HAZARD-FREE STEER-BY-WIRE IN ARTICULATED HEAVY EARTH MOVING MACHINERY USING CO-SIMULATION MODEL

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ABSTRACT

The articulated Heavy Earth Moving Machinery predominantly use hydrostatic steering, because of its reliability and redundancy. In earlier studies an energy efficient Electro-Hydrostatic Steering System was proposed, which works on Steer-by-Wire principle and comply with the safety standards. This paper presents co-simulation of a wheel loader model with hazard-free Steer-by-Wire. A co-simulation model using three software platforms; Mevea for multibody dynamics and mechanics, Simcenter AMESim for hydraulics, and MATLAB/Simulink for hydraulics, control, and data analysis, is created to analyse the hazard-free functionality of the steering. The simulation model of primary steering, which is an electric motor controlled Electro-Hydrostatic Actuator, is validated experimentally. In these heavy machines, as required by the standards there shall always be a secondary steering system for redundancy. The secondary steering, which is through a proportional control valve is modelled using the characteristics of the commercial product. There are five possible hazard scenarios in steering application of such machinery, which have been identified by the authors in earlier publication. These five hazard scenarios are realised in co-simulation model by modelling the respective faults in the primary steering, and the effectiveness of the hazard-free functionality in the steering is analysed. The study demonstrates that the novel Steer-by-Wire for articulated steering can effectively mitigate the potential hazards associated with steering in Heavy Earth Moving Machinery, moreover, co-simulation model provides an effectual mean to analyse the novel solutions.

Keywords: Articulated Steering, Steer-by-Wire, Hazard-free steering, Co-simulation model, Heavy Earth Moving Machinery

1. INTRODUCTION

The articulated steering is used commonly in Heavy Earth Moving Machinery (HEMM) for their superior performance in heavy loads and good manoeuvrability on rough terrain. The conventional articulated steering is powered by centralised hydraulic pump via priority valve and controlled by an orbital steering unit [1], [2]. Being a safety control element, steering shall be redundant and safe for operation under all operating conditions [3]. The redundancy in conventional articulated steering is achieved by the gerotor unit of the orbital steering unit, where the operator uses muscle power to steer the vehicle to safety. However, the conventional steering also has its limitations when it comes to safety as the response time and torque needed to control the vehicle in hazardous scenario depends on external factors including but not limited to vehicle speed. The human operator has limitations in terms of response time and muscle power, as a result of that, these machines are subjected to corresponding limitations specially in maximum allowed speed. Nevertheless, the electrification and autonomous trend in HEMM is changing the entire powertrain architecture and related safety requirements. The steering however because of its safety is unchanged up to a large extent in HEMM. The Steer-by-Wire (SbW) is one promising solution in this regard and has been commercially accepted in passenger cars, but because of the power level and operating conditions, it has not been the same success in HEMM.

Some studies in past have focused on the subject, but they are limited to having an energy efficient digitally controlled steering, and safety aspect is not taken into account. A pump-controlled steering is proposed by Daher et al. [4] where the volumetric displacement of the hydraulic pump is controlled in order to control the steering, the study does not consider the redundancy. Similarly, Wang et al. [5] proposed a steering with dual- mode which has two steering control elements, hence not according to the ISO standards [6] which does not allow to have separate steering control elements for redundant steering. A Steer-by-Wire (SbW) for HEMM has been proposed by authors that has potential to fulfil the required safety standards in a previous article [1]. The said study has also demonstrated that the proposed SbW is significantly energy efficient as compared to the conventional steering. The functional safety of the proposed solution has been analysed in a later article [7] and it has been found that with even low diagnostic coverage, the proposed system satisfies the standards for safety critical parts of control system. In the same article, the effectiveness of the steering has been demonstrated using a co-simulation model for one major hazard scenario.

In this article, a co-simulation model of the articulated wheel loader is made with a hazard-free Steer-by-Wire. The co-simulation model is made using three different software for their different use and advantages. The steering system consist of a primary steering which is an electric motor-controlled electrohydraulic actuator (EHA), and secondary steering is realised by proportional valve through a priority valve as shown in **Figure 1**. The electric motor-controlled EHA model is validated on a test rig and used in the steering model except the hydraulic cylinder part. There are five hazard scenarios related to steering in a wheel loader which are identified in [1]. Those hazard scenarios are modelled in present article and the effectiveness of the proposed hazard-free SbW is analysed using the wheel loader co-simulation model.

