VEHICLE-IN-THE-LOOP SIMULATION FOR AUTONOMOUS HEAVY OFFROAD AND INDUSTRIAL VEHICLES: A FRAMEWORK AND CASE STUDY

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ABSTRACT

Vehicle development requires extensive testing, especially for autonomous vehicles where a large amount of training data is essential for machine learning. If more of this testing can be conducted in simulation, significant resources can be saved, while repeatable and rapidly exchangeable test scenarios are also enabled. Vehicle-in-the-Loop (ViL) simulations provide the opportunity for highly accurate vehicle models with significantly reduced modeling time, since the real vehicles are utilized in the simulations to a large extent. Calibration and validation of digital models are also facilitated, since digitally simulated subsystems can be isolated. This study presents a framework for ViL simulation for autonomous heavy offroad and industrial vehicles. The framework comprises a versatile laboratory with four wheel hub-mounted active dynamometers, capable of handling vehicles weighing up to 65 tonnes, with a power output of up to 1.2 MW. A case study is also presented, where the framework is tested using a 10-tonne autonomous offroad vehicle. The vehicle autonomously navigates a virtual environment generated from a scan of a real-world test site, across multiple ViL simulations. It is shown that the ViL framework is real-time capable. Furthermore, results from the ViL simulations are validated against the corresponding measurements from the physical test site.

INTRODUCTION

Vehicle development is highly resource intensive (Ulrich et al., 2019) and requires extensive testing. The current shift towards increased vehicle automation further increases the need for testing, both because the autonomous functionalities need to be verified and validated, and because their development often utilizes machine learning (ML), which in turn requires a large amount of training data obtained through testing (Pandharipande et al., 2023). Performing more of the testing in simulation is desirable, since significant time and resources can be saved, repeatable and rapidly exchangeable test scenarios are enabled, and hazardous situations can be tested safely (Pandharipande et al., 2023). However, for the results and data obtained through simulations to be useful, the utilized models need to be sufficiently accurate representations of their real-world counterparts. For large and complex systems like vehicles, developing sufficiently accurate models is often difficult and highly time-consuming. Furthermore, the parameters of certain components may not be fully specified in datasheets, and the exact behavior of some electronic components, such as ECUs or traction control systems, can be undocumented or proprietary. Hardware-in-the-Loop (HiL) simulation mitigates these problems by incorporating selected physical hardware components or systems into the simulation. When the physical hardware is used in the simulation, an accurate digital model is no longer needed. Additionally, HiL simulations are more computationally efficient, since the incorporated physical components or systems do not need to be simulated (Fathy et al., 2006). Vehicle-in-the-loop (ViL) simulations are a type of HiL simulation in which the vehicle itself serves as the physical hardware within the simulation loop, either while driving on a real surface or mounted on a test bench (Horváth et al., 2019). ViL simulations extend the advantages of conventional HiL simulations, as a substantial part of the physical vehicle is included in the simulation loop. This significantly reduces the number of vehicle components and systems needing to be modeled and simulated. ViL simulations thus combine lower modeling effort, reduced computational demand, and the ability to include undocumented or proprietary components with the benefits of simulated testing, such as resource savings, safer testing, and repeatable and rapidly exchangeable test scenarios.

HiL simulation has been studied within heavy offroad and industrial vehicles to a moderate extent, particularly in agricultural vehicles (Zhang et al., 2000; Kelber et al., 2016; Lee et al., 2017; Raikwar et al., 2019). ViL simulation on the other hand, although studied in the context of on-road vehicle development (Bock et al., 2007; Mayyas et al., 2013; Maier et al., 2018; Jeong et al., 2022; Schyr et al., 2022; Li et al., 2023), has not been examined in the literature in the context of heavy offroad and industrial vehicles, i.e. heavy vehicles used in forestry, agriculture, mining, and other industrial applications,

which are the focus of this study. The closest example found is a study by Kanchwala (2021), which also investigates ViL for an on-road vehicle, but where the vehicle was a partly offroad-capable SUV (Range Rover Sport). That study focused on the tyre and vehicle response when driving over a rectangular bump, which relates to offroad performance. However, the vehicle was still an on-road passenger vehicle, the ground model was highly simplified, tyres were not allowed to detach from the ground, and neither uphill nor downhill driving was considered.

Hence, this study presents a novel approach by extending ViL simulation to heavy offroad and industrial vehicles. Additionally, autonomous navigation in a detailed virtual environment generated from a UAV-scan of a real-world test site is performed. The performed ViL simulations include turning as well as uphill and downhill driving. Results from the most challenging of the ViL scenarios are validated against the corresponding measurements from the physical test site.

