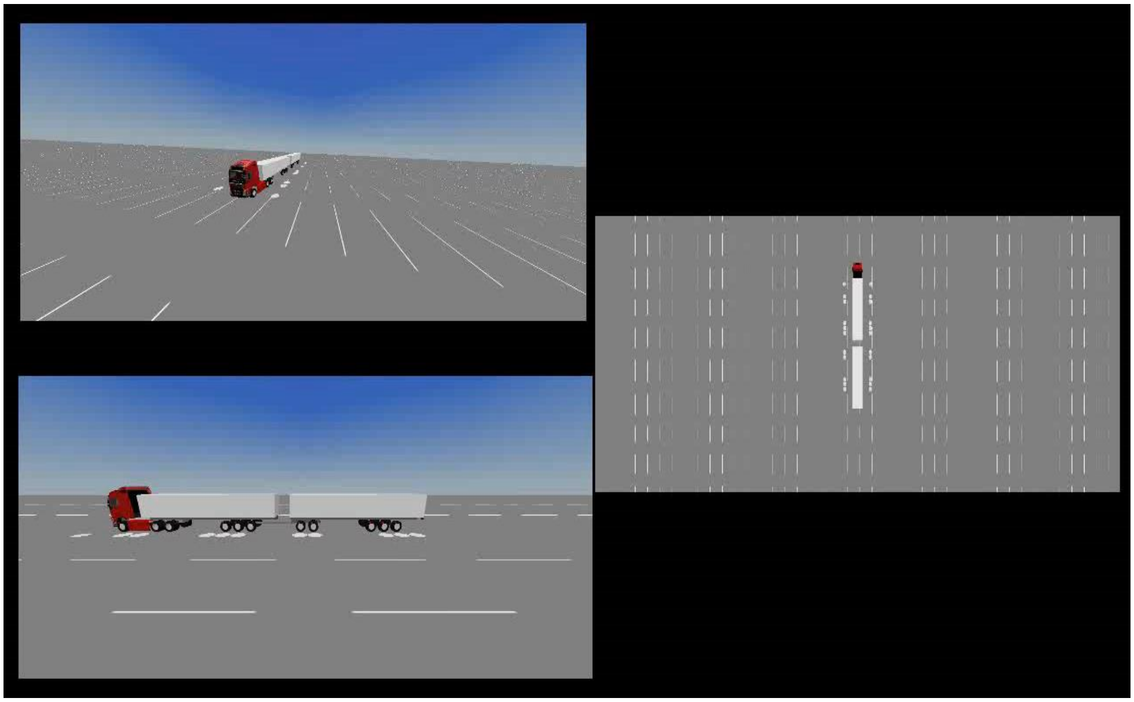
Complete Vehicle Combination Control with automated reconfiguration when connecting vehicle units with different motion capabilities

Public report



Project within **FFI Complex Control**

Author José Vilca, Leo Laine, Bengt Jacobson, Maliheh Sadeghi Kati, Jonas Fredriksson

Date 2020-03-01 21:21

Content

1. Summary

Electromobility and automation will change the way how heavy road transports are conducted today. It is foreseen that the most productive heavy vehicle combinations will be automatically configured specific transport missions in the future. Already today the commercial heavy vehicle market is launching auto-coupling systems to automate the coupling of towing units and towed units. This is a starting point for automated transformation of the combination vehicle for the specific transport mission. It is also foreseen that some strategic towed units will be configured with propulsion, braking, and steering capabilities.

This project application is solving the problem of how to automatically reconfigure the vehicle motion functionality control software when the vehicle combination is adapted for the specific transport mission. An illustrative example is if one consider A-double combination consisting of a tractor unit connected by fifth wheel connecting a semitrailer connected by auto-coupling system for drawbar to converter dolly with a fifth wheel connecting a second semitrailer (tractor, semitrailer, dolly, semitrailer). When the complete combination vehicle is connected it has certain configuration for how motion support devices can generate longitudinal, lateral and yaw motion on each unit. When the auto-coupled dolly is released it needs to automatically re-configure itself as a master unit with only one towed semitrailer unit, exactly like the first tractor unit with the semitrailer. The project aims to achieve this automatic reconfiguration within Vehicle motion mgmt functionality, the main intended user is Volvo Group Trucks Technology and research will be conducted by Chalmers University.

2. Sammanfattning på Svenska

Elektromobilitet och automatisering kommer att förändra hur tunga vägtransporter genomförs. Det förutses att de mest produktiva kombinationerna av tunga fordon automatiskt kommer att konfigureras för specifika transportuppdrag i framtiden. Redan idag lanserar den kommersiella marknaden för tunga fordon automatiska kopplingssystem för kopplingarna mellan fordonsenheter. Detta är en utgångspunkt för automatiserad om-konfigurering av kombinationsfordonet för det specifika transportuppdraget. Det förutses också att vissa strategiska bogserade enheter kommer att konfigureras med framdrivnings-, broms- och styrfunktioner.

Detta projekt belyste problemet med att automatiskt konfigurera om programvaran för styrning av fordonets funktionsfunktioner när fordonskombinationen är anpassad för det specifika transportuppdraget. Ett illustrativt exempel är om man betraktar A-dubbelkombinationen, bestående av en traktor (dragbil) ansluten med vändskiva som ansluter en semitrailer. Den semitrailern är i sin tur ansluten med autokopplingssystem för dragstång till en dolly med en vändskiva som ansluter en andra semitrailer (traktor, semitrailer, dolly, semitrailer). När det kompletta kombinationsfordonet är kopplad har det viss konfiguration för hur aktuatorerna kan generera longitudinella och laterala rörelser på varje enhet. När den auto-kopplade dolly släpps måste den automatiskt konfigurera sig själv till en huvudenhet (master) med endast en bogserad semitrailer, precis som den första

traktorenheten med semitrailer. Projektet syftar till att uppnå denna automatiska omkonfigurering inom Vehicle motion management-funktionaliteten. Den huvudsakliga användaren är Volvo Group Trucks Technology och forskning bedrevs av Chalmers University.

3. Background

The requirements of a modern road vehicle's motion control system are reaching a complexity which has mainly been seen only in flight and marine application. It should be noted that the flight and aerospace industries have large budgets with which to design and construct their aircraft and therefore could include computerized controllers and develop advanced control functionality earlier on when computers were still expensive. In marine applications, especially when building large ships, the development cost of the control system is a small fraction of the total cost, making it possible to develop advance motion control systems. When the prices of computerized controllers became lower they also started to be popular in mass produced products such as road vehicles. With this in mind a literature survey is given on what has been done within flight, then marine, and finally within road vehicles to control over-actuated systems. Aircraft are designed with more motion actuators than motions to be controlled, so called over-actuation. The motion actuators in aircraft consist of control surfaces on the wings, tail, and even on the body. The control surfaces change their angle to achieve the desired motions in roll, pitch, and yaw, see Fig 1. The left figure shows the three main rotations of the airplane. The desired rotations can be achieved by several different settings of the control surfaces shown in the right figure. In this case there are up to 11 control surfaces that can be used for generating moments in the main rotation directions. Additionally, the engine thrusters are mainly used to control the longitudinal speed but are also used for generating the desired moments. This is the essence of situations where control allocation has been used for coordination within flight control.

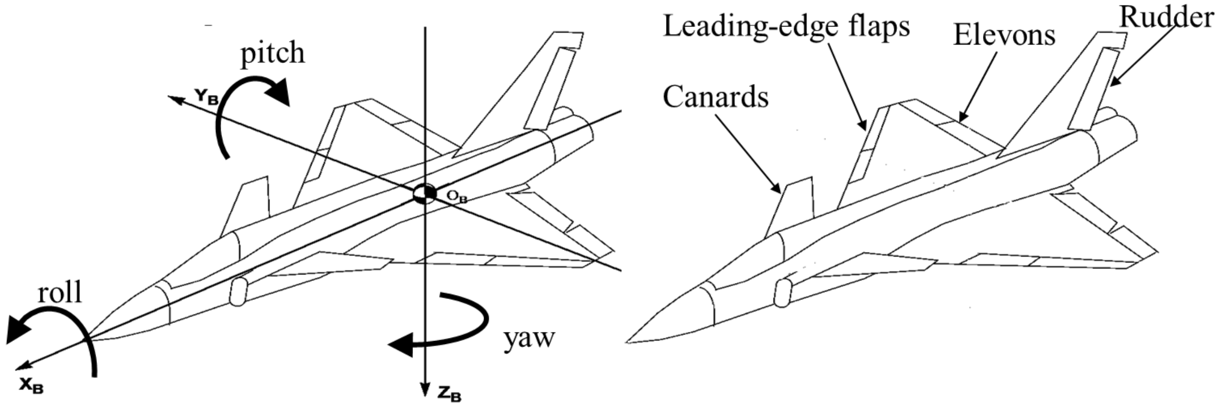


Fig. 1. *The left figure illustrates the desired moments, roll, pitch, and yaw, shown in the body-fixed reference frame. The right figure illustrates the available control surfaces which are used to generate the desired moments.*

Over-actuation in aircraft was mainly done to improve performance and redundancy. One of the first attempts to address the over-actuation problem was done by using pseudo-controllers. They are also called pure mode controllers, for flight modes such as Dutch roll1, roll and spiral modes. The pseudocontrol variables are related by eigenvectors of the response modes to the motion actuators in a 'mixing' matrix which is used for allocation. The strength and weakness of the pseudo-controller is that pure modes can be achieved but not the maximum attainable moment in arbitrary directions. The first real attempt to separate the control law for the roll-, pitch-, and yaw-motion, v, and control allocation of the specific actuators, ***u***, see also Fig. 2. The control allocation is seen as a constrained problem with maximum and minimum limits of the motion actuators. In [2] a direct allocation solution is given for the two attainable moment set problem, in roll and yaw, that guarantees the maximum motion can be generated within the constraints of attainable moments. The direct allocation uses a geometric approach to solve the allocation problem. The limits of the actuators are projected through the control effectiveness matrix ***B*** to give the two dimensional geometry of the attainable moment set. Direct allocation solutions for the three attainable moment set problem is given. The limits in rate of change of the motion actuators are addressed and how they can contribute to catastrophic pilot induced oscillations if they are not included in the constrained control allocation formulation.