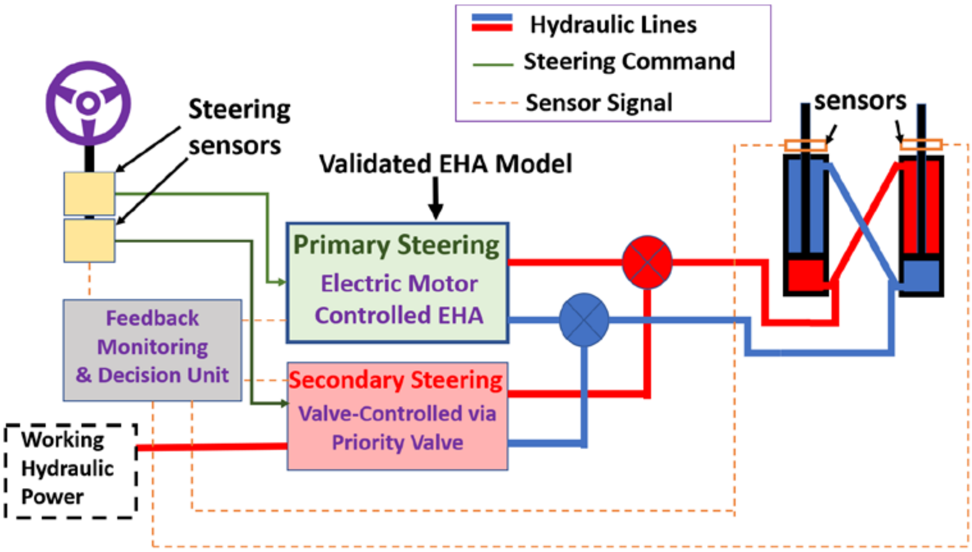

Figure 1: Topology of the novel hazard-free steering system

The next section describes the experimental setup of electric motor-controlled EHA and it's modelling and validation, as it has been used as the primary steering in the co-simulation model. The third section describes the co-simulation model in details and the steering architecture and operation of steering in hazard-free mode. The results of the steering effectiveness in different hazard scenarios are presented in fourth section where the results of the normal operation and in event of hazard related to steering are presented. Finally, the future aspects of the study are discussed with conclusion.

2. ELECTRO-HYDRAULIC ACTUATOR TEST-RIG AND MODEL VALIDATION

2.1. Experimental set-up

An electric motor-controlled EHA set-up is used to validate the model for the primary steering. The setup consists of a crane with double acting hydraulic actuator, where load on the tip of the crane can produce resistive and overrunning external load, i.e., 1st and 4th quadrant operations. The same test rig can be operated with three different EHA configurations with single or double pumps, the description of those is out of scope of this study. For this paper, the single pump EHA with pilot-operated check valves is used. The test rig and the schematics are shown in **Figure 2**, whereas the main components of the test rig are listed in **Table 1**.

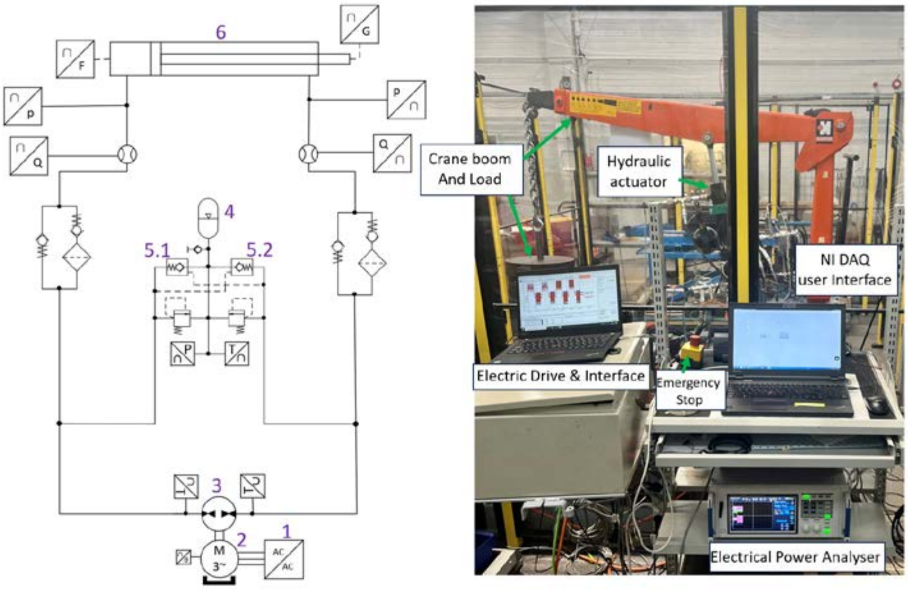

Figure 2: Hydraulic schematics and test-rig overview of electro-hydraulic actuator

Table 1: Main components of EHA and their specification

Component	Manufacturer and code	Main Parameters
Electric Drive	Unidrive SP1406	Nominal Power 5.5kW, Max Continuous output current 11A
Electric Motor	Emerson 115U2C300	Rated power 2.54 kW, Rated speed 3000 rpm
Hydraulic Pump	Casappa PLM20.14R0	14.53 cc/rev
Accumulator	Parker AD100A20T9A1	Volume 1L, max pressure 200 bar
Pilot Check Valve	Sun hydraulics CKCB	Cracking pr. 0.3bar, Pilot ratio 3:1
Hydraulic Cylinder	Miro C-10	60/30-400

The hydraulic system schematic shown on the left of **Figure 2** works in closed-circuit configuration. The Hydraulic pump (3) is driven by Electric Motor (2) which in turn is controlled by the electric drive (1). The differential volume of the hydraulic cylinder (6) is compensated by an accumulator (4) through pilot-operated check valves (5.1) and (5.2). When the cylinder is in extension stroke and have a resistive force, the pressure in piston side of the cylinder is high which opens pilot check valve (5.2). The differential volume of cylinder means the flow going in the piston side of cylinder is higher than the flow coming out of the cylinder from rod side, in this extension stroke. The opening of pilot check valve (5.2) ensures the low-pressure side which is rod side of the cylinder in this case, is connected to accumulator which then acts as a pressurized reservoir and makes up the flow difference and pump supplies required flow to the piston side of the cylinder. The pilot check valves also ensure the minimum pressure in low pressure side of the hydraulic circuit during assistive load operation cycle. The passive hydraulic safety is ensured by the two pressure relief valves and the filters on both sides of the circuit entraps any contamination in hydraulic fluid.

