilt out” and “Lift out”-bars present the mechanical energies outputted from the tilting and lifting cylinders respectively. The “Total out”-bar presents the sum of the outputted cylinder energies. The “Total in”-bar illustrates the total energy from the pump into the fluid power system. Only the positive cylinder power values are taken into account in the integration of the energies consumed by cylinders because the loader under study is not equipped with energy recuperation system.

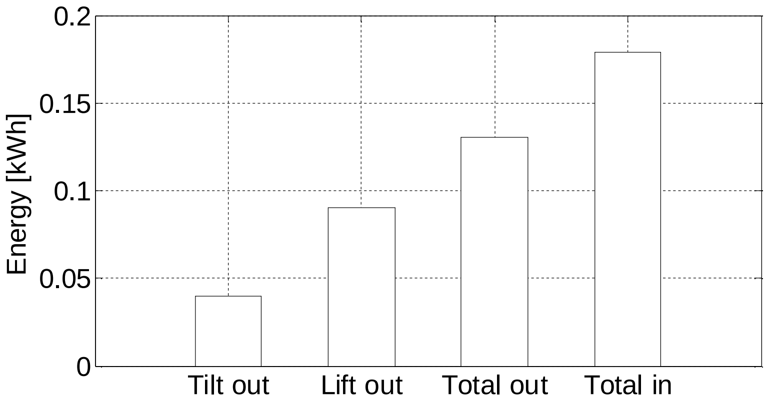


Figure 19. System input and output energy (performance no. 2) [90]

The overall energy efficiency of the working hydraulics is calculated based on the total hydraulic energy input and the total mechanical energy output. Figure 20 illustrates significant variation in the overall energy efficiency depending on the driving style.

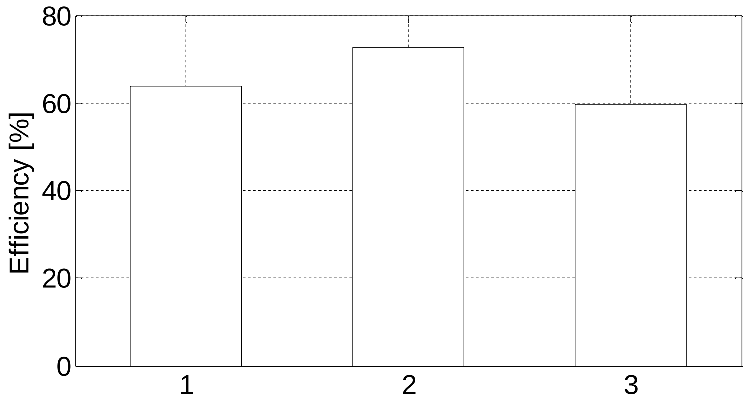


Figure 20. Overall efficiency of the three different driving styles [90]

Numerous factors in the driving style have an effect on the overall energy efficiency of the working hydraulics. The piston velocities, the cylinder forces and the scooping trajectory are the most significant factors. A detailed analysis of the driving styles requires extensive research work and it will be a topic of a future research. A coarse comparison of the driving styles can be carried out based on the piston velocity plots. The piston velocity plots offer data how the lifting and tilting cylinders have been used with respect to each other. The piston velocity correlates also often with the cylinder forces. The piston velocities of all the performances are presented in the Figure 21 - Figure 23.

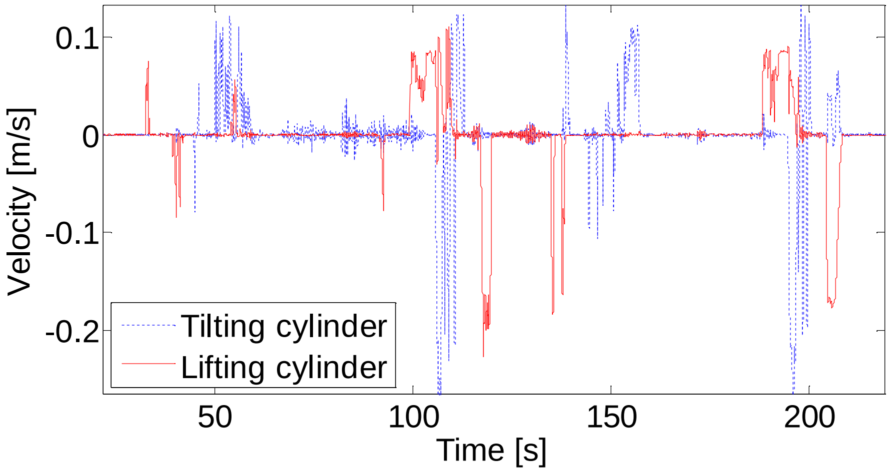


Figure 21. Piston velocity (performance no.1) [90]

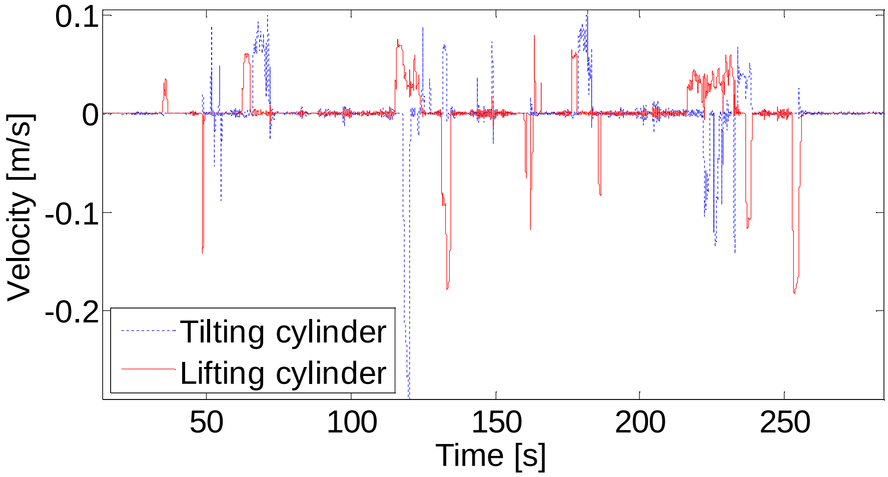


Figure 22. Piston velocity (performance no. 2) [90]

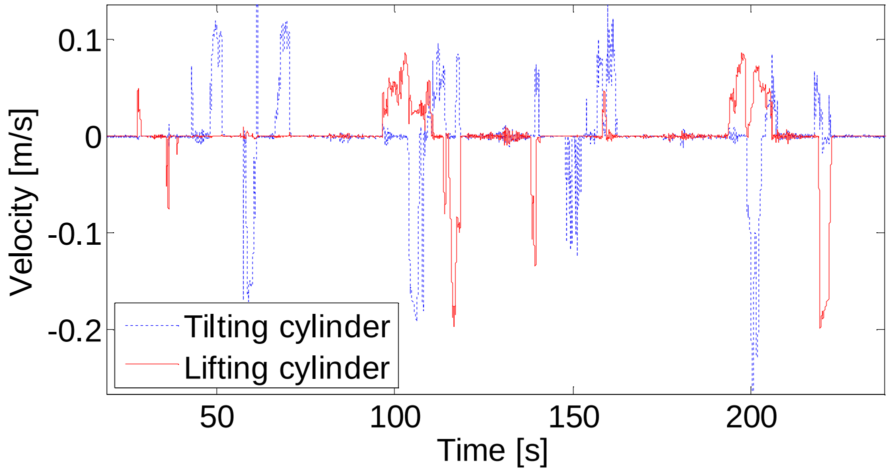


Figure 23. Piston velocity (performance no. 3) [90]

The driving performance no. 2 is carried out using smaller piston velocities than others. This has resulted also to longest total time. Thus, the highest overall efficiency is not necessary correlating with best productivity of the loader. The magnitudes of the piston velocities of the performances no. 1 and 3 are close to each other. The most obvious difference is that the piston velocities of the performance no. 1 are jerkier.

4. HIL simulation setup for electro-hydraulic hybrid power transmission of NRMM

In this chapter, an experimental development of a HIL simulation setup for testing the prototype of an integrated electro-hydraulic energy converter (IEHEC) is described. The objective is to develop a mechanical level HIL simulation setup which enables testing of the functionality of IEHEC as a component of different NRMM. A novel control interface is proposed because suitable control interface meeting the requirements of the current setup was not found.

Fluid power systems are commonly used in power transmissions of NRMM. The key advantage of the fluid power systems is the high power density. The energy efficiency of the systems has a potential to be improved significantly. Normally, the fluid power transmission lines are flexible hoses and pipes of small diameter which cause remarkable power losses. In many applications remarkable energy losses occur also because of the lack of energy recovery e.g. during the lowering of the payload. The directional control valves of the conventional fluid power systems also cause power losses. An improvement in the poor energy efficiency of the conventional fluid power systems can be achieved by a hybrid technology. The IEHEC enables the power transmission using electric cables and the recovery of the released potential or kinetic energy. In the electrical cables the power losses are negligible in comparison to the losses occurring in the long hydraulic transmission lines. [97]

The IEHEC (Figure 24) has been proposed to improve the energy efficiency aspects mentioned above. The key component of the IEHEC is newly designed liquid cooled electrical machine in which hydraulic fluid can be used as cooling media. Liquid cooling enables to reduce the dimensions of the electrical machine and thus increase the power density [98]. The most suitable places for IEHEC in NRMM are actuators that carry out work cycle in which the kinetic or potential energy is available for recovery e.g. lifting cylinders in cranes and grippers that tend to open by the payload mass and gravity [99].

Figure 24. IEHEC [98]

Figure 25 shows an example of the main power transmission system of NRMM together with the integrated electro-hydraulic actuator system. System in question follows serial hybrid transmission line architecture. It offers the possibility to recover the potential energy into electrical form to be stored in electrical energy storage. [98]

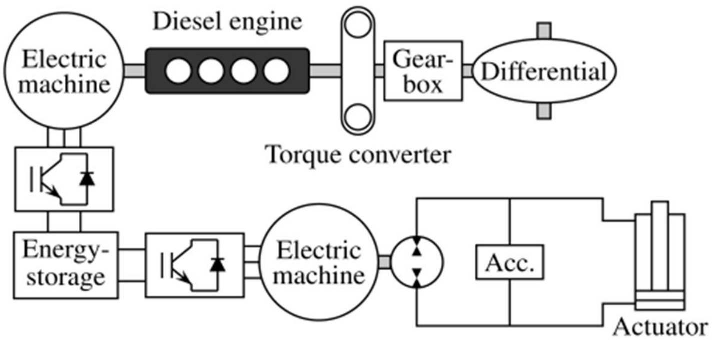


Figure 25. Structure of a hybrid power transmission using IEHEC to operate a cylinder [98]

Asymmetric hydraulic cylinder is a commonly used component in producing forces and movements in NRMM. Together with a pump-controlled fluid power system asymmetric cylinder can cause problems due to the differential volumes in the chambers. Pump-controlled systems are commonly operated in a closed-loop, where it is essential to maintain the even volume flows in the input and output ports of the pump. The uneven volume flows can be balanced by pilot operated check valves (Figure 26) [97], [100], [101].

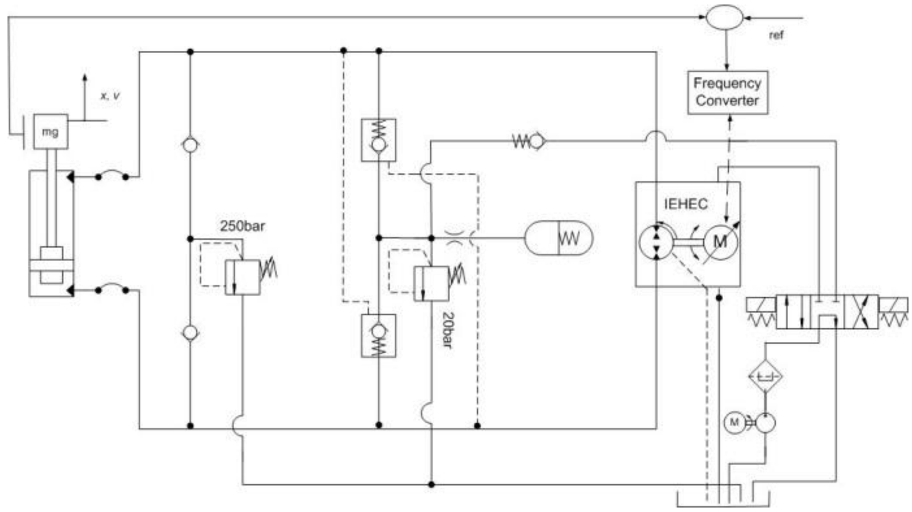


Figure 26. Electro-hydraulic hybrid actuator system [97]

4.1 Log crane

A virtual model of a log crane is used together with the physical prototype of IEHEC during the development of the control interface. The main dimensions and the locations of the lifting cylinder and the load of the simulated log crane are shown in Figure 27. The total mass of the crane without the load is 800 kg and the mass of the logs in the grapple is 260kg.

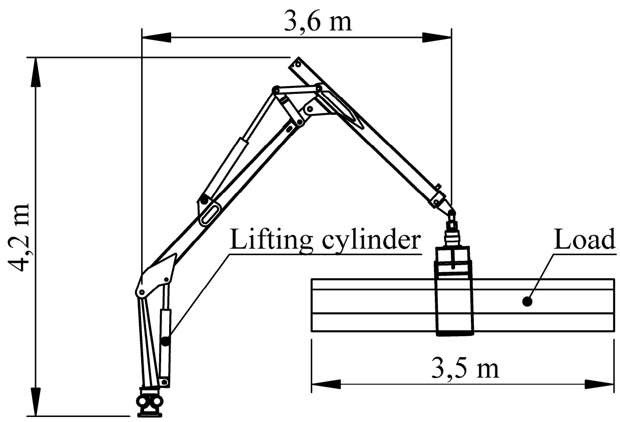


Figure 27. Log crane

4.2 Test rig

A test rig is a necessary subsystem of HIL simulation setup that enables realistic loadings for IEHEC. The main components of the test rig are presented in Figure 28. IEHEC is operating the working cylinder. The loading cylinder is connected between the frame of the test rig and the working cylinder. A force sensor is connected between the working and loading cylinders. The piston positions are measured by the position sensor. The loading cylinder is controlled by high bandwidth proportional cartridge valves. The rotational speed reference of the IEHEC is the input that makes the system move. The speed reference is inputted to the frequency inverter that is driving IEHEC's electrical machine. A real-time controller board is controlling the test rig and communicating with the real-time simulation model.

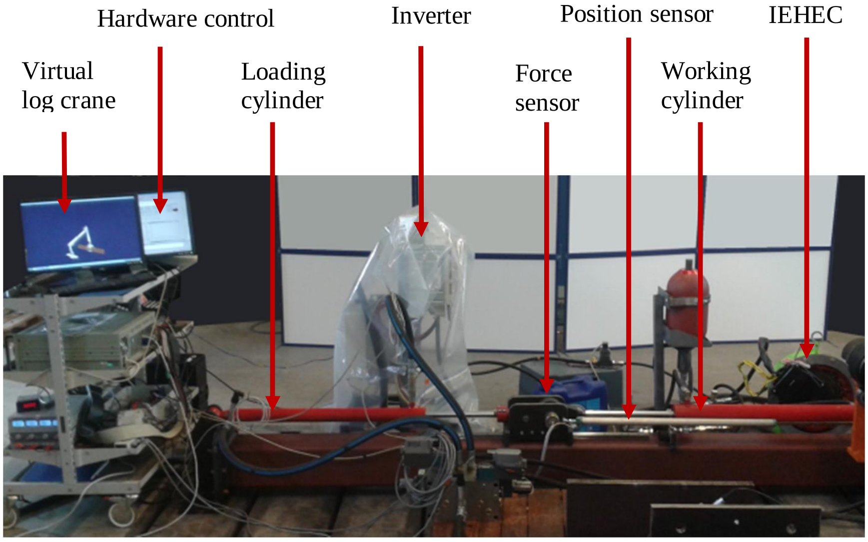


Figure 28. Test rig

Dimensions of hydraulic cylinders in different NRMM have significant variations. The signals sent through the control interface are scaled respect to the cylinder dimensions of virtual machine and the working cylinder. Due to the scaling, a need for changing the working cylinder of the test rig is avoided, when the cylinder size of the simulated machine is changed. The scaling factor is the ratio of the areas of the working cylinder's piston and the virtual machine's piston. The scaling of the force and motion signals enables correct pressure level and rotational speed for the IEHEC in spite of the different cylinder sizes. The effect of the cylinder size to the cylinder friction and damping is ignored. However, when the cylinder sizes are relatively close to each other the error is not significant. The lifting cylinder of the virtual log crane was simulated using the test rig. The other actuators of the log crane model were not actuated during the experimental tests. The load was hold continuously in the log grapple.

4.3 HIL simulation control interfaces

Three alternative control interfaces were studied and compared.