METHOD

Laboratory for ViL Testing

The NUVE-LAB vehicle testing laboratory is a state-of-the-art facility designed to enable comprehensive testing and evaluation of modern vehicles, with a particular focus on electric and hybrid systems. The laboratory is equipped with four hub-mounted active dynamometers, each capable of delivering up to 100 kNm of torque and 300 kW of power per wheel, depending on gear configuration. This configuration allows for the precise emulation of a wide range of driving conditions, including uphill and downhill scenarios, and supports the implementation of realistic test cycles for battery-powered vehicles, encompassing both charging and discharging operations.
In addition to its dynamometer capabilities, NUVE-LAB incorporates advanced battery emulation technology, which enables the replication of various battery constructions and chemistries. This feature, combined with high-precision measurement equipment and the ability to perform hydraulic system load testing, provides a versatile and controlled environment for the assessment of vehicle performance under diverse operational conditions.
The laboratory infrastructure is engineered to accommodate vehicles weighing up to 65 tonnes, with a maximum wheel power output of 1.2 MW. To ensure measurement accuracy and minimize the influence of external vibrations, the entire test setup is mounted on a 500-tonne air-suspended steel-reinforced concrete block. Environmental control systems within the facility allow for the simulation of extreme ambient temperatures, up to 55 °C, thereby facilitating the evaluation of vehicle performance and reliability in harsh climatic conditions.
Safety is a critical aspect of the laboratory's design. NUVE-LAB is equipped with advanced safety systems, including real-time monitoring of all test parameters and automatic shutdown mechanisms in the event of anomalies. The facility also maintains robust emergency response protocols, which are regularly reviewed and updated to ensure compliance with current standards and regulations.

In summary, the NUVE-LAB integrates an active dynamometer system, battery emulation, environmental control, and comprehensive safety systems to enable the development, testing, and validation of next-generation vehicles.

Physical Vehicle

The vehicle used in the ViL case study is a 10-tonne mobile research platform called AORO (Autonomous Offroad Robotics lab). AORO is a collaborative effort between Luleå University of Technology, The Swedish University of Agricultural Sciences and the Cluster of Forest Technology focusing on forestry automation made real at full-scale. To this end, the AORO consortium utilizes this full-scale vehicle to research, develop and test automated functionalities in real environments.

The vehicle control system consists of a UEISIM main control and I/O unit for analog, digital, and CAN communication with sensors, actuators and the driveline control system. Communication is also done with other on-board PC-based computers, which assist with object recognition and decision making in autonomous mode. These computers communicate via Ethernet. The vehicle can also be controlled manually via remote control.

The vehicle comprises two main chassis parts connected by a hydraulically actuated articulated joint. The front part houses a conventional 4-stroke diesel engine and all its required auxiliaries. This 129 kW engine is the main power source for all vehicle functions. Mounted to the engine's output shaft are two hydraulic pumps installed in series: one delivers power to the driveline (maximum of 450 bar and 130 cm^3 per revolution), and the other powers the remaining hydraulic functions of the vehicle (maximum of 300 bar and 140 cm^3 per revolution).
The rear part primarily serves as a platform for testing auxiliary equipment and functions, which are expected to be powered mainly hydraulically. Hydraulic directional valves from Parker (maximum flow rate of 170 l/min) are used to power and control the connected equipment. Sensors directly attached to the valve outputs enable pressure measurement for the connected systems. At the time of these tests, a full-scale forestry crane of the model Cranab FC8DT is installed at the rear of the AORO vehicle. The maximum lifting capacity is 4.6 kN at the maximum reach of 10 m, and its total weight (with grapple and rotator) is 1.5 tonnes.

The driveline comprises a hydrostatic power transmission from Poclain. The system can output a starting torque of about 11.5 kNm per wheel and close to 14 kNm at 2 m/s ground speed. The previously mentioned hydraulic pump supplies power from the diesel engine. The pump is connected to four identical hydraulic wheel motors mounted at the wheel hubs. The pump has a variable displacement, controlled by an external signal, which determines the rotational speeds of the motors. Each motor has two fixed displacements (full or half) which the Poclain system selects based on the vehicle's ground speed and speed signal input. Given that configuration, motor displacements can be changed so that several "gears" can be iterated through going up or down in desired vehicle speed. Three different gears are currently

utilized: first gear with full displacement on all motors; second gear, where one axle is shifted to half displacement; and third gear, where both axles are shifted to half displacement. The final gear hence doubles the speed of the vehicle at a given pump displacement.
Complementary to the driveline is an optionally activated anti-spin system (from Poclain) that tracks the wheel motor angular speeds, compares those to a theoretical speed and, if needed, restricts hydraulic flow to the individual motor. To do so, the articulated joint's turning angle, as well as the vehicle geometry needed for calculating the theoretical wheel motor speeds, are input to the system.

To enhance offroad performance, the vehicle is equipped with 1 m long hydraulically actuated pendulum arms, which can be individually controlled by an electro-hydraulic system. This allows each wheel a vertical movement of 1 m from its lowest to its highest position. Furthermore, IMU data can be used as input to actively control the pendulum arms. The hydraulic cylinders controlling the movement of the pendulum arms have pressure sensing, enabling ground pressure to be calculated. The cylinders are also equipped with precise position sensing to track the pendulum arm positions. Additionally, both the front and rear pair of pendulum arms have an internal connection between the left and right side cylinders, where controllable valves enable fluid displacement between them. The mode when the pendulum arm cylinders of the front or rear axle are connected, with the controllable valves fully open, is called "passive mode". When a wheel on an axle in passive mode encounters a ground obstacle, oil can pass freely between the pendulum arm cylinders to maintain a uniform ground pressure between the left and right side, while traversing the obstacle. This allows for an effective dampening effect for the axle currently run in passive mode. Both axles are never run in passive mode simultaneously, as this would compromise roll stability, making it similar to that of a bicycle. To counteract vehicle roll, the axle not currently in passive mode is either kept stationary or is actively controlled.

