A novel mechatronic running gear: concept, simulation and scaled roller rig testing

Bernhard KURZECK and Luciano VALENTE

Institute of Robotics and Mechatronics
DLR (German Aerospace Center)
Oberpfaffenhofen, 82234 Wessling, Germany

ABSTRACT

Common running gears - consisting of a bogie with wheelsets – are well-proven in railway practice. However, they have disadvantages in two areas: Under special running conditions (very high speed and in narrow curves) running stability problems or high wear can occur. Also the bogies restrain some aspects of the vehicle design. Therefore, typically vehicle layouts are long single coaches with two bogies or articulated trains with Jacobs-bogies and a shorter carbody. These concepts do not seem to be the optimum regarding light weight design. Additionally, the usual wheel diameter of 900 mm enforces a floor height of at least 750 mm in the area over the axle. In this area it is not possible to realize two decks because of the limited vehicle height.

Within the DLR internal research project “Next Generation Train“ (NGT) a novel train concept is developed consisting of a high speed double-decker trainset with continuous floors on both levels and two axle centre coaches. With a length of 20 m, the two axle coaches offer a very high light-weight-potential, but special running gears are needed with a controlled pair of independently rotating wheels (IRW), which can be arranged as single wheel pairs or in a bogie. In order to enable a lower floor over the running gears, both wheels are connected by a cranked beam. Each wheel has a traction motor, which is also used as actuator for the track guiding and radial steering in curves. This mechatronic running gear should offer a better running performance than a conventional running gear under all operation conditions in combination with a low maintenance effort.

The challenges for the development of a mechatronic track guidance system are to find a robust sensor to detect the current lateral position of the wheels relative to the track, which can be placed in a real running gear, a robust control algorithm, which is able to adjust itself to alternating operation conditions and a powerful actuator to realize the commands of the control system. A 1:5 scaled roller rig is used for the development of the sensor concept, the validation of the simulation models and the testing of different control algorithms. The running dynamics of the whole vehicle is studied and improved using Multi-Body-System-(MBS)-Simulations. This ambitious concept of a passenger running gear has a realization horizon of approximately ten years.

1. INTRODUCTION

The basic idea of the novel mechatronic running gear concept consists of independently rotating wheels with a mechatronic guidance system to overcome the disadvantages of conventional wheelsets under certain operating conditions. At most operation conditions a conventional wheelset offers a good guidance quality, but at very high speed and in narrow curves problems can occur on vehicles with conventional wheelsets, for instance instability (high speed) or high wear and vibrations (curves). In principle, the problems should disappear by using independently rotating wheels (IRW). Otherwise, vehicles with independently rotating wheels – without an active guidance system - often need a higher maintenance effort to ensure low wear at the wheels, because of the reduced centering effect of independently rotating wheels.

The aim of the concept is the development of a running gear, which offers gear under all operation conditions in combination with a low maintenance effort a better running performance than a conventional running. This means a lower emission level of vibrations to the ground and the air as well as less friction at curves and therefore a lower need of traction energy.

Additionally, the running gear concept enables more comfortable train concepts such as low floor trams or double deck trains with two continuous decks, because of the abdication of the wheelset axle. The principle is applicable to bogies as well as running gears with a single pair of wheels.

These features are preconditions for the realization of the DLR “Next generation Train” (NGT, Fig. 1). The DLR-Project NGT is an internal research project and was started in 2007. Eight DLR institutes are engaged in different rail specific topics such as aerodynamics, structural design, energy systems, new materials, passenger comfort, running dynamics and vehicle concepts. The aim is the coordination and the common presentation of the different rail vehicle research activities performed by various DLR institutes in the NGT as integration platform.