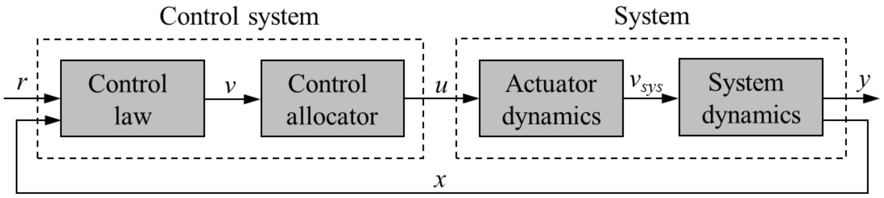


Fig. 2. *Illustration of how the control law for motion is separated for the control allocator within the control system.*

Reconfigurable aircraft that can handle actuator failure are highly desirable. This is accomplished through offline calculation using nonlinear constrained optimization of different ’mixer’ solutions for different failure scenarios of the motion actuators. If failure is detected, the nominal entry control mixer is exchanged. Real time adaptive control allocation is suggested instead for handling the failure of motion actuators for a high performance aircraft. To be fully able to use control allocation online to achieve full manoeuvrability, efficiency, and handle failure/saturation effectively, which is not possible by using

direct allocation methods or pseudo inverses, an optimization formulation for the control allocator has to be included. This has become feasible due to the increased computational capacity available in the control system. An evaluation of different optimization formulations can addressed with error minimization,

control minimization, and mixed minimization formulation for the control allocator are discussed. The mixed minimization formulation is solved by rewriting it to a linear program formulation and solving it with the simplex method. Profound work on real-time implementation in aircraft using standard methods of constrained control allocation with optimization formulation can be done. It uses active set method to solve optimized allocation problem. A reconfigurable motion control system for the space manoeuvring vehicle X-40A is proposed. It uses inverse dynamics for designing the control law for roll, pitch, and yaw motion. The three desired motion accelerations were allocated on the six available motion actuators by using constrained control with a mixed optimization formulation to minimize the allocation error and the use of control signals. Most of the real-time control allocation discussed above is what one could call one-step predictors.

They allocate the desired motions on the available motion actuators with consideration to the position and rate of change limits of actuators with what is attainable in one time step. However, when it is possible to include the dynamics of the motion actuators and predict several time steps ahead, a more sophisticated allocation can be performed, also called Model Predictive Control Allocation. This can be used for a re-entry vehicle's guidance and control system. The sequential quadratic programming formulation is rewritten into a linear complementary problem, which can guarantee convergence to an optimal solution within a finite number of iterations if some conditions of the problem statement are fulfilled. This would open up for real time implementation of MPC-CA when the computing capacity is increased within a vehicle's control system.

Marine vehicles, like aircraft, are also configured to be over-actuated in order to increase their maneuverability and performance. Typical motion actuators within marine applications are rudders and propeller or jet thrusters. Depending on whether the marine vehicle is operating on water or is a submersible, the desired motions of the vehicle can differ. However, similar to flight applications, marine vehicles are often equipped with more rudders and thrusters than needed to control the motion. One special issue when steering ships in water is that when the vehicle is travelling at low speed the rudders only generate steering force when thrust is used. This complicates the control allocation of the available motion actuators and cannot be solved with convex quadratic programming. An analytical solution to the non-convex rudder and propeller control allocation at low speed is proposed. Due to this non-convex control allocation problem, the allocation law is suggested to be pre-calculated offline by using multi-parametric nonlinear programming. This is done for marine surface vessels with rudders. However, the author also concludes by pointing out the weakness that the offline computed control allocation law does not easily admit online reconfiguration unless several cases are pre-computed. This means that all types of possible failures of the motion actuators have to be anticipated in advance. Singularity avoidance is suggested by using a locally convex quadratic reformulation of the allocation problem. A control-Lyapunov design approach is used to derive an optimizing nonlinear control allocation. This leads to asymptotic optimality and therefore the optimal solution is not needed to be found at each time step compared to a direct nonlinear programming approach. The singularities that occur for marine motion actuators clearly complicate the control allocation.

The main degrees of freedom controlled in a road vehicle, single unit, are the longitudinal, lateral, and yaw motions. These motions are generated with different types of motion actuators. In the early days of road vehicle design, these motion actuators were solely controlled by the driver. Today, more and more of the actuator functionality is software controlled. This, in combination with newly added functionalities, such as individually controlled mechanical brakes, and the increased number of actuators, makes it possible to achieve these three basic road vehicle motions with several different inputs Contrary to flight and marine applications, road vehicles have not traditionally been viewed as over-actuated systems. Instead, different subsystems and their functionalities have coexisted to give the desired performance. These functionalities are, for example Anti-lock Braking Systems (ABS), Electronic Stability Control (ESC), and Traction Control Systems (TCS). They have specific purposes without really viewing the complete vehicle performance.

This is elegantly can be illustrated using the ’ball in a bowl’ analogy. The ball represents the vehicle states and how they are kept in the stable region of operation, represented by the walls of the bowl, by the system controller. In the left illustration of Fig. 3 it is shown how today’s coexistent functionalities do not provide smooth walls on the bowl due to the fact that they only become active when the vehicle is almost unstable.

Additionally, the traditional functionalities are not coordinated sufficiently to give smooth walls as illustrated in the right Fig. 3.

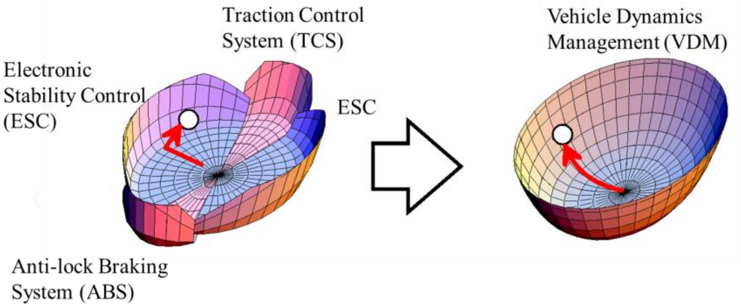


Fig. 3. *Illustration of traditional coexistent functionalities such as ABS, VSC, and TCS and their ability to keep the vehicle in the stable region (left) and how a highly integrated and coordinated control system such as Vehicle Dynamics Management (VDM) can keep the vehicle in the stable region (right), Illustration from [18].*

The concept of the smooth bowl is called Vehicle Dynamics Management (VDM). The following elements are used to achieve the VDM: hierarchical functional partitioning, feedforward force and moment control for the vehicle dynamics, and a nonlinear optimum distribution method which coordinates the operations of each motion actuator. The distribution of the global chassis forces and moment are allocated onto longitudinal and lateral wheel forces by using a optimization function which minimizes the error in global forces and minimizes the slip ratio of each wheel. Different types of wheel force distributors are designed for handling a road vehicle with independently steered, driven, and braked wheels.

A quadratic programming based control allocation method is used for coordinating the available motion actuators for an over-actuated road vehicle. The allocation method is similar to what has been used within flight and marine applications. It can be shown that different vehicle configurations with

mechanical braking and steering were successfully allocated to achieve the desired side slip and yaw rate of the vehicle. For the side slip and yaw rate a Linear Quadratic Regulator control law was used. However, the limits on the motion actuators included only tyre force and steering angle limits. Additionally, no detailed

consideration to actual actuator limits in position or rate of change for mechanical brakes or steering was performed. Yaw stabilization of road-vehicles is suggested by using control allocation. The allocation scheme is calculated offline by using multi parametric nonlinear programming. However, offline solutions will have difficulties to include all types of motion actuator failures that can occur to be safe and redundant. Sequential quadratic programming based control allocation is used as a traction force distributor. The optimization in the control allocation is based upon error in the desired and actual slip in the wheel motors. The desired slip is based on friction estimation. Inverse dynamics are used to calculate the global forces and moment of the vehicle and control allocation is used to distribute the task on to the available actuators. A least squares optimization formulation on tyre grip potential is used for the control allocator. The objective is to keep each wheel's tyre grip potential low and preferably equal.

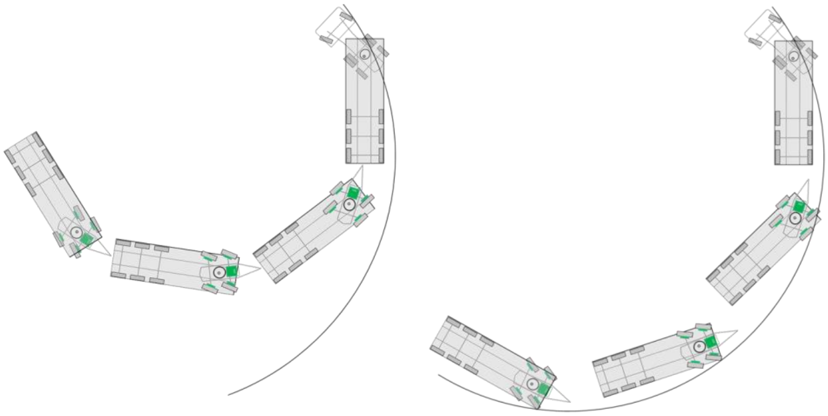
Untripped rollover prevention is proposed by using mechanical brakes. A linear control law is used for reducing the lateral acceleration. If it is higher than a certain threshold in lateral acceleration, then the control law applies the total braking force. The total braking force is then distributed onto the mechanical brakes by using weighted least squares control allocatio. This will prevent untripped rollover crashes but with the compromise that the vehicle must depart from the desired path to some extent. Fault detection and fault compensation was studied for over-actuated electric vehicles. It can be shown how a single unit vehicle's Vehicle motion mgmt could be offline and online re-configurable for different vehicle configurations. In addition, the control allocation was formulated such that it always prioritized vehicle stability before energy management.