The National Instruments' CompactRIO modules with LabVIEW Field-Programmable Gateway Arrays (FPGA) is used for data acquisition. The pressure is recorded on both sides of the cylinder and also for the accumulator, whereas the flow is only recorded for piston side of the cylinder, Trafag 8891 pressure sensors and gear type flow meter from Kracht are used for respective purpose. The position of the cylinder is recorded by draw-wire displacement sensor from Micro-Epsilon, whereas electric motor rotational speed is recorded in drive. There are other sensors in test-rig like temperature and force sensors, but their measurements have not been used for present article.

2.2. Modelling and validation

A simulation model of the test set-up is made using physics-based modelling in MATLAB/Simulink environment. The electric motor is controlled using field-oriented control strategy and the details about the electric motor model and control can be found in [8]. The Schlösser mathematical loss coefficient model [9] is used for hydraulic pump where the loss coefficients has been adjusted using experimental data. The modelling of rest of the hydraulic system has been done in similar way as [10] and [11], whereas the friction in hydraulic cylinder is realised using LuGre friction model. As, the load on the tip of crane is provided using the circular metal disc weights of 25 kg each, in simulation model the mass of other parts of the crane boom and load support along with mechanical advantage has been taken into account and the effect of extension of cylinder rod is accommodated using varying joint angles. The overall mechanical advantage including the mass of crane boom and load support varies from '1.594' when cylinder is fully retracted, to '1.686' when it is fully extended.

The results of experimental and simulation model are shown in **Figure 3** and **Figure 4** for two different speed and load profiles. Because of certain temporary physical limitation on test-rig, the operation is subjected to limitations on power of electric motor and stroke of hydraulic cylinder.

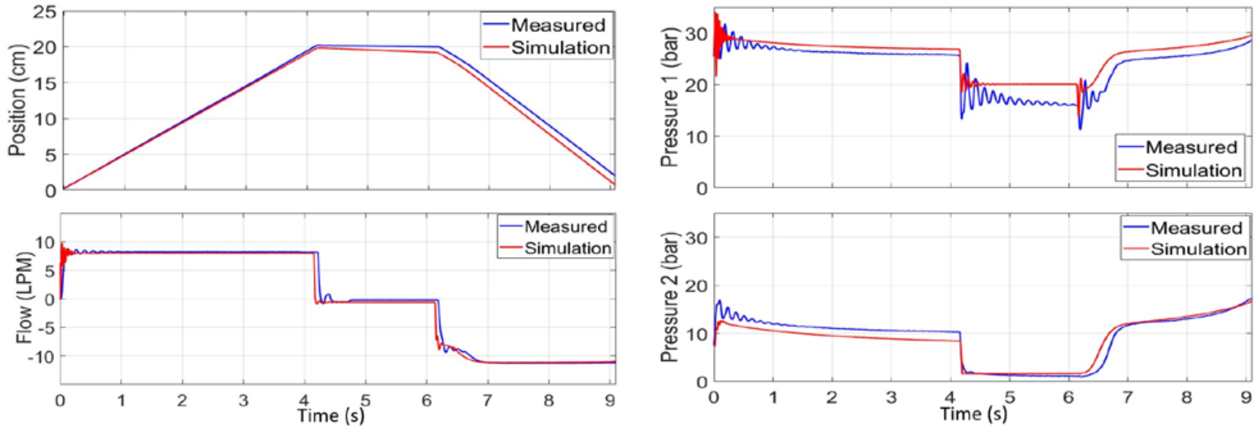

Figure 3: Measurement and simulation results for 600 rpm and 175 kg load

Figure 3 shows the results for 600 rpm of electric motor speed and load mass of 175 kg on the tip of the crane. It is worth noting that the actual load acting on the hydraulic cylinder will be higher because of mass of crane boom, load support, and mechanical advantage of the boom. The figure shows position of cylinder, flow in the piston side of cylinder, and pressure on piston and rod side of cylinder termed as ‘Pressure 1’ and ‘Pressure 2’, respectively.

Figure 4 shows the results for operation at 400 rpm of electric motor speed and 100 kg of load mass on the tip of the boom. As the hydraulic accumulator is an important part in this kind of closed-circuit configuration, the pressure is plotted for experiment and simulation model in **Figure 5.** The model performs satisfactorily and agrees with experimental data for both operating conditions.