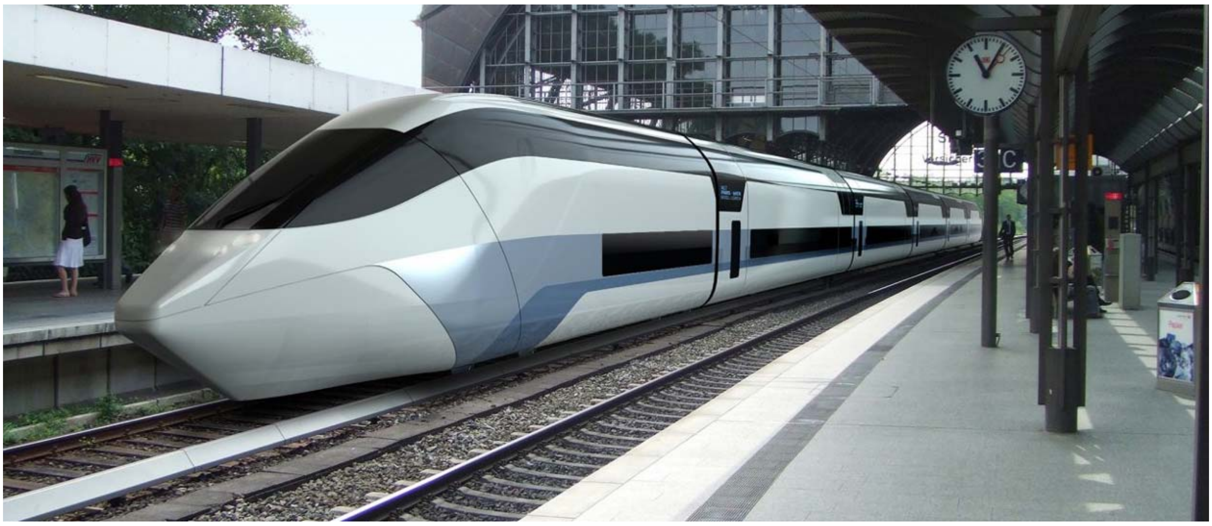


Fig. 1: DLR "Next Generation Train“ (design study by ids, Hamburg)

The concept of the NGT consists of a high speed double-decker trainset. The centre coaches are a specialty of the train concept. They are planned as two axle vehicles. Continuous floors on both levels allow the passengers to easily walk trough the train on both decks. For those coaches, it is not possible to use wheelsets with conventional wheel diameter and one axle because of the limited vehicle height. Therefore the independently rotating wheels with a mechatronic track guidance systems are one of the main features.

Many good concepts for mechatronic track guidance systems are published, yet [1]. However, only a few were tested on roller rigs or in vehicles [2]. From the authors’ point of view, adequate and robust sensors in combination with an intelligent control system are the main challenges for a mechatronic track guidance system.

Especially in a high speed train, an active track guidance system is a very ambitious challenge and requires high demands of the sensor and control system. For instance, the sensor must be able to identify the position of the wheels relative to the track and the control system must be fast enough to avoid flange contact even at highly disturbed tracks at high speed.

Section 2 of this paper describes the concept of the mechatronic running gear. In the first step of the research activities, a scaled 1:5 roller rig is build (sec. 3) and a model of the scaled roller rig is set up as Multi-Body-System (MBS). In the roller rig force-torque-sensors are used for the indirect position measurement. The MBS-model can be validated by measurements at the test rig. Then, the validated model is used for the design process of the control-algorithms, which are tested on the roller rig. Only a model-based control system is able to meet the high demands under the different operation conditions of a train.

Parallel a MBS-model of the 1:1 trainset is set up (sec. 4) to investigate the running behavior of the two axle coaches and to define the suspension requirements. Later, the developed control algorithms will be transferred into a MBS-model of a 1:1 vehicle to demonstrate in the simulation the functional capability and the advantages under different operation conditions.

Currently this work has the function of a demonstrator and to identify the further research emphasis for an implementation in a real vehicle concept. At the end this novel mechatronic running gear will increase the competitiveness and acceptance of the railway by a cost-effective and low emission running gear.

2. CONCEPT

The mechatronic wheel pairs, which are an enhancement of the mechatronic wheelset [3], are the main issue of the running gear. In the paper of BRUNI et.al. [1] the following classification of the concepts for steering of IRW, which were presented in the past, is suggested:

- Driven independently rotating wheels (DIRW) [3], [4] and
- Directly steered wheels (DSW) [5], [6].