It can be shown for a brake- and steer-by-wire how optimal control allocation is designed to coordinate motion actuators, four brakes and front axle steering. The control allocation approach will allow automated coordination to achieve a motion trajectory in the road plane. This will also have the benefit of that when actual abilities of actuators are used, actuator failure can then be compensated for directly by the control allocation. For the front axle steering, a speed dependent angle limitation was introduced, the limitation is calculated by using the vehicle's wheelbase and understeer gradient to assure that the steering angle is sufficient enough to achieve the lateral acceleration of the vehicle at any speed but not larger than that. A constant steering rate limit was used.

When it comes to commercial heavy vehicles control allocation have been used for designing stability control systems. A first real-time performance study was conducted for trucks. Vehicle combinations such as trucks might have up to 40-50 actuators that need to be coordinated, the results confirms the realtime performance for both the active-set and primal-dual interior point solvers. The single unit Vehicle motion mgmt. for single unit truck was further developed by using control allocation. The control allocation was for the first time combined with the driver's steering capability. The control allocation limits the aggressiveness of actuator coordination depending on how talented the truck driver is and gives steering force feedback to the driver about the trucks performance envelope.

However, very few have derived Control allocation for articulated vehicles. It was derived for an A-double combination with 22 wheels, 4 bodies (tractor,semitrailer,dolly,semitrailer) with individual wheel propulsion and braking and each axle had steering capability. The control effectiveness matrix $\boldsymbol{B}(\psi_{1..3}, \varphi_{1..22},)$ was steered axle angle and articulation angle dependent. The $\boldsymbol{B}$-matrix was generated by using Lagrange formulation of the vehicle combination system.

In the future, the vehicle motion mgmt in commercial heavy vehicles needs to be automatically re-configured when different units are auto coupled or de-coupled, see Fig. 4 for illustration. The (a) illustration shows how a A-quadruple is connected by three smart dolly units with own propulsion and steering, with a single control effectiveness matrix ***B*** used for coordinating all actuators within the vehicle combination. When connected as long vehicle combinations the smart dolly units will be slave units to first master unit, the tractor. When automatically separated it each tractor and dolly unit becomes their own master unit and here now four individual control effectiveness matrices ***B*** needs to automatically be derived and re-configured in the motion management of each new master.



(a) (b)

Fig. 4. *Illustration of A-quadruple (a) and when it is separated into (b) four separated tractor/smart dolly semitrailer combinations.*

The mathematical formulation of control allocation for coordination when the system has more input signals $u \in R^m$ than virtual signals controlled $v \in R^k$, $k<m$. The idea is to map the virtual control input onto u, $v \longmapsto u$.

$$u = \arg\min \left\| W_u \left(u_{des} - u \right) \right\|_p^p + \gamma \left\| W_v \left(Bu - v \right) \right\|_p^p \qquad \text{(eq. 1.)}$$

$$\text{subject to } \underline{u} \le u \le \bar{u}$$

Where ***B***(ψ1..3, φ1..22,) is the control effectiveness matrix. The project aims to address to handle the re-configuration automatically. Each vehicle unit needs to provide motion capabilities from equipped actuators and their efficiency to generate global forces yaw moments and articulation angle moments. The Vehicle motion mgmt. is a key enabler for when automation is introduced in large scale in Volvos different products (trucks, buses, construction equipment) and for electro-mobility with distributed propulsion on different vehicle units in the combination vehicle. Fig. 6 illustrates Vehicle Motion Functionality Reference Architecture which has been developed within Volvo GTT since 2010. A public description of the reference architecture can be found in [34]. The Figure shows how the motion planning of the vehicle separated into different prediction horizons Transport mission mgmt., Route Mgmt, Route situation mgmt., Traffic Situation mgmt., Vehicle motion and power Mgmt, and finally motion support device mgmt. The key interface to automate Volvo's product line is between Traffic Situation mgmt. and Vehicle motion and Power mgmt. Traffic domain only wants to send an acceleration and steer request that is automatically distributed by Vehicle motion domain between the available actuators. Each domain propagates its status and capability to the upper domain.

This project will focus on the Vehicle Motion mgmt. and how the actuator coordination can be automatically be reconfigured when combination is automatically transformed. Follow ISO 26262 safety standard and propose how to make robust and fault tolerant embedded control system.

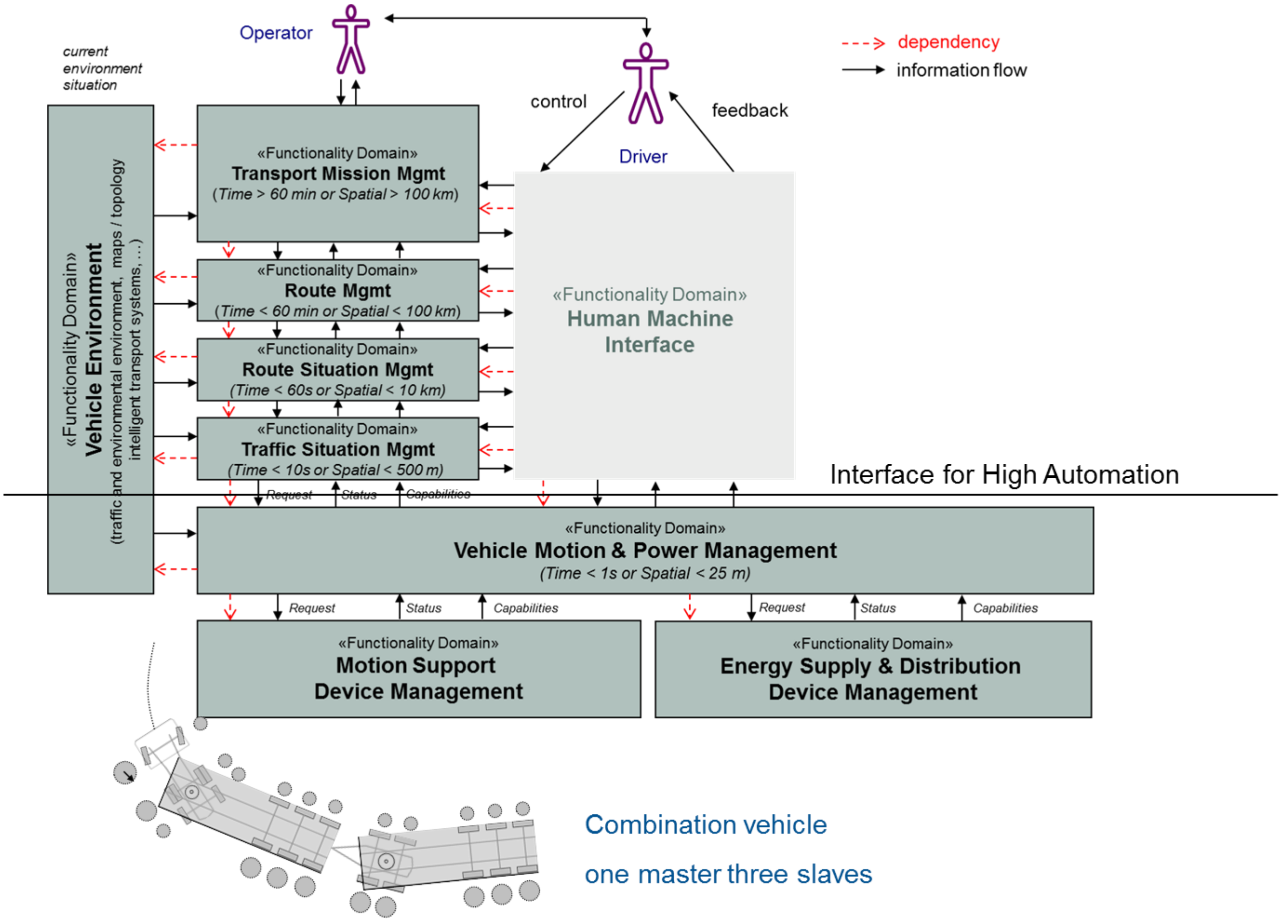


Fig. 6. *Vehicle Motion Functionality Reference Architecture (VeMFRA) and its functionality domains to meet new features and vehicle configurations, from [33].*

4. Purpose, research questions and method

- How should a reconfigurable Vehicle Motion Function Architecture look?
- How can Vehicle Motion Control be generalized/parameterized so that it can handle various set of towed units?
- How can future standardized interfaces for communication and couplings look like for multiple unit commercial vehicles.

5. Objective

The project application addresses the topic of Modular function architecture within the FFI strategic programme Complex control. The project aimed at

1. Refining and validating the principles for the layered vehicle control function architecture (VeMFRA) currently being developed at VGTT.
2. Extending the control function architecture with principles and guidelines for handling control of complex vehicle configurations
3. Extending the control function architecture with principles and guidelines for advanced driveline control of hybrids or fully electric vehicles.
4. Developing, applying, integrating and demonstrating the VemFRA principles in a real truck.

Objective number 1 resulted in a more maintainable, reusable and robust function and software architectures due to its reduced complexity. By this it contributes not only to the objectives of the Complex control programme but also to Electronics, Software and Communication (EMK).

The project also connected to Traffic safety and Automated Vehicles (TSAF) FFI programme as it in practice is a critical enabler for automation of road transport systems. Without a good and well-structured control function architecture, it is extremely impractical and very expensive and error-prone to develop such complex control systems that is needed by autonomous vehicles. The project focuses on the integrated vehicle and what kind of vehicle motion management is needed when road transports includes distributed electric propulsion and automation in highway traffic.

Finally, this project also connected to Efficient and Connected Transport Systems (EUTS) FFI programme about integrated transport systems. The proposed control function architecture paves the way for seamless connectivity between platooning and long combination vehicles (high capacity vehicles). This is possible due to the proposed auto reconfiguration needed in the embedded motion control software.

6. Results and deliverables

WP-1: Automatic reconfiguration software for actuator coordination

- **Automatically reconfigure vehicle to switch between master or slave formulation.**

A dynamic reconfiguration of the Dolly to switch between master and slave mode was designed (cf. Fig 6.1 and 6.2).

In Master mode, the Dolly is able to control its actuator based on the current capabilities of the whole system and the assigned task, e.g., following a pre-defined path. The design follows the principle of the VEMFRA (VEhicle Motion Functional Reference Architecture) (cf. Section 3) which centralizes the information and decision in the VMM layer (Vehicle Motion Management). This allows to performs several driving maneuvers, e.g., forward, reverse, parking, etc. Moreover, the Master mode includes the auto coupling and decoupling of the fifth wheel of the Dolly to a semi-trailer.