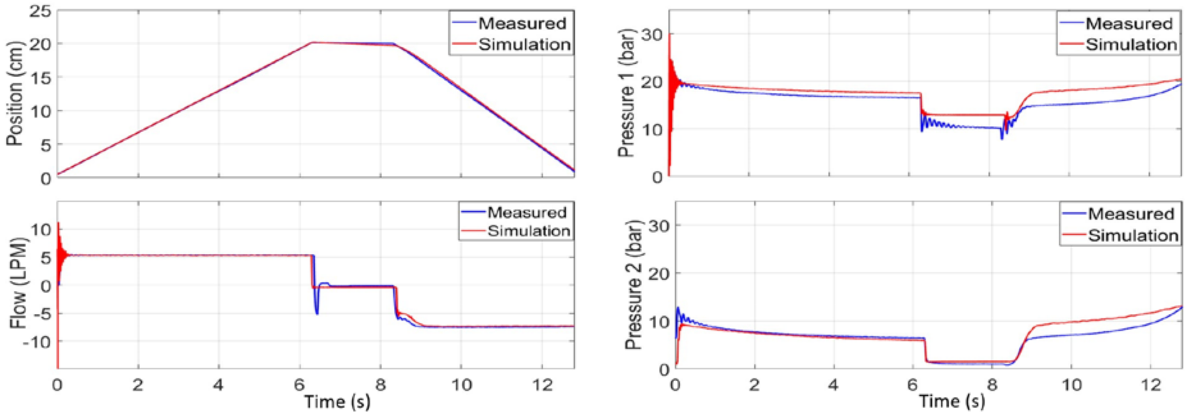

Figure 4: Measurement and simulation results for 400 rpm and 100 kg load

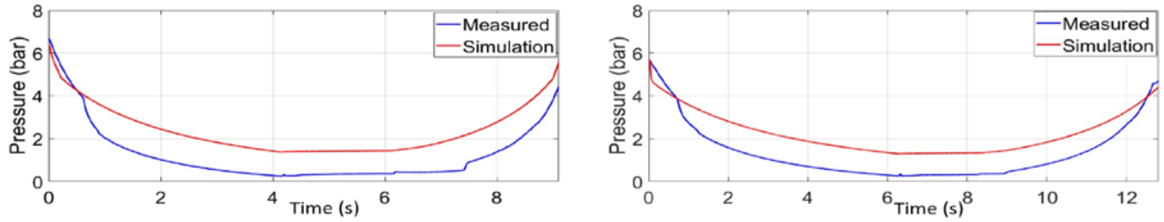

Figure 5: Accumulator pressure at 600 rpm (left) and 400 rpm (right)

3. CO-SIMULATION MODEL OF WHEEL LOADER WITH HAZARD-FREE STEER-BY-WIRE

3.1. Co-simulation model of Wheel Loader

The co-simulation model of a 16-ton wheel loader is made using three software MATLAB/Simulink, Simcenter AMESim, and Mevea [12] for their respective advantages. Mevea is a digital twin technology and simulation platform, its own physics engine simulates mechanics, hydraulics, power transmission, and operating environment of the machine. Siemens’ AMESim has advantage of object-oriented programming with its inbuilt hydraulics, mechanics, and interface libraries. Whereas MATLAB/Simulink has the advantage of better data handling, controller design, and ability to interact with multiple software simultaneously. The wheel loader multibody dynamics model which interacts with real world like environment is modelled in Mevea, the steering actuators along with secondary steering hydraulics and connection of primary and secondary steering are done in AMESim, whereas the previously described electric motor-controlled EHA model with overall control, steering command, and signal monitoring is in MATLAB/Simulink. The operation of the wheel loader can be controlled via a physical joystick, keyboard control, or a script of commands. **Figure 6** shows the overall structure of the co-simulation model. The blocks in **Figure 6** represents the part of the entire co-simulation model realized in respective software, whereas arrow shows the direction of data flow between them. It is worth noting that only steering is powered and controlled by MATLAB/Simulink and AMESim, the rest of the operation including driving the wheel loader and working implements is solely modelled and controlled in Mevea. The steering operation can also be controlled using an external joystick or keyboard control, but to keep the uniformity of command, steering reference is given in MATLAB/Simulink. The data flows in real time between different software which is handled in MATLAB/Simulink. The movement of the wheel loader is observed visually in Mevea while all the data and control are monitored in MATLAB/Simulink.