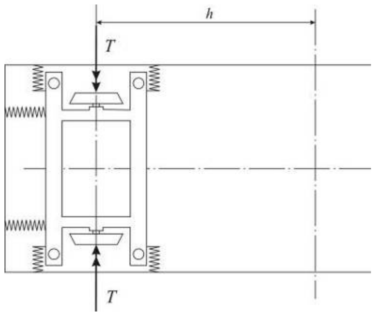
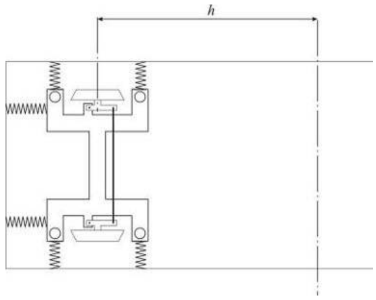
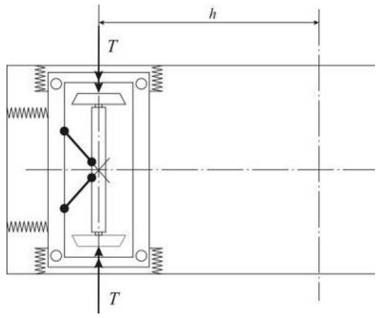
Driven Independently Rotating Wheels (DIRW)	Directly Steered Wheels (DSW)	NGT Concept
		
[3], [4]	[5][6]	

Fig. 2: Steering principles for independently rotating wheels

The concept of the driven independently rotating wheels (Fig. 2) consists of two wheels mounted at a frame. The wheels are steered by applying differential traction or braking torques on both wheels. The springs between the frame and the carbody or a bogie frame allow a limited rotational movement around the vertical axis.

The directly steered wheels have a coupled rotational degree of freedom. The wheels can be steered by applying differential traction / braking torques on both wheels or by an actuator.

The novel NGT concept is a combination of both (Fig. 2): The authors think that both wheels need a tough connection with a beam without any joints except for the wheel rotation. The beam can have a U-shape with respect to the low floor. The aim of the concept is to ensure the same running quality compared to wheelsets and also to improve the running behavior in operation conditions, in which a conventional wheelset reaches its limits – in particular:

- At (very) high speed large yaw dampers are necessary for the stability of the hunting mode.
- In curves with (very) small radii large creeps occur and produce the related problems: wear, corrugation, noise and higher traction effort.

The traction motors of the independently rotating wheels are also used as actuator for the track guidance of the wheel pairs and a radial steering in curves. Therefore, each wheel pair is able to rotate around the vertical axis (Fig. 2). Given that the rotation velocity of each wheel is controlled and that the wheel pair is held in a radial position, the creep can be minimized by force controlling.

The general idea is to assemble a comprehensive simple mechanical system and use an intelligent but robust control system. In principle, the control scheme for the mechatronic guidance is quite simple (Fig. 3): A sensor detects the lateral displacement between the centre of the wheel pair and the track centerline. The controller calculates the necessary differential torque for both wheels, which is passed to an actuator - for example a motor – that applies the torque on the wheel. For some applications a torque, proportional to the lateral displacement and its derivation, is sufficient. In principle, this system combines perfectly the demands for curving (radial steering) and running stability.

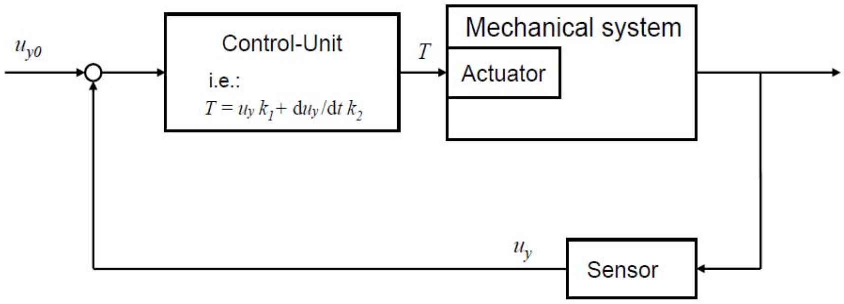


Fig. 3: Control for mechatronic guidance

The simulations done by WICKENS, GOODALL and LI [7], [8] demonstrate the theoretical advantages of vehicles with active steered independently rotating wheels, regarding the running stability and the curving performance.

Unfortunately, in railway practice, the conditions are more complex than ideal simulation models. Therefore, no realization of such a system at a real vehicle exists. From the author's point of view, the following reasons are responsible for this situation:

1. The measurement of the lateral displacement is difficult. In principle, practicable sensors to measure the lateral displacement for railway application are not available.
2. The various operation condition of a vehicle – especially of a high speed train – (nearly straight high speed lines, conventional lines with lower speed and many curves, and the situation at entering stations with many small S-curves partial without transition curves) require different control algorithms.
3. Each wheel has one traction converter and one motor. This is a quite expensive solution. But the authors expect that the costs for electronic components will further decrease in the next decade. Some light rail concepts already include single driven wheels. Therefore, it is assumed, that the costs of the converters and motors will be less important for the realization.
4. And last but not least, the system must meet all safety requirements.