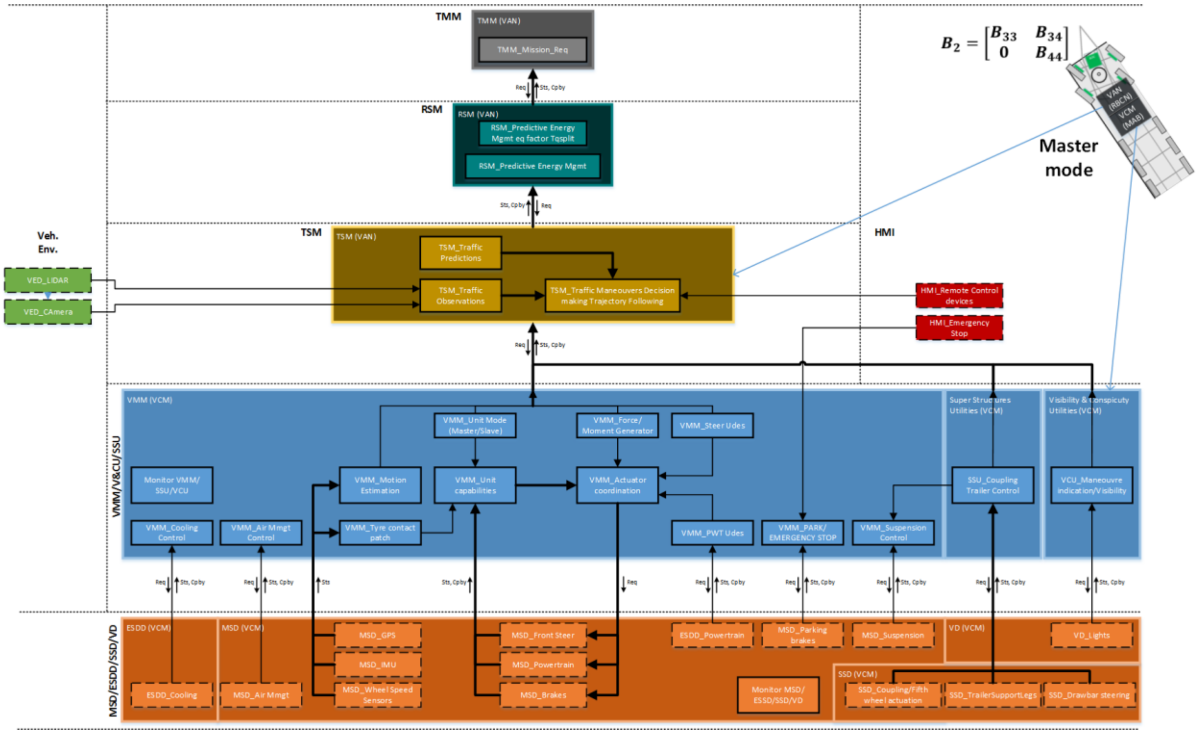


Figure 6.1. Functional diagram of Dolly in master mode

In Slave mode, the dolly is coordinated by the main unit in the tractor. The tractor send the request to its actuators and Dolly's one based on the information of the whole A-double combination. The coordination of propulsion, steering and braking can improve the maneuverability and stability of the articulated vehicle. Furthermore, the use of electric rear axle in the Dolly contributes to propulsion and power regeneration towards a reduction of the fuel consumption.

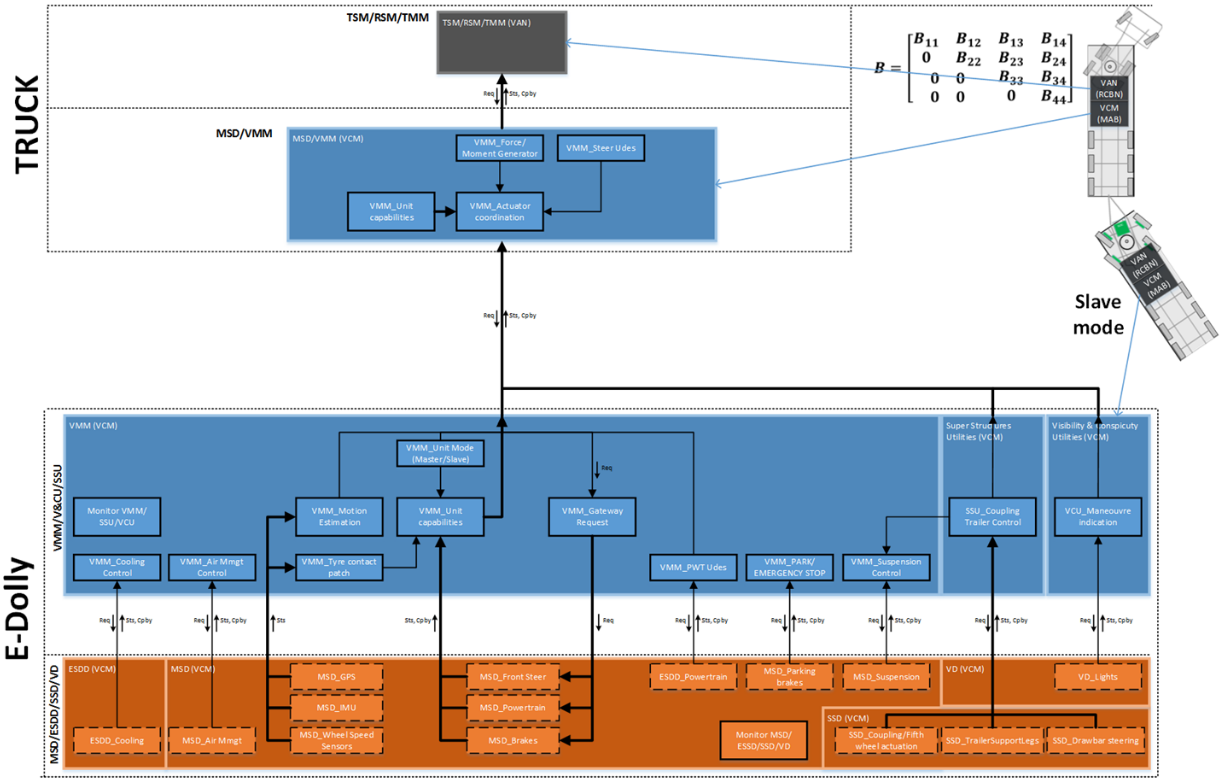
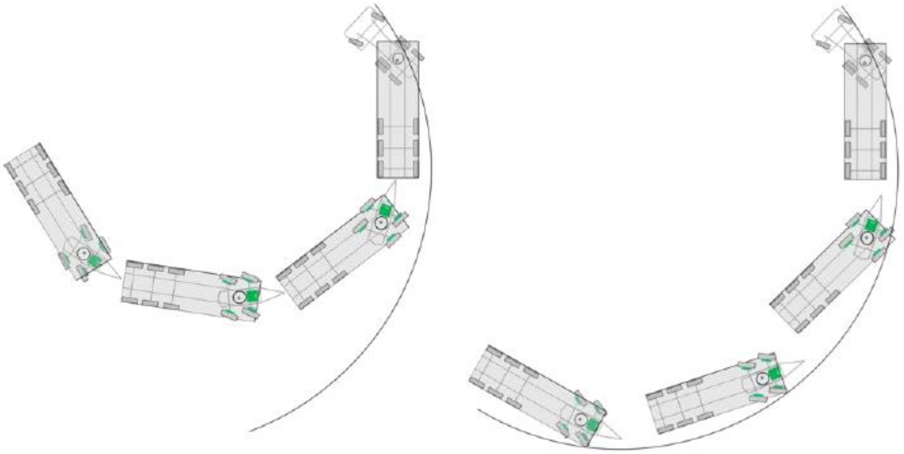


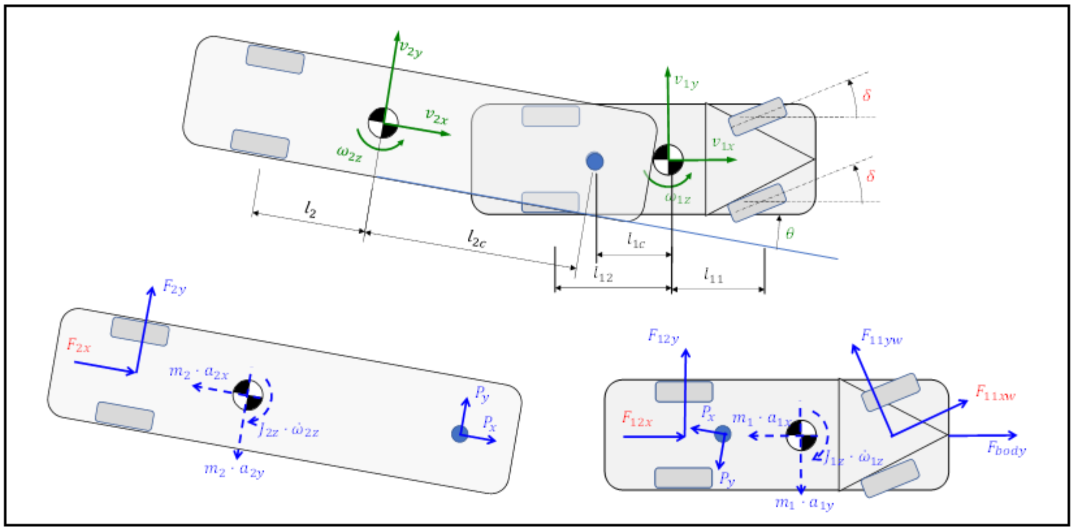
Figure 6.2. Functional diagram of Dolly in master mode