Vehicle Digital Twin

A real-time multi-physics digital twin of the AORO vehicle has been developed to support testing, research, and development of its hardware, software, and control algorithms, thereby contributing to research and development in autonomous heavy offroad and industrial vehicles in general. The real-time capability of the digital twin enables it to be run not only digitally, but also in a HiL or ViL configuration (Fathy et al., 2006). The digital twin features a multibody simulation (MBS) model, detailed driveline and pendulum arm hydraulics, flexible tyres, co-simulation capabilities, and emulation of both vehicle-internal proprioceptive sensors and exteroceptive sensors such as a forward-facing camera and an RTK-GPS sensor. The digital twin is run in the real-time multi-physics solver Mevea (Mevea).

The MBS model development was facilitated by utilizing a detailed CAD model of the AORO vehicle, which was available since the vehicle was developed in-house at Luleå University of Technology. The bodies constituting the vehicle were extracted from the CAD data along with their detailed graphics, joint positions, mass, center of gravity, and moments of inertia. Detailed CAD models were used for visualization graphics, while simplified collision graphics were created to reduce computational load during collision calculations. Since movement of the crane was outside the scope of this study the digital twin had 9 internal degrees of freedom (DOF) and 15 DOF with respect to its environment.

Each individual tyre was modeled as five discs distributed along its width, creating a simplified three-dimensional representation of the tyre. At each simulation time step, each tyre had a single point of contact with the ground model, where the friction was described by the LuGre friction model and the flexible behavior by an assigned spring stiffness and damping coefficient.

The hydraulics calculations in Mevea utilize the lumped fluid theory (Watton, 1989), which is computationally efficient, making it advantageous for use in real-time applications (Rahikainen et al., 2018). To better capture high frequency behavior, which is commonly seen in hydraulic systems, the time step for the hydraulics calculations can be set separately as the general simulation time step divided by a chosen integer value. This enables the hydraulics calculation time step to be significantly smaller than the general simulation time step.
The hydraulics of the driveline, pendulum arms and articulated joint were modeled in detail. The diesel engine, which supplies power to the hydraulic system, was also included in the model. The crane was outside the scope of this study and its hydraulics were thus not included. The characteristics of the hydraulic components were obtained from their datasheets and drawings and implemented as parameters in the hydraulic model. The bulk moduli of the oil and hydraulic hoses were also specified in the model, with the hose values taken from Johnston et al. (2010), and included in the calculations.

For camera emulation and high visualization fidelity Mevea can run in co-simulation with the game engine Unity (Unity). The digital twin was used in this setup in a pilot study (Lehto et al., 2024), where a detector trained solely on auto-annotated images from a virtual environment, with minimal optimization, learned to detect timber logs in a challenging real-world dataset with an average precision (AP50) of 36%. Optimization strategies that would likely improve the AP50 were also identified.
Numerous other co-simulation options are available in Mevea, either through software specific APIs, which are available for e.g. Unity and ROS (ROS), or through more general protocols such as TCP/IP.

More information about the vehicle digital twin and its modeling can be found in Lehto et al. (2023).

Environment Model

The digital model used as the ViL simulation test environment was a UAV-scanned replica of the physical test environment at OuluZone in Oulu, Finland. It was created using the following three steps.

Step 1 – Aerial LiDAR and RGB Data Acquisition

A DJI Matrice 300 RTK UAV equipped with a DJI Zenmuse L1 lidar captured a dense, distance-intensity-RGB-fused point cloud of the operation area, consisting of approximately 100 million points.

Step 2 – Semantic Segmentation
Instead of converting the point cloud directly to a mesh, it was first divided into smaller pieces spatially. Then, image-based semantic segmentation was performed on raw 2D-images from the UAV by feeding them to a DeepLab V3+ network (Ariram et al., 2021). The network assigned classes to the pixels, such as asphalt, grass, building, human, etc. After the classification, each pixel's class was back-projected to its corresponding lidar point.

Step 3 – Object-Wise Mesh Generation and Tiling
Mapping the semantic segmentation classifications onto the 3D point cloud enabled partitioning of the point cloud into clusters representing either discrete objects or spatially coherent surface areas. Each cluster was then converted into a mesh using geometry appropriate to the object type, typically relying on primitive shapes such as planes, cylinders, and cuboids to ensure computational efficiency and shape fidelity. For larger continuous areas (e.g., roads or terrain patches), the surface was divided into regular tiles, for example 10×10 m, to allow loading only the relevant segments and thereby reduce computational load. To maintain real-time simulation performance, polygon resolution was adjusted, prioritizing high-detail areas that were critical to the simulation scenario. For realistic visualization, per-point color values were either upsampled to generate high-resolution textures or replaced with representative material textures (e.g., asphalt, vegetation). In some cases, recognized objects were directly substituted with geometric proxies, for instance, by replacing a detected cylindrical trash bin with a simple cylinder primitive.

More information about the environment model generation is available in Lehto et al. (2023).

