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Holistic process-oriented Approach to Test Bench Control for Mobile Machines

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Abstract

The requirements for modern drivetrains are increasing across all industries. Even mobile working machines such as agricultural and construction machinery are subject to increasingly higher demands in terms of efficiency and CO_2 emissions. To verify these requirements and drive further development, it is necessary for testing processes to comprehensively evaluate the machine and its operational processes. For this purpose, the MOBiL testing approach was developed at the Institute of Mobile Machines. This approach incorporates parallel drivetrains, information flow and the environment of the driving and working task. To implement this approach in a complete vehicle testbench, a framework was developed that enables fully individual driving and working tasks of a mobile working machine to be replicated on a test bench. The basis for this framework is the Robot Operating System (ROS), which runs various nodes. Individual nodes control the different testing subsystem, such as the 4-WD-Acoustic-Chassis Dynamometer, the driving robot, or a PTO test stand. Starting from a simulation node, the subsystems are controlled and reflect their respective measured variables back into the system. These variables are then returned to the simulation and collected along with data from the simulation. All nodes are interchangeable, allowing suitable specifications, simulations, and hardware to be used depending on the scenario: For instance, a tractor with a PTO-driven implement like a baler or a rotary harrow driving on a field. This allows tests on the powertrain and its controls to be reproducibly researched on a test bench. Therefore, efficient, and customized testing processes for a wide range of applications and vehicles are enabled.

Introduction

The technological pressure on the further development of mobile machinery remains high, even after the tightening of exhaust emission limits by the EU. Energy efficiency and CO_2 neutrality are major focus areas. In line with the Green Deal, net greenhouse gas emissions are to be reduced by at least 55 % by 2030 compared with 1990 levels. [1] This affects not only on road vehicles but also mobile machinery. Many municipalities, companies and their customers are attaching increasing importance to CO_2 emissions. This favors the purchase of more efficient work machines, even if these have higher acquisition costs due to the increased development effort.

In order to further advance the development of these topics, it is necessary to improve not only individual components, but the entire system within its work process. The levers and opportunities at this level to improve efficiency and CO2 emissions are significant. In addition to the working machine considered here and its working function in the process, the process itself and the operator are also decisive factors in the overall system. [2]

The examination of components, subsystems and subfunctions of entire machines on hardware in the loop (HiL) test stands is state of the art. In these examinations, the subsystems are operated as realistically as possible. Embedding the subsystem in the test bench creates an environment that is close to the application. This is achieved by simulating interfaces in information, energy and material flow. Based on load cycles or simulations, the individual variables are determined depending on time and/or state. Typical applications are engines, transmissions, parts of powertrains, or the testing of entire traction drives on a roller dynamometer. Work drives are also investigated using these methods as far as this is possible. Depending on the basis of the interface simulation, this method can take into account the influences of other subsystems in the process. Due to the complexity of such interrelationships, driving and working drives are usually considered in isolation from each other. The effort required to simulate interactions in the entire system does not correspond to the outcome. However, the potential of a holistic approach is lost, and optimization of subsystems is not considered in the context of their interactions.

To perform a comprehensive analysis and fully exploit the potential, it is necessary to consider the entire machine in its operating process. One way to do this is to conduct field experiments. Field experiments have the advantage of being realistic, as they simulate the real application of the machine. However, they have the disadvantage of poor reproducibility. It is difficult to produce reproducible results, especially if comparisons are to be made over a long period of time. Also, controlled variation of individual boundary conditions is not always possible. A controlled and reproducible environment is provided by the use of test benches. As already described, the knowledge and technology for investigating individual subsystems within test benches already exists. The methodology for the joint investigation of different drives within a process has also been researched (Chapter 2 “MobiL”).

However, there is still a lack of a structure/framework and control for the combined use of different individual test benches to conduct process-oriented investigations of driving and working drives, a design for which is presented in chapter 3 “Testing Framework”.