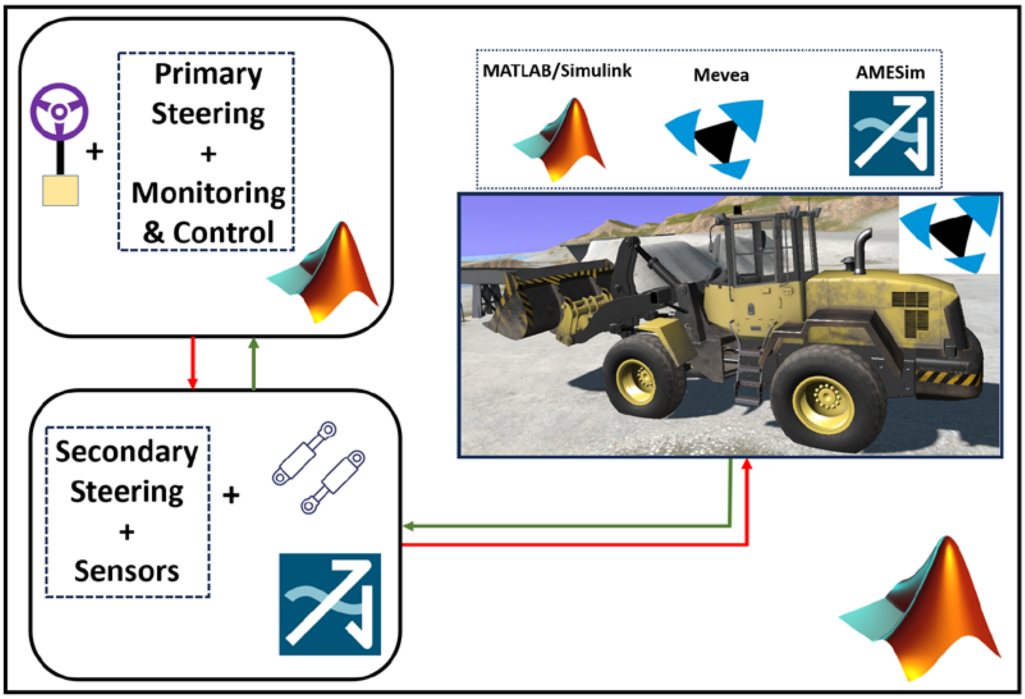

Figure 6: Co-simulation model overall structure

3.2. Hazard-free Steer-by-Wire

Figure 7 shows the schematics of the steering system where primary steering is realised via previously described validated model of electric motor-controlled EHA whereas secondary steering is using proportional valve through priority valve. More details of the steering system, its operation, and it's potential to comply with required standards can be found in [1], [7]. In normal conditions, the main steering operation is performed by controlling the electric motor in EHA, the operation of which is described in **section 2**. In case of a hazard scenario, the locking valves (4.1, 4.2) mechanically isolates the primary steering and operation can be continued with secondary steering. In secondary steering, the priority valve (5) sends the flow to the other hydraulic function when there is no demand for steering application. When the secondary steering is activated, and the proportional valve (6) have flow demand the flow is directed to steering operation. The control block diagram and signal flow for the above-mentioned hazard-free steering operation of wheel loader co-simulation model are presented in **Figure 8**. The main values and parameters of the components used in the steering are presented in **Table 2**. It shall be noted that the parameters of the electric motor-controlled EHA except hydraulic cylinder, which is used as primary steering are same as described **Table 1** in **Section 2.1**.

For this paper to keep the uniformity of the operation, the steering actuator position command (X_{ref}) is provided in MATLAB/Simulink, whereas the rest of the operation of the wheel loader is controlled in Mevea via keyboard control. The same command is provided separately for primary and secondary steering to make model partially in accordance with category 3 architecture of ISO 13849-1 [13], however the fault diagnosis does not fully comply with the said category, so the overall steering co-simulation model is not entirely in compliance with category 3 architecture. Nevertheless, it is worth noting that the overall architecture has potential to fully comply with category 3 architecture, this has been described in detail in [7].

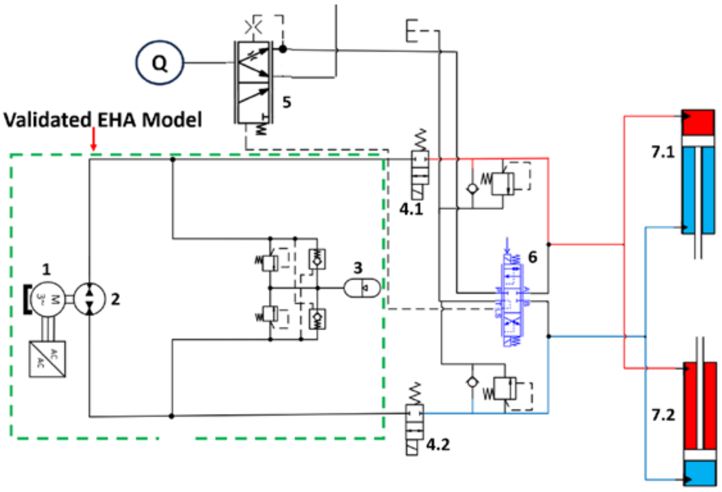

Figure 7: Schematics of steering system

Table 2: Parameters of steering system components

Component	Main Parameters
Steering actuator	80/50 stroke – 340mm
Proportional valve	Nominal flow – 50 LPM, corresponding pressure drop - 15 bar, LS port.
Priority valve	Characteristic flow – 70LPM, corresponding pressure drop- 20 bar, spring pressure – 10 bar.
Constant flow source	68 LPM
Locking valves	Nominal flow – 70LPM, corresponding pressure drop – 5 bar.
Pressure relief valves	210 bar with anti-cavitation.

