A Research Facility for the Next Generation Train Running Gear in True Scale

Andreas Heckmann, Daniel Lüdicke, Alexander Keck and Björn Goetjes

The running gears of DLR's long-term project Next Generation Train utilize independently rotating wheels with mechatronic track guidance, direct drives close to the wheels and are optimized for low weight. On the basis of encouraging research results so far, DLR decided to design and build a true scale prototype of the NGT running gear and use it as a research facility. It is the intention to improve, validate and demonstrate the mechanical and mechatronic design, sensor and actuator lay-out step by step and finally approach the Technology Readiness Level 6. By the end of 2022, this prototype will be put into operation considering low speed scenarios up to max. 5 m/s at an in-house integration test rig. This is the current task, which is reported on in the paper. However, this work is supposed to prepare advanced performance experiments up to 350 km/h on external roller rigs and at railway test tracks later on.

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Abstract. The running gears of DLR's long-term project Next Generation Train utilize independently rotating wheels with mechatronic track guidance, direct drives close to the wheels and are optimized for low weight. On the basis of encouraging research results so far, DLR decided to design and build a true scale prototype of the NGT running gear and use it as a research facility. It is the intention to improve, validate and demonstrate the mechanical and mechatronic design, sensor and actuator lay-out step by step and finally approach the Technology Readiness Level 6. By the end of 2022, this prototype will be put into operation considering low speed scenarios up to max. 5 m/s at an in-house integration test rig. This is the current task, which is reported on in the paper. However, this work is supposed to prepare advanced performance experiments up to 350 km/h on external roller rigs and at railway test tracks later on.

1 Background and Motivation

The long-term research project Next Generation Train (NGT) [1] considers running gears with independently rotating and driven wheels (IRW). This configuration offers the capability of almost perfect steering along curves and facilitates continuous floors even on the lower level of a double-deck carbody, which would have to be stepped for a conventional wheelset axle.

However, the task of guidance along the track or the lateral dynamics of the IRW, respectively, relies on active control that is intended to guarantee safety, stability and robustness and to minimize wear and noise, cf. [2], [3]. Until the near past, the control design as a major research topic was intensively investigated in theory and in multi-body simulation, while hardware demonstration was performed using a 1:5 scale experimental running gear, see e.g. [4].

On the basis of the encouraging research results so far, DLR decided to design and build a true scale prototype of the NGT running gear and use it as a research facility. Related objectives are to improve, validate and demonstrate the mechanical and mechatronic design, as well as the sensor and actuator lay-out step by step and finally approach the Technology Readiness Level (TRL) 6.

The first project phase includes production and individual qualification of all components and their assembly. This phase will be concluded until the end of 2022 by demonstrating the mechatronic guidance capabilites in low speed scenarios at the in-house integration test rig. These scenarios are supposed to prepare advanced performance experiments on external roller rigs and at outdoor railway test tracks in later project stages.

This paper introduces the NGT running gear design in Sec. 2, the in-house integration test rig is presented in Sec. 3, while the structure of the mechatronic guidance control is given in Sec. 4. Sec. 5 is dedicated to simulation and implementation scenarios tailored to showcase the running gear capabilites. A short summary and an outlook conclude the paper.

2 Running Gear Design Principles and Features

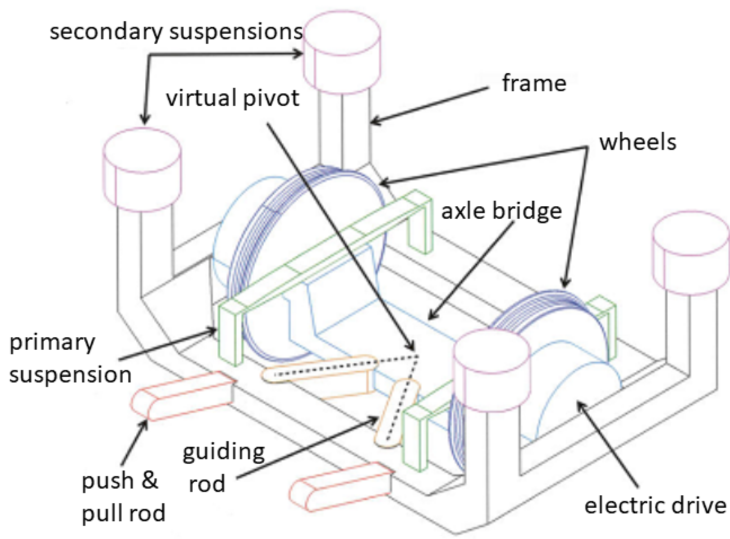

Fig. 1. Sketch of the conceptual design of the NGT running gear.