Case Study Setup

To test the ViL framework available in the NUVE-LAB, a case study was conducted using the physical AORO vehicle, its real-time digital twin, and the virtual environment generated through scanning the OuluZone test site.
The aim of the case study was to test the overall functionality of the framework and evaluate its ability to replicate realistic driving conditions. The evaluation, presented in the Results section, compares test runs at the physical OuluZone test site with the corresponding tests performed using the ViL framework.

The setup of the different parts of the ViL framework, tailored to this specific case study, is described in this section.

ViL Simulation and Signal Flow Setup
A simplified description of the ViL signal flow for the case study is presented in Figure 1.

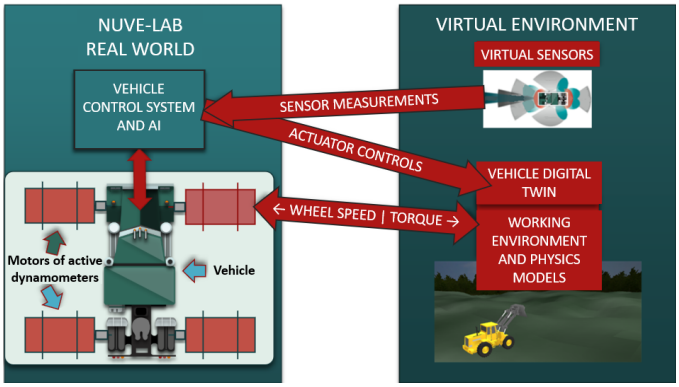

Figure 1: Simplified Description of the ViL Simulation Setup and the Data Exchange Between Test Vehicle, Dynamometer and Virtual Environment

The AORO vehicle is speed controlled. When attempting to drive forward, at the set target speed, it applies torque to its wheels. This torque is measured by the wheel hub dynamometers and sent to the Mevea simulation software. Based on this torque the simulation software calculates the resulting wheel speeds for the next control cycle and these values are sent back to the dynamometers, which then allow the wheels to rotate at this speed. The interaction between the Mevea simulation software and the dynamometer control system is presented in Figure 2.

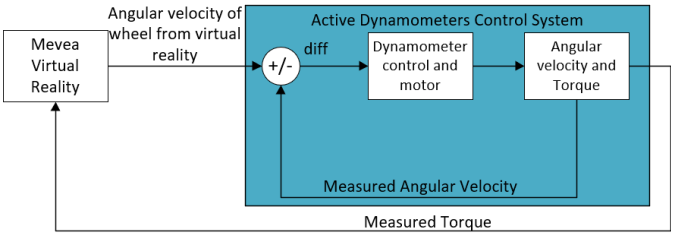

Figure 2: Control Loop for Driving Resistance in Dynamometer ViL Setup

In the ViL tests, the physical AORO control system was connected to the vehicle's digital twin, steering it autonomously along the same GPS paths in the virtual OuluZone environment as during the real-world test drives. The GPS data for the control system was produced by a virtual sensor attached to the digital twin. GPS and steering signals were transferred between the vehicle's digital twin and the vehicle control system via socket connection. A detailed description of the ViL signal flow is presented in Figure 3, which also illustrates how the speed and torque signals pass through a MATLAB/Simulink interface when transferred between Mevea and the dynamometer control system Horiba STARS.

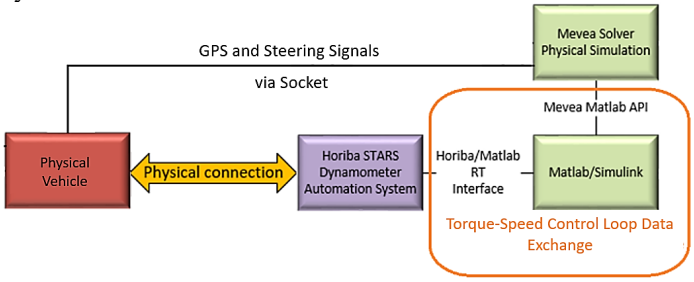

Figure 3: Interfaces Present During the Test Run

Vehicle Digital Twin and Environment Model Setup

The full digital version of the AORO vehicle digital twin was adapted to fit the ViL test scenario. Since the driveline of the real AORO vehicle was included in the simulation loop through the wheel hub dynamometers, the simulated hydraulic driveline of the full digital twin was removed. It was replaced with individual torque sources for each wheel, controlled by input signals from the dynamometer control system (see Figure 3). However, the other hydraulics, e.g. the hydraulically actuated articulated joint and the pendulum arm hydraulics, were kept in the digital twin.

Since neither the wheel hub-mounted dynamometers nor the tyre model in the digital twin account for the rolling resistance of the tyres, it was modeled separately. To achieve this, disc brakes with a constant pressing force between the brake pads and discs, were applied to the wheels of the digital twin. This setup was already implemented in the full digital version of the digital twin. The pressing force was then calibrated during the initial ViL tests (see the Results section).

The digital twin followed the same pre-determined GPS paths that the physical vehicle had previously followed. Therefore, the emulated RTK-GPS sensor in the digital twin was used to generate the GPS-position signal, which was transmitted to the control system of the physical vehicle (see Figure 3).