Background

Mobile Working Machine and Process

According to Mobile Working Machines [3], mobile working machines are defined as:

“Mobile working machines have a certain task of doing a working process” and they are mobile. Therefore, they use a drive technology with a traction drive and they have a work function with significant energy shares in both, in mobility and in work function." Examples for mobile working machines are excavators, wheel loaders, forklift trucks, combine harvesters and tractors with their implements. These machines share a common structure as shown in Figure 1. [3,4]

In this publication we use the tractor and its various implements as an example. A tractor is a universal machine that is mainly used for agricultural purposes and has two main tasks: field work and transport. While performing field work the tractor combined with an implement can be considered as mobile working machine.

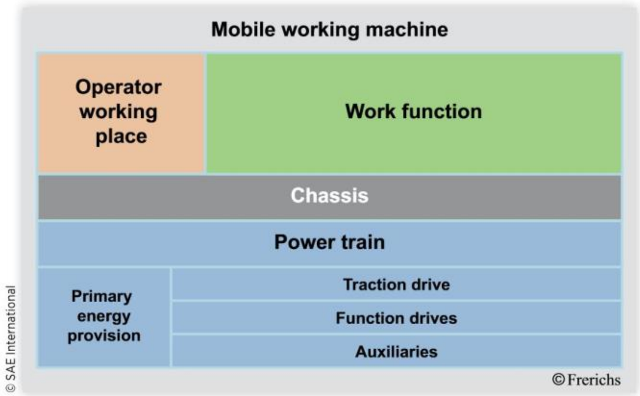


Figure 1. Division of a mobile working machine [3]

MOBiL - Testing Approach

Model-based development and testing is widely used today in the form of the X-in-the-loop (XiL) approach and is used in particular in the development of electronic control units (ECUs), but also in the testing of entire subsystems in the development of passenger cars and commercial vehicles development. The „X" in XiL stands for any „unit under test", i.e. test specimens that are tested in a complete vehicle simulation in a closed reaction loop („in the loop"). Depending on availability, simulation models or real vehicle components on test benches are used. In order to benefit from the previously described advantages of model-based development and testing for mobile machines, it is necessary to adapt the XiL approach to the special needs and boundary conditions of these vehicles and their processes and to extend it accordingly.

In the case of a mobile working machine, the driving or transport task is supplemented by one or more specific working tasks for which the mobile working machine is technically equipped accordingly. To adapt to this topology the following elements were added to the testing framework:

- Parallel structures for information and power flow
- Nodes for the distribution of information and power among the parallel structures
- Adapted driver system and vehicle environment for the driving and work task

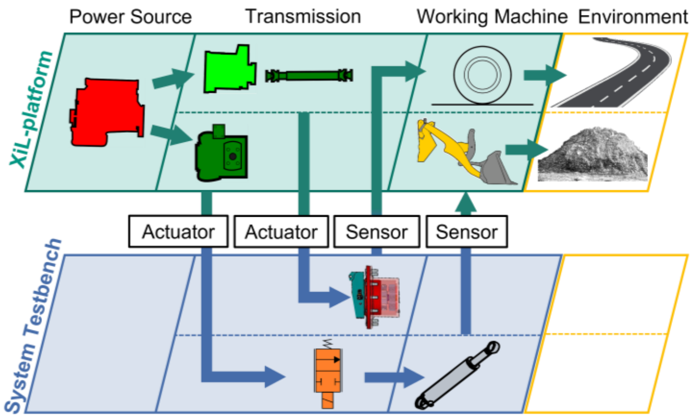


Figure 2. Parallel architecture for a wheel loader, based on [5]

To implement the MOBiL method, the individual test stands and their residual system simulation are interconnected by the central control system. For the complete system integration of the (sub-)system under investigation, a coupling of measurement and simulation variables is necessary. The necessary feedback of measurement signals from the simulation into the test bench technology and vice versa is the essential task, but also challenge, in the implementation of the MOBiL method. By means of a suitable visualization for the evaluation of the measured data, it is possible to make the system behavior recognizable in a meaningful way even to a less experienced operator. The control loop is closed by integrating the operator into the test environment. The way in which the operator performs the tasks assigned to him or her has a significant influence on the system behavior due to the individual vehicle operation.