Fig. 1 showcases the conceptual design of the NGT running gear. The axle bridge carries the wheels and the electric drives and is capable of rotating around a virtual pivot constituted by the arrangement of two guiding rods. These guiding rods and the primary suspensions connect the axle bridge to the frame which in turn is linked to the carbody or integration test rig, respectively, by secondary suspensions and push and pull rods.

The design of the axle bridge is tailored to have low floors even in double-deck trains. The guidance function is accomplished by applying differential torques to the wheel drives that initiate a yaw motion of the axle bridge. This way, the running gear is capable of steering into curves and counteract disturbances, e.g. introduced by rail irregularities. Wear and noise reduction are additional benefits that are targeted.

The electrical engines are permanent magnet synchronous motors that directly drive the wheels without gears. They provide 180 kW and 2050 Nm, each. They are spring-mounted to the axle bridge in order to reduce the unsprung mass, improve the track-friendliness and protect the engines from highly dynamic track excitations.

The overall weight of the complete running gear amounts to 3000 kg, which is the result of an elaborate optimization in order to reduce the weight and reserve as much payload capacity as possible [5].

3 Integration Test Rig

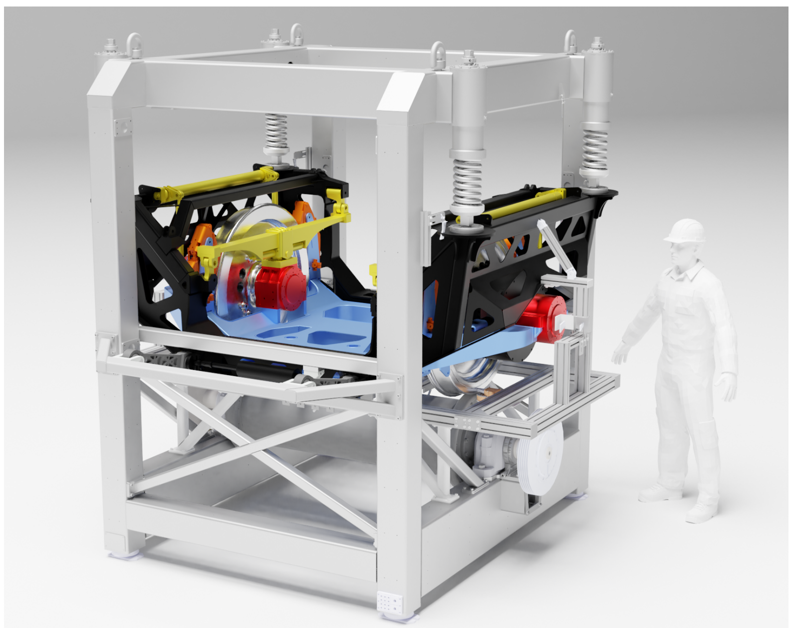

Fig. 2. Rendering of the NGT running gear assembled at its integration test rig.

Fig. 2 presents a rendering of the assembled NGT running gear based on its CAD design. The specific components of the integration test rig, i.e. the cage, the reference measurement frame and the rollers that represent the rails, are kept in white in order to focus the visual attention to the actual running gear.

Due to conditions given by the building where the test rig is to be located, the overall weight of the complete configuration is specified not to exceed 5000 kg. Compared to industrial wheelset roller rigs that may weigh $7.6 \cdot 10^5$ kg, see e.g. [6] or even complete vehicle roller rigs, see e.g. [7] and [8, Ch. 19], this offers the opportunity to transport the complete facility and exhibit it at pertinent fairs.

With this background, the diameter of the rollers have been specified to only 600 mm. The assumption that the associated stronger coupling of the yaw and vertical motion of the running gear requires additional control considerations compared to the flat track situation turned out to be irrelevant so far, but will be kept under investigation. Two alternative rail gauges can be manually adjusted, namely 1435 and 1465 mm.