To ensure precise GPS positioning in the virtual environment, a handheld RTK-GPS sensor was used to measure the coordinates of a well-defined point in the physical test environment. The coordinates were then applied to the corresponding point in the digital environment model as the origin of the GPS coordinate system. For more details about the emulated RTK-GPS signal and the virtual environment, see Lehto et al. (2023).

Laboratory and Physical Vehicle Setup

During the tests the vehicle was rigidly mounted to the laboratory floor, as shown in Figure 4.

Figure 4: The AORO Vehicle Connected to the NUVE-LAB Dynamometers for ViL Testing

To prevent unintended movement of actuators such as the steering and pendulum arm cylinders during the ViL tests, their control signal cables were physically disconnected. Mechanical stoppers were also installed to prevent unintended movements caused by hydraulic valve leaks.

To prepare the dynamometers for ViL testing, several initialization steps were taken:

1. The torque and rotational speed limits were set according to the vehicle's specifications, so that its limits could not be exceeded during the tests. The positive rotational direction was also defined in the dynamometer controller to align with the simulation environment.
2. The tests were conducted with the tyres in place, since they were difficult to remove. Their inertia was therefore measured and accounted for in the dynamometer controller settings.
3. The rotational speed of each tyre was individually set by the dynamometer controller, using a control mode referred to as “Single-speed mode".
4. The PI controller of the dynamometers was tuned for the specific vehicle and the gears in use (lower gears resulted in a stiffer system; see the Results section). The objective was to achieve as realistic and stable speed and torque curves as possible, for which the P-value was the main tuning parameter. Higher P-values generated an overall stiffer system, which resulted in less low-amplitude speed and torque noise at constant speeds, but introduced high-amplitude torque peaks during transients such as turning, bumps, and accelerations. The P-value was set as high as possible to minimize low amplitude noise, while being low enough to not cause excessively high torque peaks, which could also trip the chosen torque safety limits. Finally, the I-parameter was used for fine-tuning. When properly adjusted it appeared to slightly reduce low amplitude noise without causing noticeably higher torque peaks. Further details about the dynamometer PI controller tuning are provided in the Results section.

RESULTS AND DISCUSSION

The ViL simulation framework was evaluated by replicating multiple test scenarios, which were previously performed in the physical world, in a ViL setup. These scenarios included turning at standstill, autonomously following an S-shaped GPS path up a varying slope, straight-line uphill and downhill driving, and driving at varying speeds on flat ground while following pre-determined speed curves. All test runs were performed on relatively even asphalt surfaces to minimize confounding variables introduced by the terrain.

A full analysis of all results from all the test scenarios is outside the scope of this study. However, this section presents a validation of the most important ViL test scenario, comparing it to the corresponding scenario from the physical world. This section also describes the initial ViL simulation framework testing and rolling resistance calibration, as well as the dynamometer PI controller tuning.

Initial Testing and Rolling Resistance Calibration

To test the overall functionality of the ViL simulation framework and its real-time capability, a few simplified tests were first performed. The first test excluded any turning and steering commands, and the speed command of the AORO vehicle was manually controlled using its remote control. The closed-loop ViL framework described in Figure 3 (excluding the GPS and steering signals) was observed to function as intended: the speed of the vehicle’s digital twin was controllable through the ViL setup, and the ViL framework operated in real-time using a time step of 1 ms for the main simulation and 33 µs for the hydraulics calculations. It was later observed that all the described ViL test scenarios could

be run in real-time using these same time steps. The Mevea multi-physics simulation and MATLAB/Simulink were run on a workstation PC with an Intel 10900KF CPU, an Nvidia RTX 2080 SUPER GPU, and 32 GB of RAM. The Horiba STARS software was run on a workstation PC with an Intel Xeon E-2176G CPU, 32 GB of RAM, and no external GPU.

The disc brakes of the digital twin were calibrated to account for the rolling resistance of the tyres, so that when running at a constant speed of 0.75 m/s on flat ground in the ViL setup, the average pressure over the hydraulic motors (of the physical AORO vehicle) was the same as during the physical tests.

Dynamometer PI Controller Tuning

The first PI controller tuning step was conducted with the digital twin driving in a straight line on a flat surface, adjusting the physical AORO vehicle's target speed using its remote control, and thereby adjusting the speed of the digital twin. It was observed that enabling the lowest gears on the AORO vehicle made the system stiffer, with faster acceleration and torque responses, which in turn required more careful PI controller tuning. When the speed and torque curves were deemed stable enough on remote control, using automatic gear changing over the full gear range, the next tuning step was initiated.

In the second tuning step, the vehicle followed pre-determined speed curves on flat ground, ramping up between various target speeds in a step-wise fashion, using automatic gear changing. This test was more aggressive with faster accelerations, and required further tuning where P was the main tuning parameter. With the I-parameter at 1.0, increasing the P-parameter reduced the oscillations of the speed and torque curves and made them stabilize quicker at each new target speed. However, when excessively increasing P, short but high amplitude torque spikes were observed in the acceleration phases. A suitable compromise for the speed ramp-up test was considered to be at an I-value of 1.0 and a P value of 15.