In the first control interface (option 1) the signal of force sensor connected between the working cylinder and the loading cylinder is the input into the multibody simulation. The piston velocity is returned from the multibody simulation and the velocity is used as a reference value for the loading cylinder. The loading cylinder is closed loop velocity controlled. The connections of the option one are shown in Figure 29.

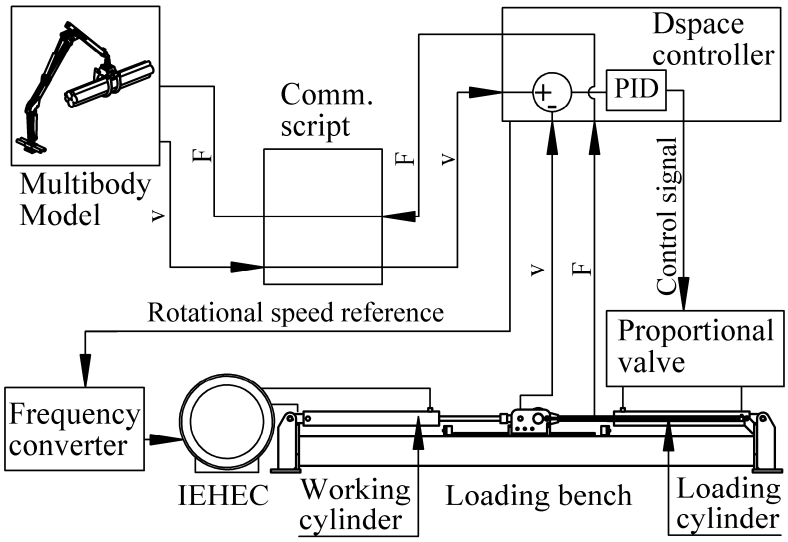


Figure 29. Connections between the multibody simulation and the hardware (option 1)

In the second and third options the loading cylinder is controlled by a closed loop force controller. The reference signal of the servo controller is the force acting in the multibody model. The input force of the multibody simulation is calculated by closed loop proportional-integral-derivative (PID) controllers (Figure 30).

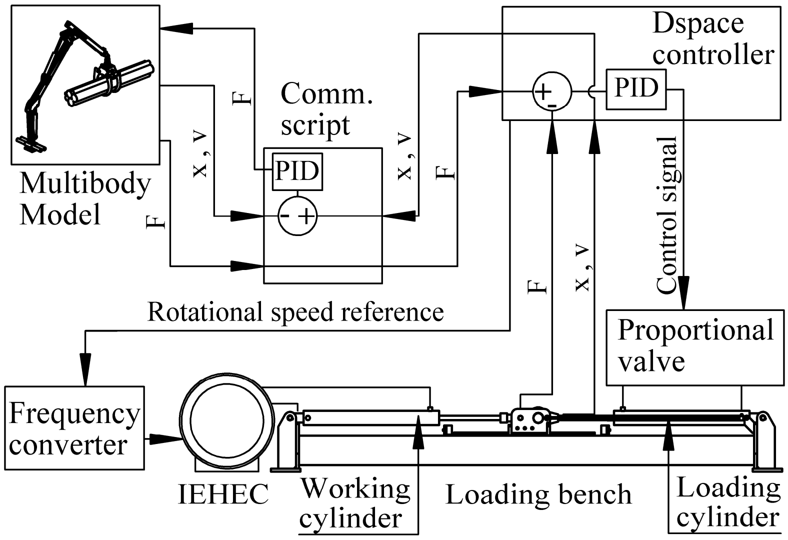


Figure 30. Connections between the multibody simulation and the hardware (options 2 and 3)

The controller of the second option calculates the input force based on the velocity difference of the test rig and the multibody model. In the third option, the first controller is calculating the velocity reference signal based on the position difference of the test rig and the multibody model. The second controller is calculating the input force for the multibody model based on the calculated velocity reference and the velocity of the multibody model.

Completely virtual simulations are carried out to obtain reference results for the HIL simulations. The fluid power circuit including IEHEC is modelled by Simulink using the modelling principles presented in Chapter 2.4. The same multibody model is used for the virtual and HIL simulations.

An example of the IEHEC control signal used in experimental tests is shown in Figure 31.

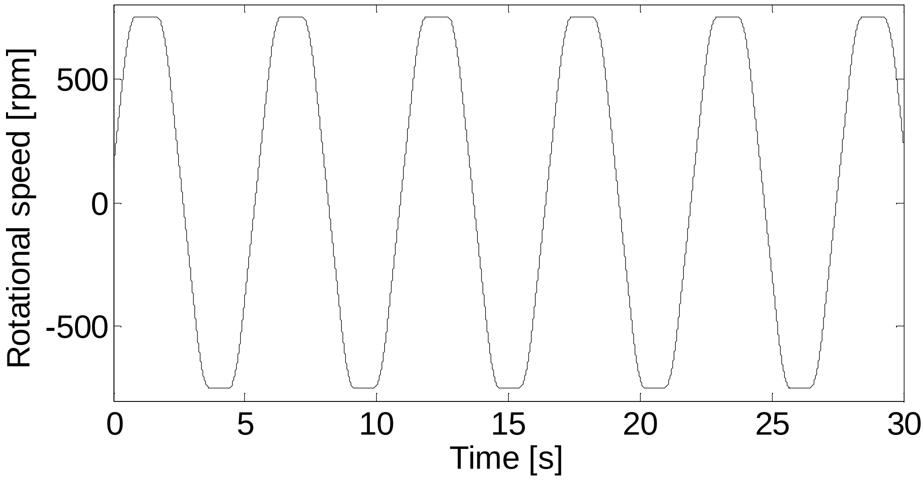


Figure 31. Rotational speed reference signal of IEHEC

4.4 Results related to development of control interface for HIL simulation setup

4.4.1 Control interface option 1

Cylinder force and piston velocity of the lifting cylinder of the multibody model during the HIL simulation and the virtual simulation are shown in Figure 32 and Figure 33.

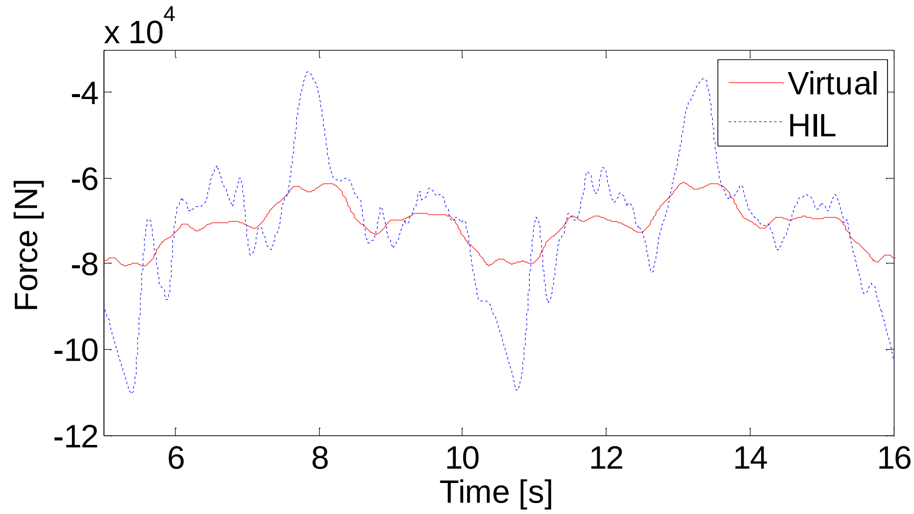


Figure 32. Cylinder force (option 1)

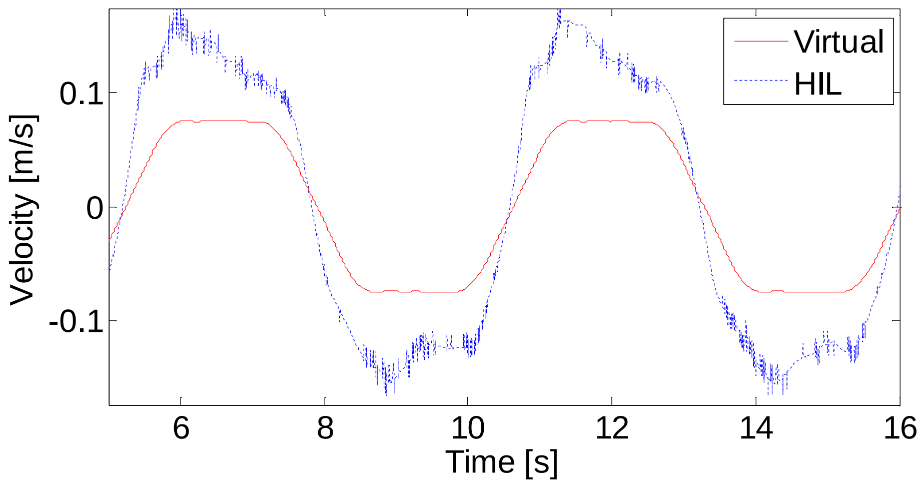


Figure 33. Piston velocity (option 1)

With the current hardware the first option was found problematic. In theory the method is correct but the experimental tests revealed force peaks when the direction of the movement is changed. These are caused by the inertia and the friction of the components of the test rig. The peaks in the force sensor signal rise over the correct level. Thus, the peaks are causing too high piston velocity in the multibody model. Because of stability problems the first option was tested at lower velocity than the others.

4.4.2 Control interface option 2

Cylinder force and piston velocity of the lifting cylinder of the multibody model using the HIL simulation and using the virtual simulation are shown in Figure 34 and Figure 35.

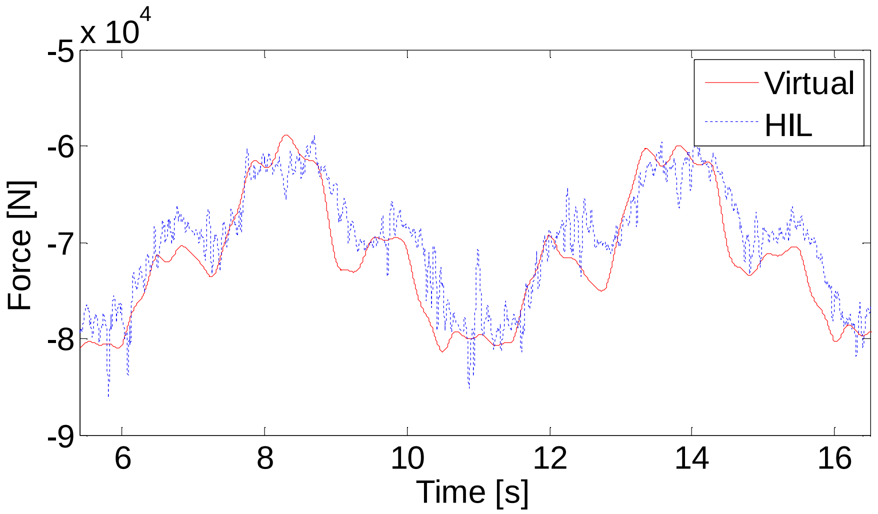


Figure 34. Cylinder force (option 2)

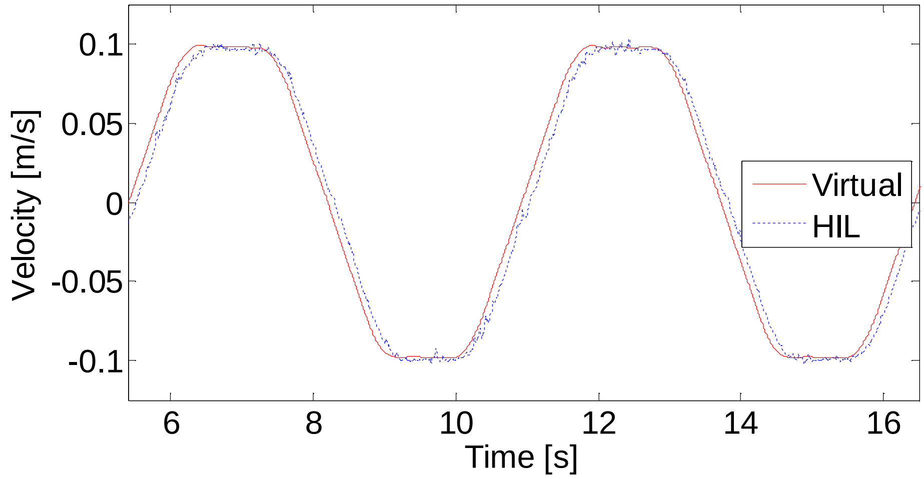


Figure 35. Piston velocity (option 2)

The mechanical power of the lifting cylinder of the multibody model in the cases of the virtual simulation and the HIL simulation are shown in Figure 36. The mechanical power of the real working cylinder connected to IEHEC is also illustrated. All the three curves are close to each other.

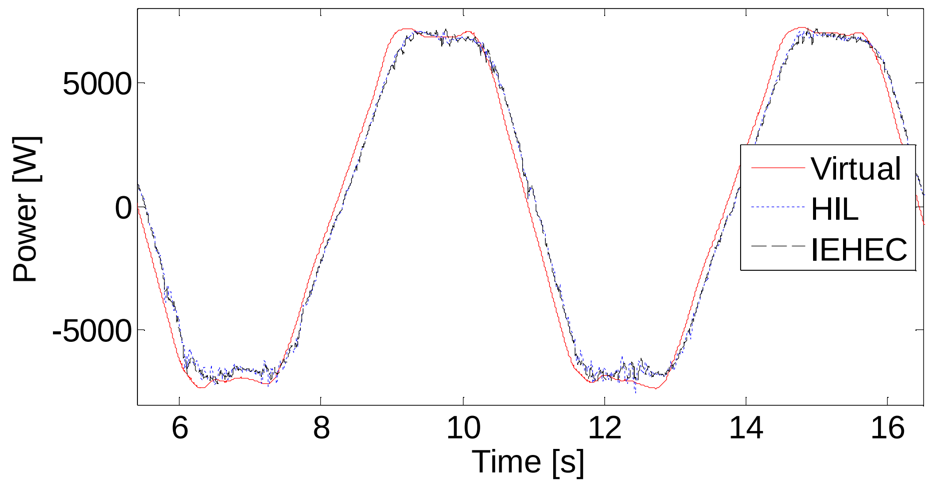


Figure 36. Mechanical cylinder power (option 2)

The second control interface option achieves high accuracy compared to the first option. The cylinder force and piston velocity are close to the results of the virtual simulation. Noticeable vibration appears in the cylinder force.

4.4.3 Control interface option 3

Cylinder force and piston velocity of the lifting cylinder of the multibody model using the HIL simulation and using the virtual simulation are shown in Figure 37 and Figure 38.

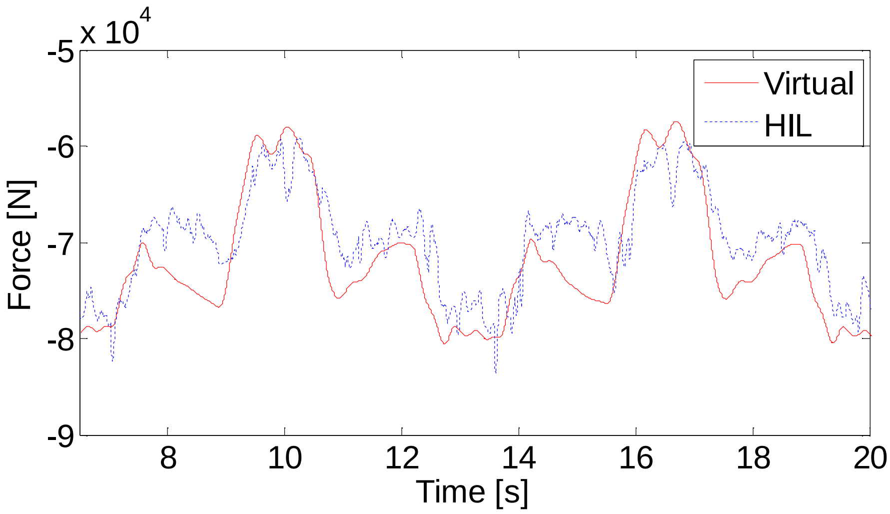


Figure 37. Cylinder force (option 3)

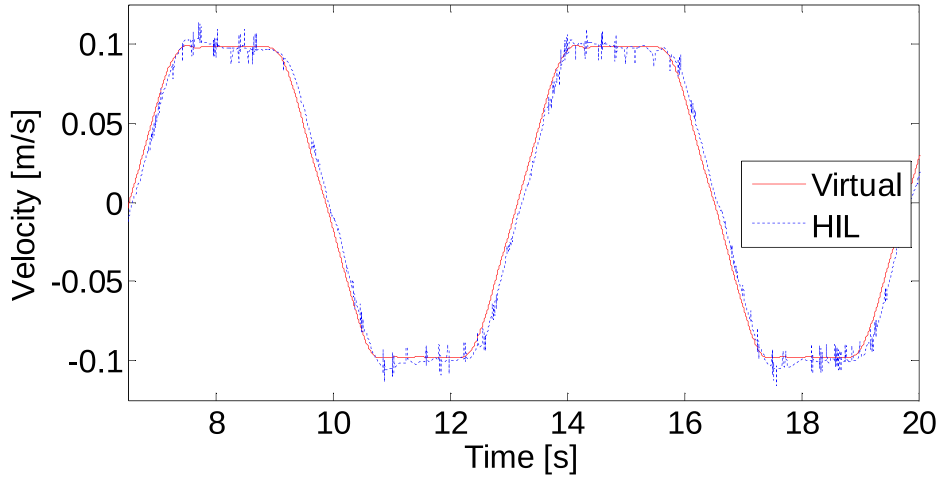


Figure 38. Piston velocity (option 3)

The mechanical power of the lifting cylinder of the multibody model in the cases of the virtual simulation and the HIL simulation are shown in Figure 39. The mechanical power of the real working cylinder connected to IEHEC is also shown.