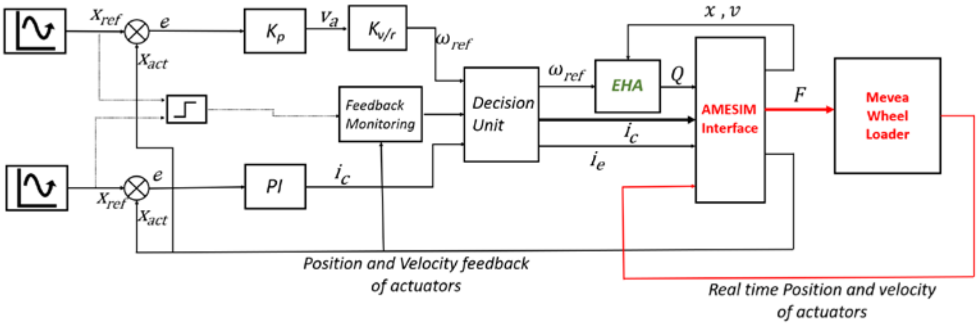

Figure 8: Control diagram and signal flow

For the primary steering, the actual position of the steering actuator (X_{act}) is taken from AMESim where virtual sensors are used. In primary steering, the rotational speed command to the electric motor (ω_{ref}) is provided by simple P controller (K_p). The velocity command of the linear steering actuator (V_a) is converted in rotational speed command of the electric motor by coefficient ($K_{v/r}$) [2]. The validated EHA model takes the electric motor speed reference, and position and velocity of the steering actuators (x,v) from AMESim, and provides the hydraulic flow (Q) to AMESim where steering actuators are present. For the secondary steering, a PI controller is used, which provides the valve command signal (i_c) to the load sensing proportional valve in AMESim. The integral element (I) is used here because of the additional non-linearity introduced by the dead zone, which further is used because of the characteristics of proportional valve. The feedback monitoring unit receives the position and velocity of the actuators along with the steering signal in form of 1-, 0, or 1, according to the presence of steering signal and its direction. The decision unit takes the command signal from both steering channel and signal from feedback monitoring unit. In normal operation, the decision unit directly sends the electric motor speed reference command to EHA and locking valve signal (i_e) accordingly. If it detects any anomaly in the steering command and the actual steering signals, it isolates the primary steering by stopping the EM and deenergising the locking valves for rest of the operation and send the secondary steering command signal onwards.

The steering force command (F) goes to the wheel loader in Mevea, and based on the Mevea solver, the real time position and velocity of both the steering actuators is received back to AMESim, where it converts to corresponding force and pressure requirement. The MATLAB/Simulink environment connects, monitors and handles the data flow between different software in real time.

4. HAZARD-FREE STEERING OPERATION OF WHEEL LOADER

To demonstrate the behaviour of wheel loader in case of a hazard scenario in steering a normal cycle of the steering is chosen so that the steering actuators complete one full cycle of movement, whereas the wheel loader was moved on similar path. The different hazard scenarios are injected by altering the speed command of the electric motor in primary steering accordingly. The severity, possible cause, and consequences of these hazard scenario are described in detail in [1].

First, the wheel loader is operated with primary steering only without any faults, to compare the results further with the hazard scenario. **Figure 9 (left)** shows the steering actuator position, electric motor speed, and pressure in both chambers of the steering actuator. The position of only one actuator is shown as command is given to control the single actuator position and the other moves in mirror action. As the wheel loader in Mevea interacts with real-world like environment which includes the sand, the gravel and other forces on a non-uniform ground, the effects of these uncertain ground forces on steering can be seen in the position and pressure response. The dynamic response of electric motor-controlled EHA can be improved with better control strategies as demonstrated in [14] [15] but considered to be out of scope of current study. **Section 4.1** to **Section 4.5** shows the results for different hazard scenarios while **Table 3** summarise the results briefly.

The faults are considered only in primary steering channel for the study i.e., EHA, as purpose of this part of the study is to analyse the overall behaviour and effectiveness of redundant steering channel in case of different hazard scenarios. However, there is always a possibility for faults in other parts of the system including secondary steering channel, and sensors, for which the relevant safety guidelines shall be followed for redundancy in secondary channel.

4.1. Hazard 1: - Loss of power in primary steering

The loss of power in primary steering is a major hazard and can become even more dangerous if machine is working at a place where co-workers or bystanders are present. This is modelled by forcefully stopping the electric motor of EHA at a time when steering command is present. The electric motor is stopped at t= 7s, and the secondary steering became effective in 600ms, and vehicle is controlled. It is worth noting that this time includes time in detections of fault, isolating primary steering and secondary steering controlling the vehicle. As can be seen by electric motor speed and valve command plot, the electric motor stops at 7s and after 600ms, the valve fully takes the control of the operation. During the loss of steering power, the pressure in steering actuators jumped to a high peak because of effectively absence of the control of steering and presence of external forces. Figure 9 (right) shows the steering actuator position, the excerpted view at the time of hazard, electric motor speed and valve command for respective modes of steering, and pressure in both chambers of the steering actuators. The subsequent hazards scenario sections show the similar plots for respective hazards.