- **Update control allocation parameters and control effectiveness matrix.**

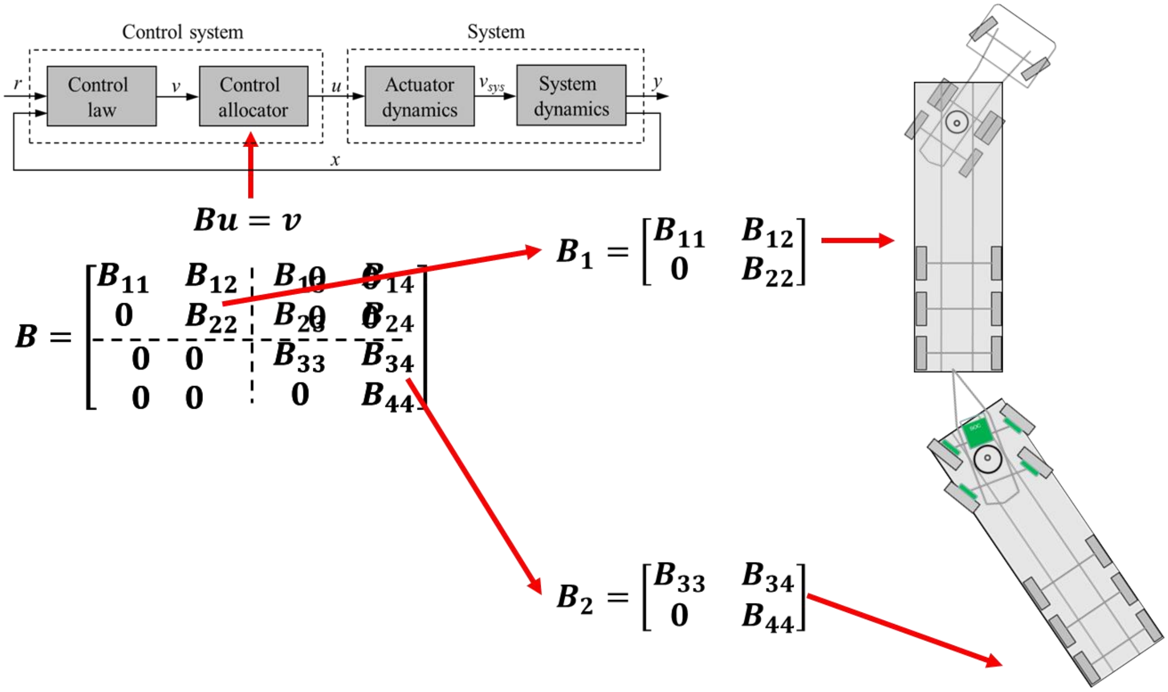
When the tractor switches between master of the A-double and master of only the first semitrailer, and the dolly goes from slave to master of the 2nd semitrailer, the B matrices need to be shifted. The B-matrices for the smaller combination vehicles are sub-matrices of the larger ones. In principle, one could assemble/de-assemble the matrices to handle an even longer vehicle to split up as shown in the following figure:



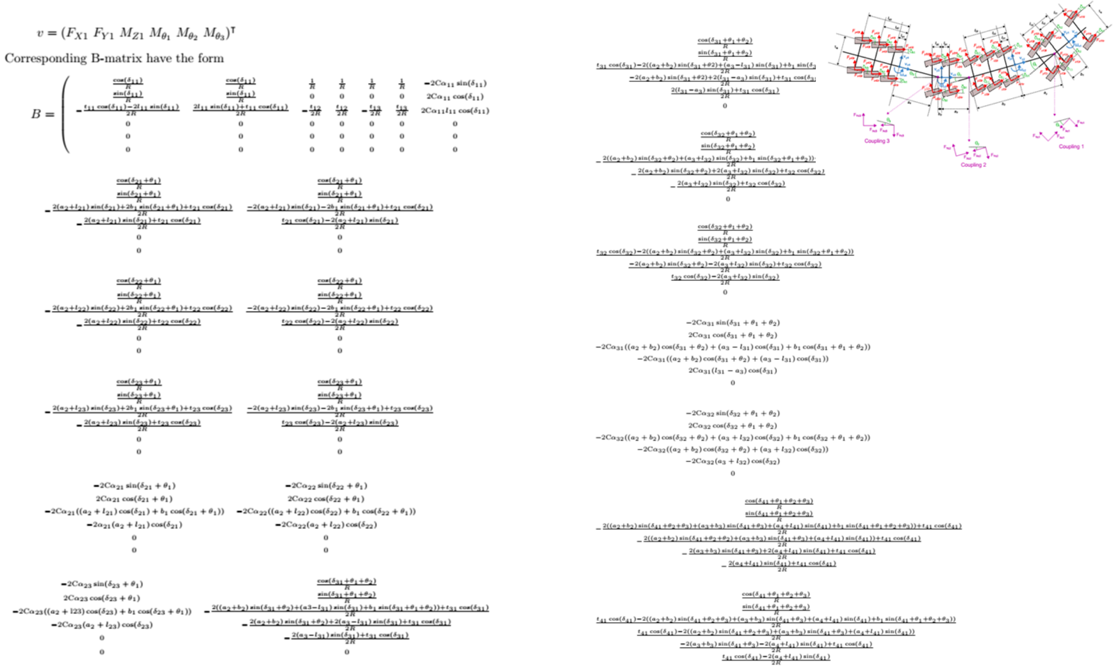
A structured variable naming is essential. For simplest possible combination vehicle, tractor + semitrailer, next figure shows the model with variables.



The concept for Re-Configuration is shown in the following figure.



The complexity of the matrices is visualised in next figure. Use of symbolic tools such as Mathematica is almost a must to be able to guarantee correct expression for each matrix element.



$$v = (F_{X1}\ F_{Y1}\ M_{Z1}\ M_{\theta_1}\ M_{\theta_2}\ M_{\theta_3})^\intercal$$

Corresponding B-matrix have the form

$$B = \left(\begin{matrix} \frac{\cos(\delta_{11})}{R} & \frac{\cos(\delta_{11})}{R} & \frac{1}{R} & \frac{1}{R} & \frac{1}{R} & \frac{1}{R} & -2C\alpha_{11}\sin(\delta_{11}) \\ \frac{\sin(\delta_{11})}{R} & \frac{\sin(\delta_{11})}{R} & 0 & 0 & 0 & 0 & 2C\alpha_{11}\cos(\delta_{11}) \\ -\frac{t_{11}\cos(\delta_{11})-2l_{11}\sin(\delta_{11})}{2R} & \frac{2l_{11}\sin(\delta_{11})+t_{11}\cos(\delta_{11})}{2R} & -\frac{t_{12}}{2R} & \frac{t_{12}}{2R} & -\frac{t_{13}}{2R} & \frac{t_{13}}{2R} & 2C\alpha_{11}l_{11}\cos(\delta_{11}) \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{matrix} \right.$$

$$\begin{matrix} \frac{\cos(\delta_{21}+\theta_1)}{R} & \frac{\cos(\delta_{21}+\theta_1)}{R} \\ \frac{\sin(\delta_{21}+\theta_1)}{R} & \frac{\sin(\delta_{21}+\theta_1)}{R} \\ -\frac{2(a_2+l_{21})\sin(\delta_{21})+2b_1\sin(\delta_{21}+\theta_1)+t_{21}\cos(\delta_{21})}{2R} & \frac{-2(a_2+l_{21})\sin(\delta_{21})-2b_1\sin(\delta_{21}+\theta_1)+t_{21}\cos(\delta_{21})}{2R} \\ -\frac{2(a_2+l_{21})\sin(\delta_{21})+t_{21}\cos(\delta_{21})}{2R} & \frac{t_{21}\cos(\delta_{21})-2(a_2+l_{21})\sin(\delta_{21})}{2R} \\ 0 & 0 \\ 0 & 0 \end{matrix}$$

$$\begin{matrix} \frac{\cos(\delta_{22}+\theta_1)}{R} & \frac{\cos(\delta_{22}+\theta_1)}{R} \\ \frac{\sin(\delta_{22}+\theta_1)}{R} & \frac{\sin(\delta_{22}+\theta_1)}{R} \\ -\frac{2(a_2+l_{22})\sin(\delta_{22})+2b_1\sin(\delta_{22}+\theta_1)+t_{22}\cos(\delta_{22})}{2R} & \frac{-2(a_2+l_{22})\sin(\delta_{22})-2b_1\sin(\delta_{22}+\theta_1)+t_{22}\cos(\delta_{22})}{2R} \\ -\frac{2(a_2+l_{22})\sin(\delta_{22})+t_{22}\cos(\delta_{22})}{2R} & \frac{t_{22}\cos(\delta_{22})-2(a_2+l_{22})\sin(\delta_{22})}{2R} \\ 0 & 0 \\ 0 & 0 \end{matrix}$$

$$\begin{matrix} \frac{\cos(\delta_{23}+\theta_1)}{R} & \frac{\cos(\delta_{23}+\theta_1)}{R} \\ \frac{\sin(\delta_{23}+\theta_1)}{R} & \frac{\sin(\delta_{23}+\theta_1)}{R} \\ -\frac{2(a_2+l_{23})\sin(\delta_{23})+2b_1\sin(\delta_{23}+\theta_1)+t_{23}\cos(\delta_{23})}{2R} & \frac{-2(a_2+l_{23})\sin(\delta_{23})-2b_1\sin(\delta_{23}+\theta_1)+t_{23}\cos(\delta_{23})}{2R} \\ -\frac{2(a_2+l_{23})\sin(\delta_{23})+t_{23}\cos(\delta_{23})}{2R} & \frac{t_{23}\cos(\delta_{23})-2(a_2+l_{23})\sin(\delta_{23})}{2R} \\ 0 & 0 \\ 0 & 0 \end{matrix}$$

$$\begin{matrix} -2C\alpha_{21}\sin(\delta_{21}+\theta_1) & -2C\alpha_{22}\sin(\delta_{22}+\theta_1) \\ 2C\alpha_{21}\cos(\delta_{21}+\theta_1) & 2C\alpha_{22}\cos(\delta_{22}+\theta_1) \\ -2C\alpha_{21}((a_2+l_{21})\cos(\delta_{21})+b_1\cos(\delta_{21}+\theta_1)) & -2C\alpha_{22}((a_2+l_{22})\cos(\delta_{22})+b_1\cos(\delta_{22}+\theta_1)) \\ -2\alpha_{21}(a_2+l_{21})\cos(\delta_{21}) & -2C\alpha_{22}(a_2+l_{22})\cos(\delta_{22}) \\ 0 & 0 \\ 0 & 0 \end{matrix}$$