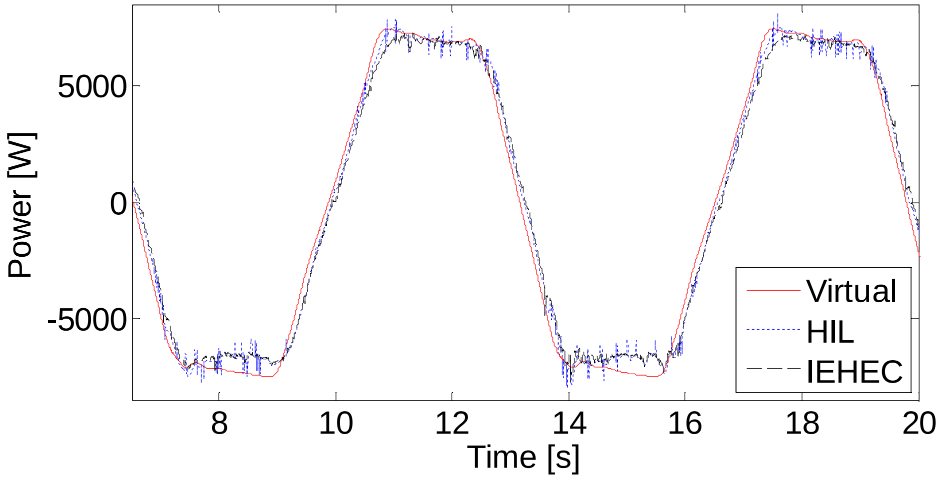


Figure 39. Mechanical power (option 3)

Using the third control interface option, the vibration of the cylinder force is significantly lower compared to the second interface option. Otherwise the accuracy of the cylinder force is at the same level than using the second option. The piston velocity of the HIL simulation has small peaks with duration of approximately one simulation time step. The peaks are probably originating from the sensor noise which is amplified by the numerical noise during the simulation. The closed loop position controller included in the third option removes the possibility of drifting during long simulations. Regarding the results presented above, the control interface option no. 3 is recommended to be used in the future.

5. Discussion

Studies in the extent presented in this work cannot be found in the literature. The results can be considered as novel. Virtual environments and real-time simulation are mainly used for user training and control hardware / software testing [19], [55]. In this work these methods and tools are demonstrated as they apply into R&D of complete non-road mobile machinery systems.

References related mechanical level hardware-in-the-loop simulations are often related to rotating electric or hydraulic machines [58], [102]. References related to linear actuators can be found from field of active suspension systems of vehicles [103], [104] and flight control of airplanes [105], [106]. Though these systems have very different properties compared to system presented in this work. Mechanical level HIL simulation setups for simulating hydraulic cylinder or electro-hydraulic energy converter connected to NRMM has not been proposed in the reference articles.

Two separate methods how VERS can effectively be utilized in early and later stages of R&D process of NRMM are given. The methods and tools demonstrated open new possibilities that cannot be achieved by using the traditional ones.

The experimental studies related finding suitability of VERS to assessing effects of human operators on the life-cycle efficiency of NRMM were carried out with small number of test drivers. This could affect to the reliability of the results. Though, significant variations between results of test drivers were found. Thus, the number of test drivers appears to be sufficient for the scope of this work. The effects of varying torque and speed on the efficiency of the diesel engine was not taking into account. This is limiting the accuracy of the simulated fuel consumptions. In the future studies more detailed diesel engine efficiency chart could be used. Only one loading and hauling case was studied. Varying hauling distances, minerals and other environmental factors would have an effect on the numerical results. The accuracy of the simulation model is limited and physical phenomena which are considered less significant for human experience are neglected. The detailed verification of the simulation model has not been carried out. However, the model is based on physical equations which are widely acknowledged in literature. The accuracy of the model is adequate for comparing differences between human operators, even though absolutely accurate numerical results were not obtained. User experience in the VERS of this study has not been verified by driving the tests using the real machine.

The detailed verification of the log crane simulation model used in HIL simulation interface studies has not been carried out. However, the model is based on physical equations which are widely acknowledged in literature. The results of control interfaces are presented only for one repeating working cycle. Thus, a possibility exists that some phenomenon in HIL simulation control interface have been missed. The working cycle used in the tests consists of typical operating velocities of hydraulic cylinders used in NRMM. Thus, the control interface appears to be suitable for HIL simulations in typical conditions.

By adding VERS into more traditional R&D process need some added resources such as software and hardware environments and personnel specialized in using the tools. The investment cost is approximately between 50k€ to 150k€. The payback time is short if these tools are effectively implemented in the R&D process. The main benefit is the significantly lower physical prototyping cost. Also time to market becomes shorter and reliability of the R&D process becomes better.

In this work virtual environment and real-time simulation based methods for improving life-cycle efficiency of non-road mobile machinery were presented. Such a study of this extend has not been proposed in the reference articles.

More research needs to be carried out for better understanding of the effect of the human operators on the mobile machinery. Further research could aim to create guidelines about how to optimize the driving style of NRMM. An experimental study with a larger test group would provide a useful knowledge for developing improved fluid power transmissions for NRMM.

Future work will also include simulation of real working cycles of the log crane using the HIL simulation setup. The robustness and the adaptation of the proposed control interface in different situations will be verified. The actual energy saving potential of IEHEC solution compared to the conventional valve controlled fluid power circuit can be found out. The energy efficiency of the IEHEC at different working cycles will be analysed. The developed HIL simulation setup will be used for finding suitable applications for IEHEC in working machines.

6. Conclusions

Large amount of beneficial methods for education, product development and research of NRMM has become available frequently due to the development of virtual environment and real-time simulator technologies. In this work two new methods that take advantage of VERS have been introduced. The case studies are carried out using mining loader and log crane. Typically, different NRMM have many similarities in technology and in mechanical structure. Thus, the methods described in this work can be considered valid for most of the other machines also.

The process for assessing effects of human operators on the life-cycle efficiency of mobile machinery using VERS was introduced and realized. The process was used in two case studies. The first study concentrated in effects of the operators on the overall efficiency of the mining loader. In the second study, the suitability of a VERS was evaluated to study the effects of driving styles on energy consumption of working hydraulics of working machines. VERS was found to be a cost-effective and powerful tool in assessing the effects of varying performances and driving styles of human operators on life-cycle efficiency of NRMM.

Experimental studying and development of novel control interfaces for HIL simulation of Electro-Hydraulic Energy Converter as a part of power transmission of NRMM was carried out. Novel ideas in selecting the quantities transmitted through the interface back and forth were presented. In particular using virtual closed loops to approximate variables typically obtained by using inverse dynamic model is rarely used in literature.

In the simulator, the variables that have an effect on the efficiency of the machine are easily available. The variables can contain physical quantities or other indicators that can be easily measured. It would be complex and expensive to research these variables using physical prototypes. A great benefit of using virtual environment and real-time simulator is the possibility to provide fixed conditions for all participants, ensuring comparability of the results. The NRMM manufacturers may gain considerable benefits by taking advantage of virtual environments and real-time simulators.

Using VERS in early phase of machine’s R&D process improves the understanding of the interactions between the machine and the human operator. This enables user-centered design of NRMM. In VERS critical machine design errors can be found in early phase of the development process. This enables also testing of new machine concepts with lower economical risk.

References

[1] T. Norgate and N. Haque, "Energy and greenhouse gas impacts of mining and mineral processing operations," *Journal of Cleaner Production,* vol. 18, no. 3, pp. 266-274, 2010.

[2] D. Barić, G. Zovak and M. Periša, "Effects of Eco-Drive Education on the Reduction of Fuel Consumption and CO2 Emissions," *Promet-Traffic&Transportation: Scientific Journal on Traffic and Transportation Research,* vol. 25, no. 3, pp. 265-272, 2013.

[3] A. Sadrpour and J. Jin, "The Role of Operator Style on Mission Energy Requirements for," in *American Control Conference (ACC),* Portland, Oregon, USA, 2014.

[4] M. Bohman, *On Predicting Fuel Consumption and Productivity of Wheel Loaders,* Master's Thesis, Luleå, Sweden: Luleå University of Technology, 2006.

[5] R. Filla, "A Methodology for Modeling the Influence of Construction Machinery Operators on Productivity and Fuel Consumption," in *Digital Human Modeling,* Springer Berlin Heidelberg, 2009, pp. 614-623.

[6] G. Korlath, "Mobility analysis of off-road vehicles: Benefits for development, procurement and operation," *Journal of Terramechanics,* vol. 44, no. 5, p. 383–393, 2007.

[7] M. Maesano, R. Picchio, A. L. Monaco, F. Neri, B. Lasserre and M. Marchetti, "Productivity and energy consumption in logging operation in a," *Ecological Engineering,* vol. 57, pp. 149-153, 2013.

[8] W. R. Nugent, "Virtual Reality: Advanced Imaging Special Effects Let You Roam in Cyberspace," *Journal of American Society for Information Science,* vol. 42, no. 8, pp. 609-617, 1991.

[9] M. A. Gigante, "Virtual Reality: Definitions, History and Applications," in *Virtual Reality Systems*, London, Academic Press, 1993, pp. 3-14.

[10] J. R. Wilson, "Effects of participating in virtual environments A review of current knowledge," *Safety Science*, vol. 23, no. 1, pp. 39-51, 1996.

[11] A. Carrie, Simulation of Manufacturing Systems, John Wiley and Sons, 1988.

[12] "Oxford English Dictionary, The definitive record of the English language," [Online]. Available: www.oed.com. [Accessed 20 2 2015].

[13] A. Maria, "Introduction to Modeling and Simulation," in *Proceedings of the 29th Conference on Winter Simulation*, Atlanta, Georgia, USA, 1997.

[14] D. T. McRuer and E. S. Krendel, *AGARDograph No.188, Mathematical models of human pilot behaviour*, Neuille sure seine, France: North Atlantic Treaty Organization, 1974.

[15] D. P. F. Möller, Introduction to Transportation Analysis, Modeling and Simulation, Springer London, 2014.

[16] C. G. Cassandras and S. Lafortune, "Introduction to Discrete-Event Simulation," in *Introduction to Discrete Event Systems*, Springer US, 2008, pp. 557-615.

[17] C. F. Brüning, "Simulation, an introduction and survey," in *AGARD Conference proceedings No. 79*, Neuille sur seine, France, 1971.

[18] W. F. Bauer, "Aspects of Real-Time Simulation," *Electronic Computers, IRE Transactions on*, Vols. EC-7, no. 2, pp. 134-136, 1958.

[19] W. H. Dunn, C. Eldert and P. V. Levonian, "Digital Computer for Use in an Operational Flight Trainer," *Electronic Computers, IRE Transactions on*, Vols. EC-4, no. 2, pp. 55-63, 1955.

[20] S. Cotin, H. Delingette and N. Ayache, "Real-Time Elastic Deformations of Soft Tissues for Surgery Simulation," *IEEE Transactions on visualization and computer graphics*, vol. 5, no. 1, pp. 62-73, 1999.

[21] P. Korkealaakso, *Real-time simulation of mobile and industrial machines using the multibody simulation approach*, PhD thesis, Lappeenranta: Lappeenranta University of Technology, 2009.

[22] S. Moisio, *A soft contact collision method for real-time simulation of triangularized geometries in multibody dynamics*, PhD thesis, Lappeenranta: Lappeenranta University of Technology, 2013.

[23] W. Karwowski, International encyclopedia of ergonomics and human factors, CRC Press, 2006.

[24] J. Viitaniemi, S. Aromaa, S. P. Leino, S. Kiviranta and K. Helin, "Integration of User-Centred Design and Product Development Process within a Virtual Environment," VTT, Espoo, 2010.

[25] J. Montonen, J. H. Montonen, P. Immonen, K. Murashko, P. Pomarev, T. Lindh, P. Lindh, L. Laurila and J. Pyrhönen, "Electric Drive Dimensioning for a Hybrid Working Machine by Using Virtual Prototyping," in *Electrical Machines (ICEM), 2012 XXth International Conference on* , Marseille, 2012.

[26] H. Yousefi, A. M. Soleimani and H. Handroos, "Human Centered Design of Mobile Machines by a Virtual Environment," in *Human Centered Design: First International Conference*, San Diego, CA, USA: Springer, 2009.

[27] M. D. Bauer and D. W. Rosen, "An approach to integrated product/process desing via virtual prototyping," in *Proceedings of DETC'97 1997 ASME Design Engineering Technical Conferences*, Sacramento, California, 14-17, 1997.

[28] J. Kuusisto, T. Kaapu, A. Ellman and T. Tiainen, "Developing VIP2M: A virtual environment for prototyping mobile work machines," in *International design conference - Design*, Dubrovnik, Croatia, 2012.

[29] J. Heikkinen, *Virtual technology and haptic interface solutions for design and control of mobile working machines*, PhD thesis, Lappeenranta: Lappeenranta University of Technology, 2013.

[30] P. M. Korkealaakso, A. J. Rouvinen, S. M. Moisio and J. K. Peusaari, "Development of a real-time simulation environment," *Journal of Multibody system dynamics*, vol. 17, no. 2-3, pp. 177-194, 2007.

[31] Y. Xiaochen, *Virtual Reality Environment For Development and Simulation of Mobile Machine*, Master's Thesis, Tampere: Tampere University Of Technology, 2011.

[32] M. Kallmann, P. Lemoine, D. Thalmann, F. Cordier, N. Magnenat-Thalmann, C. Ruspa and S. Quattrocolo, "Immersive vehicle simulators for prototyping, training and ergonomics," in *Proceedings of the Computer Graphics International (CGI'03), (pp. 90-95)*, 2003.

[33] A. Peternier, S. Cardin, F. Vexo and D. Thalmann, "Practical Design and Implementation of a CAVE Environment," in *Proceedings 2nd International Conference on Computer Graphics Theory, (pp. 129-136).*, 2007.

[34] J. Heikkinen, *Integration of Real-Time Simulator, Motion Platform and Haptics*, Master's Thesis, Lappeenranta, Finland : Lappeenranta University of Technology, 2009.

[35] J. Kuusisto, A. Ellman, T. Kaapu and T. Tiainen, "Effect of the immersion level of a virtual loader simulator on the sense of presence," in *Proceedings of the ASME 2011 World Conference on Innovative Virtual Reality WINVR2011*, Milan, Italy, 2011.

[36] H. N. Koutsopoulos, A. Polydoropoulou and M. Ben-Akiva, "Travel simulators for data collection on driver behavior in the presence of information," *Transportation Research Part C,* vol. 3, no. 3, pp. 143-159, 1995.

[37] H. H. Valverde, "A Review of Flight Simulator Transfer of Training Studies," *Human Factors: The Journal of the Human Factors and Ergonomics Society,* vol. 15, no. 6, pp. 510-522, 1973.

[38] G. Matthews, T. J. Sparkes and H. M. Bygrave, "Attentional Overload, stress, and simulate Driving Performance," *Human Performance,* vol. 9, no. 1, pp. 77-101, 1996.

[39] E. M. Kolasinski, "Simulator sickness in virtual environments," U.S. Army Research Institute for the Behavioral and Social Sciences, 1995.

[40] T. A. Stoffregen, L. J. Hettinger, M. W. Haas, M. M. Roe and L. J. Smart, "Postural Instability and Motion Sickness in a Fixed-Base Flight Simulator," *Human Factors: The Journal of the Human Factors and Ergonomics Society,* vol. 42, no. 3, pp. 458-469, 2000.

[41] *Virtual reality environments - photograph,* Cargotec, 2014.

[42] C. Rah and M. Park, "Statistical Modeling of the Sensory-Perception Process of Computational Driver Models for Vehicle Simulations," *Human Factors and Ergonomics in Manufacturing & Service Industries,* vol. 21, no. 2, pp. 188-206, 2011.

[43] K. Hughes and X. Jiang, "Using Discrete Event Simulation to Model Excavator Operator Performance," *Human Factors and Ergonomics in Manufacturing & Service Industries,* vol. 20, no. 5, pp. 408-423, 2010.