Especially topics 1 and 2 are current research requirements and will be investigated in this project. In literature [1][4] two general principles of the measurement of the lateral deviation are proposed:

- A direct measurement between wheel mounting and the rails by mechanic, optic or magnetic sensors.
- An indirect measurement using the relative rotational speed of the wheels [4] or forces and torques between the wheel and the frame [9].

The direct method is very critical in the harsh environment of railway operation. Therefore, the indirect method is preferred. The sensors should identify the wheel rail contact position by force measurement. Two positions are thinkable: in the bearings or inside the axle. The relative rotational speed of the wheels can be used additionally. On its own the quality of the rotational speed measurement is critical because of the influence of the wheel profile (wear) and friction conditions.

The general idea of the concept is the reduction of mechanical components and the substitution of their function by the control system for better life cycle costs. The common use of the motors for traction and guidance reduces the number of actuators. The need of a convertor for each motor could increase the effort, but the authors expect that further developments in the field of power electronics will enable motors and converters for each wheel with a power range up to 250 kW for acceptable costs in the next years.

Controlled independently rotating wheels with radial steering should have no stability limits on straight tracks (no yaw damper necessary) as well as very low creep and wear at curves. Low creeps at curving are useful to avoid any kinds of friction induced vibrations, which cause noise (curve squealing) and wear. These aspects are important for the maintenance effort.

However, the uncommon dimensions of the centre coaches (short axle base and large height) in combination with two single axle running gears may require new dynamic concepts for the suspensions in order to reach at least the same ride comfort in comparison to conventional high speed coaches. This aspect is considered in sec. 4.

3. SCALED ROLLER RIG

In the first step, different possible solutions for the sensors are investigated. Therefor, a test bed is set up using the existing DLR 1:5 scaled roller rig (Fig. 4) to analyze the performance of sensors and test different control algorithms. Currently, at the roller rig the lateral position is indirectly measured by a force and torque-sensor at the mounting of the stub shafts of the wheels, but other measurement principles are possible (i.e. bearing).

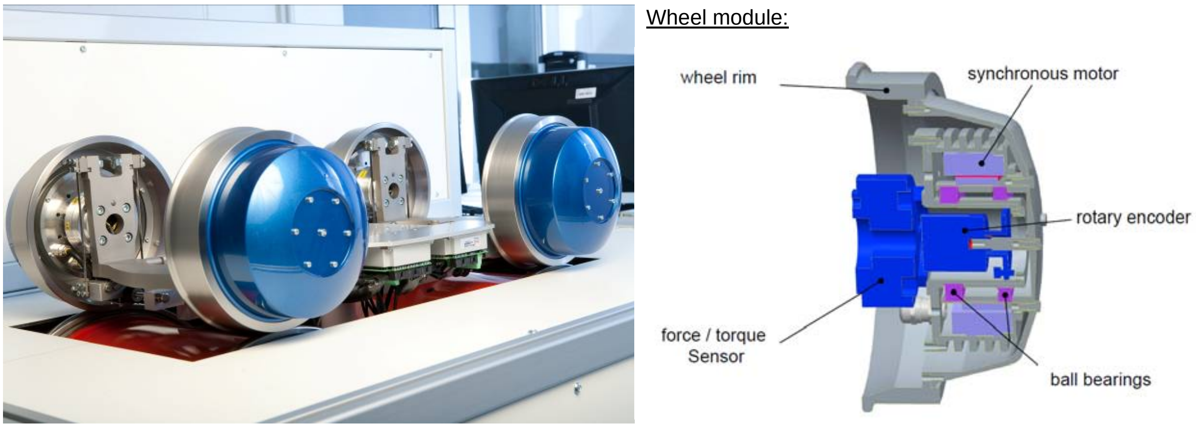


Fig. 4: Scaled 1:5 bogie on roller rig

Fig. 5 shows the integration of the force and torque sensor in the wheel mounting and the equation for the calculation of the lateral contact point position y_{CP}. At the roller rig, with conical wheel profiles, the relationship between y_{CP} and the lateral displacement of the wheel pair is linear. However, in case of worn profiles it must be considered that there is a nonlinear relationship between the lateral displacement and the contact position of the wheel and that the rolling radius r of the wheel has also a non linear function.