$$\begin{matrix} -2C\alpha_{23}\sin(\delta_{23}+\theta_1) & \frac{\cos(\delta_{31}+\theta_1+\theta_2)}{R} \\ 2C\alpha_{23}\cos(\delta_{23}+\theta_1) & \frac{\sin(\delta_{31}+\theta_1+\theta_2)}{R} \\ -2C\alpha_{23}((a_2+123)\cos(\delta_{23})+b_1\cos(\delta_{23}+\theta_1)) & -\frac{2((a_2+b_2)\sin(\delta_{31}+\theta_2)+(a3-l_{31})\sin(\delta_{31})+b_1\sin(\delta_{31}+\theta_1+\theta_2))+t_{31}\cos(\delta_{31})}{2R} \\ -2C\alpha_{23}(a_2+l_{23})\cos(\delta_{23}) & -\frac{2(a_2+b_2)\sin(\delta_{31}+\theta_2)+2(a_3-l_{31})\sin(\delta_{31})+t_{31}\cos(\delta_{31})}{2R} \\ 0 & -\frac{2(a_3-l_{31})\sin(\delta_{31})+t_{31}\cos(\delta_{31})}{2R} \\ 0 & 0 \end{matrix}$$

$$\begin{matrix} \frac{\cos(\delta_{31}+\theta_1+\theta_2)}{R} \\ \frac{\sin(\delta_{31}+\theta_1+\theta_2)}{R} \\ \frac{t_{31}\cos(\delta_{31})-2((a_2+b_2)\sin(\delta_{31}+\theta 2)+(a_3-l_{31})\sin(\delta_{31})+b_1\sin(\delta_3}{2R} \\ \frac{-2(a_2+b_2)\sin(\delta_{31}+\theta 2)+2(l_{31}-a_3)\sin(\delta_{31})+t_{31}\cos(\delta_3}{2R} \\ \frac{2(l_{31}-a_3)\sin(\delta_{31})+t_{31}\cos(\delta_{31})}{2R} \\ 0 \end{matrix}$$

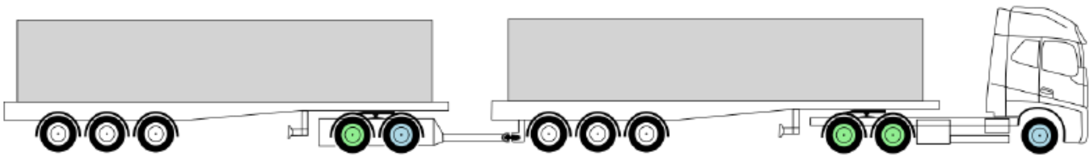
$$\begin{matrix} \frac{\cos(\delta_{32}+\theta_1+\theta_2)}{R} & \frac{\cos(\delta_{32}+\theta_1+\theta_2)}{R} \\ \frac{\sin(\delta_{32}+\theta_1+\theta_2)}{R} & \frac{\sin(\delta_{32}+\theta_1+\theta_2)}{R} \\ -\frac{2((a_2+b_2)\sin(\delta_{32}+\theta_2)+(a_3+l_{32})\sin(\delta_{32})+b_1\sin(\delta_{32}+\theta_1+\theta_2))}{2R} & \frac{t_{32}\cos(\delta_{32})-2((a_2+b_2)\sin(\delta_{32}+\theta_2)+(a_3+l_{32})\sin(\delta_{32})+b_1\sin(\delta_{32}+\theta_1+\theta_2))}{2R} \\ -\frac{2(a_2+b_2)\sin(\delta_{32}+\theta_2)+2(a_3+l_{32})\sin(\delta_{32})+t_{32}\cos(\delta_{32})}{2R} & \frac{-2(a_2+b_2)\sin(\delta_{32}+\theta_2)-2(a_3+l_{32})\sin(\delta_{32})+t_{32}\cos(\delta_{32})}{2R} \\ -\frac{2(a_3+l_{32})\sin(\delta_{32})+t_{32}\cos(\delta_{32})}{2R} & \frac{t_{32}\cos(\delta_{32})-2(a_3+l_{32})\sin(\delta_{32})}{2R} \\ 0 & 0 \end{matrix}$$

$$\begin{matrix} -2C\alpha_{31}\sin(\delta_{31}+\theta_1+\theta_2) \\ 2C\alpha_{31}\cos(\delta_{31}+\theta_1+\theta_2) \\ -2C\alpha_{31}((a_2+b_2)\cos(\delta_{31}+\theta_2)+(a_3-l_{31})\cos(\delta_{31})+b_1\cos(\delta_{31}+\theta_1+\theta_2)) \\ -2C\alpha_{31}((a_2+b_2)\cos(\delta_{31}+\theta_2)+(a_3-l_{31})\cos(\delta_{31})) \\ 2C\alpha_{31}(l_{31}-a_3)\cos(\delta_{31}) \\ 0 \end{matrix}$$

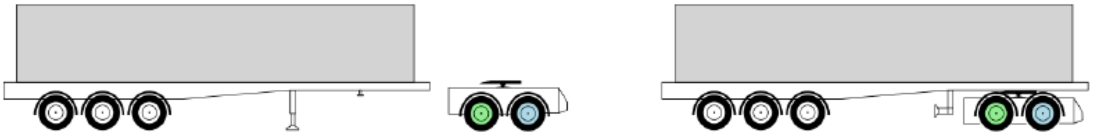
$$\begin{matrix} -2C\alpha_{32}\sin(\delta_{32}+\theta_1+\theta_2) \\ 2C\alpha_{32}\cos(\delta_{32}+\theta_1+\theta_2) \\ -2C\alpha_{32}((a_2+b_2)\cos(\delta_{32}+\theta_2)+(a_3+l_{32})\cos(\delta_{32})+b_1\cos(\delta_{32}+\theta_1+\theta_2)) \\ -2C\alpha_{32}((a_2+b_2)\cos(\delta_{32}+\theta_2)+(a_3+l_{32})\cos(\delta_{32})) \\ -2C\alpha_{32}(a_3+l_{32})\cos(\delta_{32}) \\ 0 \end{matrix}$$

$$\begin{matrix} \frac{\cos(\delta_{41}+\theta_1+\theta_2+\theta_3)}{R} \\ \frac{\sin(\delta_{41}+\theta_1+\theta_2+\theta_3)}{R} \\ -\frac{2((a_2+b_2)\sin(\delta_{41}+\theta_2+\theta_3)+(a_3+b_3)\sin(\delta_{41}+\theta_3)+(a_4+l_{41})\sin(\delta_{41})+b_1\sin(\delta_{41}+\theta_1+\theta_2+\theta_3))+t_{41}\cos(\delta_{41})}{2R} \\ -\frac{2((a_2+b_2)\sin(\delta_{41}+\theta_2+\theta_2)+(a_3+b_3)\sin(\delta_{41}+\theta_3)+(a_4+l_{41})\sin(\delta_{41}))+t_{41}\cos(\delta_{41})}{2R} \\ -\frac{2(a_3+b_3)\sin(\delta_{41}+\theta_3)+2(a_4+l_{41})\sin(\delta_{41})+t_{41}\cos(\delta_{41})}{2R} \\ -\frac{2(a_4+l_{41})\sin(\delta_{41})+t_{41}\cos(\delta_{41})}{2R} \end{matrix}$$

$$\begin{matrix} \frac{\cos(\delta_{41}+\theta_1+\theta_2+\theta_3)}{R} \\ \frac{\sin(\delta_{41}+\theta_1+\theta_2+\theta_3)}{R} \\ \frac{t_{41}\cos(\delta_{41})-2((a_2+b_2)\sin(\delta_{41}+\theta_2+\theta_3)+(a_3+b_3)\sin(\delta_{41}+\theta_3)+(a_4+l_{41})\sin(\delta_{41})+b_1\sin(\delta_{41}+\theta_1+\theta_2+\theta_3))}{2R} \\ \frac{t_{41}\cos(\delta_{41})-2((a_2+b_2)\sin(\delta_{41}+\theta_2+\theta_3)+(a_3+b_3)\sin(\delta_{41}+\theta_3)+(a_4+l_{41})\sin(\delta_{41}))}{2R} \\ \frac{-2(a_3+b_3)\sin(\delta_{41}+\theta_3)-2(a_4+l_{41})\sin(\delta_{41})+t_{41}\cos(\delta_{41})}{2R} \\ \frac{t_{41}\cos(\delta_{41})-2(a_4+l_{41})\sin(\delta_{41})}{2R} \end{matrix}$$



(a) A-double combination vehicle with e-dolly.



About B-matrix

There are still different alternative ways to build up the B-matrix: selecting acceleration or tyre forces as virtual control vector, and also involving coupling forces. Hence, there is more research needed to find out which concept is best for vehicle motion and energy control as well as standardisation of signal- and parameter-interface between units.

There are methods to ”solve” $\boldsymbol{v} = \boldsymbol{B} \cdot \boldsymbol{u}$ as an optimization problem. A unique solution is seldom found since B matrix most of the times is flat, i.e. has more columns than rows.