[44] J. Karjalainen, *Powerwall / Virtual reality environment - photograph,* VTT Technical Research Centre of Finland.

[45] A. Pazooki, S. Rakheja and D. Cao, "Modelling and validation of off-road vehicle ride dynamics," *Mechanical Systems and Signal Processing,* vol. 28, pp. 679-695, 2012.

[46] J. E. Heikkinen and H. Handroos, "Design of a Human Machine Interface for a Mobile Machine using Simulation in Virtual Reality Environment," *International Review on Modelling and Simulations (I.RE.MO.S.),* vol. 6, no. 1, pp. 284-290, 2013.

[47] J. E. Heikkinen and H. M. Handroos, "Haptic Controller for Mobile Machine Teleoperation," *The International Review of Automatic Control,* vol. 6, no. 3, pp. 228-235, 2013.

[48] F. Rebelo, P. Noriega, E. Duarte and M. Soares, "Using Virtual Reality to Assess User Experience," *Human Factors,* vol. 54, no. 6, pp. 964-982, 2012.

[49] M. Plavšić, G. Klinker and H. Bubb, "Situation Awareness Assessment in Critical Driving Situations at Intersections by Task and Human Error Analysis," *Human Factors and Ergonomics in Manufacturing & Service Industries,* vol. 20, no. 3, pp. 177-191, 2010.

[50] M. G. Lenné, T. J. Triggs, C. M. Mulvihill, M. A. Regan and B. F. Corben, "Detection of Emergency Vehicles: Driver Responses to Advance Warning in a Driving Simulator," *Human Factors,* vol. 50, no. 1, pp. 135-144, 2008.

[51] A. Koustanaï, V. Cavallo, P. Delhomme and A. Mas, "Simulator Training With a Forward Collision Warning System Effects on Driver-System

Interactions and Driver Trust," *Human Factors*, vol. 54, no. 5, pp. 709-721, 2012.

[52] D. Maclay, "Simulation gets into the loop," *IEE Review*, vol. 43, no. 3, pp. 109-112, 1997.

[53] M. Karkee, B. L. Steward, A. G. Kelkar and Z. T. Kemp II, "Modeling and real-time simulation architectures for virtual prototyping of off-road vehicles," *Virtual Reality*, vol. 15, no. 1, pp. 83-96, 2011.

[54] A. Bouscayrol, "Different types of Hardware-In-the-Loop simulation for electric drives," in *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium on*, Cambridge, 2008.

[55] R. Isermann, J. Schaffnit and S. Sinsel, "Hardware-in-the-loop simulation for the design and testing of engine-control systems," *Control Engineering Practice*, vol. 7, no. 5, pp. 643-653, 1999.

[56] R. Trigui, B. Jeanneret, B. Malaquin, F. Badin and C. Plasse, "Hardware In the Loop Simulation of a Diesel Parallel Mild-Hybrid Electric Vehicle," in *Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE*, Arlington, 2007.

[57] J. Timmermans, J. V. Mierlo and P. Lataire, "Test platform for hybrid electric power systems: Development of a HIL test platform," in *Power Electronics and Applications, 2007 European Conference on*, Aalborg, 2007.

[58] Z. H. Akpolat, G. M. Asher and J. C. Clare, "Experimental dynamometer emulation of non-linear mechanical loads," *IEEE trans. on Industry Application*, vol. 35, no. 6, pp. 1367-1373, 1999.

[59] Y. Nam and S. K. Hong, "Force control system design for aerodynamic load simulator," *Control Engineering Practice*, vol. 10, no. 5, pp. 549-558, 2002.

[60] S. C. Oh, "Evaluation of motor characteristics for hybrid electric vehicle using the HIL concept," *IEEE trans. on Vehicular Technology*, vol. 53, no. 3, pp. 817-824, 2005.

[61] J. E. Heikkinen, T. Minav, J. Pyrhönen and H. Handroos, "Real-time HIL-simulation for testing of electric motor drives emulating hydraulic systems," *Review of Electrical Engineering (IREE)*, vol. 7, no. 6, pp. 6084-6092, 2012.

[62] W. Rulka and E. Pankiewicz, "MBS Approach to Generate Equations of Motions for HiL-Simulations in Vehicle Dynamics," *Multibody System Dynamics*, vol. 14, no. 3-4, pp. 367-386, 2005.

[63] B. Siciliano and O. Khatib, Springer Handbook of Robotics, 35-65: Springer-Verlag Berlin Heidelberg, 2008.

[64] D. Schütz and F. M. Wahl, Robotic Systems for Handling and Assembly, Springer-Verlag Berlin Heidelberg, 2010.

[65] F. Aghili, "A unified approach for inverse and direct dynamics of constrained multibody systems based on linear projection operator: applications to control and simulation," *Robotics, IEEE Transactions on*, vol. 21, no. 5, pp. 834-849, 2005.

[66] A. Fumagalli and P. Masarati, "Real-time inverse dynamics control of parallel manipulators using general-purpose multibody software," *Multibody System Dynamics*, vol. 22, no. 1, pp. 47-68, 2009.

[67] S. Driscoll, *The Design and Qualification of a Hydraulic Hardware-in-the-Loop Simulator*, PhD thesis, Georgia Institute of Technology, 2005.

[68] A. Kővári, "Real-Time Modeling of an Electro-hydraulic Servo System," in *Computational Intelligence in Engineering*, Springer, 2010, pp. 301-311.

[69] Z. Jiao, J. Gao, Q. Hua and S. Wang, "The Velocity Synchronizing Control on the Electro-Hydraulic Load Simulator," *Chinese journal of aeronautics*, vol. 17, no. 1, pp. 39-46, 2004.

[70] A. R. Enes and W. J. Book, "A Hardware-in-the-Loop Simulation Testbed for Emulating Hydraulic Loads Representing the Complete Dig Cycle of a Construction Machine," in *Proceedings of IMECE2008, ASME 2008 International Mechanical Engineering Congress and Exposition*, Boston, Massachusetts, USA: ASME, 2008.

[71] R. Ahlawat, S. Jiang, D. Medonza and M. H. Smith, "On emulating engine and vehicle transient loads for transmission-in-the-loop experiments," *Mechatronics,* vol. 22, no. 7, pp. 989-996, 2012.

[72] W. Schiehlen, "Multibody system dynamics: Roots and perspectives," *Multibody System Dynamics 1,* p. 149–188, 1997.

[73] A. A. Shabana, "Flexible multibody dynamics: Review of past and recent Developments," *Multibody System Dynamics 1*, p. 189–222, 1997.

[74] W. S. Yoo, K. N. Kim and H. W. Kim, "Developments of multibody system dynamics: computer simulations and experiments," *Multibody System Dynamics 18,* pp. 35-58, 2007.

[75] P. E. Nikravesh, "An overview of several formulations for multibody dynamics," in *Product Engineering*, Springer Netherlands, 2005, p. 189–226.

[76] A. A. Shabana, Computational dynamics, John Wiley & Sons, 2001.

[77] A. A. Shabana, Dynamics of Multibody Systems, Cambridge University, 2005.

[78] Y. Chen and J. Wang, "Vehicle-longitudinal-motion-independent real-time tire-road friction coefficient estimation," in *Decision and Control (CDC), 2010 49th IEEE Conference on,* Atlanta, GA, 2010.

[79] H. Merrit, Hydraulic control systems, New Jersey: John Wiley & Sons, 1967.

[80] H. Handroos, *Methods for combining a Theoretical and an Empirical Approach In Modelling Pressure and Flow Control Valves for CAE-programs for Fluid Power Circuits,* PhD thesis, Tampere, Finland: Tampere University of Technology, 1990.

[81] R. Åman, *Methods and models for accelerating dynamic simulation of fluid power circuits,* PhD thesis, Lappeenranta : Lappeenranta University of Technology, 2011.

[82] L. O. Luostarinen and H. Handroos, "Using Simulation in Virtual Reality Environment to find effects of human operators on the life-cycle efficiency of

off-highway working vehicles," *International Review on Modelling and Simulations (IREMOS)*, vol. 6, no. 5, pp. 1629-1636, 2013.

[83] A. Mikkola, *Studies on fatigue damage in a hydraulically driven boom system using virtual prototype*, PhD thesis, Lappeenranta : Lappeenranta University of Technology, 1997.

[84] J. Watton, Fluid power systems: modeling, simulation, analog and microcomputer control, Prentice Hall International (UK) Ltd., 1989.

[85] A. Okapuu-von Veh, R. J. Marceau, A. Malowany, P. Desbiens, A. Daigle, E. Garant, R. Gauthier, A. Shaikh and J. C. Rizzi, "Design and operation of a virtual reality operator-training system," *Power Systems, IEEE Transactions on*, vol. 11, no. 3, pp. 1585-1591, 1996.

[86] R. Riener, M. Frey and T. Pröll, "Phantom-based multimodal interactions for medical education and training: the Munich knee joint simulator," *Information Technology in Biomedicine, IEEE Transactions on*, vol. 8, no. 2, pp. 208-216, 2004.

[87] S. Noth, I. Iossifidis and E. Schrowangen, "Using ego motion feedback to improve the immersion in virtual reality environments," in *Robotics (ISR), 2010 41st International Symposium on and 2010 6th German Conference on Robotics (ROBOTIK)* , Munich, Germany, June, 2010.

[88] B. Laha, D. A. Bowman and J. D. Schiffbauer, "Validation of the MR Simulation Approach for Evaluating the Effects of Immersion on Visual Analysis of Volume Data," *Visualization and Computer Graphics, IEEE Transactions on*, vol. 19, no. 4, pp. 529-538, 2013.

[89] J. Heikkinen and L. Luostarinen, "Virtual environment for investigating Human Machine Interface in machines with hydraulic transmissions," in *Proceedings of the 7th FPNI PhD Symposium on Fluid Power*, Reggio Emilia, Italy, June, 2012.

[90] L. O. Luostarinen, R. Åman and H. Handroos, "Tool for studying effects of human operators on energy consumption of working hydraulics of off-highway working vehicle," in *Proceedings of the 8th FPNI Ph.D Symposium on Fluid Power (FPNI2014)*, Lappeenranta, Finland, 2014.

[91] R. Matthews, D. Seedah, M. Ates, K. J. Kim, K. G. Anderson, J. Vaughn, D. Dardalis, H. Lijun and R. Harrison, "Estimating Texas Motor Vehicle Operating Costs: Final Report," Center for Transportation Research at The University of Texas at Austin, Nowember, 2011.

[92] "Fuel Properties Comparison, Alternative Fuels Data Center (AFDC)," [Online]. Available: www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf.

[93] F. Melzer, "Symbolic computations in flexible multibody systems," *Nonlinear Dynamics,* vol. 9, no. 1-2, pp. 147-163, 1996.

[94] H. J. Yim and S. B. Lee, "An integrated CAE system for dynamic stress and fatigue life prediction of mechanical systems," *Journal of Mechanical Science and Technology,* vol. 10, no. 2, pp. 158-168, 1996.

[95] T. T. Rantalainen, A. M. Mikkola, S. M. Moisio and G. B. Marquis, "A Method for Obtaining the Dynamic Stress History from a Flexible Multibody Simulation Using Sub-Modeling," *Mechanics Based Design of Structures and Machines,* vol. 41, no. 3, pp. 316-336, 2013.

[96] T. T. Rantalainen, A. M. Mikkola and T. J. Björk, "Sub-modeling approach for obtaining structural stress histories during dynamic analysis," *Mechanical Sciences,* vol. 4, no. 1, pp. 21-31, 2013.

[97] R. Åman, P. Ponomarev, L. Luostarinen, H. Handroos, J. Pyrhönen and L. Laurila, "Experimental Analysis of Electro-Hydraulic Hybrid Actuator System for Off-Highway Working Vehicles," in *8th FPNI Ph.D Symposium on Fluid Power (FPNI2014)*, Lappeenranta, Finland, 2014.

[98] P. Ponomarev, R. Åman, H. Handroos, P. Immonen, J. Pyrhönen and L. Laurila, "High Power Density Integrated Electro-Hydraulic Energy Converter for Heavy Hybrid Off-Highway Working Vehicles," *IET Electrical Systems in Transportation,* vol. 4, no. 4, pp. 114-121, 2014.

[99] R. Åman, H. Handroos, P. Ponomarev and J. Pyrhönen, "Utilisation of Electro-Hydraulic Hybrid Actuator System in Off-Highway Working Vehicles," in *8th International Conference on Fluid Power Transmission and Control (ICFP 2013),* Hangzhou, China, 2013.

[100] R. Rahmfeld, *Development and Control of Energy Saving Hydraulic Servo Drives for Mobile Systems,* PhD thesis, Harburg: Technical University of Hamburg, 2002.

[101] M. Ivantysynova, "Energy saving hydraulic actuators for mobile machines," in *1st Bratislavan Fluid Power Symposium*, Bratislava, Slovak Republic, 1998.

[102] C. Wang, Z. Jiao, S. Wu and Y. Shang, "An experimental study of the dual-loop control of electro-hydraulic load simulator (EHLS)," *Chinese Journal of Aeronautics,* vol. 26, no. 6, p. 1586–1595, 2013.

[103] S. B. Choi, Y. T. Choi and D. W. Park, "A Sliding Mode Control of a Full-Car Electrorheological Suspension System Via Hardware in-the-Loop Simulation," *Journal of Dynamic Systems, Measurement, and Control,* vol. 122, no. 1, pp. 114-121, 2000.

[104] S.-H. Hwang, S.-J. Heo, H.-S. Kim and K.-I. Lee, "Vehicle Dynamic Analysis and Evaluation of Continuously Controlled Semi-Active Suspensions Using Hardware-in-the-loop Simulation," *Vehicle System Dynamics: International Journal of,* vol. 27, no. 5-6, pp. 423-434, 1997.

[105] T. Steinbauer, G. Leiprecht and W. Havraneck, "High performance HIL real time for the Airbus A380 electrical backup hydraulic actuators," in *UKACC Control 2004 Mini Symposia*, Bath, 2004.

[106] M. Karpenko and N. Sepehri, "Hardware-in-the-loop simulator for research on fault tolerant control of electrohydraulic actuators in a flight control application," *Mechatronics,* vol. 19, no. 7, pp. 1067-1077, 2009.

PART II: PUBLICATIONS

Publication I

L. O. Luostarinen and H. Handroos

Using Simulation in Virtual Reality Environment to find effects of human operators on the life-cycle efficiency of off-highway working vehicles

Reprinted from

International Review on Modelling and Simulations (IREMOS), vol. 6, no. 5, pp. 1629-1636, 2013, with permission from Praise worthy prize S.r.l.

Praise Worthy Prize

International Review on Modelling and Simulations (I.RE.MO.S.), Vol. 6, N. 5
ISSN 1974-9821 October 2013

Using Simulation in Virtual Reality Environment to Find Effects of Human Operators on the Life-Cycle Efficiency of Off-Highway Working Vehicles

Lauri O. Luostarinen, Heikki Handroos

Abstract – *Virtual Reality (VR) environments and real-time simulators are becoming more and more important tools in R&D process of off-highway working vehicles. The virtual prototyping techniques enable faster and more cost-efficient development of machines compared to use of real life prototypes. Possibilities of virtual prototypes should be studied to take full advantage of them. The objective of this article is to study the process of using a VR environment with a real-time simulator for assessing effects of human operators on the life-cycle efficiency of working vehicles. As a test case human in the loop simulations are ran by virtual prototype of Load Haul Dump (LHD) underground mining vehicle. Results of test drivers are compared and discussed. The simulation model of the LHD is based on multibody dynamics. The model also includes models of diesel engine, mechanical driveline and fluid power system. The study shows that state of the art real-time working machine simulators are capable to solve factors related to life-cycle efficiency such as energy consumption and productivity among others. A significant variation between the test drivers is found. The study shows that VR environment can be used for assessing human effects on the life-cycle efficiency of working vehicles.*

***Keywords**: Construction Machinery, Efficiency, Energy, Human, Simulation, Virtual Reality, Working Vehicle*

I. Introduction

The emergence of real-time simulation and Virtual Reality (VR) technology has enabled the virtual prototypes to be used in R&D processes of mobile working vehicles [1]-[3]. Real-time simulation is essential in cases which require a human operator to participate the simulation process, e.g. research of human-machine interface (HMI) or research of human effect on the machine performance.

Virtual prototypes have several advantages over physical ones when carrying out research [4], [5]. For example, the conditions of experimental tests can be set equal for all participants, and uncommon and dangerous conditions can be studied safely. Furthermore, data acquisition is relatively easy in VR because real sensors are not required. Use of the virtual prototype is cost effective in most cases, because manufacturing of the physical prototype can be avoided.

VR environments and real-time simulators are becoming more and more important tools in R&D process of off-highway working vehicles due to many advances of them. Still companies have much to work integrating VR-tools properly into their R&D and business processes [4].