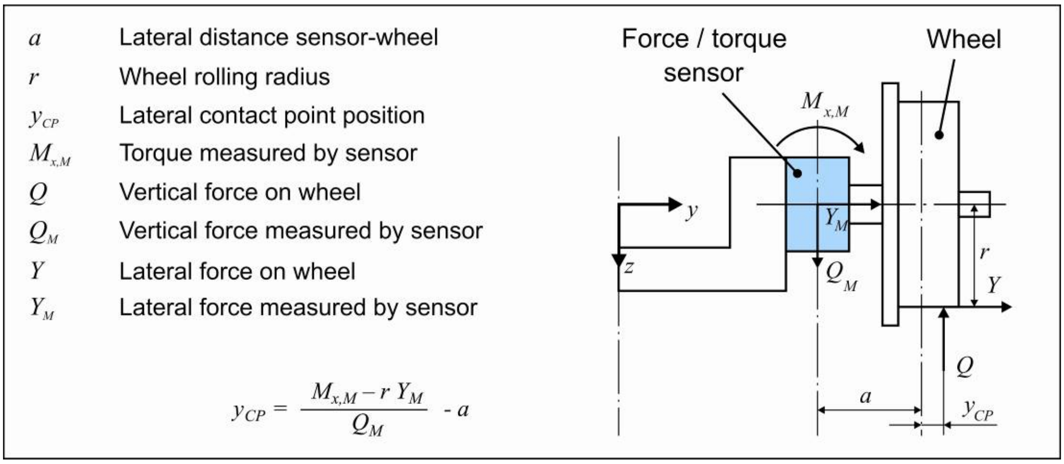


Fig. 5: Principle of axle mounted force/torque sensor

The wheel construction for the roller rig with the motor and the sensors is shown in Fig. 4 (left). The wheels have a conical profile. The motor and the force sensor are in-house developments of the DLR Institute of Robotics and Mechatronics, originally used in light weight robots.

Considering the different operation conditions of a train, the control algorithm should be developed on the basis of the real system. Therefore, the real system is analyzed and the relationship between input (applied torque) and output (lateral movement) is modeled.

In the next step it is planned, to invert the achieved equations and to implement them into the control algorithm. At first, this will be done for the system on the roller rig. Additionally a simulation model of the 1:5 scaled bogie with a control system is set up in the MBS-Software SIMPACK. The model is validated with the roller rig before transferring the control algorithms into the simulation model of a 1:1 scaled vehicle.

4. IMPLEMENTATION INTO THE DLR NEXT GENERATION TRAIN

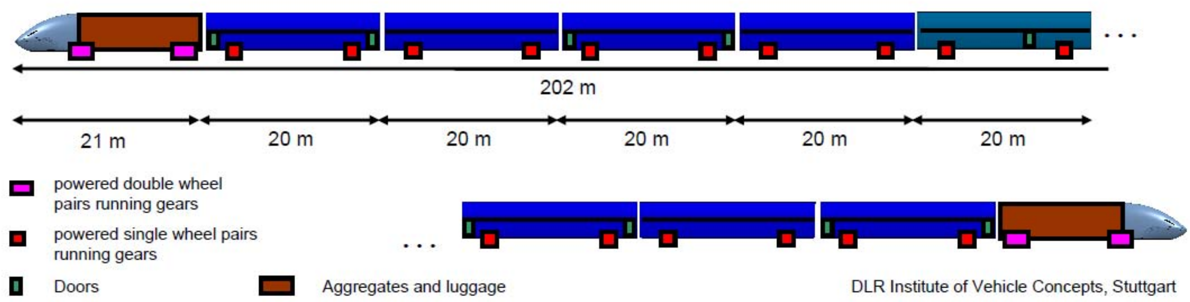


Fig. 6: Train configuration of the DLR "Next Generation Train“

The NGT is a high speed double-deck trainset with continuous floors on both levels for a maximum operation velocity of 400 km/h. Each wheel is powered separately to reach good acceleration behavior. The engines of the 8 centre coaches provide 44 % of the traction power. The remaining traction power is concentrated in the end vehicles.

The centre coaches have a length of 20 m (Fig. 7). With an axle distance of 14 m, the car body can have a large width. The width and the continuous floors on both decks are one precondition for a high passenger comfort. As result of the low number of wheel pairs per length, the utilization factor of the axle load of 16 t is nearly optimal.