The third tuning step involved the most challenging ViL scenario, which was autonomous driving along an S-shaped GPS path, starting from flat ground and then up a varying slope, with the AORO vehicle trying to keep a constant speed of 0.75 m/s. It was observed that the previously obtained P and I values resulted in an excessively stiff system for this scenario, with short torque spikes exceeding the set torque safety limits of 10 kNm per wheel, causing the dynamometer system to shut down and go into safety idle mode. The high torque spikes were observed during turning, when driving up steep slopes, and most severely with a combination of both. This made the S-shaped path scenario increasingly challenging the longer it progressed, since the slope angle got successively steeper. Lowering the P value appeared to decrease the stiffness of the system and thereby reduce the amplitude of the torque spikes. Table 1 presents the third tuning step, with the S-shaped path scenario completion percentage as a function of the used PI controller parameters.

Table 1: S-Shaped Path Scenario Completion With Respect to PI Controller Parameters

I	P	Test completion [%]
1.0	15	21
1.0	8	81
1.0	6.5	81
1.0	5	100

Table 1 shows that with an I value of 1.0, lowering P to 5 enabled completion of the S-shaped path scenario.

As a final fourth tuning step, I values between 0.5 and 1.5 were evaluated in combination with the P value of 5. The S-shaped path scenario could be completed with all those combinations, and the effect on the speed and torque curves were relatively marginal. At an I value of 0.8 the speed and torque curves were perceived as the least oscillatory. Therefore, the resulting settings from the PI controller tuning were a P value of 5 and an I value of 0.8.

Validation of the S-shaped GPS Path Test Scenario

The most challenging of the test scenarios, but also the scenario considered the most important, was the autonomous driving along an S-shaped GPS path. Starting from flat ground, the AORO vehicle follows an S-shaped path up a slope with increasing steepness, while trying to maintain a constant speed of 0.75 m/s. This scenario was considered the most important since it was the most complex, involving multiple subsystems and slope variations in one test.

A key aspect of validity in ViL testing is that the loads on the physical driveline are the same as they would be in the corresponding physical test scenario. To assess this, the pressure over one of the hydraulic wheel motors during the S-shaped path scenario was compared between the ViL simulation and the corresponding physical real-world test run. In a hydraulic driveline, the pressure over the hydraulic motor is directly proportional to its torque output at a given motor displacement ("gear"). The hydraulic motor of the front left wheel was chosen for this comparison. Figure 5 presents the unfiltered pressure curves from the ViL simulation and the real-world test run.

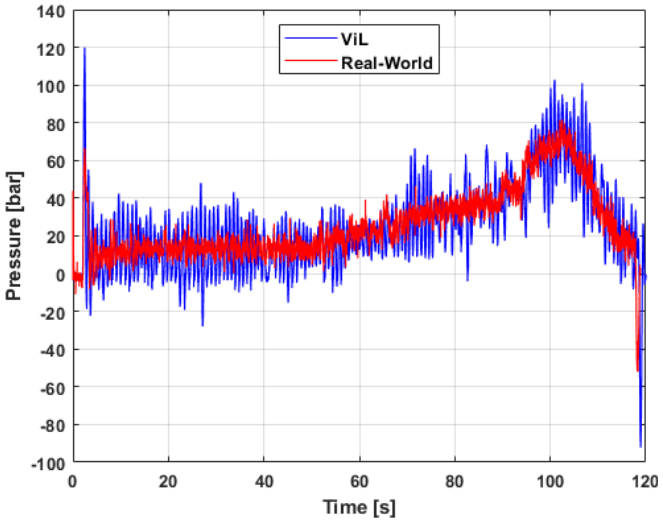

Figure 5: Unfiltered Pressure Curves of the Front Left Wheel Motor from the ViL Simulation and the Real-World Test Run

Figure 5 shows that the ViL and real-world pressure curves appear to follow a very similar trajectory. Both curves show some oscillations, but these are more pronounced in the curve from the ViL simulation. For both curves the highest amplitude component of the oscillations has a frequency of about 1 Hz, but some lower amplitude components with higher frequencies are also present. A hypothesis is that the ViL setup might currently be amplifying some pre-existing natural frequencies of the vehicle and/or vehicle digital twin. A more comprehensive analysis of the frequency components and their root causes is planned, and is discussed further in the Future Research section.

To evaluate the overall agreement between the ViL simulation and the real-world test beyond the oscillatory effects, a low-pass filter was applied to remove most of the oscillations and noise. MATLAB was used to apply a Butterworth filter with a cut-off frequency of 0.3 Hz and order 4 to the data from both tests. The resulting filtered curves are presented in Figure 6. To align the curves on the time axis, synchronization was based on the point in Figure 6 where pressure first begins to rise in each curve, which was defined as the time 0 s. The curves in Figure 5 were also synchronized using this same reference point from the filtered data.