Virtual environment can bring user centred design into a new level.

Dynamic field of view analysis in virtual environment has been developed to ensure performance, ergonomics and safety of the vehicle already in early design phase [6]. VR environment has also been used to develop novel HMI. A multipurpose haptic interface for controlling teleoperated mobile working machines has been developed and tested in VR [7].

In advanced companies VR environments are used by product development teams to review the design already in early phase.

The potential problems in the design can be identified easier when the whole team can analyse the full size virtual model of the new product together.

In this study an underground mining loader, also called Load-Haul-Dump (LHD) vehicle, is studied as a test case. Life-cycle efficiency of mining machines is an important issue because the production of primary metals can be expected to increase in the future due to the increasing global demand for end products. Like other industrial sectors, the mining industry is facing pressure to reduce environmental impact. It has been found that the loading and hauling stage has the most significant contribution to CO_2 emissions for iron ore and bauxite production [8].

The energy efficiency of the off-highway heavy-duty working vehicles has been studied extensively in recent years.

Manuscript received and revised September 2013, accepted October 2013

A current research topic of considerable interest has been hybrid powered construction machinery, which are able to cut down fuel consumption and emissions [9], [10]. Notwithstanding the obvious importance of energy efficient technology, it must be noted that the human operator of an off-highway vehicle has very significant effect on the overall efficiency. Also the energy storage, which is one of the most expensive components in the hybrid vehicle, is difficult to be dimensioned without studying the realistic work tasks with human operators in a realistic work environment. To carry out this with a real machine prototype is very expensive and time-consuming. VR environment provides a really cost effective tool for such design. Determining the peak power of combustion engine is a similar issue.

The aim of the present article is to study the process of using the VR environment with a real-time simulator for assessing effects of human operators on the life-cycle efficiency of working vehicles. A small test group performed certain work cycle in VR environment. Factors related to life-cycle efficiency were defined, calculated and compared between the participants.

The work cycle was to transport a pile of rocks to the dumping place in a virtual underground mine environment with a mining loader. The virtual mining loader used in this study is illustrated in Fig. 1.

The simulation results show that the effect of the human operator on the life-cycle cost of the mining loader can be assessed in a VR environment. The factors calculated from data show significant variation between test drivers. The results are compared with those presented in literature. Understanding the effects of human operator to the system enables better optimisation of vehicles during product development.

The paper is organized as follows. First, the R&D process utilising VR based simulator is described in general. Then, the detailed process to assess effects of human operators on the working machine is described. In the following chapter, a test case that follows the previously described processes is presented. Finally, the results are presented together with discussion and conclusions. The novelty of the present study is in the demonstration of capabilities of very advanced virtual 3-D environment equipped with a physically adequate multibody simulation model to track the variations in performance of work tasks between individual test drivers on the basis of a number of measures.

Fig. 1. Illustration of virtual LHD

II. VR Based Simulator in the R&D Process

A design and development process of a HMI for a mobile machine using a simulator model and VR environment has been introduced and realized by Heikkinen [7]. The full R&D process of a HMI has been carried out successfully in VR environment. The article also highlights a several important details that need to be considered during the process.

The most effective and profitable way to take advantage of VR environments and simulators is to utilise them from the very beginning of the R&D process. Possibility to carry out user tests in early phase can reveal problems in the design which would be much more expensive to discover and change in later phases. In addition, cost savings can be achieved because the building and instrumentation of physical prototype for research purposes can be avoided. Virtual testing also enables the manufacturers to try radical new design solutions which would be technologically and economically very difficult to prove by other means.

Factors related to human operator of the vehicle should be studied in early phase user testing as well. Fig. 2 shows ideal design process of working machine utilising VR based simulator as the main testing tool. Assessment of human related factors is included in the testing and development block. That part of the process is introduced in detail in Fig. 3.

III. Description of the Process

III.1. Simulation Laboratory

The simulation laboratory used in this study is developed for investigating HMIs of off-highway vehicles. The main targets in the development of the laboratory were high immersion level and flexibility to test various HMI issues.

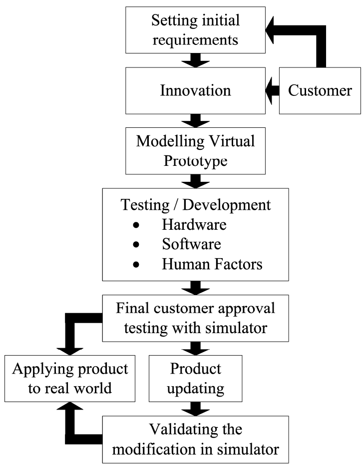


Fig. 2. Ideal VR based R&D process of working machine

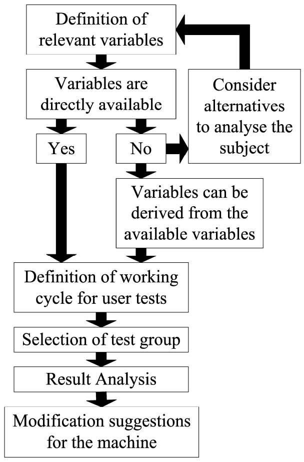


Fig. 3. Process for assessing effects of human operators on the vehicle in VR

The laboratory includes four 3D screens, a six degree-of-freedom (DOF) multipurpose motion platform, an optical user's head tracking system, typical controllers of real off-highway vehicles, a surround stereo system, and hardware for creating high frequency vibrations. The simulation laboratory is illustrated in Fig. 4. More detailed description can be found in [2].

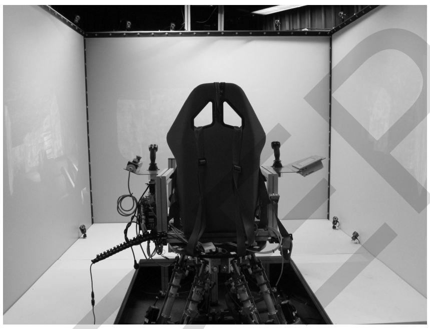


Fig. 4. Overview of the simulation laboratory

III.2. Mining Loader

As a test case, an underground mining loader is studied. The simulation model of the LHD includes accurate models of all the essential parts of power transmission, such as fluid power system and mechanical driveline. LHDs are structurally very close to wheel loaders that are commonly used for surface mining and earth moving. The loader consists of a rear-body and front-body which are connected to each other by an articulated joint. Steering of the loader is implemented by rotating the articulated joint using hydraulic cylinders. At the front end the LHD has a boom structure that is used to move and to actuate the bucket.

In the boom structure, a hydraulic lift cylinder adjusts the height of the bucket and a tilt cylinder actuates the inclination of the bucket. Due to the geometry of the boom structure, the lift cylinder also has a slight effect on the bucket inclination.

The LHD includes a conventional mechanical driveline consisting of diesel engine, torque converter, gearbox, differentials and planetary gears. The model of the diesel engine is based on the engine with displacement of 7.2 litres and power of 220 kW. The simulated mining loader has a bucket with a volume of 4.6 m3. The weight of the loader in operating condition is 26 000 kg. The hauling capacity is 10 000 kg.

III.3. Simulation of Mining Loader

The real-time simulation software used in the research has been under development since 2002 [3]. The software is an accurate high performance tool for real-time multibody simulation of complex machines coupled with additional functionality, such as modelling of hydraulics, particle systems and connections with real controlling hardware. The software includes features for visualisation of the virtual environment and the simulation data, as well. Simulation models can be created by using the graphical user interface.

In the core of the dynamic solver, the formulations are based on the Newton–Euler equations. The description of the dynamics of mechanical parts is based on Eq. (1) [3]:

$$M\ddot{q} + Q^c = Q^e + Q^v \tag{1}$$

where q is the vector of n generalized coordinates which define the position and orientation of each body in the system, M is the mass matrix, Q^e is the vector of generalized forces, Q^v is the quadratic velocity vector that includes velocity-dependent inertia forces, and Q^c is the vector of constraint forces related to a chosen set of generalized coordinates [3], [5].

The fluid power system of the mining loader consists of hydraulic pumps, cylinders and valves, which are connected to each other by the pipeline. The fluid power system is used for steering the articulated joint and for actuating the boom structure of the bucket.

The simulation model of the fluid power system is based on the assumption that the pressure is evenly distributed in control volumes [11]-[14]. Fig. 5 illustrates how a simple fluid power circuit with the valve-controlled double-acting cylinder is divided into control volumes.

The pressure build-up in each control volume can be described by the conventional continuity equation (2) by Merritt [11]:

$$\dot{p} = \frac{B_e}{V}\left(\sum Q_{in} - \sum Q_{out} - \dot{V}\right) \tag{2}$$

where $\dot{p}$ is the first time derivative of pressure, B_e is the effective bulk modulus of the volume, V is the studied volume, Q_{in} and Q_{out} are volume flows in and out of the volume. $\dot{V}$ describes the alternation of the control volume, e.g. actuator movement.

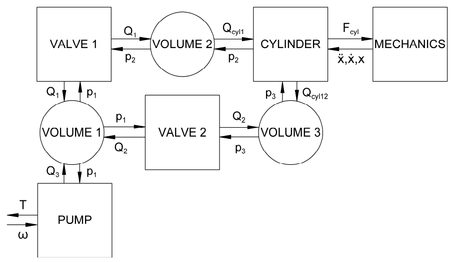


Fig. 5. Simple fluid power circuit divided in control volumes [14]

Models of mechanical power transmission components are based on well known analytic mathematical equations.

III.4. Selection of Variables

Depending on the complexity of the simulation model thousands or even millions of variables are available from the simulation. It is not possible or reasonable to log all the data available. Depending on the working cycle and the amount of test drivers the user tests can take several hours. It is important to consider carefully that all the relevant variables are logged, in other case user tests need to be run again. Some variables may not be directly available from the simulation. In that case, the variables need to be derived from the available ones or an alternative method to assess the issue must be found.

In Table I is presented the variables selected to indicate life-cycle efficiency of the loader in the current test case.

TABLE I
VARIABLES SELECTED TO LOG FROM SIMULATION

Variable	Available directly from simulation
Simulation time	Yes
Diesel engine power output	Yes
Total Energy Consumption	Yes
Collisions against the mine walls	Yes
Hydraulic forces of lift and tilt cylinders	Yes
RMS of Cylinder Forces	No
Working Productivity	No
Structural stresses on critical components	No

The engine output power equals to the angular velocity and the torque of the output shaft at the time step. The energy consumption is energy output from the diesel engine and does not take the efficiency of the engine into account. The productivity can be described as the amount of rocks transported by a litre of fuel or as the amount of rocks transported in an hour. The productivity indicators are calculated based on the energy consumption, simulation time and amount of transported rocks.

The number of collisions evidently affects the durability and service costs of the machine. In addition, the speed of the collisions is an important factor as it determines the momentum of the machine during the collision; the higher the momentum, the greater the probability of the damage. Serious damage requires extra maintenance, which has a negative effect on the life-cycle costs.

Selection of factors indicating energy consumption such as diesel power and fuel consumption is trivial but selection of factors indicating durability, fault probability and so on is more complex.

Stress in critical parts of the mechanical structure is in proportion to the forces to which the part is subjected. The stress history determines the fatigue life time of the structure. Reliable real-time stress analysis techniques are still under research and development [15].

Stress history would be possible to assess and to analyse by logging constraint forces or deformations of bodies and by performing finite element (FE) analysis later [16].

At the current study cylinder force history was considered sufficiently accurate for relative comparison of participants. The root mean square (RMS) values of cylinder forces are calculated to create factors indicating durability of the boom, which is one of the critical mechanical structures. The RMS of the cylinder force is calculated by Eq. (3):

$$RMS(F) = \sqrt{\frac{\sum_{k=0}^{N} F_k^2}{N}} \tag{3}$$

where F_k is the cylinder force at each time step and N is number of time steps.

III.5. Design of Working Cycle

To compare results of several test drivers, the working cycle of the user tests must be fixed. In the real world the working vehicles carry out varying tasks which often can be divided into subtasks. When planning the work cycle, it must be considered which results in each situation need to be found. This helps to define the correct work cycle for simulator tests.

For the case study a work cycle that is the most typical for the real loader is selected. The test drivers are supposed to move a fixed-sized pile of rocks from loading point to the dumping point.

Fig. 6 illustrates the route in the virtual mine. The starting point is in the upper left corner. Loading point is located in the upper right corner and dumping point in the lower right corner. The dumping point is located 14.5 m lower level than the loading point. Distance between the loading and dumping points is approximately 110 m.

The volume of the rock pile was approximately 11m3, corresponding to 27 000 kg of rocks. After the whole rock pile has been hauled to the dumping point, the loader is parked next to the dumping point.

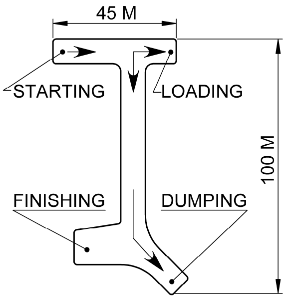


Fig. 6. Route of the testing task

All the test persons performed the same task. Each person performed the task twice and had a 15 minute break between the runs. The task was divided into two sub tasks to lower the probability of cyber-sickness, i.e., symptoms of motion sickness. Researchers have suggested two different reasons for cyber-sickness.

The first theory is based on conflicting cues and the second theory is based on postural instability [17]-[19].

III.6. Test Group

Selection of tests drivers has influence on the results, especially when the effect of human operator on the vehicle is studied. Size of the group and participants' experience levels should be considered carefully to achieve statistically valid results.

In this study, the test group is relatively small consisting of five male participants who performed the same task in the virtual mine. The mean age of the group was 28.6 years and the standard deviation 4.22. Table II presents the experience levels of the participants.

The objective was to study the process of using a VR environment for assessing effects of operators so larger group was not considered to be necessary.

TABLE II
EXPERIENCE LEVELS OF THE PARTICIPANTS

Participant ID	VR experience	Off-highway vehicle experience
1	Novice	Competent
2	Expert	Novice
3	Competent	Expert
4	Novice	Competent
5	Novice	Expert

Prior to the study, the participants gained familiarity with the simulator in order to be able to perform the task fluently. Participant 4 suffered from a bout of cyber-sickness during the test. However, he was able to perform the test to the end.

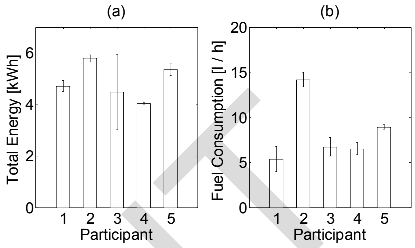
IV. Results of Simulation

The results are illustrated by histograms and time domain curves.

The histograms present the mean values and the standard deviations of the two test runs for each participant. Significant variation between participants was found.

IV.1. Energy Consumption

The total energy consumption and the average rate of fuel consumption are illustrated in Figs. 7.



Figs. 7. Consumptions: (a) Total energy consumption
(b) average rate of fuel consumption

The energy content of diesel fuel varies around 10 kWh / litre [20]. The efficiency of a heavy-duty diesel engine varies typically between 25 and 45 percent depending on the operating point [21]. Specific assessment of the engine efficiency on every time step is excluded and the average efficiency of the diesel engine is assumed to be 34 percent during the task. The energy consumption was converted to fuel consumption, which indicates the amount of fuel consumed in an hour. The highest fuel consumption was 14.8 litres / hour (Participant 2, Run 2). The mean fuel consumption of all the runs was 8.3 l/h.

A strong linear correlation between engine power, load factor and fuel consumption has been found [22].

Many off-highway working vehicles are structurally relative similar, although configurations vary because the machines are developed for different tasks. Unfortunately, the amount of data of fuel consumption of construction vehicles publicly available is limited. Thus, it is justified to compare the energy consumption results of this study to several different type of working machines. Achieved results of fuel consumption are compared to data available for excavators, bulldozers and wheel loaders, which are all structurally close to the mining loader. The consumption rates compared based on the amount of fuel consumed in an hour. The variations in hauling distances and in ore in question have the effect on the fuel consumption.

Wheel loaders with diesel engines of around 100 kW and displacement of 5.9 litres have been reported to consume from 3.0 to 6.4 litres per hour, while the load factor of the engines varied within a range of 9 to 25 percent. The loaders were run in a real working environment for approximately 119 hours using petroleum diesel [23]. While considering approximately the same sized engine as used in this study bulldozer consumption is reported to be below 20 l/h at loading factor less than 35% [22]. It has been found that an excavator with an engine size close to the size of the engine simulated in this research consumes from 8,7 to 23,8 litres of fuel per hour depending on the operating mode [24].

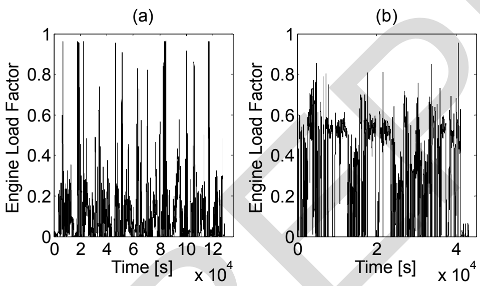
Based on the reference data reviewed above the energy consumption results of this study are reasonable. The values may not be absolutely correct with real world values, but the accuracy of the fuel consumption data is adequate for comparison of the performances of the participants and to find the most efficient and productive operating style.