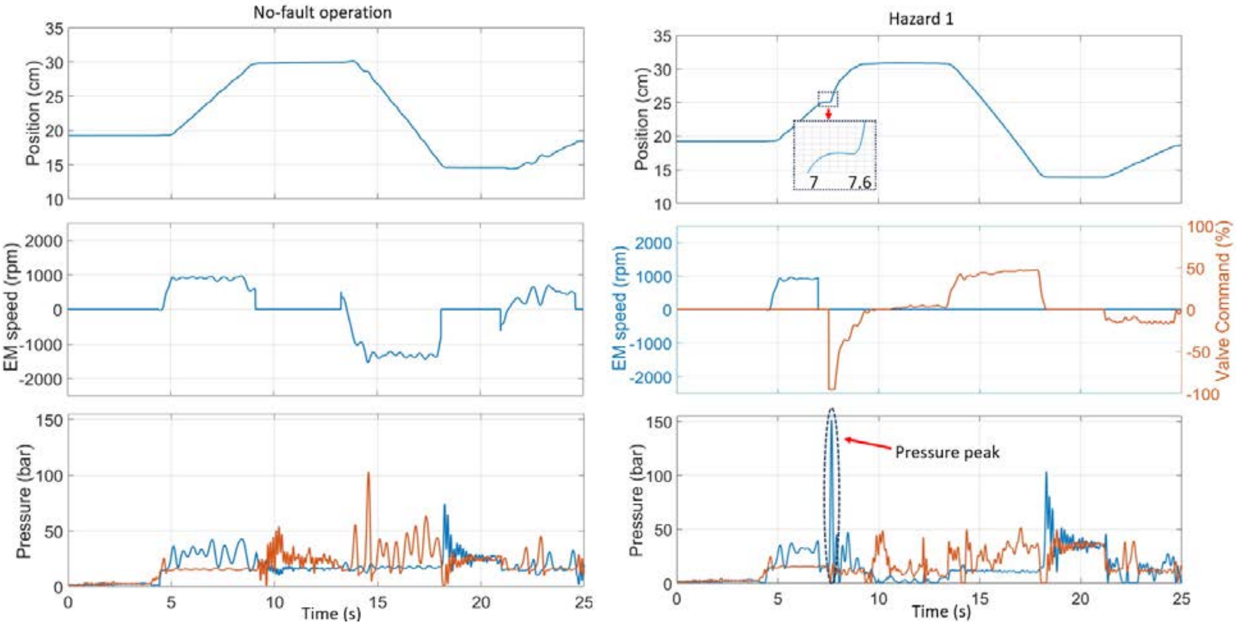

Figure 9: Operation with EHA steering (left), loss of power in primary steering (right)

4.2. Hazard 2: - Unintended vehicle steer

Unintended vehicle hazard is modelled by starting the electric motor in primary steering at t= 3s, when the steering command is not present. The unintended movement of the steering is detected, and the primary steering is isolated for rest of the operation and operation is completed with secondary steering. **Figure 10 (left)** shows the similar plots as in Hazard 1 case, the total time to control the vehicle by secondary steering is around 400ms. The pressure peaks are also observed in this case even if there is a control element present, as the electric motor speed is increased suddenly and that tries to move steering actuators with a very high speed, resulting in high forces. Further the switching between primary and secondary steering created the sudden change in pressures of the steering, hence the peak can be observed in both sides of the chamber.

4.3. Hazard 3: - Steer in opposite direction as commanded

The rotational speed command of the electric motor of EHA is inverted to create the scenario when the steering operation starts in opposite direction as commanded. As a result of that, when the steering command starts at t=4.6s, the steering actuator moves in opposite direction as commanded, the results are shown in **Figure 10 (right).** It took overall around 500ms to detect the fault and start the operation by secondary steering, while it took more time to catch up with the actual command. The pressure peaks in this case can be attributed to the switching between primary and secondary steering, as the locking valves close and the proportional valve starts operation. The proportional valve opens to its maximum capacity as it tries to bring the actuator back to the normal position quickly, resulting in sudden pressure rise, the other side of pressure meanwhile takes a dip.

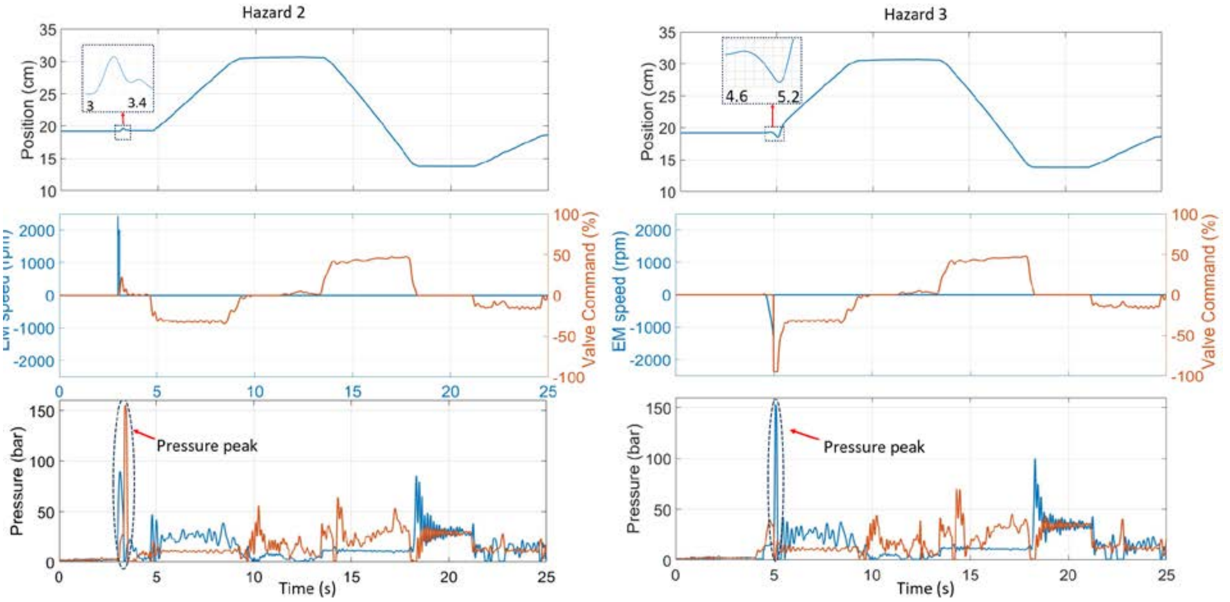

Figure 10: Unintended vehicle steer (left), steer in opposite direction as commanded (right)