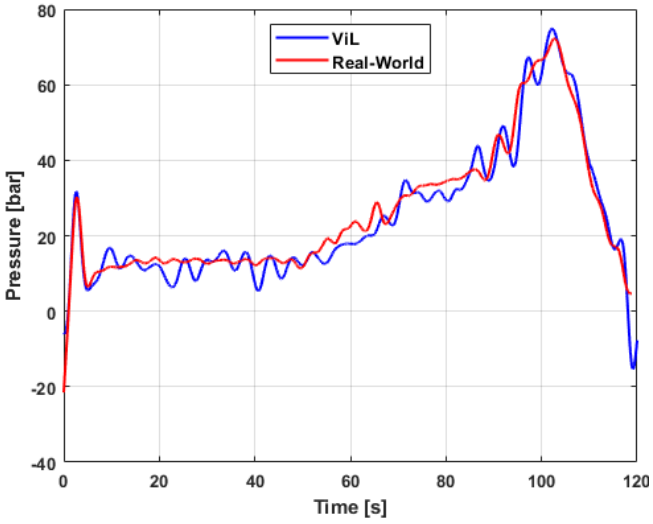

Figure 6: Filtered Pressure Curves of the Front Left Wheel Motor from the ViL Simulation and the Real-World Test Run

Figure 6 shows that the overall accuracy of the ViL simulation is high, since the ViL and real-world pressure curves overlap to a large extent. The ViL simulation captures both the general properties such as the overall pressure at each time period, as well as more subtle details such as small intermittent fluctuations in the real-world pressure. However, these smaller fluctuations are sometimes more pronounced in the ViL simulation, especially between 8 s and 48 s. It has been noted that the digital ground model's mesh appears to have a more uneven driving surface than the real-world test site, especially on some sections. This could explain the differences entirely or in part. Investigation of the differences between the filtered curves is discussed in the Future Research section.

CONCLUSION

A ViL simulation framework for autonomous heavy offroad and industrial vehicles was realized. The framework featured four hub-mounted active dynamometers capable of handling vehicles weighing up to 65 tonnes, torques up to 100 kNm per wheel, power outputs up to 300 kW per wheel, and a total power output of up to 1.2 MW. A case study was conducted to test and validate the ViL simulation framework. It was demonstrated that the framework could be run in a closed-loop setup in real-time using 1 ms as the main simulation time step and 33 µs for the hydraulics calculations. Tuning the PI controller of the dynamometers was shown to be important for reducing oscillations and high amplitude torque spikes. The ViL simulation framework showed a high degree of validity when comparing results from the most complex simulated scenario with those from the corresponding real-world test run.

FUTURE RESEARCH

This study presents the first implementation, use case, and validation of the ViL simulation framework. As expected at this early stage, much research remains to be done. To begin with, as detailed in the Results section, only the most complex and important of the test scenarios was partially validated in this study. Validation of the remaining scenarios is planned as future work. These scenarios were selected to provide different useful insights and include turning at standstill, straight-line uphill and downhill driving, and driving at varying speeds on flat ground while following pre-determined speed curves.

Further validation and analysis of the S-shaped GPS path scenario is also of interest. For example, as mentioned in the Results section, the different frequency components observed in the unfiltered pressure curves in Figure 5 will be further analyzed, along with trying to identify their root causes. The other test scenarios may also aid in this investigation. The amplitude differences between the two filtered curves in Figure 6, mainly between 8 s and 48 s, will also be further investigated. This includes analyzing potential impacts from different ViL framework parameters and components, such as the ground model, which is likely a significant contributor.

Further investigation of the effects of dynamometer PI controller tuning is also of interest. More precise tuning could also reduce the oscillations seen in Figure 5 further, at least to some extent. The role of the digital twin tyre parameters, such as the stiffness and damping coefficient, will also be considered, although initial observations suggest they may not be the primary cause.

Another future direction involves using both ViL and real-world test data to fine-tune the fully digital version of the vehicle's digital twin. Comparing results from all three modalities (fully digital, ViL, and real-world) should help to isolate certain model components. For example, the impact of the digital twin's tyre model could be highlighted by comparing the ViL simulation with the real-world test, since they both utilize the same physical hydraulic driveline.

Looking further ahead, even more complex ViL scenarios, such as offroad driving in deformable and more uneven terrains, represent an interesting area of future research. Using ViL simulation to perform or facilitate ML for autonomous

vehicle development is also a promising direction for future research. This could be either through training in a ViL simulation setup, using ViL data to tune and validate the fully digital version of the digital twin for training purposes, or a combination of both.

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REFERENCES

Ariram, S., Pennanen, T., Tikanmaki, A., and Roning, J. 2021. "Garbot - Semantic Segmentation for Material Recycling and 3D Reconstruction Utilizing Robotics". In *2021 IEEE International Conference on Mechatronics and Automation, ICMA 2021*, 1255–60.

Bock, T., Maurer, M., and Färber, G. 2007. "Validation of the Vehicle in the Loop (VIL) - A Milestone for the Simulation of Driver Assistance Systems". In *IEEE Intelligent Vehicles Symposium*, 612–17.

Fathy, H. K., Filipi, Z. S., Hagena, J., and Stein, J. L. 2006. "Review of Hardware-in-the-Loop Simulation and Its Prospects in the Automotive Area". In *Proceedings of SPIE - The International Society for Optical Engineering 6228*.

Horváth, M. T., Lu, Q., Tettamanti, T., Török, Á. and Szalay, Z. 2019. "Vehicle-In-The-Loop (VIL) and Scenario-In-The-Loop (SCIL) Automotive Simulation Concepts from the Perspectives of Traffic Simulation and Traffic Control", *Transport and Telecommunication 20*, No.2, 153–61. DOI: 10.2478/ttj-2019-0014.