The integration test rig is dedicated to the assembly and initial implementation of the running gear. It is the main objective to ensure that all sensors provide signals and all actuators deliver torques as they are supposed to, before costly measurement sessions at external roller rigs are allocated. This is why the maximum running speed is limited to 5 m/s. Advanced configurations such as independently rotating right and left rollers in order to emulate the running along curves, the introduction of lateral roller excitations or sophisticated vibration isolation measures are also not considered.

A magnet particle roller service brake that provides up to 820 Nm and an additional fail safe brake are attached to the roller axle. The replacement of the service brake by a motor drive has been taken into account for later upgrades.

Initially, coil springs are installed as secondary suspensions and are capable of applying vertical loads up to 135 kN. In the course of the project, it is intended to replace these coil springs by active components.

The automation and real-time environment of the research facility is equipped to cope with about 200 measurement channels that are provided for operational and reference purposes.

4 Control Structure

The research facility is dedicated to the active lateral guidance of the NGT running gear, which relies on two subtasks:

- The lateral position of the running gear with respect to the track center line is an important measurement in order to organize lateral guidance, but is difficult to measure in daily operation on a real track. This is why observation of this quantity has been proposed in [9] and will be prototyped in true scale at the research facility. Three alternative sensor configurations and three different nonlinear filter algorithms, the Extended Kalman Filter, the Unscented Kalman Filter and the Ensemble Kalman Filter have been analyzed with promising results in previous research efforts, cp. [10].
- The guidance function for the NGT running gear utilizes differential torques applied by the wheel drives. The set-up and validation of the control of these torques is a major challenge. Two alternative control approaches, namely state feedback and nonlinear dynamic inversion control, are to be compared with respect to performance and robustness in future research activities, cp. [11], [4].

Fig. 3 displays the specific control structure as it is used to generate the simulation results below. The observer here employs only three measurement signals, namely the angular velocities of the left and the right wheel, ω_l and ω_r, the yaw angle of the axle bridge ψ. This basic sensor configuration is proven to

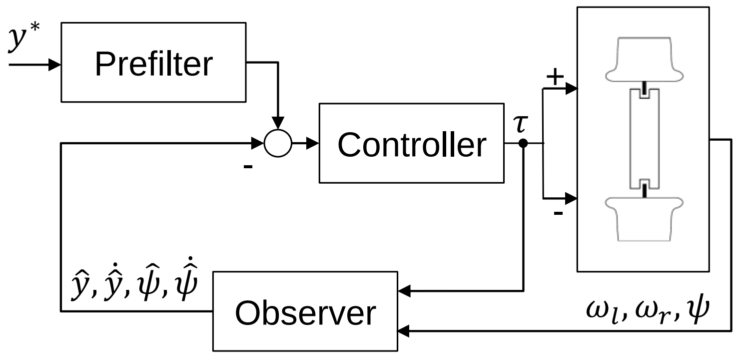

Fig. 3. Basic control structure of the NGT running gear.

be sufficient in order to provide observability of the system. The incorporation of additional signals such as the yaw rate $\dot{\psi}$ and the lateral acceleration $\ddot{y}$ improves the accuracy of the observation due to sensor fusion, but is not discussed in this paper. The Extended Kalman Filter algorithm provides the observation $\hat{y}$ of the lateral position y, and of the other states $\dot{y}$, ψ and the yaw angle rate $\dot{\psi}$ as well, cp. [9].

Feedback of the estimated state values with coefficients k_y, $k_{\dot{y}}$, k_ψ and $k_{\dot{\psi}}$ is applied to control the differential torque τ according to (1):

$$\tau = \left[k_y(v_R), k_{\dot{y}}(v_R), k_\psi(v_R), k_{\dot{\psi}}(v_R) \right] \begin{bmatrix} \hat{y} \\ \dot{\hat{y}} \\ \hat{\psi} \\ \dot{\hat{\psi}} \end{bmatrix} . \tag{1}$$

Since the system characteristic strongly depend on the running velocity v_R, these coefficients are scheduled with respect to v_R, e.g. $k_y = k_y(v_R)$.

The prefilter in Fig. 3 incorporates the set-point or demand value y^* to effect the equilibrium and steady state solution of the closed loop, see [12, Sec. 6.2].

5 Simulation Scenarios for the Implementation

Four different simulation scenarios have been defined in order to provide a basis for the following activities:

- the design of the integration test rig,
- the set-up of the associated real-time environment,
- the comparison of the different observation and control approaches and
- the demonstration of the running gear capabilities.