IV.2. Diesel Engine Load Factor

The load factors of the diesel engine was calculated based on the angular speed and torque of engine output shaft, which results to the current output power of the engine. The output power is divided by maximum power of the engine to get the load factor.

Analysis of load factor data reveals that the engine loading was very low during the task. It was observed that the participants were driving relatively carefully and slowly.

Participant 2 had exceptional high engine loading compared to the other drivers. As an example of the engine loadings, the lowest and the highest loading curves are presented in Figs. 8.



Figs. 8. Diesel engine load factors: (a) the lowest loading (b) the highest loading

IV.3. Total Time

Times elapsed in work cycle are illustrated in Figs. 9 for every participant. The results show that Participant two performed the task fastest, and consumed the greatest amount of fuel. On the other hand, Participant one used the longest time to complete the task but failed to have the smallest energy consumption.

IV.4. Productivity

Two indicators of productivity are calculated with respect to the amount of consumed energy and time used for performing the task. Figs. 10 illustrate the average rates at which participants transported the rocks and the average amounts of rocks in cubic meters that participants were able to transport with one litre of fuel.

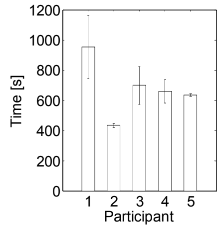
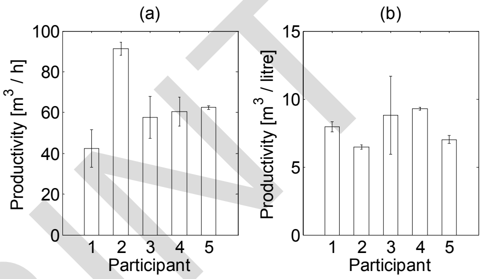


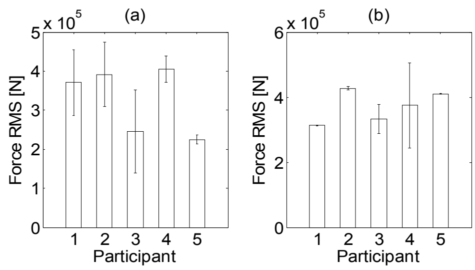
Fig. 9. Total time for completion of the task



Figs. 10. Productivity: (a) as function of time (b) as function of fuel consumption

IV.5. Cylinder Forces

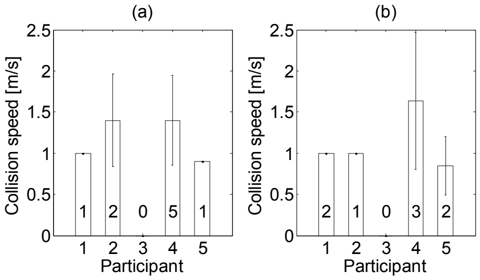
The mean values of RMS forces of lift and tilt cylinders are presented in Figs. 11. The force sums are in relation to the stress history, maintenance need and fatigue life time of the boom structure.



Figs. 11. RMS force values: (a) lift cylinder; (b) tilt cylinder

IV.6. Collisions

Collisions of the front-body were significantly less frequent than collisions of the rear-body. The mean value of the collision speeds between the front-body and the mine was 1.25 m/s. The mean values of collision speeds between rear-body and mine walls are presented in Figs. 12 for each participant. The total numbers of collisions during the test run are presented as numeric values inside the bars.



Figs. 12. Collisions of the rear-body against the mine walls:
(a) during the first test runs; (b) during the second runs

Collisions between the bucket and the mine occur whenever the rocks are loaded into the bucket. Therefore, slow bucket collisions were very common. Hard collisions (over 0.5 m/s) between the bucket and the mine were uncommon.

The collision data shows that the driving style of some participants is more expensive with respect to the life-cycle cost than the style of most of the participants. Real world data of the correlation between the collision speed and maintenance need was not available. The results show that the tendency of the operator to collide can be found in VR environment.

V. Discussion

The case study was carried out by taking advantage of the R&D processes introduced in this article. The comparisons of the attained simulation data show significant variation between the participants.

One general meter indicating human effect on the life-cycle efficiency seems to be impossible to define because the human operator influences to number of factors such as energy consumption, productivity, stress history, fatigue life time and maintenance need of the machine.

The process introduced previously provides the method to find relative differences between participants or technical solutions. This requires that only the variable of interest is changed and other conditions in simulator are maintained unchanged.

V.1. Limitations

The group of participants in this study was relatively small. However, since clear differences between participants were found already in a small group, differences would have been found also within a larger group. Only one loading and hauling case was studied. Varying hauling distances, minerals and other environmental factors would have an effect on the numerical results. The accuracy of the simulation model is limited and physical phenomena which are considered less significant for human experience are neglected. The detailed verification of the simulation model has not been carried out.

However, the model is based on physical equations which are widely acknowledged in literature. The accuracy of the model is adequate for comparing differences between human operators, even though absolutely accurate numerical results were not obtained.

User experience in the VR environment of this study has not been verified by driving the tests using the real machine.

VI. Conclusion

The process of using VR environment for assessing effects of human operators on the life-cycle efficiency of working vehicles was introduced and realized. The methods used for this research can be applied to most of the off-highway working vehicles because the machines typically have much similarity. VR is an effective tool in assessing the variations in driving styles of human operators. The biggest benefit of using VR environment is the possibility to provide constant conditions for all participants, ensuring comparability of the results. The off-highway working vehicle manufacturers may gain considerable benefits by taking advantage of VR.

More research needs to be carried out for better understanding of the effect of the human operator on the working vehicles. Further research could aim to create guidelines about how to optimize the driving style of off-highway working machines. Development of more efficient technology and mitigation of the impact of human operators on the life-cycle cost are both areas worthy of further investigation when developing the future working vehicles.

Acknowledgements

This research was carried out as part of the EFFIMA program of the Finnish Metals and Engineering Competence Cluster (FIMECC).

References

[1] J. Viitaniemi, S. Aromaa, S-P. Leino, S. Kiviranta and K. Helin, *Integration of User-Centred Design and Product Development Process within a Virtual Environment*, 2010, ISBN 978-951-38 7489-6 (URL: http://www.vtt.fi/publications/index.jsp)

[2] J. Heikkinen, L. Luostarinen, Virtual environment for investigating Human Machine Interface in machines with hydraulic transmissions, *Proceedings of the 7th FPNI PhD Symposium on Fluid Power, pp. 225-234, Reggio Emilia, Italy, June 2012.*

[3] P.M. Korkealaakso, A.J. Rouvinen, S.M. Moisio, J.K. Peusaari, Development of a real-time simulation environment, *Journal of Multibody system dynamics, Vol. 17*(Issue2-3)*:177-194, April 2007.*

[4] M. Karkee, B.L. Steward, A.G. Kelkar, Z.T. Kemp II, Modeling and real-time simulation architectures for virtual prototyping of off-road vehicles. *Virtual Reality - Special issue on Virtual Manufacturing and Construction, Vol. 15*(Issue 1)*: 83-96, March 2011.*

[5] P.M. Korkealaakso, *Real-Time Simulation of Mobile and Industrial Machines Using the Multibody Simulation Approach,* Ph.D. dissertation, Dept. Mech. Eng., Lappeenranta University of Technology, Lappeenranta, Finland, 2009.

[6] S. Aromaa, J. Viitaniemi, N. Philippon, New task-related dynamic field of view analysis in virtual environment, NES2012. The 44th Annual International Nordic Ergonomics and Human Factors Society Conference. Stockholm, August 2012, Book of abstracts. NES2012 Ergonomics for sustainability and growth. KTH Royal Institute of Technology; School of Technology and Health, Division of Ergonomics. Stockholm (2012).

[7] Heikkinen, J.E., Handroos, H., Design of a human machine interface for a mobile machine using simulation in virtual reality environment, (2013) *International Review on Modelling and Simulations (IREMOS),* 6 (1), pp. 284-290.

[8] T. Norgate, N. Haque, Energy and greenhouse gas impacts of mining and mineral processing operations, *Journal of Cleaner Production, Vol. 18*(Issue 3)*:266–274, February 2010.*

[9] T. Lin, Q. Wang, B. Hu, W Gong, Development of hybrid powered hydraulic construction machinery, *Automation in Construction, Vol. 19*(Issue 1)*:11–19, January 2010*

[10] S. Hui, J. Junqing, Research on the system configuration and energy control strategy for parallel hydraulic hybrid loader, *Automation in Construction, Vol. 19*(Issue 2)*:213–220, March 2010.*

[11] H.E. Merritt, *Hydraulic Control Systems* (John Wileys and Sons, 1967).

[12] H. Handroos, Methods for combining a Theoretical and an Empirical Approach In Modelling Pressure and Flow Control Valves for CAE-programs for Fluid Power Circuits, Ph.D. dissertation, Laboratory of Hydraulics and Automation, Tampere University of Technology, Finland, 1990.

[13] A. Mikkola, *Studies on fatigue damage in a hydraulically driven boom system using virtual prototype simulations*, Ph.D. dissertation, Dept. Mech. Eng., Lappeenranta University of Technology, Finland, 1997.

[14] R. Åman, *Methods and models for accelerating dynamic simulation of fluid power circuits,* Ph.D. dissertation, Laboratory of Intelligent Machines, Lappeenranta University of Technology, Finland, 2011.

[15] T.T. Rantalainen, A.M. Mikkola, S.M. Moisio, G.B. Marquis, A Method for Obtaining the Dynamic Stress History from a Flexible Multibody Simulation Using Sub-Modeling, *Mechanics Based Design of Structures and Machines, Vol. 41*(Issue 3)*:316–336, April 2013.*

[16] S. Frimpong, Y. Li, Stress loading of the cable shovel boom under in-situ digging conditions, *Engineering Failure Analysis Vol. 14*(Issue 4)*:702–715, June 2007.*

[17] E.M. Kolasinski, Simulator sickness in virtual environments (ARI Tech. Rep. 1027), *U.S. Army Research Institute for the Behavioral and Social Sciences, May 1995.*

[18] H.B. Duh, D.E. Parker, J.O. Philips, T.A. Furness "Conflicting" Motion Cues to the Visual and Vestibular Self- Motion Systems Around 0.06 Hz Evoke Simulator Sickness, *Human Factors, Vol. 46*(Issue 1)*:142-153, January 2004.*

[19] T.A. Stoffregen, L.J. Hettinger, M.W. Haas, M.M. Roe, L.J. Smart, Postural Instability and Motion Sickness in a Fixed-Base Flight Simulator. *Human Factors, Vol. 42(Issue 3):458–469, January 2000.*

[20] Fuel Properties Comparison, Alternative Fuels Data Center (AFDC), 2013, Available from: http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf

[21] R. Matthews, D. Seedah, M. Ates, K.J. Kim, K.G. Anderson, J. Vaughn, D. Dardalis, H. Lijun, R. Harrison, Estimating Texas Motor Vehicle Operating Costs: Final Report, *Center for Transportation Research at The University of Texas at Austin, November 2011.*

[22] V. Kecojevic, D. Komljenovic, Impact of Bulldozer's Engine Load Factor on Fuel Consumption, CO2 Emission and Cost, *American Journal of Environmental Sciences, Vol.7*(Issue 2)*:125-131, 2011.*

[23] H.C. Frey, W. Rasdorf, P. Lewis, Comprehensive Field Study of Fuel Use and Emissions of Nonroad Diesel Construction Equipment, Journal *of the Transportation Research Board, Vol. 2158:69-76, August 2010.*

[24] S. Abolhasani, H.C. Frey, K. Kim, W. Rasdorf, P. Lewis, S. Pang, Real-World In-Use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators, *Journal of the Air & Waste Management Association, Vol. 58*(Issue 8)*:1033-1046, August 2008.*

Authors' information

Lappeenranta University of Technology,
Laboratory of Intelligent Machines,
Skinnarilankatu 34,
53850 Lappeenranta, Finland.
Tel: +358 50 4642520
E-mails: lauri.luostarinen@lut.fi
heikki.handroos@lut.fi

Lauri Luostarinen received the M.Sc., degree from Lappeenranta University of Technology, Lappeenranta, Finland, in 2010. He is currently working in the Laboratory of Intelligent Machines at Lappeenranta University of Technology. His research interests include Virtual Realities, HMI in off-highway working vehicles, Human effects on machines and Robotics.

Heikki Handroos has been a professor of Machine Automation in Lappeenranta University of Technology since 1993. He earned his M.Sc. and D.Sc. degrees in Tampere University of Technology, 1985 and 1991. His research interests range from modelling, simulation and control of mechatronic systems to off-road vehicle transmissions and robotics. He has published about 200 scientific journal and conference papers.

Publication II

L. O. Luostarinen, R. Åman, H. Handroos

Tool for studying effects of human operators on energy consumption of working hydraulics of off-highway working vehicle

Reprinted from

8th FPNI Ph.D Symposium on Fluid Power, 2014, Lappeenranta, Finland, with permission from ASME Digital Collections

Publication III

R. Åman, P. Ponomarev, L. O. Luostarinen, H. Handroos, J. Pyrhönen, L. Laurila

Experimental Analysis of Electro-Hydraulic Hybrid Actuator Systems in Off-Highway Working Vehicle

Reprinted from

8th FPNI Ph.D Symposium on Fluid Power, 2014, Lappeenranta, Finland, with permission from ASME Digital Collections

Publication IV

L. O. Luostarinen, R. Åman, H. Handroos

Development of Control Interface for HIL Simulation of Electro-Hydraulic Energy Converter

Reprinted from

International Review on Modelling and Simulations (IREMOS), vol. 7, no. 4, pp. 653-660, 2014, with permission from Praise worthy prize S.r.l.

International Review on Modelling and Simulations (I.RE.MO.S.), Vol. 7, N. 4
ISSN 1974-9821 August 2014

Development of Control Interface for HIL Simulation of Electro-Hydraulic Energy Converter

Lauri O. Luostarinen, Rafael Åman, Heikki Handroos

Abstract – *High energy efficiency has become an important topic in the world of off-highway working vehicles because of environmental and economic demands. Hardware-in-the-loop (HIL) simulation is a cost effective and powerful tool to study novel energy efficient power transmission solutions of working vehicles. HIL simulation enables comprehensive testing of novel hardware components and subsystems without the presence of the whole experimental working vehicle. The objective of this article is to develop a control interface for HIL simulation of electro-hydraulic energy converter (IEHEC). IEHEC consists of a hydraulic pump-motor and an integrated electrical permanent magnet synchronous motor-generator. IEHEC is capable to reduce power losses compared to conventional valve controlled fluid power systems. An energy recovery of potential and kinetic energies is also possible using IEHEC. In this article, alternative HIL control interfaces were studied experimentally. The results of HIL simulations were compared to reference results obtained from completely virtual simulations. The results show that a functional and accurate control interface was found. The developed interface will be used in the future to test the suitability of IEHEC for different working machines.* ***Copyright © 2014 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Hardware-In-The-Loop, Hybrid Power Transmission, Interface, Simulation, Working Machine*

I. Introduction

Off-highway working vehicles are used for various tasks e.g. for extracting and harvesting natural resources.

They are essential for current standard of living. High energy efficiency of the working machines ensures the competitiveness of the manufacturers under environmental and economic pressure.

Power transmissions of working machines are typically based on fluid power systems. The key advantage of the fluid power systems is the high power density but the energy efficiency of the systems has a potential to be improved significantly.

Normally, the fluid power transmission lines are flexible hoses and pipes of small diameter which cause remarkable power losses. In many applications remarkable energy losses occur also because of the lack of energy recovery e.g. during the lowering of the payload. The directional control valves of the conventional fluid power systems also cause power losses. An improvement in the poor energy efficiency of the conventional fluid power systems can be achieved by an electro-hydraulic hybrid technology which enables the power transmission using electric lines and the recovery of the releasing potential or kinetic energy. In the electrical cables the power losses are negligible in comparison to the losses occurring in the hydraulic transmission lines [1]. In this article an integrated electro-hydraulic energy converter (IEHEC) is proposed to improve the energy efficiency aspects mentioned above. The key component of IEHEC is newly designed liquid cooled electrical machine in which hydraulic fluid can be used as cooling media. Liquid cooling enables to reduce the dimensions of the electrical machine and thus increase the power density [2]. Suitable places for IEHEC in working vehicles are all actuators that carry out work cycle in which the kinetic or potential energy is available for recovery e.g. lifting cylinders in cranes and grippers that tend to open by the payload mass and gravity [3].

Fig. 1 shows an example of the main power transmission system of an off-highway working vehicle together with the integrated electro-hydraulic actuator system. System in question follows serial hybrid transmission line architecture and it offers the possibility to recover the potential energy into electrical form to be stored in electrical energy storage [1].