The application of the MOBiL method allows an early testing of components and subsystems of a mobile working machine and the investigation of the interactions between the subsystems. In addition to the use of standardized load cycles, it is possible to easily apply real applications of the subsystem by means of field measurements. This eliminates time- and cost-intensive field testing of vehicles and their subsystems. Depending on the evaluation or cost function stored, the method can be used to match the subsystems of a mobile machine together optimally. Furthermore, complex systems can be examined, optimized and validated in various test scenarios. [5]

Testing Framework

According to [4], a mobile working machine has a traction drive and a working drive and has significant energy shares in both drives in order to perform a work process. To test a mobile working machine holistically in this respect, it must be possible to load and test all its output drives on test stands. In order to meet this requirement, a framework is presented below that takes different test benches into account.

Figure 3 shows an overview of the testing framework. Shown in red is the mobile working machine, which consists of the three departments energy storage, energy conversion and power transmission. The energy storage provides the propulsion energy and is usually a fuel tank or battery storage. The energy conversion converts the stored energy into rotational energy. An example of this is the internal combustion engine or an electric motor. The rotational energy is then passed on through gears. An example of this is the transmission that operates the machine's traction drive. A power take-off shaft is also driven directly by the engine via the transmission and drives attachments behind a tractor, for example. Electric implement interfaces provide power from the on-board electrical system. Many work drives use hydraulic actuators, so mobile work machines usually provide a flow of hydraulic oil, operated by levers or joysticks in the cab. A special feature is the PowerBeyond connection in agricultural machinery, which allows a direct, uncontrolled use of the pump volume flow.

Different test benches must be used for each of the traction and work drives shown in figure 3. For the traction drive, a chassis dynamometer is suitable for testing. An power take-off brake covers the mechanical output drives. Hydraulic an electric output drive must be tested by suitable load units.The test stands communicate with the environment either in real operation via the work process or via HiL simulation software. Another possibility is to map reality in simulations and thus derive the target values for the test stands.

The machine itself is controlled by a human operator, who can be replaced by a driving robot during the tests for better reproducibility of the results.

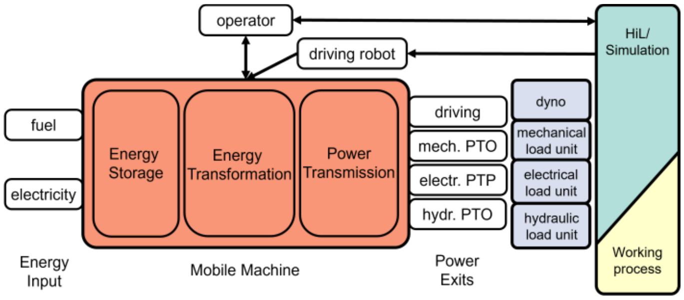


Figure 3. Testing Framework for a Mobile Machine

Technical Implementation

4WD-Acoustic-Chassis-Dynamometer (AARP)

The 4-wheel drive acoustic chassis dynamometer covers a wide range of different vehicles: From passenger cars to vans to mobile working machines, even the largest vehicles can enter the test stand through the hinged doors and be examined, some examples and the technical details can be seen in Figure 4 and Table 1. Due to the four individually driven rollers, almost all conceivable scenarios can be realized: performance measurements, functional tests, dynamic examinations, efficiency/fuel consumption, driving and working cycles, assistance systems, acoustics/NVH and much more.

Several test modes are available for tests on the dynamometer:

- Road Simulation
- Force control
- Velocity control

These modes can be operated manually, by playing a cycle or via external interfaces. The four individually controllable rollers also allow differential speeds/torques between the wheels and axles. A pull-down device allows variable loading of the axles to simulate additional loads.