Jeong, J., Karbowski, D., Kim, N., Han, J., Stutenberg, K., Di Russo, M., and Grave, J. 2022. "Vehicle-In-The-Loop Workflow for the Evaluation of Energy-Efficient Automated Driving Controls in Real Vehicles". *SAE Technical Papers 2022*.

Johnston, D. N., Way, T. M. and Cone, K. M. 2010. "Measured Dynamic Properties of Flexible Hoses". *Journal of Vibration and Acoustics 132,* No. 2, 0210111–18. DOI: 10.1115/1.4000774

Kanchwala, H. 2021. "ORES: A Chassis Dynamometer for off-Road Vehicles", *Mechanics and Industry 22*. DOI: 10.1051/meca/2021004

Kelber, C. R., Reis, B. R. R., and Figueiredo, R. M. 2016. "Improving Functional Safety in Autonomous Guided Agricultural Self Propelled Machines Using Hardware-in-The-Loop (HIL) Systems for Software Validation". In *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 1438–44.

Lee, C. J., Jeon, C. W., Han, X. Z., Kim, J.-H., and Kim, H.-J. 2017. "Electro-Hydraulic Steering Control System for Automated Steering of an Agricultural Tractor". In *2017 ASABE Annual International Meeting.*

Lehto, M., Lideskog, H., and Karlberg, M. 2024. "Log Detection for Autonomous Forwarding Using Auto-Annotated Data from a Real-Time Virtual Environment". In *ISTVS 2024 | 21st International and 12th Asia-Pacific Regional Conference of the ISTVS*. DOI: https://doi.org/10.56884/XD21D6FR

Lehto, M., Tikanmäki, A., Lindbäck, T., Lideskog, H., and Karlberg, M. 2023. "Modeling and Verification of a Full-Scale Forestry Vehicle Real-Time Multi-Physics Digital Twin". In *16th European-African Regional Conference of the ISTVS*. DOI: https://doi.org/10.56884/TSOG1043.

Li, H., Makkapati, V. P., Wan, L., Tomasch, E., Hoschopf, H. and Eichberger, A. 2023. "Validation of Automated Driving Function Based on the Apollo Platform: A Milestone for Simulation with Vehicle-in-the-Loop Testbed". *Vehicles 5*, No. 2, 718–31. DOI: 10.3390/vehicles5020039.

Maier, F. M., Makkapati, V. P. and Horn, M. 2018. "Environment Perception Simulation for Radar Stimulation in Automated Driving Function Testing". *Elektrotechnik und Informationstechnik 135*, No. 4–5, 309–15. DOI: 10.1007/s00502-018-0624-5

Mayyas, A., Prucka, R., Pisu, P. and Haque, I. 2013. "Chassis Dynamometer as a Development Platform for Vehicle Hardware In-the-Loop "VHiL,"". *SAE International Journal of Commercial Vehicles 6*, No. 1, 257–67. DOI: 10.4271/2013-01-9018

Pandharipande, A., Cheng, C.-H., Dauwels, J., Gurbuz, S. Z., Ibanez-Guzman, J., Li, G., Piazzoni, A., Wang, P. and Santra, A. 2023. "Sensing and Machine Learning for Automotive Perception: A Review". *IEEE Sensors Journal 23*, No. 11, 11097–115. DOI: 10.1109/JSEN.2023.3262134

Rahikainen, J., Mikkola, A., Sopanen, J. and Gerstmayr, J. 2018. "Combined Semi-Recursive Formulation and Lumped Fluid Method for Monolithic Simulation of Multibody and Hydraulic Dynamics". *Multibody System Dynamics 44*, No. 3, 293–311. DOI: 10.1007/s11044-018-9631-x

Raikwar, S., Jijyabhau Wani, L., Arun Kumar, S. and Sreenivasulu Rao, M. 2019. "Hardware-in-the-Loop Test Automation of Embedded Systems for Agricultural Tractors". *Measurement: Journal of the International Measurement Confederation 133*, 271–80. DOI: 10.1016/j.measurement.2018.10.014

Schyr, C., Inoue, H., and Nakaoka, Y. 2022. "Vehicle-in-the-Loop Testing-a Comparative Study for Efficient Validation of ADAS/AD Functions". In *ICCVE 2022 - IEEE International Conference on Connected Vehicles and Expo.* DOI: 10.1109/ICCVE52871.2022.9742737

Ulrich, K. T.; Eppinger, S. D.; and Yang, M. C. 2019. *Product Design and Development*. McGraw-Hill Education, New York, NY.

Watton, J. 1989. *Fluid Power Systems: Modeling, Simulation, Analog, and Microcomputer Control*. Prentice Hall International, Hemel Hempstead.

Zhang, Q., Reid, J. F. and Wu, D. 2000. "Hardware-in-the-Loop Simulator of an off-Road Vehicle Electrohydraulic Steering System". *Transactions of the American Society of Agricultural Engineers 43*, No. 6, 1323–30.

WEB REFERENCES

www.mevea.com
www.ros.org
www.unity.com

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