The variables in $\boldsymbol{u}$ is often rather obvious:

$$\boldsymbol{u} = \textbf{"actuatables"} = [T_{Prop1} \quad T_{Prop2} \quad T_{Brk1} \quad \cdots \quad T_{BrkN} \quad \delta_{11} \quad \delta_{31}]$$

But which variables to request, the virtual control variables $\boldsymbol{v}$**,** are far from obvious: Main alternatives are:

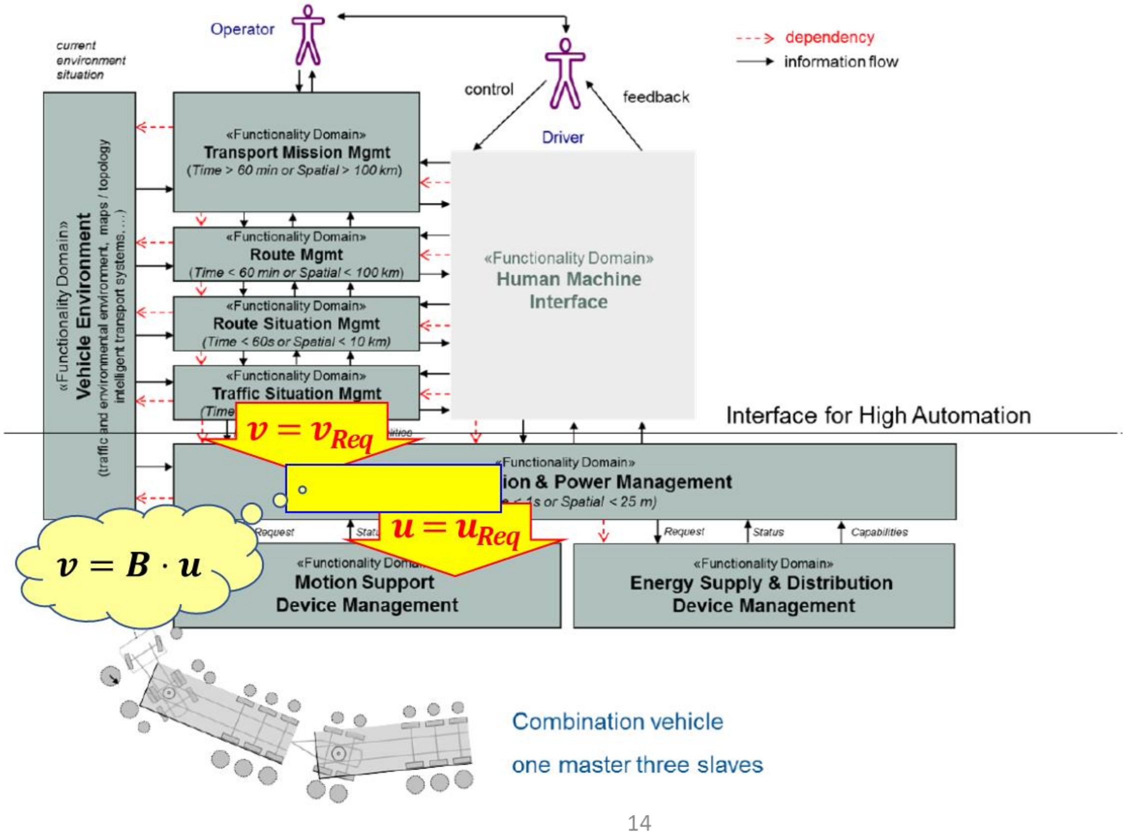
$$\boldsymbol{v} = \boldsymbol{motion} = [\dot{v}_{1x} \quad \dot{\kappa} \quad \dot{\theta}]$$

or

$$\boldsymbol{v} = \boldsymbol{forces} = [F_{1x} \quad M_{1z} \quad M_{2z}]$$

But the project has also shown that it works to use coupling forces as part of the v vector:

$$\boldsymbol{v} = \boldsymbol{forces} = [F_{1x} \quad M_{1z} \quad P_y]$$



- **Send and receive configuration parameters between vehicle units**

A communication between vehicles is essential to the status of the system and make a reliable coordination of the combination. A CAN bus (Controller Area Network) through the all units is implemented using the standard trailer connector. The Volvo CAN (250 kbps) allows to send the status of the main systems of Dolly to the Tractor and vice versa.

WP-2: Downloading of SW and design configuration

- **Downloading SW and design configuration communication between vehicle units to achieve plug and play.**

Each vehicle has its own main module (VCM) where the information is centralized, and the control is executed (cf. Fig 6.3 and 6.4). Each VCM has connection to Volvo CAN for exchanging information to the other VCM. The downloading of the Sw is made by ethernet connection.

The vehicle used as a tractor is a standard Volvo truck. Some modifications were required to get the centralized system in control for:

- External request for steering

- External accelerator and brake pedal requests
- External request for forward and reverse
- External parking brake request
- External request for suspension
- External request for auto coupling and decoupling

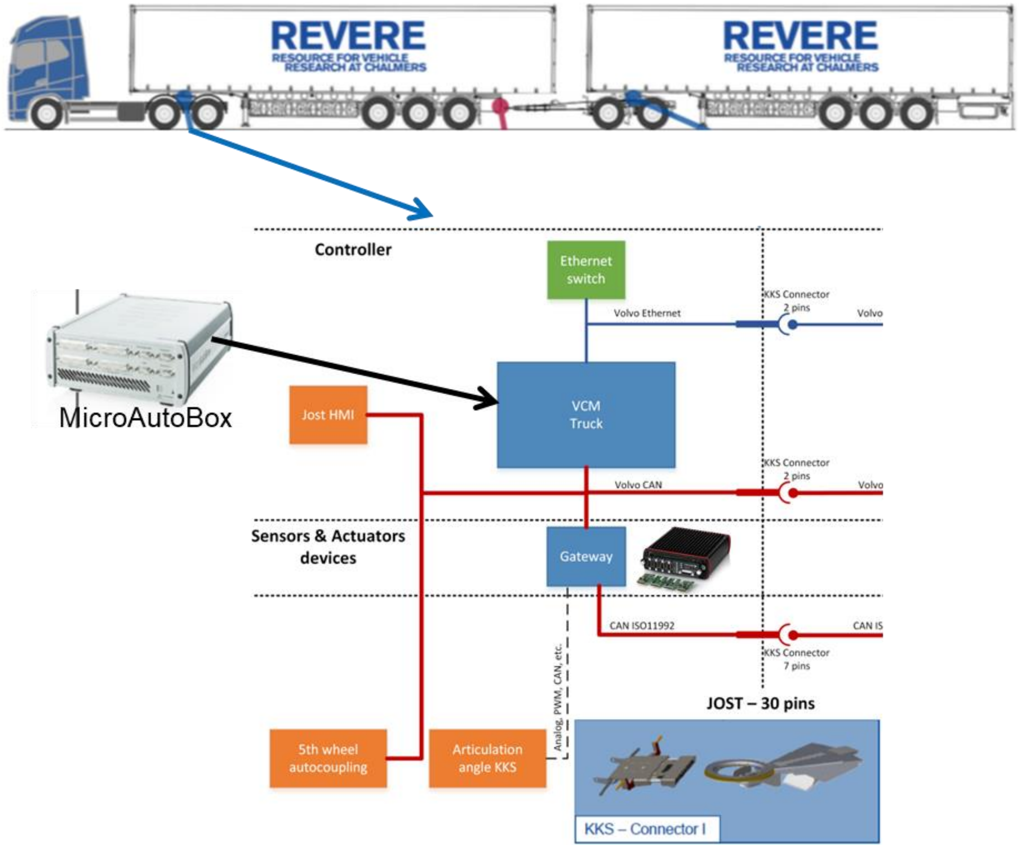


Figure 6.3. Reference electrical architecture for tractor

The Dolly requires additional considerations to perform the master or slave mode. The swap between modes is made by detecting when the tractor and semi-trailer are connected through the drawbar of the Dolly. The tractor will send the confirmation to the Dolly via Volvo CAN. In this sense, the centralized system of the Dolly controls:

- Individual brake per wheel
- Steering system based on Volvo rear axle steering
- Suspension and lights
- Parking brake

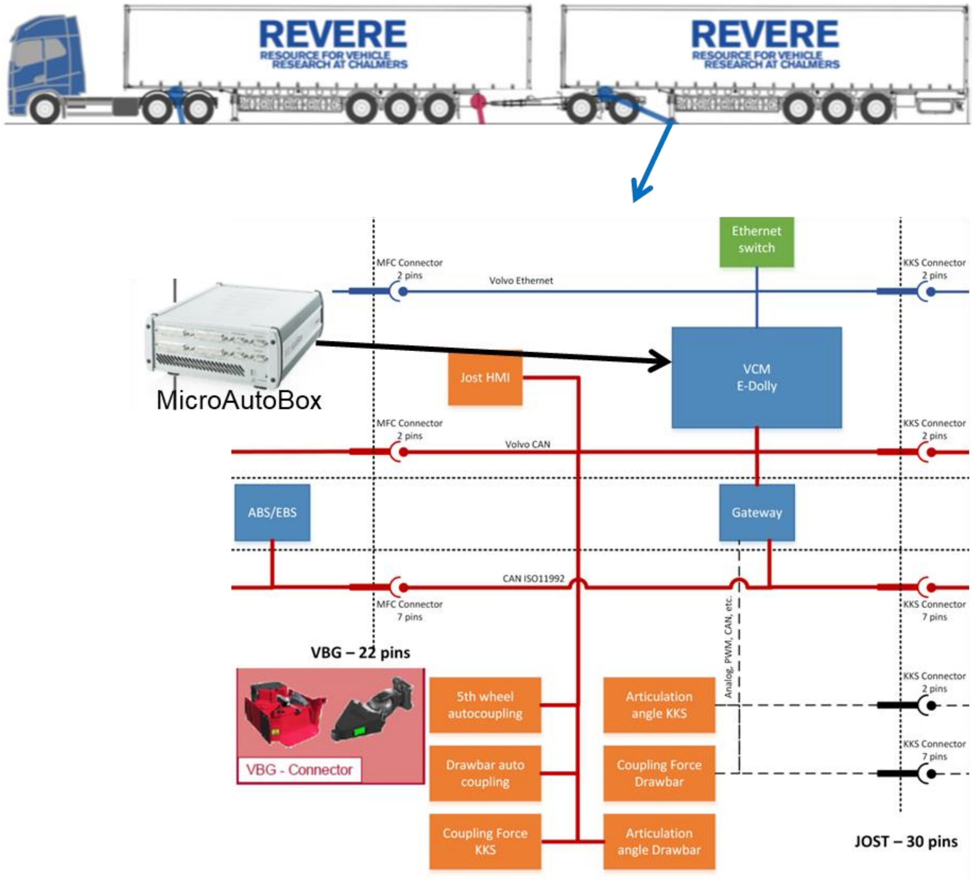


Figure 6.4. Reference electrical architecture for Dolly

WP-3: Virtual Testing platform

- **Testing of splitting vehicle combination during different test**

The simulation environment was built in Matlab/Simulink based on Volvo truck model library. The models cover all cases, the slave mode (full A-double combination, Fig 6.5) and master mode (Dolly, Fig 6.6). The models are used to evaluate the control algorithm for coordination of the actuators in all modes.