Table 1. Technical specification 4WD-Acoustic-Chassis-Dynamometer

Driving axles	1 ... 4 (tandem axles)
Max. vehicle Value L x W x H	18 m x 4 m x 4.5 m
Wheel base adjustment	2.05 ... 8.00 m
Permissible maximum weight	56 t (while mounting max. 40 t)
Testing velocity	0 ... 160 km/h
Traction force	70 kN (110 kN peak) per roller
Drives (motor/generator):	300 kW (450 kW peak) per motor
Axle load simulation	10 t per axle
Acoustic properties	Semi-anechoic room Room class 1 Lower cut off frequency 50 Hz Upper cut off frequency 17 kHz Lower sound level 30 dB

Figure 4. Various applications on the chassis dynamometer

Software

The Robot Operating System (ROS) is an open source framework from the field of robotics. It provides communication layers and management tools for easier software development. Individual program components are organized in nodes. Nodes can exchange messages via topics. Requested and available data is managed by a central roscore. The communication is based on Ethernet, whereby individual nodes can also run decentralized on different computers. This structure is ideally suited for the intended test bench control, since additional test benches can be connected modularly via ethernet.

The implemented control software is designed to provide one node per test bench or task. A core node is the chassis dynamometer node, which handles the communication between ROS Topics and the chassis dynamometer. For this purpose, the node receives setpoint values and control commands via ROS topics on the one hand. On the other hand, it is connected to the test bench computer via Ethernet and communicates with it using the SCI protocol. This is a proprietary protocol based on TCP/IP from the test bench manufacturer MAHA. The communication takes place with a maximum frequency of 20 Hz. In order to be able to read in actual values of the test bench with a higher frequency of up to 100 Hz, another node reads in these values directly via a CAN interface and makes them available as ROS topics. Setpoint values which can be send to the test bench are:

- rotation speed (alternator mode, motor mode, 4 quadrant mode)
- torque
- acceleration

Each of these values can be send individually for each roller. The actual values provided for each roller by the test bench are:

- force
- rotation speed

Other nodes accept setpoints as ROS Topics and pass them on locally to the controllers of the additional test stands, such as the driving robot or the power take-off brake. Setpoints can be fed in via different possibilities. One possibility is to provide a cycle in the form of a table whose values are sent off as setpoints at a time-defined interval. Another possibility is the integration of simulation software. Especially for the software IPG CarMaker/TruckMaker a communication via Ethernet over UDP is possible.

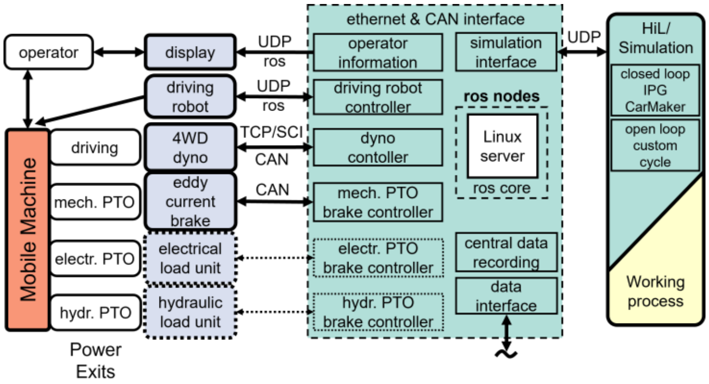


Figure 5. Structure of the software

Simulation Integration and Operator Interface

To realistically represent the driving and working function of the machines in the framework, it is necessary to model them digitally. For example, representative cycles can be used for individual drives or for the entire system. These are then demanded in the test depending on time, distance, speed, or other variables. This is usually an open-loop control that can be implemented well but offers little freedom for individual customization. In order to gain more freedom in the design of the test cycle and a faster creation of the individual cycles, a model-based approach is used. Drive and working function are represented in individual interchangeable models, which can also be linked to each other.