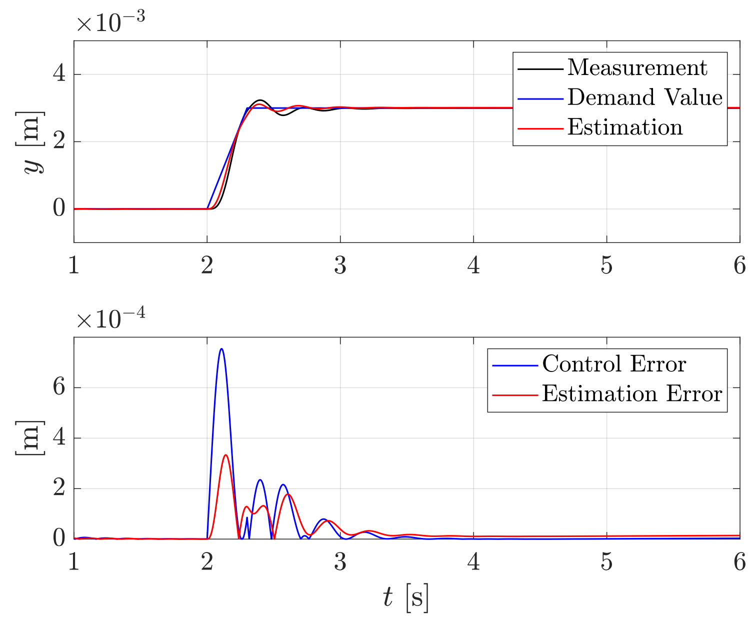

Fig. 4. Simulation results of Scenario 2.

The scenarios that are currently used for virtual tests in multi-body simulation consider

Scenario 1: straight running of the running gear along the track center line,
Scenario 2: straight running, but with lateral offset to the track center line,
Scenario 3: artificial hunting motion with various speeds and frequencies and
Scenario 4: stochastic transient trajectories to emulate rail irregularities.

In the simulations presented below, observer, control and a detailed multi-body model of the running gear including the integration test rig are simulated in closed loop. They are organized as a co-simulation of the multi-body code Simpack and Matlab$^{\mathrm{TM}}$, where the observation and control algorithms are prepared to be used in the real-time environment later on.

The upper plot of Fig. 4 shows the running gear running centered at 5 m/s speed, before the lateral offset of 3 mm is commanded to be reached within 0.3 s. The second plot below presents the estimation error $|y - \hat{y}|$ and the control error $|y - y^*|$.

Fig. 5 presents results of a simulation of Scenario 4. It is associated to the excitations that are introduced by rail irregularities on a real track. However, the rollers of the integration test rig are not capable of reproducing these excitations. In order to nevertheless analyze the control performance for given disturbances, Scenario 4 is defined in the following way: stochastic irregularities are not represented by the associated motion of the rollers, but introduced by transient set-point variations of the lateral control, instead. Again, the running

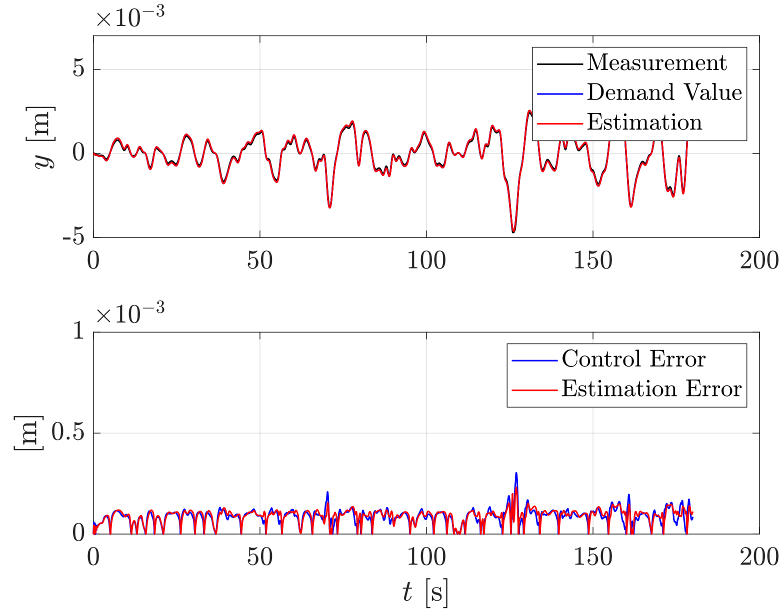

Fig. 5. Simulation results of Scenario 4.

gear runs at 5 m/s in the simulation to which Fig. 5 refers to. The control error here reaches values up to 0.3 mm.