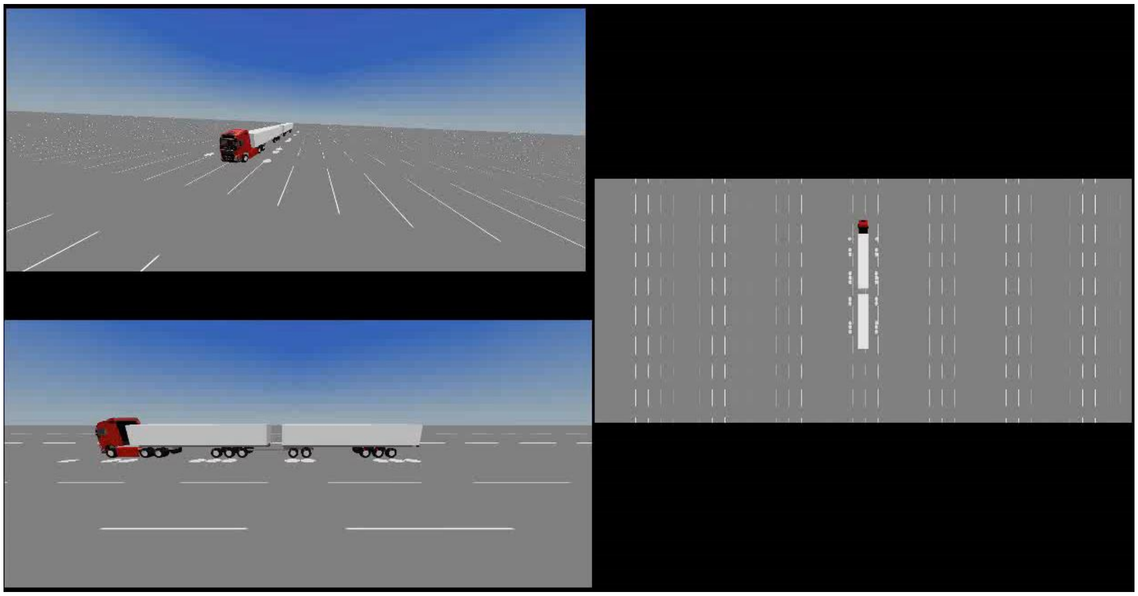


Figure 6.5. Simulation of Dolly as slave (A-double) in Matlab/Simulink

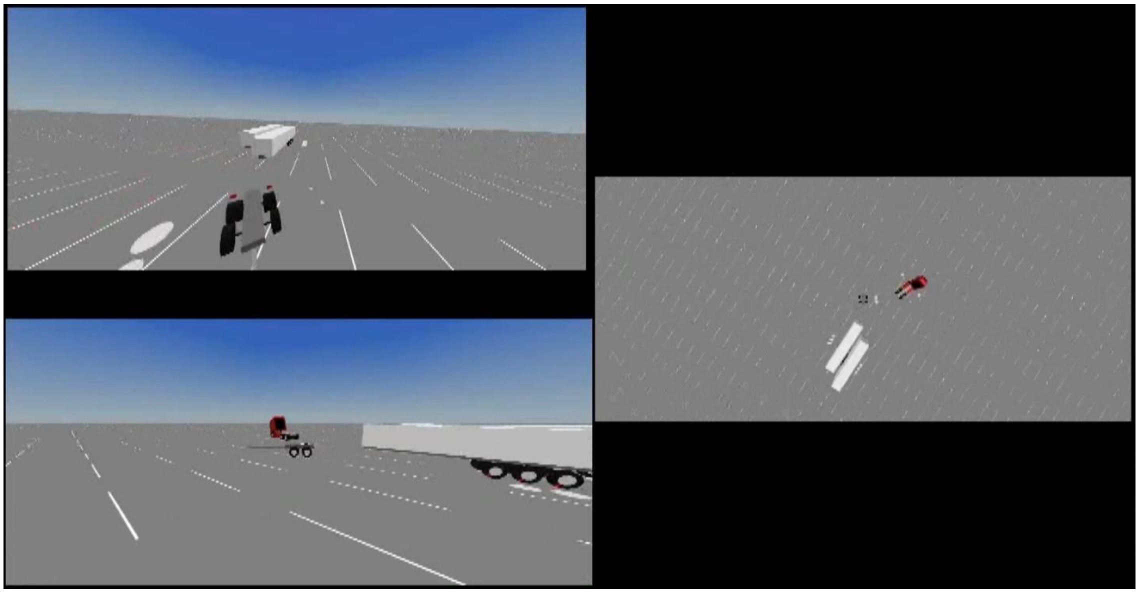


Figure 6.Simulation of Dolly as master in Matlab/Simulink

WP-4: Real Testing platform

- **Testing of splitting vehicle combination during different test cases**

The Revere tractor and the Volvo eDolly (cf. Fig. 7) were used for testing of:

- The centralized architecture of each vehicle
- Auto coupling and decoupling to the trailers
- The communication between vehicles
- The master/slave mode of the dolly
- The actuator coordination of all vehicles.

Several results were shown on the presentation and demo day on 2019-11-13. Some information and picture are filtered in order to keep Volvo confidentiality. The eDolly will be officially presented in the coming weeks.

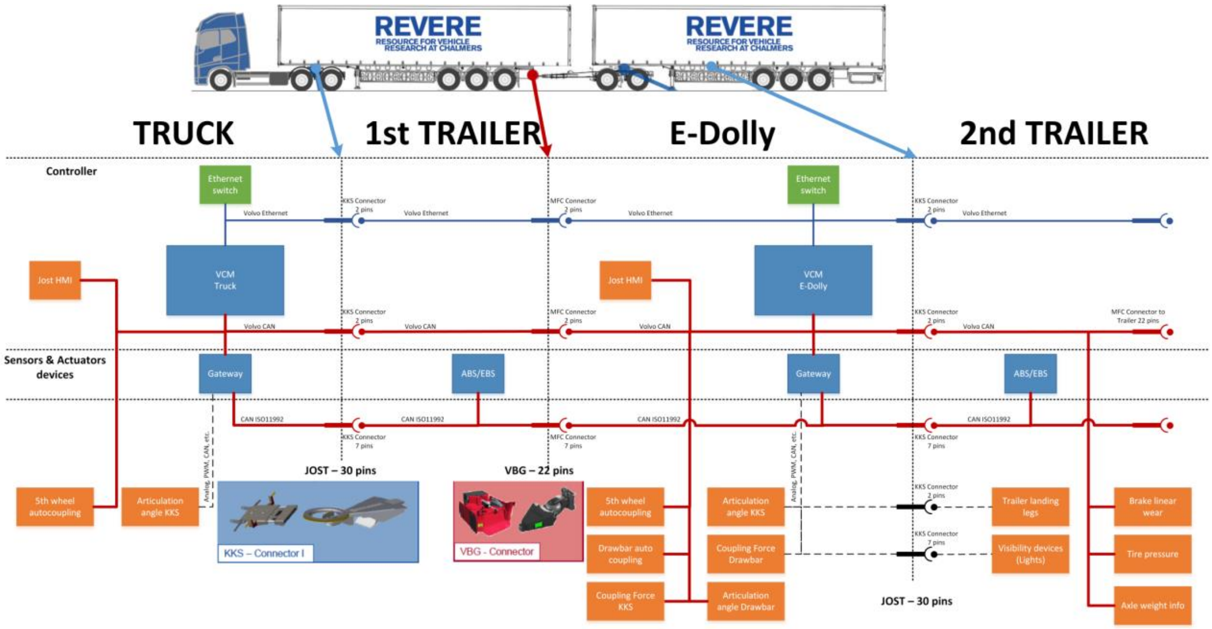


Figure 6.7. Architecture of the tractor and Dolly

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	x	
Be passed on to other advanced technological development projects	x	
Be passed on to product development projects		Needs more research
Introduced on the market		Needs more research and development
Used in investigations / regulatory / licensing / political decisions	x	An update of the existing trailer connection signal interfaces is needed.

7.2 Publications

[1] Bengt Jacobson et al, Section *4.5.2.2 Articulated Vehicles*, in *Vehicle Dynamics Compendium*, https://research.chalmers.se/publication/513850, 2019.

[2] Maliheh Sadeghi Kati et al, *Distributed Control Allocation for Multi-trailer Commercial Heavy Vehicles*, In preparation 2020

[3] Leo Laine et al, *AutoTransform and auto-reconfigure vehicle unit and vehicle combination for the mission. E-dolly can transform itself to VERA or e-dolly*, 23 Jan 2020, Filed Patent P2020-0045, 2020

[4] Leo Laine et al, *AutoTransform and auto-reconfigure vehicle unit and vehicle combination for the mission. E-dolly can transform itself to VERA or e-dolly*, 21 Jan 2020, Filed Patent P2020-0036, 2020

[5] Leo Laine et al, *E-DOLLY evasive manoeuvre support. E-dolly can transform itself to VERA or e-dolly*, 20 Jan 2020, Filed Patent P2020-0030, 2020

8. Conclusions and future research

The project have shown how the “B-matrix” (or influence/efficency matrix) for control allocation can be assembled for A-double. The matrix consist of sub-matrices which can be directly re-used for Tractor+Semi and Dolly+Semi. Hence, the transition between the slave and master modes is facilitated.

There are still different alternative ways to build up the B-matrix: selecting acceleration or tyre forces as virtual control vector, and also involving coupling forces. Hence, there is more research needed to find out which concept is best for vehicle motion and energy control as well as standardisation of signal- and parameter-interface between units.

9. Participating parties and contact persons

Participants are from Volvo GTT and Chalmers.

Contact persons:

- Leo Laine, Volvo GTT and Chalmers
- Bengt Jacobson, Chalmers, Vehicle Dynamics
- Jonas Fredriksson and Maliheh Sadeghi Kati, Chalmers, Mechatronics