The testing framework offers an interface for the use of cycles as well as for the connection of a simulation environment. The import and use of cycles is done by a custom tool. For the traction drive, this can also be used to create a profile of the track. IPG CarMaker/TruckMaker is used as the simulation environment on a dedicated computer. By using different models, tests can be implemented very flexibly and individually. It also has the advantage that it is easily expandable, so that, for example, models for the work drive can be additionally integrated there. However, other environments such as Simulink Realtime can also be used for the simulation of the working function.

Despite its advantages, a driving robot is not always used for complex and individual experiments. Therefore, relevant information about the state and the virtually implemented environment must be provided to the operator. This is done through an appropriate user interface. For cycles, the operator is shown the speed curve and the height profile as well as his current position and speed. (Figure 6) When using IPG CarMaker/TruckMaker, the operator can also be presented with a view of the virtual environment through IPG Movie. (Figure 7) Additional visualizations for the working drive are possible.

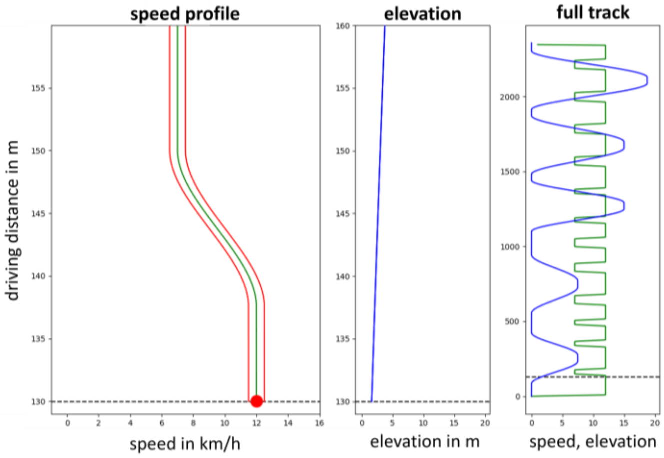


Figure 6. Operator GUI for driving visualization [6]

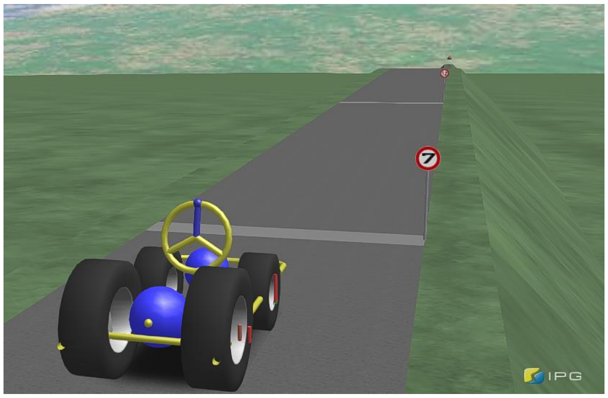


Figure 7. Operator GUI for driving with IPG Movie [6]

Validation

A number of studies have already been carried out to validate the testing framework. After verification of the technical function and safety mechanisms, the individual control options of the roller dynamometer and the control by cycles and simulation were investigated. In a master's thesis, the load on the traction drive was investigated in detail using a Fendt Vario 412. [6]

It has been shown that the force control of the roller test bench works very well, both in open loop and closed loop. The forces at each wheel follow their setpoints, while the speed is determined by the driver. In Figure 8 you can see results from the open loop force control experiments. A variety of different driving situations are possible. In open loop, the forces of each wheel can even be controlled individually, while in closed loop, through IPG CarMaker/TruckMaker, only a total traction force with a fixed distribution to the wheels is possible. Driving virtually around curves is not yet feasible in either mode. As stated in open loop the forces can be controlled individually but only dependent by distance or time. This theoretically enables the representation of the forces during cornering through the application of pre-calculated cornering forces. However, these forces are ideal and do not depend on the actual speed. Different resistances within the drive train to the individual wheels can also mean that the desired cornering wheel speeds are not achieved. For virtual cornering a closed loop is required in force control mode, also taking the wheel speed into account. In the current state the closed loop is only implemented via IPG CarMaker/TruckMaker which does not support individual wheel forces on the test bench side in its standard implementation. Further adjustments or the implementation of a custom simulation are necessary for this.