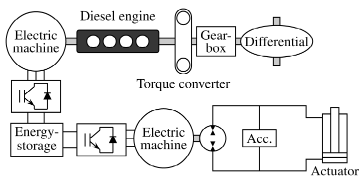


Fig. 1. Structure of a hybrid power transmission using IEHEC to operate a cylinder [2]

After careful simulations of IEHEC, a physical prototype was manufactured. The testing of the prototype was started by efficiency and characteristic measurements. [2] The next step is to test functionality of IEHEC as a component of working machines and to find suitable applications for IEHEC. This will be carried out using hardware-in-the-loop (HIL) simulation. This article describes the work carried out to enable the HIL testing.

HIL simulation is an important tool to reduce development time and to ensure reliability and safety of complex components and systems [4]. In HIL simulation the real constraints (e.g. sensor accuracy, signal noise, sampling period of an embedded controller, modulation frequency and fault operations) of the hardware are taken into account in the simulation loop [5]. Studies related to integration of virtual prototyping, HIL simulation, and human-in-the-loop simulation into R&D processes has been published recently with promising results [6],[7].

Modern working machines are equipped with intelligent control systems and the machines can be decomposed into subsystems: the embedded controller, the power electronics set, the actuator and the mechanical power transmission. HIL simulation can be applied to the subsystems at three different levels.

In the first case, the embedded controller is under test. The simulation of the other parts (power electronics, actuators, mechanical power transmission and mechanical load) is carried out in real-time by virtual models. A signal conditioning board is required to enable communication between the simulation and the controller board under test. The embedded controller is working as it were connected into a real machine. This method can be called “signal level HIL simulation” [5]. The signal level HIL simulation has been often employed in aerospace and automotive applications for assessment of controller boards [8].

In the second case (power level HIL simulation), in addition to the embedded controller, also power electronics are tested. The other parts are simulated. Control signals and power variables are transferred between the hardware and the virtual model. A second power electronics set must be connected to the virtual simulation to provide the load for the power electronics under test [5].

In the last case (mechanical level HIL simulation), the whole drive (control, power electronics and actuator) is evaluated. The mechanical construction of the working machine is simulated. The subsystems of the drive under test are connected normally as in a real machine. Another actuator is often used to provide mechanical load for the actuator under test. The reference signal for the loading actuator is from the simulation model. The mechanical response of the actuator under test is returned to the simulation model [5].

Appropriate control interface of the HIL simulation depends on the system in question. For the mechanical level HIL simulation the suitable physical parameters for the control interface can be e.g. position, velocity, acceleration or force.

The load machine has typically force or velocity servo control (torque and rotational velocity servo control for rotational systems). In some cases, the selection of the control interface depends on the operation mode of the system [9]-[16].

A reliable study of working machines using mechanical level HIL simulation requires running of an accurate simulation model of the machine on real-time. Multibody simulation approach has been applied to generate real-time models for HIL-simulations [10],[17]. Versatile real-time simulation software with user-friendly graphical modelling features is an important tool in rapid development of accurate mechanical level HIL simulation setups.

Inverse dynamics (ID) is a classical method to solve the input force of a model if the desired motion is known [18]-[20]. Thus, ID extends the possible control interfaces of HIL simulation setups. Real-time ID solution of a complex multibody system is a problematic task and requires a lot of computing power [21]. Availability of versatile real-time multibody modelling and simulation software with ID solver is very limited on the market. Thus, the experimental HIL simulation tests were not carried out using ID.

This paper is organized as follows. First, the integrated electro-hydraulic energy converter (IEHEC) is introduced. Then, simulation models and a test rig are described. In the following chapter, three alternative HIL simulation control interfaces are introduced. Finally, the results are presented together with discussion and conclusions.

This article introduces an experimental study to develop a HIL simulation control interface for electro-hydraulic actuator system. Based on the results a functional and reliable interface was found. The developed HIL simulation setup enables further research, in which suitability of the electro-hydraulic actuator system for different working vehicles will be studied.

II. IEHEC

IEHEC is the principal component of the studied hybrid actuator system (Fig. 2). The energy converter consists of a hydraulic pump-motor and an integrated electrical permanent magnet synchronous motor-generator [3].

Fig. 2. Prototype of IEHEC

Integrated energy converter can be driven in all four-quadrant modes. Thus, it can produce the hydraulic power required by the actuator or recover the energy released by the actuator mechanism [3].

Fig. 3 shows the circuit diagram of the electro-hydraulic hybrid actuator system. The hydraulic machine is directly driven by an electrical motor. The pump-controlled fluid power systems have many advantages of which the biggest is the reduction of hydraulic losses in comparison to the conventional directional valve operated systems. Unfortunately, these systems have also disadvantages.

Asymmetric hydraulic cylinder is a commonly used component in producing forces and movements in working vehicles. Together with a pump-controlled fluid power system asymmetric cylinder can cause problems due to the differential volumes in the chambers. Pump-controlled systems are commonly operated in a closed-loop, where it is essential to maintain the even volume flows in the input and output ports of the pump.

The uneven volume flows can be balanced by pilot operated check valves (Fig. 3) [1], [22]-[24].

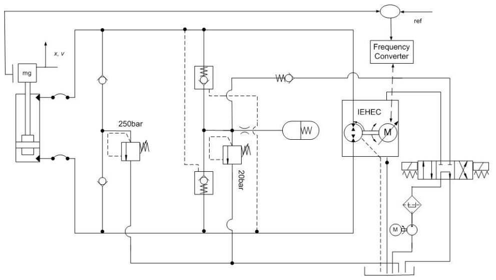


Fig. 3. Electro-hydraulic hybrid actuator system

III. Simulation of IEHEC operating the Lifting Cylinder of a Log Crane

In this chapter simulation models, a test rig and the HIL simulation control interfaces are introduced.

III.1. Modelling

As a case study, a log crane (Fig. 4) is modelled using high performance real-time simulation software which has been under development since 2002. The software has been optimised for modelling and simulation of off-highway working vehicles. In the core of the dynamic solver, the formulations are based on the Newton–Euler equations. The description of the dynamics of mechanical parts is based on Eq. (1) [25]:

$$M\ddot{q} + Q^c = Q^e + Q^v \tag{1}$$

where q is the vector of n generalized coordinates which define the position and orientation of each body in the system, M is the mass matrix, Q^e is the vector of generalized forces, Q^v is the quadratic velocity vector that includes velocity-dependent inertia forces, and Q^c is the vector of constraint forces related to a chosen set of generalized coordinates [25],[26].

The main dimensions and the locations of the lifting cylinder and the load of the simulated log crane are shown in Fig. 4. The total mass of the crane without the load is 800 kg and the mass of the logs in the grapple is 260kg.

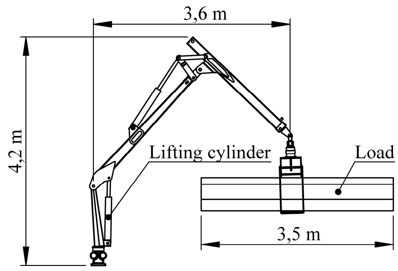


Fig. 4. Log crane

Completely virtual simulations are run to obtain reference results for the HIL simulations. The fluid power circuit including IEHEC is modeled by Simulink.

The same multibody model is used for the virtual and HIL simulations.

The simulation model of fluid power system is based on lumped parameter modelling method [27]. The valve, pump and cylinder models calculate the incoming and outgoing flows which are used in the volume models to calculate the associated pressures according to Equation (2) [28]:

$$\dot{p} = \frac{B_e}{V}\left(\sum Q_{in} - \sum Q_{out} - \dot{V}\right) \tag{2}$$

where $\dot{p}$ is the first time derivative of pressure, B_e is the effective bulk modulus of the studied system, V is the studied model, Q_{in} and Q_{out} are volume flows in and out of the volume, and $\dot{V}$ is the alternation of the physical volume in a component as a function of time, e.g. actuator on movement. In the virtual simulations the multibody model and the fluid power circuit model are run synchronously. The position and the speed of the lifting cylinder are inputted from multibody system into the fluid power model and the force is returned from the fluid power model into the multibody system (Fig. 5).

The interface of the virtual simulation is commonly used. Thus, the results of virtual simulations are used as reference for HIL simulation results.

III.2. Test Rig

The test rig enables testing IEHEC as a part of virtual working vehicle by means of HIL simulation in two operating modes.

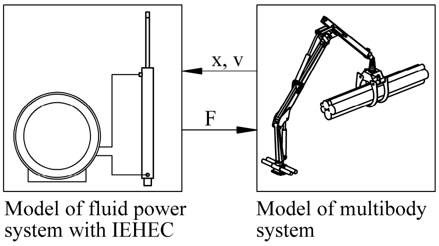


Fig. 5. Connections of the simulation models [22]

The first operating mode is the work cycle mode using the electric machine of IEHEC as motor connected to the hydraulic pump. The other mode is the energy recovery mode while direction of operation is reversed. [29] The test rig is illustrated in Fig. 6.

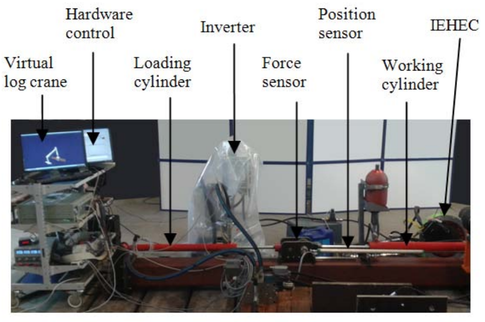


Fig. 6. Test rig

The loading cylinder is controlled by high bandwidth proportional cartridge valves. The rotational speed reference of the IEHEC is the input that makes the system move. The speed reference is inputted to the frequency inverter that is driving IEHEC's electrical machine.

Sometimes small-rate power systems are firstly used to validate control algorithms before implementation on a full-rate power system [5]. In this study, the loading cylinder of the test rig is capable to produce only fifty percent of the maximum lifting cylinder force of the log crane. The problem was overcome by down scaling the force of the multibody model by fifty percent before realizing the force by the loading cylinder and vice versa. Because the main objective of the study is to study HIL simulation control interfaces, the down scaling of the force is acceptable.

Dimensions of hydraulic cylinders in different working machines have significant variations. To avoid the need for changing the working cylinder of the test rig every time the cylinder size of the simulated working machine is changed the signals sent through the control interface are scaled. The scaling factor is the ratio of the areas of the test rig working cylinder's piston and the working machine's piston.

The scaling of the force and motion signals enables correct pressure level and rotational speed for the IEHEC in spite of the different cylinder sizes.

The effect of the cylinder size to the cylinder friction and damping is ignored. However, when the cylinder sizes are relatively close to each other the error is not significant.

III.3. HIL Simulations Control Interfaces

Three alternative control interfaces were studied to connect the electro-hydraulic actuator hardware into the multibody simulation model of the log crane. Two separated computers are used in all the setups.

One computer is equipped with Dspace real-time controller board which is dedicated for real-time control of the hardware. Another computer is dedicated for running the multibody model and a script handling the data between the simulation model and the controller of the hardware. With the structure of two separated computers the safety functions of the physical hardware can be guaranteed easier. Data connections of the HIL simulation setups are illustrated in Fig. 7.

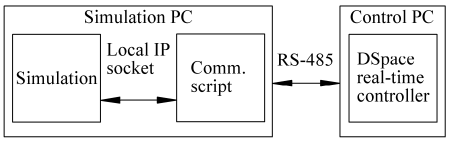


Fig. 7. Data connections

The test rig simulates the lifting cylinder of the log crane. The other actuators of the virtual log crane were not actuated during the experimental tests. The load was hold continuously in the log grapple. An example of the IEHEC control signal used in experimental tests is shown in Fig. 8.

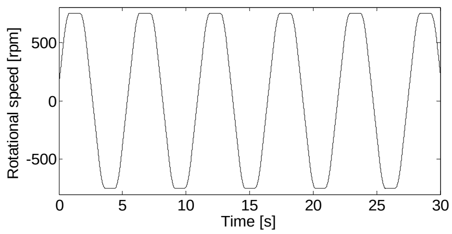


Fig. 8. Rotational speed reference signal of IEHEC

In the first control interface the signal of force sensor connected between the working cylinder and the loading cylinder is the input into the multibody simulation. The piston velocity is returned from the multibody simulation and the velocity is used as a reference value for the loading cylinder. The loading cylinder is closed loop velocity controlled. The connections of the first interface are shown in Fig. 9.

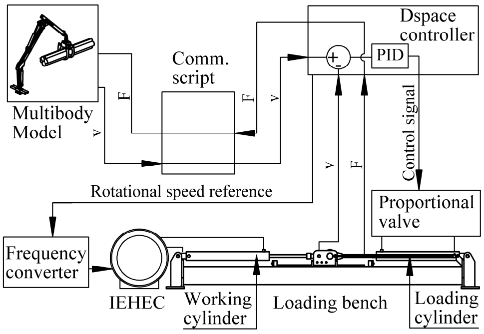


Fig. 9. Connections between the multibody simulation and the hardware in the first interface option

In the second and the third control interfaces the loading cylinder is controlled by a closed loop force controller. The reference signal of the servo controller is the force acting in the multibody model.

The input force of the multibody simulation is calculated by closed loop proportional-integral-derivative (PID) controllers (Fig. 10).

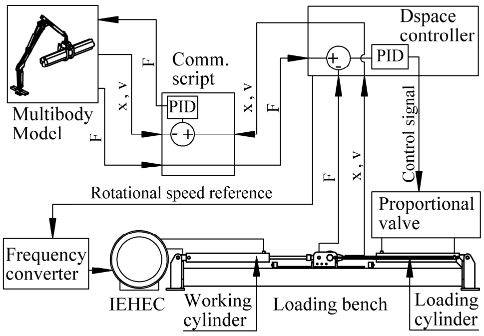


Fig. 10. Connections between the multibody simulation and the hardware in the second and the third interface options

The controller of the second setup calculates the input force based on the velocity difference of the test rig and the multibody model. In the third control interface option, one controller is calculating a velocity reference signal based on the position difference of the test rig and the multibody model.

Another controller is calculating the input force based on the calculated velocity reference and the velocity of the multibody model.

IV. Results and Analysis

In the case of second and third control interfaces the input force signals of the multibody model calculated by the PID controllers were saved during the HIL simulations. Forward dynamic simulations were run again by feeding the saved force signal into the multibody.

The results of these resimulations are used to verify the results of HIL simulations. Completely virtual simulations were also run to obtain more basis of comparison for the results of the HIL simulations.

Control interface 1

Cylinder force and piston velocity of the lifting cylinder of the multibody model during the HIL simulation and the virtual simulation are shown in Fig. 11 and Fig. 12.

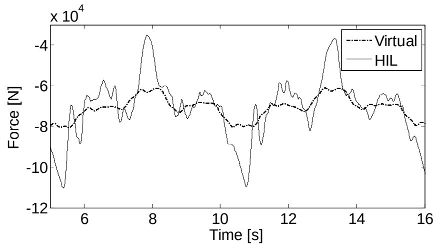


Fig. 11. Cylinder force using the first control interface

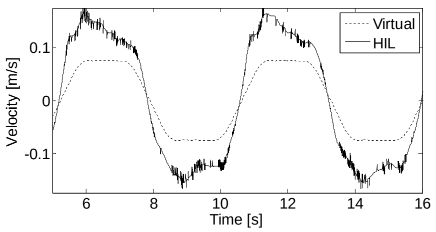


Fig. 12. Piston velocity using the first control interface

With the current hardware the first method was found problematic. In theory the method is correct but the experimental tests revealed that the inertia and the friction of the components of the test rig cause force peaks when the direction of the movement is changed.

The peaks in the force sensor signal rise over the correct level. Thus, the peaks are causing too high piston velocity in the multibody model. Because of stability problems the first control interface was tested at lower velocity than the others.

Control interface 2

Cylinder force and piston velocity of the lifting cylinder of the multibody model using the HIL simulation, the virtual simulation and the resimulation are shown in Fig. 13 and Fig. 14.

The second control interface achieves very high accuracy compared to the first interface option. The cylinder force and piston velocity are close to the results of the virtual simulation. Noticeable vibration appears in the cylinder force. The velocity of the resimulation indicates that the force signal has a slight inaccuracy.

The mechanical power of the lifting cylinder in the cases of the HIL simulation and the virtual simulation are shown in Fig. 15.