4.4. Hazard 4: - Oversteer

Oversteer can be termed as a condition when the steering actuators move ah higher speed than commanded. The speed of the electric motor in EHA raised to a value higher than actual command at t=16s to model this which results into faster movement of the actuator. It took around 600ms for the system to detect the fault and start the operation with secondary steering, as shown in **Figure 11 (left)**. The pressure peaks in this case have similar behaviour and can be explained by same phenomena, as in the case of opposite direction steering in previous section. It can be observed that the peaks occur not at the time of hazard, i.e., t= 16s, but when the secondary steering is activated.

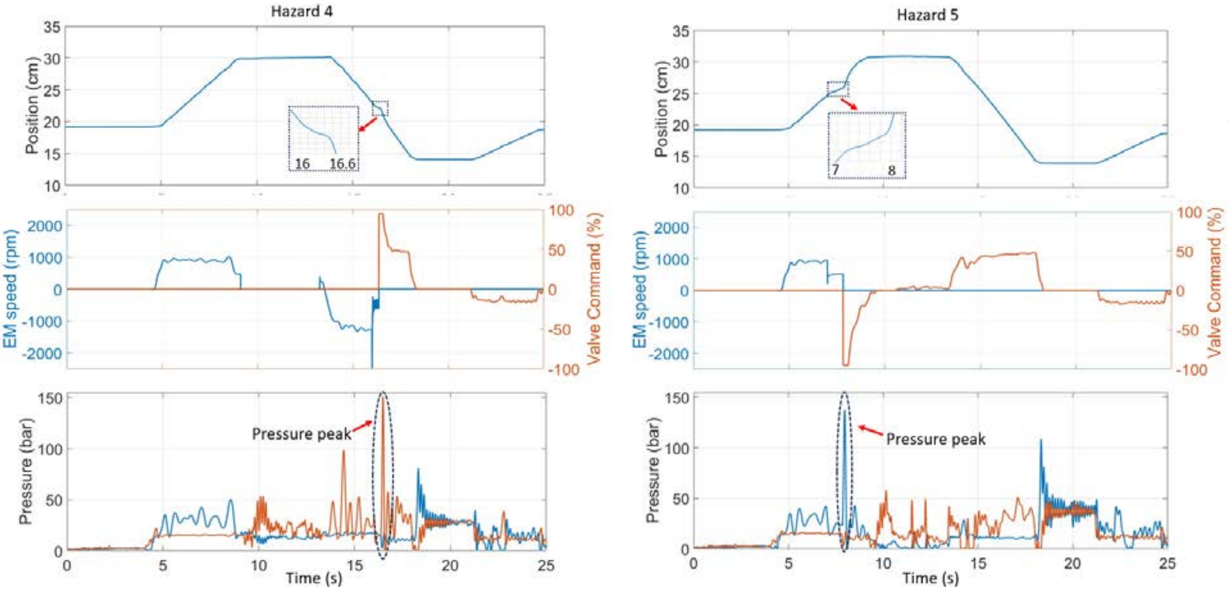

Figure 11: Oversteer (left), understeer (right)

4.5. Hazard 5: - Understeer

Understeer can be termed as when the steering actuator moves at less velocity then commanded. Similar to the oversteer case, the electric motor speed in primary steering is reduced to an arbitrary value at t=7s, which resulted in slower movement of the actuator. Although there is a fault in the primary steering, it is still moving, hence it took almost 1s to detect it and start operation with secondary steering. Once more the pressure peaks in this case have similar behaviour as previous two hazard scenarios and have the similar reason behind them.

Table 3: Summary of the Hazard scenarios

Hazard Scenario	Fault in Primary steering simulation method	Reaction time
Loss of power in primary steering	EM stopped when steering command is present	600ms
Unintended steer	EM started without steering command	400ms
Steer opposite then commanded	EM steed inverted as commanded	500ms
Oversteer	EM speed raised higher than required	600ms
Understeer	EM speed decreased than required	1s

5. CONCLUSION AND OUTLOOK

In this study a co-simulation model of a wheel loader with hazard-free steer-by-wire is created. The hydrostatic steering consists of a primary steering which is an electric motor controlled electro-hydraulic actuator, is experimentally validated on a test bench. The five possible hazard scenarios related to steering in a wheel loader operation are modelled, and the effectiveness of the novel steering system is analysed. It has been demonstrated that the novel steering system is effective in any hazard scenario where primary steering have some faults. The time of reaction to activate secondary steering in event of a hazard varies for different failure. However, with suitable control strategies and effective fault diagnosis in the steering, the reaction time can be improved. The study demonstrates the novel steer-by-wire for heavy earth moving machinery is effective in a hazardous scenario in steering, also the co-simulation model can be an effective solution to study novel solutions.

The study of steering and the analysis of intended functionality and behaviour is strictly within the domain of simulation using partially validated model, in this article. There is no hardware in control or sensor elements is involved, which will contribute to additional complexity in prototyping. The future work in the direction includes advanced fault detection techniques using machine learning and deep learning, followed by prototyping and proof of concept.

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