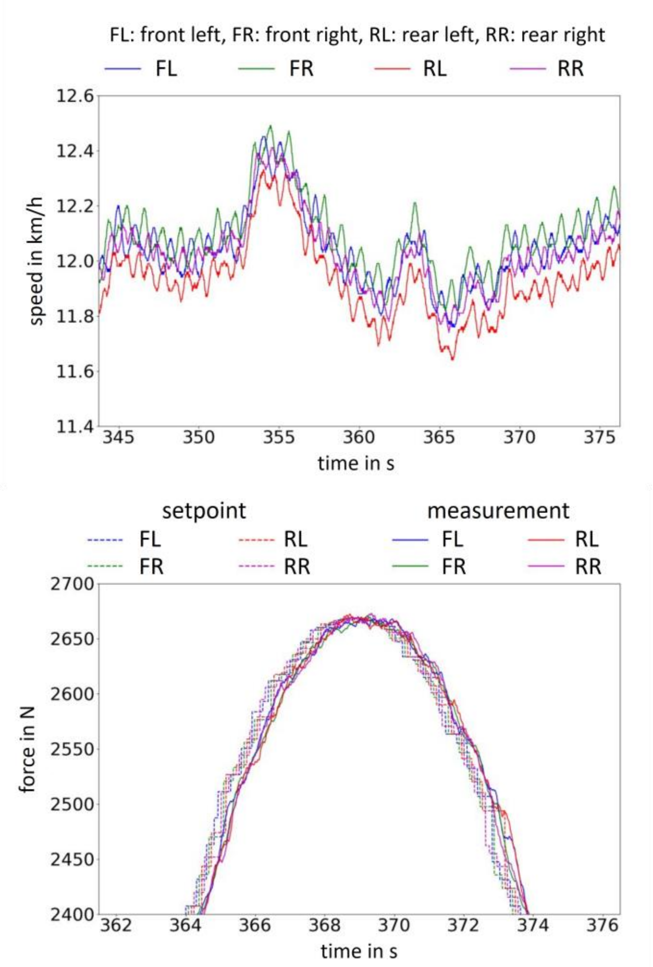
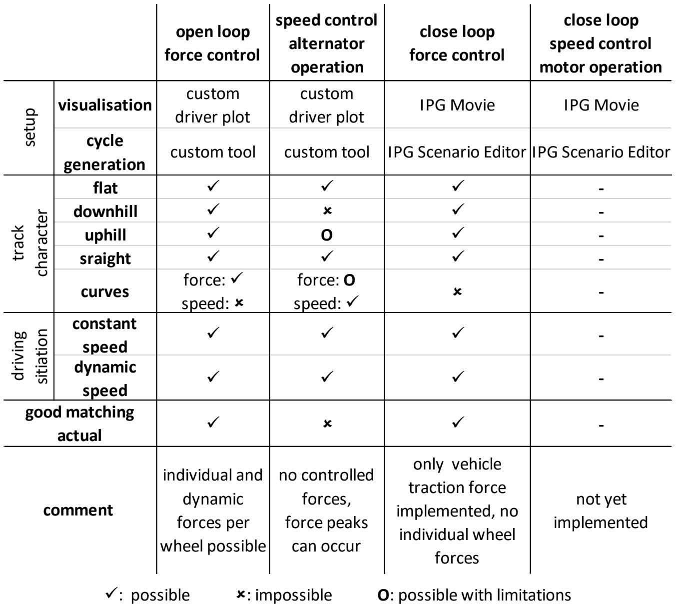


Figure 8. Roller speed and force while in open loop force control mode [6]