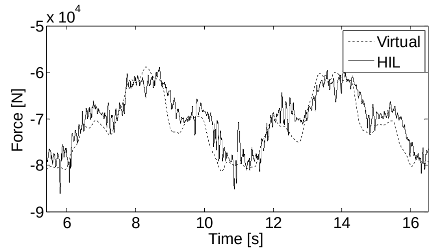


Fig. 13. Cylinder force using the second control interface

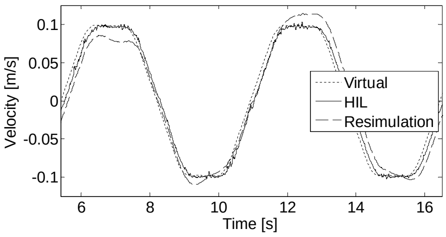


Fig. 14. Piston velocity using the second control interface

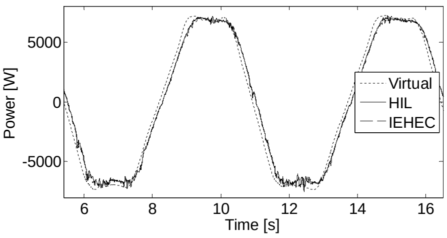


Fig. 15. Mechanical cylinder power using the second control interface

The mechanical power of the working cylinder connected to IEHEC is also illustrated. All the three curves are close to each other.

Control interface 3

Cylinder force and piston velocity of the lifting cylinder of the multibody model using the HIL simulation, the virtual simulation and the resimulation are shown in Fig. 16 and Fig. 17.

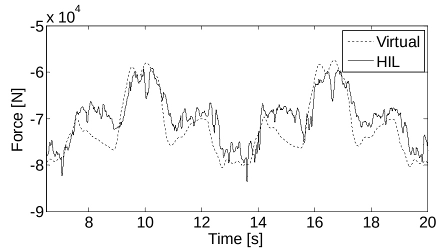


Fig. 16. Cylinder force using the third control interface

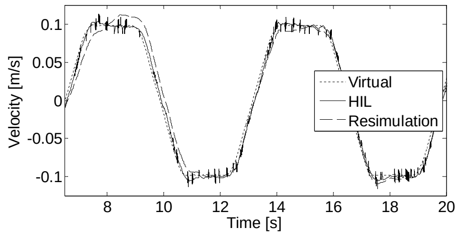


Fig. 17. Piston velocity using the third control interface

The vibration of the cylinder force is significantly lower compared to the second interface option.

Otherwise the accuracy of the cylinder force is at the same level than using the second interface. The piston velocity of the HIL simulation has small peaks which duration is approximately one simulation time step. The peaks are probably originating from the sensor noise which is amplified by the numerical noise during the simulation. The piston velocity of the resimulation follows the other velocity signals with a high accuracy.

The mechanical power of the lifting cylinder in the cases of the HIL simulation and the virtual simulation are shown in Fig. 18. The mechanical power of the working cylinder connected to IEHEC is also shown.

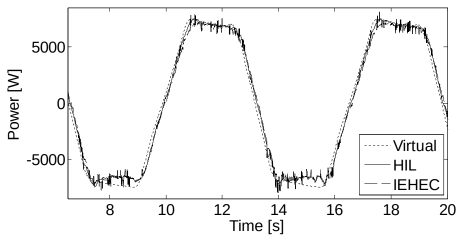


Fig. 18. Mechanical power using the third control interface

V. Conclusion

Alternative control interfaces for HIL simulation of working machine operated by IEHEC were studied. The third control interface option introduced in this article was found to be functional, reliable and the most accurate. Future work will include simulation of real working cycles of the log crane and to find out the actual energy saving potential compared to the conventional valve controlled fluid power circuit. The energy efficiency of the IEHEC at different working cycles will be analyzed. The HIL simulation setup will be used for finding suitable applications for IEHEC in working machines.

References

[1] R. Åman, P. Ponomarev, L. Luostarinen, H. Handroos, J. Pyrhönen, L. Laurila, Experimental Analysis of Electro-Hydraulic

Hybrid Actuator System for Off-Highway Working Vehicles, *8th FPNI Ph.D Symposium on Fluid Power (FPNI2014)*, Lappeenranta, Finland, June 2014.

[2] P. Ponomarev, R. Åman, H. Handroos, P. Immonen, J. Pyrhönen, L. Laurila, High Power Density Integrated Electro-Hydraulic Energy Converter for Heavy Hybrid Off-Highway Working Vehicles, *IET Electrical Systems in Transportation*, Accepted to be published 2014.

[3] R. Åman, H. Handroos, P. Ponomarev, J. Pyrhönen, Utilisation of Electro-Hydraulic Hybrid Actuator System in Off-Highway Working Vehicles, *8th International Conference on Fluid Power Transmission and Control (ICFP 2013), pp. 232-236, Hangzhou, China, April 2013.*

[4] D. Maclay, Simulation gets into the loop, *IEE Review, Vol. 43(*Issue 3*): 109 – 112, May 1997,* http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=590793&queryText%3DSimulation+gets+into+the+loop

[5] A. Bouscayrol, Different types of Hardware-In-the-Loop simulation for electric drives, *Industrial Electronics, 2008. ISIE 2008. IEEE International Symposium on, pp. 2146-2151, Cambridge, June-July 2008,* http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4677304&tag=1

[6] Luostarinen, L.O., Handroos, H., Using simulation in virtual reality environment to find effects of human operators on the life-cycle efficiency of off-highway working vehicles, (2013) *International Review on Modelling and Simulations (IREMOS)*, 6 (5), pp. 1629-1636.

[7] Heikkinen, J.E., Handroos, H., Design of a human machine interface for a mobile machine using simulation in virtual reality environment, (2013) *International Review on Modelling and Simulations (IREMOS)*, 6 (1), pp. 284-290.

[8] R. Isermann, J. Schaffnit, S. Sinsel, Hardware-in-the-loop simulation for the design and testing of engine-control systems, *Control Engineering Practice, Vol. 7(*Issue 5*): 643–653, May 1999,* http://www.sciencedirect.com/science/article/pii/S0967066198002056

[9] Y. Nam, S.K. Hong, Force control system design for aerodynamic load simulator, *Control Engineering Practice, Vol. 10(*Issue 5*):549-558, May 2002,* http://www.sciencedirect.com/science/article/pii/S0967066102000047

[10] Heikkinen, J.E., Minav, T.A., PyrhÃ¶nen, J.J., Handroos, H.M., Real-time HIL-simulation for testing of electric motor drives emulating hydraulic systems, (2012) *International Review of Electrical Engineering (IREE)*, 7 (6), pp. 6084-6092.

[11] Z.H. Akpolat, G.M. Asher, J.C. Clare, Experimental dynamometer emulation of non-linear mechanical loads, *IEEE trans. on Industry Application., Vol. 35(*Issue 6*):1367-1373, November/December 1999,* http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=806051

[12] M. Ganchev, Control unit for a laboratory motor test bench for monitoring and controlling PMSM and induction motor, *EPE'07, Aalborg, Denmark, September 2007,* http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4417431

[13] A. Kuperman, R. Rabinovici, Virtual torque and inertia loading of controlled electric drive, *IEEE trans. on Education, Vol. 48(*Issue 1*):47-52, February 2005,* http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1393102

[14] S.C Oh, Evaluation of motor characteristics for hybrid electric vehicle using the HIL concept, *IEEE trans. on Vehicular Technology, Vol. 53(*Issue 3*): 817-824, May 2005,* http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1433227

[15] L. Gauchia, J.M. Martinez, M. Chinchilla, J. Sanz, Test bench for the simulation of a hybrid power train, *EPE'07, Aalborg (Denmark), September 2007,* http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=4417235

[16] R. Trigui, B. Jeanneret, B. Malaquin, F. Badin, C. Plasse, Hardware In the Loop Simulation of a Diesel Parallel Mild-Hybrid Electric Vehicle, *Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE, pp. 448,455, September 2007,* http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4544167

[17] W. Rulka, E. Pankiewicz, MBS Approach to Generate Equations of Motions for HiL-Simulations in Vehicle Dynamics, *Multibody System Dynamics, Vol. 14(*Issue 3-4*):367-386, November 2005,* http://link.springer.com/article/10.1007%2Fs11044-005-1144-8

[18] B. Siciliano, O. Khatib, Springer Handbook of Robotics (Springer-Verlag Berlin Heidelberg, 2008, pp. 35-65).

[19] D. Schütz, F.M. Wahl, Robotic Systems for Handling and Assembly (Springer-Verlag Berlin Heidelberg, 2010, pp. 39-57).

[20] F. Aghili, A unified approach for inverse and direct dynamics of constrained multibody systems based on linear projection operator: applications to control and simulation, *Robotics, IEEE Transactions on, Vol. 21(*Issue 5*):834,849, October 2005,* http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1512343

[21] A. Fumagalli, P. Masarati, Real-time inverse dynamics control of parallel manipulators using general-purpose multibody software, *Multibody System Dynamics, Vol. 22(*Issue 1*):47-68, August 2009,* http://link.springer.com/article/10.1007%2Fs11044-009-9153-7

[22] L.O. Luostarinen, R. Åman, H. Handroos, Virtual simulator to test suitability of integrated electro-hydraulic energy converter in different types of working machines, *9th JFPS International Symposium on Fluid Power, Matsue, Japan, October 2014,* Accepted to be published.

[23] R. Rahmfeld, *Development and Control of Energy Saving Hydraulic Servo Drives for Mobile Systems*, Ph.D. dissertation, Technical University of Hamburg-Harburg, 2002.

[24] M. Ivantysynova. Energy saving hydraulic actuators for mobile machines. *1st Bratislavan Fluid Power Symposium, Bratislava, Slovak Republic, 1998.*

[25] P.M. Korkealaakso, A.J. Rouvinen, S.M. Moisio, J.K. Peusaari, Development of a real-time simulation environment, *Journal of Multibody system dynamics, Vol. 17*(Issue2-3)*:177-194, April 2007,* http://link.springer.com/article/10.1007%2Fs11044-007-9040-z

[26] P.M. Korkealaakso, *Real-Time Simulation of Mobile and Industrial Machines Using the Multibody Simulation Approach*, Ph.D. dissertation, Dept. Mech. Eng., Lappeenranta University of Technology, Lappeenranta, Finland, 2009, http://urn.fi/URN:ISBN:978-952-214-792-9

[27] H. Handroos, *Methods for combining a Theoretical and an Empirical Approach In Modelling Pressure and Flow Control Valves for CAE-programs for Fluid Power Circuits*, Ph.D. dissertation, Laboratory of Hydraulics and Automation, Tampere University of Technology, Finland, 1990.

[28] H.E. Merritt, *Hydraulic Control Systems* (John Wileys and Sons, 1967).

[29] R. Åman, H. Handroos, J. Wilenius, P. Ponomarev, Test rig for integrated hydraulic-electric power transmission with real-time simulated loads, *7th FPNI Ph.D Symposium on Fluid Power (FPNI2012), Reggio Emilia, Italy, June 27-30.*

Authors' information

Lappeenranta University of Technology,
Laboratory of Intelligent Machines,
Skinnarilankatu 34,
53850 Lappeenranta,
Finland.

Lauri Luostarinen received the M.Sc., degree from Lappeenranta University of Technology, Lappeenranta, Finland, in 2010. He is currently working in the Laboratory of Intelligent Machines at Lappeenranta University of Technology. His research interests include Virtual Realities, HMI in off-highway working vehicles, Human effects on machines and Robotics.
E-mail: lauri.luostarinen@lut.fi
phone: +358 50 4642520

Rafael Åman earned his M.Sc. and D.Sc. degrees, major in mechatronics, in Lappeenranta University of Technology, 2007 and 2011, respectively. He has worked as researcher in the Laboratory of Intelligent Machines (LUT) since 2006. His research interests include simulation of fluid power circuits, hybrid power transmissions and energy recovery via fluid power systems.

E-mail: rafael.aman@lut.fi

Heikki Handroos has been a professor of Machine Automation in Lappeenranta University of Technology since 1993. He earned his M.Sc. and D.Sc. degrees in Tampere University of Technology, 1985 and 1991. His research interests range from modelling, simulation and control of mechatronic systems to off-road vehicle transmissions and robotics. He has published about 200 scientific journal and conference papers.

E-mail: heikki.handroos@lut.fi

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

592. HAJIALI, ZUNED. Computational modeling of stented coronary arteries. 2014. Diss.

593. UUSITALO, VILLE. Potential for greenhouse gas emission reductions by using biomethane as road transportation fuel. 2014. Diss.

594. HAVUKAINEN, JOUNI. Biogas production in regional biodegradable waste treatment – possibilities for improving energy performance and reducing GHG emissions. 2014. Diss.

595. HEIKKINEN, JANNE. Vibrations in rotating machinery arising from minor imperfections in component geometries. 2014. Diss.

596. GHALAMCHI, BEHNAM. Dynamic analysis model of spherical roller bearings with defects. 2014. Diss.

597. POLIKARPOVA, MARIIA.Liquid cooling solutions for rotating permanent magnet synchronous machines. 2014. Diss.

598. CHAUDHARI, ASHVINKUMAR. Large-eddy simulation of wind flows over complex terrains for wind energy applications. 2014. Diss.

599. PURHONEN, MIKKO. Minimizing circulating current in parallel-connected photovoltaic inverters. 2014. Diss.

600. SAUKKONEN, ESA. Effects of the partial removal of wood hemicelluloses on the properties of kraft pulp. 2014. Diss.

601. GUDARZI, DAVOOD. Catalytic direct synthesis of hydrogen peroxide in a novel microstructured reactor. 2014. Diss.

602. VALKEAPÄÄ, ANTTI. Development of finite elements for analysis of biomechanical structures using flexible multibody formulations. 2014. Diss.

603. SSEBUGERE, PATRICK. Persistent organic pollutants in sediments and fish from Lake Victoria, East Africa. 2014. Diss.

604. STOKLASA, JAN. Linguistic models for decision support. 2014. Diss.

605. VEPSÄLÄINEN, ARI. Heterogenous mass transfer in fluidized beds by computational fluid dynamics. 2014. Diss.

606. JUVONEN, PASI. Learning information technology business in a changing industry landscape. The case of introducing team entreneurship in renewing bachelor education in information technology in a university of applied sciences. 2014. Diss.

607. MÄKIMATTILA, MARTTI. Organizing for systemic innovations – research on knowledge, interaction and organizational interdependencies. 2014. Diss.

608. HÄMÄLÄINEN, KIMMO. Improving the usability of extruded wood-plastic composites by using modification technology. 2014. Diss.

609. PIRTTILÄ, MIIA. The cycle times of working capital: financial value chain analysis method. 2014. Diss.

610. SUIKKANEN, HEIKKI. Application and development of numerical methods for the modelling of innovative gas cooled fission reactors. 2014. Diss.

611. LI, MING. Stiffness based trajectory planning and feedforward based vibration suppression control of parallel robot machines. 2014. Diss.

612. KOKKONEN, KIRSI. From entrepreneurial opportunities to successful business networks – evidence from bioenergy. 2014. Diss.

613. MAIJANEN-KYLÄHEIKO, PÄIVI. Pursuit of change versus organizational inertia: a study on strategic renewal in the Finnish broadcasting company. 2014. Diss.

614. MBALAWATA, ISAMBI SAILON. Adaptive Markov chain Monte Carlo and Bayesian filtering for state space models. 2014. Diss.

615. UUSITALO, ANTTI. Working fluid selection and design of small-scale waste heat recovery systems based on organic rankine cycles. 2014. Diss.

616. METSO, SARI. A multimethod examination of contributors to successful on-the-job learning of vocational students. 2014. Diss.

617. SIITONEN, JANI. Advanced analysis and design methods for preparative chromatographic separation processes. 2014. Diss.

618. VIHAVAINEN, JUHANI. VVER-440 thermal hydraulics as computer code validation challenge. 2014. Diss.

619. AHONEN, PASI. Between memory and strategy: media discourse analysis of an industrial shutdown. 2014. Diss.

620. MWANGA, GASPER GODSON. Mathematical modeling and optimal control of malaria. 2014. Diss.

621. PELTOLA, PETTERI. Analysis and modelling of chemical looping combustion process with and without oxygen uncoupling. 2014. Diss.

622. NISKANEN, VILLE. Radio-frequency-based measurement methods for bearing current analysis in induction motors. 2014. Diss.

623. HYVÄRINEN, MARKO. Ultraviolet light protection and weathering properties of wood-polypropylene composites. 2014. Diss.

624. RANTANEN, NOORA. The family as a collective owner – identifying performance factors in listed companies. 2014. Diss.

625. VÄNSKÄ, MIKKO. Defining the keyhole modes – the effects on the molten pool behavior and the weld geometry in high power laser welding of stainless steels. 2014. Diss.

626. KORPELA, KARI. Value of information logistics integration in digital business ecosystem. 2014. Diss.

627. GRUDINSCHI, DANIELA. Strategic management of value networks: how to create value in cross-sector collaboration and partnerships. 2014. Diss.

628. SKLYAROVA, ANASTASIA. Hyperfine interactions in the new Fe-based superconducting structures and related magnetic phases. 2015. Diss.

629. SEMKEN, R. SCOTT. Lightweight, liquid-cooled, direct-drive generator for high–power wind turbines: motivation, concept, and performance. 2015. Diss.