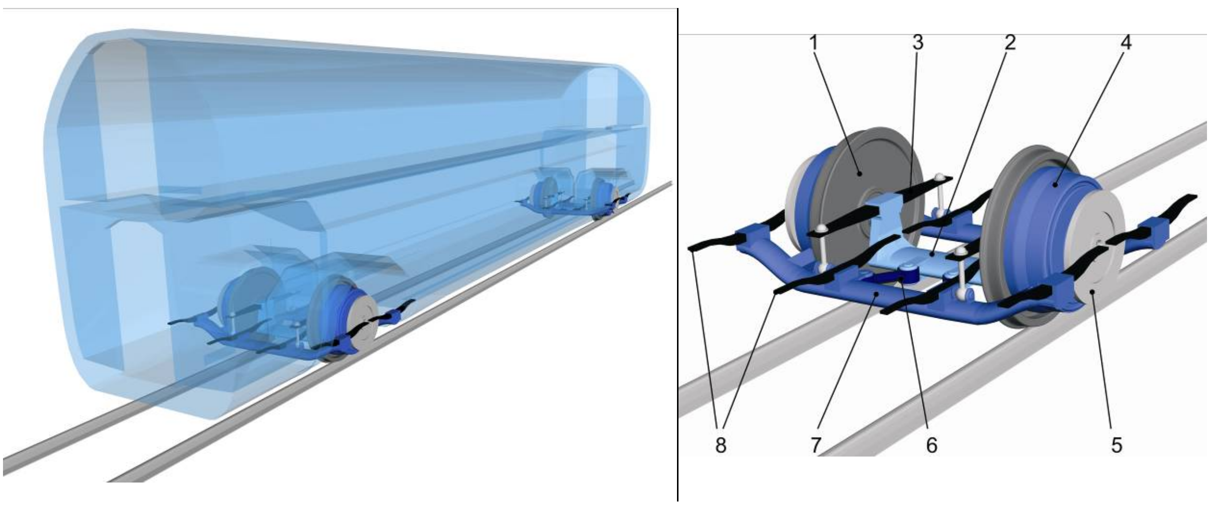


Fig. 7: View of NGT Centre Coach (SIMPACK MBS Model) and the running gear

Both wheels (1 in Fig. 7) of the running gear are connected by the cranked beam (2). The primary springs (3) are stiff in vertical direction and softer in horizontal direction. At present, the primary springs are only defined by their stiffness. The final material and design of the springs is not decided yet. Actuated fiber-reinforced plastic composite leaf springs are in discussion. The traction motor (4) and the brake discs (5) are arranged outside the wheels. Two levers (6) transfer the horizontal forces between the cranked beam and the running gear frame (7) and define the centre for rotation around the vertical axis. Also actuated fiber-reinforced plastic composite leaf springs are in discussion for the secondary suspension (8). Alternative, conventional air springs and hydraulic dampers are possible.

Currently two research activities are done parallel (Fig. 8):

- the setting up and bringing into service of the roller rig and
- the development and modeling of the running gears for the simulation of the whole train dynamics.