As an alternative to force control, speed control mode can be used in alternator operation of the motors. In this case, the test stand brakes the wheels to a certain speed setpoint if they exceed it. A traction force is therefore always required in this operating mode. The required force is self-adjusting according to the engine map and operator input. This mode is particularly suitable for tests with high demand to speed accuracy and low dynamics in force or in combination with a driving robot. While it's easy for a driver to control speed, it's next to impossible to accurately adjust traction force with the accelerator pedal. However, peaks in the force can occur during dynamic test cycles in all configurations. Cornering with defined wheel speeds is possible here if there is a persistent traction force and constant driving speed.

It has not yet been possible to implement closed loop speed control via simulation because some prerequisites for this are currently still missing on the test bench. A summary of all results is presented in Figure 9.



		open loop force control	speed control alternator operation	close loop force control	close loop speed control motor operation
setup	**visualisation**	custom driver plot	custom driver plot	IPG Movie	IPG Movie
	cycle generation	custom tool	custom tool	IPG Scenario Editor	IPG Scenario Editor
track character	**flat**	✓	✓	✓	-
	downhill	✓	×	✓	-
	uphill	✓	**O**	✓	-
	sraight	✓	✓	✓	-
	curves	force: ✓ speed: ×	force: **O** speed: ✓	×	-
driving sitiation	**constant speed**	✓	✓	✓	-
	dynamic speed	✓	✓	✓	-
good matching actual		✓	×	✓	-
comment		individual and dynamic forces per wheel possible	no controlled forces, force peaks can occur	only vehicle traction force implemented, no individual wheel forces	not yet implemented

✓: possible ×: impossible **O**: possible with limitations

Figure 9. Overview of the different control modes of the dyno [6]

For the validation of the load on working drives, the first steps have also already been completed. A tractor can be additionally loaded via a eddy current brake while driving in order to simulate the use of a baler, for example. In Figure 10 you can see the test setup, the vehicle is standing on the chassis dynamometer and is regularly secured by chains. Model-based experiments have yet to be conducted and evaluated. The simulation of a mechanically driven attachment is planned.

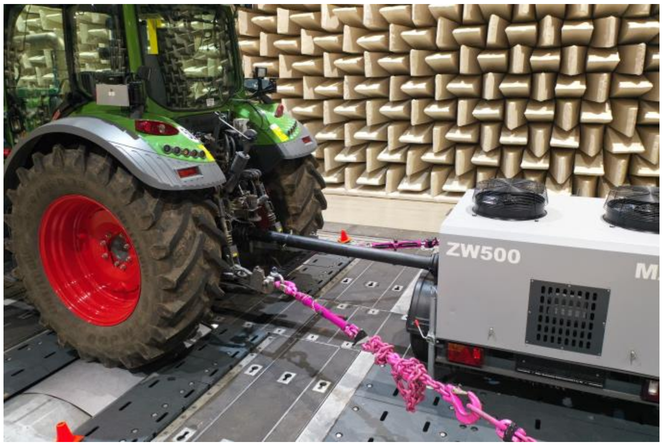


Figure 10. Tractor and eddy current brake on the test bench

Summary

The presented work introduces a holistic process-oriented approach to test bench control for mobile machines. It is based on the MOBiL method which provides the theoretical background to test both traction and work drives of a mobile machine. It is extended by a software architecture to control all different test benches and to create a connection to HiL Software. Tests with the implemented control software and a tractor as test vehicle validate the presented approach. Tests with a tractor on the roller test bench and a coupled HiL simulation in IPG Truckmaker show the possibility to control the traction forces on each wheel while maintaining a speed controlled by a driver. Tests with an additional eddy current brake on the tractors power take-off will be conducted in the future.

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Definitions/Abbreviations

MOBiL	X-in-the-loop method for mobile machines
ROS	tobot operating system
PTO	power take off
FL, FR, RL, RR	wheels: front left, front right, rear left, rear right