These scenarios illustrate an important aspect: the guidance system allows the lateral position to be freely determined within the track channel. In this way, wear can not only be reduced, but the control is also capable of ruling, at which point of the profile the wheel touches the rail and where wear takes place. This offers the opportunity to control the profile accuracy of the wheel as well and to reduce the costs associated to reprofiling efforts.

6 Summary and Outlook

The promising results of previous research on the NGT running gears motivated the decision of the DLR to build a true scale prototype and use it as research facility on mechatronic guidance. With this background, the paper introduces the design features of the NGT running gear and discusses its initial implementation and commissioning using an in-house integration test rig.

After successful operations in low speed scenarios in 2022, advanced performance tests with speeds up to 350 km/h on external test rigs are scheduled to take place in 2023 and 2024. Plans to mount the running gear to a railway vehicle and extend these experiments on real test tracks as well already exist.

The prototype is supplied with many sensors for operational use and reference purposes. In addition, elaborate physical models of the running gear persist, since they have been used for the design lay-out in simulation and will be employed for observation and control in operation. Hence, it is an obvious step to combine physical models and measurement data and to develop a digital twin. Therefore, the NGT running gear is an ideal equipment for further research on how to monitor vehicles and infrastructure.

Advanced control approaches beyond guidance e.g. associated to adhesion management and wheel slip protection are as well promising research fields to be tackled by the research facility in the future.

Appendix

The tables below list the parameter values that are applied to generate the simulation results presented in Sec. 5. The reference coordinate system is located at the top of the rollers, centralized in lateral, i.e. in y-direction and z-axis pointing downwards. The positions are specified in reference position with a vertical preload of 126 kN, applied by prestressing the secondary suspensions.

k_y	$k_{\dot{y}}$	k_ψ	$k_{\dot{\psi}}$
$9.5 \cdot 10^5$	$2.3541 \cdot 10^4$	$3.7225 \cdot 10^4$	$8.3412 \cdot 10^2$

Table 1. Values of the state feedback control for $v_R = 5$ m/s, see (1).

	mass	principal moments of inertia	center of gravity
axle bridge	740 kg	$\{624.4, 305.4, 498.7\}$ kgm^2	$\{0.02, 0, -0.411\}$ m
wheel	490 kg	$\{35.9, 61, 35.9\}$ kgm^2	$\{0, \pm 0.768, -0.49\}$ m
motor stator	110 kg	$\{18.75, 29.25, 19.5\}$ kgm^2	$\{0, \pm 0.9475, -0.49\}$ m
motor rotor	110 kg	$\{6.25, 9.75, 6.5\}$ kgm^2	$\{0, \pm 0.9475, -0.49\}$ m
frame	570 kg	$\{467, 410, 758\}$ kgm^2	$\{0, 0, -0.657\}$ m

Table 2. Inertia properties of the simulation model components.

	x	y	z	unit
position (midpoint)	0	± 0.575	-0.707	m
translational stiffness	$1 \cdot 10^6$	$1 \cdot 10^6$	$3.13 \cdot 10^6$	N/m
translational damping	$2 \cdot 10^4$	$2 \cdot 10^4$	$6.26 \cdot 10^4$	Ns/m
rotational stiffness	4583	4583	0	Nm/rad
rotational damping	91.67	91.67	0	Nms/rad

Table 3. Properties of one primary suspension component of the simulation model: Each of the two primary suspension elements is realized as a leaf spring of 1470 mm length. Its ends are attached to the frame by hinged levers of 250 mm length to constitute a Watt's linkage. The central connection of the leaf spring to the housing of the inner wheel bearing is a rubber supported pivot joint. In addition, four vertical dampers (51500 Ns/m each) and one yaw damper (30000 Nms/rad) are mounted.

	x	y	z	unit
position	± 0.85	± 1.15	-1.15	m
translational stiffness	50000	50000	88500	N/m
translational damping	0	0	10000	Ns/m

Table 4. Properties of one secondary suspension component of the simulation model: In addition to the four springs, two lateral dampers are mounted, providing $5.5 \cdot 10^6$ Ns/m damping each.

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