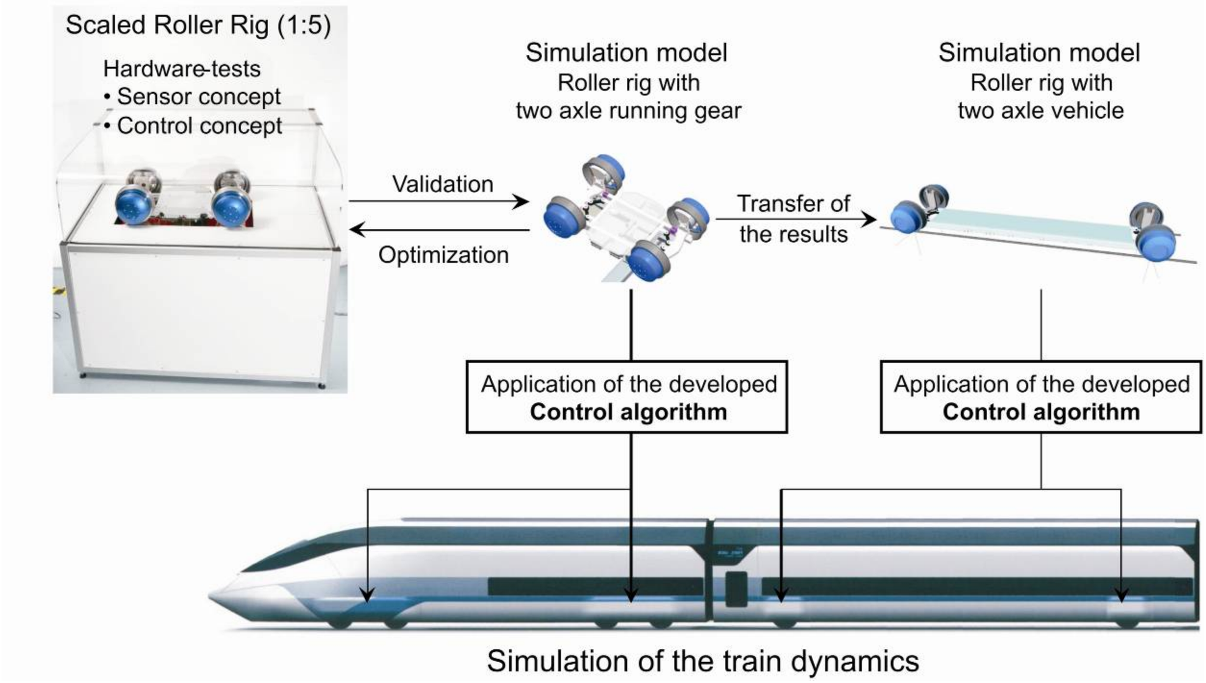


Fig. 8: Procedural method

The roller rig is the basis for the controller development. Parallel, the roller rig is modeled as Multi-Body-System (MBS) for numerical simulations in SIMPACK. The model can be validated by the roller rig and also be used for parameter variations to optimize the controller. Because of the fixed dimensions of the roller rig, the running gear is kind of a bogie, which will be used at the end coaches. It is planned to expand the simulation model of the roller rig to a vehicle with a larger axle distance similar to the centre coaches. If the control algorithms have a satisfying performance, they will be used for final numerical simulations with the whole train in SIMPACK.

It is commonly known that it is more difficult to reach a good running behavior for rail vehicles with two axles than for bogie-based vehicles, especially at higher velocities. Therefore, a feasibility study is performed with the aim to compare the behavior of the two axle coach with a conventional bogie-based high speed coach (comparable to an ICE).

Evaluation criterion for the running behavior at high speed, lower speed with bad track conditions and curves which represent the situation in stations are

- passenger comfort
- wear at wheel and rail
- energy consumption.

The test scenario consists of three tracks which represents different operation conditions (entering a station, running on a conventional line and running on a high speed line). All three tracks have the same general layout (s-curves), but the radius, the superelevation, the length of the track and the running velocity are different (Tab. 1).

	Track 1 “Entering a station”	Track 2 “Conventional line”	Track 3 “High speed line”
Running velocity	44 km/h	100 km/h	400 km/h
Curve radius	150 m	600 m	8500 m
Superelevation	0 mm	120 mm	170 mm
Grade (up and down)	-	1 %	2 %
Track irregularities	ERRI high	ERRI high	EN 14363-konform
Simulated distance	733 m	3'333 m	1'111 m
Assumed part of total running distance	3 %	7 %	90 %

Tab. 1: Track parameter

For the two-axle coach with IRW an ideal power system is assumed and a PID controller is used for the guidance. All suspension elements are passive, but inter-car springs and dampers are introduced.

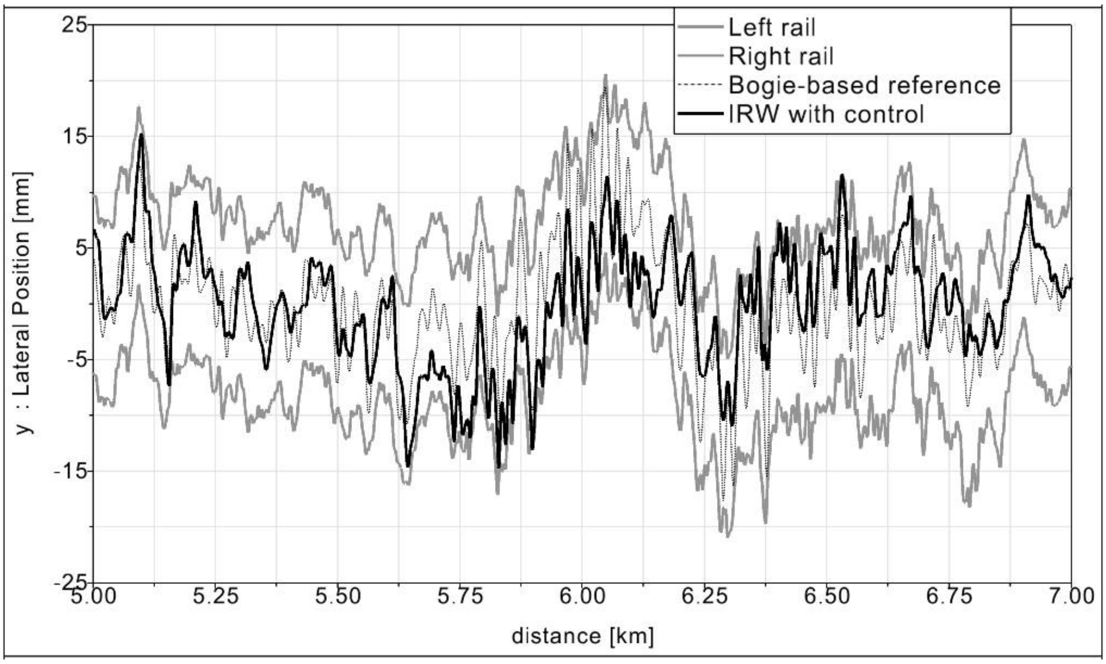


Fig. 9: Lateral wheel displacement at Track 3 – “High speed line”

After some variations of the control and suspension parameters, the IWR-vehicle reaches a good performance. Fig. 9 shows the lateral displacement of the wheelsets or wheel pairs relative to the track. In the diagram, the track gauge is reduced to the gauge clearance, but includes the lateral irregularities. The broken grey line indicates the behavior of the first wheelset of the bogie based reference vehicle. The wheelset runs mainly in the centre area and has single flange contacts. The controlled two axle IRW vehicle shows a similar behavior. However, at some times it runs at the side.

The important point is the influence of the wheel wear. The wheel wear volume for the three tacks is weighted with respect to their part of the total running distance and added afterwards. The overall wear volume of the IRW vehicle reaches only 31% of the wear volume of the reference vehicle. One reason for this is that the wheel rotational speed can change more easily, if the irregularities cause a lateral movement of the contact point of the wheel and therefore, the wheel rolling radius changes. In case of a wheelset this situation will generate a higher longitudinal creep force and higher wear.

Regarding the ride comfort, the NGT reaches with controlled IRW the comfort numbers in the same range ($N_{MV} \approx 1.3$). However, the multiple unit needs inter-car elements – for instance inter-car anti-roll devices are used. Improvements are expected by using active elements in the suspension. This should reduce the need of the inter-car elements. However, at present, a very high steering torque is needed. Improvements are expected for the steering torques by the model based controller.

From the point of view of ride comfort and regarding the wheel wear, the centre coach with the novel running gear concept seems to be possible and has some advantages in comparison to the vehicle with conventional bogies. Later the simulation of the vehicle will be used to answer the questions of

- a safety concept and safe operating states in case of failure
- layout of the suspension and arrangement of the motors with respect to low dynamic rail/wheel- forces

5. CONCLUSION

Some aspects of the DLR novel mechatronic running gear concept for the DLR “Next Generation Train” were presented. The train includes motorized centre coaches with two pairs of independently rotating wheels. An active guidance system is needed for a good running behavior. Therefore, a mechatronic system using traction motor torque control seems to be an efficient solution.

The development of a control system, including the sensors and the optimization of the suspension, is the main focus of the described research activities. One challenge is the development of an onboard sensor system that is able to identify the position of the wheels relative to the rail. The senores must be robust enough for railway praxis.

In the past, the realization fails because of

1. a lack of practicable sensors,
2. an adequate control algorithm and
3. the costs for the high number of converters and motors.

Assuming decreasing costs of electronic components, only problems 1 & 2 must be solved. Possible solutions were presented.

In the first step, the sensor concept and the control algorithm are realized at a scaled 1:5 roller rig. Additionally, the general feasibility regarding the running behavior and the wheel wear of the two axle coaches with a simplified control algorithm is shown by MBS simulations. For the development of the final model based control algorithm and the final suspension design a lot of further work has to be done.

The first simulations show that the new running gear can offer a better running performance than a conventional running gear under all operation conditions in combination with a low maintenance effort. Because of less friction at curves a lower emission level of vibrations to the ground and the air as well as a lower need for traction energy is expected.

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