A Linear Drive for an Autonomous, Magnetically Levitated Transportation Vehicle

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Abstract — **This paper describes the development, the simulation and the practical implementation of a linear drive for an autonomous magnetically levitated vehicle. In a first step the applied homopolar motor and the testbench assembly are depicted. Regarding the requirements of a transportation system not only the drive on a straight line but as well a curve run must be possible. In order to develop a curve driving strategy simulations are performed. The simulated driving behaviour is compared to corresponding measurements. After that a wireless data transmission is developed permitting an autonomous operation of the vehicle.**

I. INTRODUCTION

Magnetic levitation in conjunction with linear drives is still a very interesting field of research, because it offers and promises many technical advantages. High velocity, no wear and therefore no maintenance have to be mentioned. Hence, such a system provides a high reliability. Due to the lacking mechanical contact between the moving parts no noise arises during operation. Applications for such devices are the transportation of passengers, e.g. the well-known high-speed train Transrapid, and as well the transportation of goods, for example in clean room applications for dust-free operation or as airport luggage transportation systems.

In this paper the development of a linear drive for an autonomous, magnetically levitated luggage transportation vehicle is described. In a large industrial application multiple vehicles can be used on a long, ramified track to state a flexible and powerful overall transportation system. The track is passive, therefore system failures can occur only in the vehicle. Thus after removing the faulty vehicle off the track the system is ready for further use.

After a short introduction to the structure of the transportation system and the mode of operation of the applied homopolar motor, simulation results for the operation on a curve are described. The development and the results of a wireless data transmission are depicted. An inductive proximity sensor with an appropriate algorithm is used to detect the beginning and the end of a curve and to distinguish various curve types. The last section describes the driving results of the autonomous vehicle on a test bench and compares them to simulation results.

II. THE TRANSPORTATION SYSTEM

The presented transportation system consists of a vehicle moving along a passive track. The vehicle comprises a bogie with a propulsion and levitation head on each corner and a luggage shell on top of the vehicle. Two cross bars connected by a main bar form the bogie. The track, composed of two straight lines, that are connected by a 90° curve, has two passive rails, one for levitation and lateral guidance and one for the propulsion. Due to the passive rail design the track arrangement is inexpensive and easy to build. Optionally the vehicle is supplied with a contactless energy transmission situated below the motor. Fig. 1 displays the test bench of the transportation system.

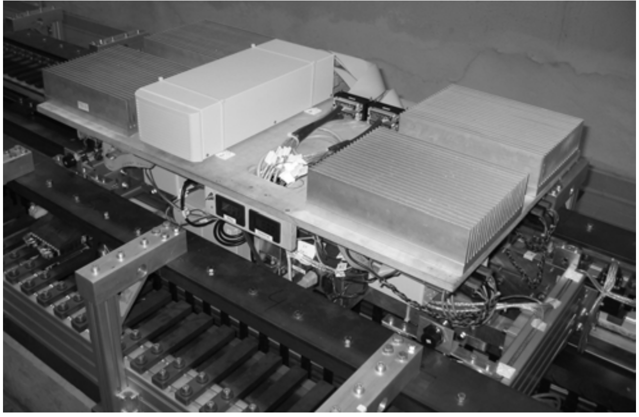

Figure 1. Test bench of the transportation system.

A short-stator type permanent-field linear homopolar motor has been chosen because of the motor's advantages for the transportation system [1], [2]. The permanent-magnet excitation increases vastly the efficiency of the motor in comparison to electrically excited machines. The contactless bearing of the vehicle is realized in accordance with the principle of electromagnetic levitation. Permanent magnets compensate the static load of the vehicle, while the current in the coils stabilizes the U-core shaped levitation magnet in its working point. The levitation air gap is set in a way that the current in the coils is minimized. In order to obtain higher reluctance forces for the lateral guidance the reaction rail is slotted. The power converters for levitation and propulsion are mounted on the vehicle. Eddy current sensors detect the air gap of the levitation system. Three light barriers at each propulsion head are used to measure the position of the vehicle at regular intervals of 10 mm.

Because of the principle of motor, bearing magnets and the contactless energy transmission, the transportation system has no wear and therefore requires no maintenance.

III. THE HOMOPOLAR MOTOR

The principle of the applied double-sided homopolar motor is shown in Fig. 2. Two rare-earth permanent magnets generate the excitation flux. The flux is guided by flux concentrating pieces in the track and closes through the armature and the U-shaped yoke. As a result, the flux density under pole A is high, whereas it is low under pole B. If the armature coils, designed as a conventional 4-pole travelling-field winding, are fed with field-oriented current the propulsion force under pole A is high, whereas it is low in the opposite direction under pole B due to the modulation of the flux density. The resulting force acts into the driving direction.

Because of the double-sided design of the motor the normal forces in the symmetrical position are equal to zero. As a result of a vertical displacement, normal forces are created, whereas the propulsion force remains constant. Compared to other motor principles the normal forces are rather small. In spite of the large airgap the motor achieves a high efficiency.

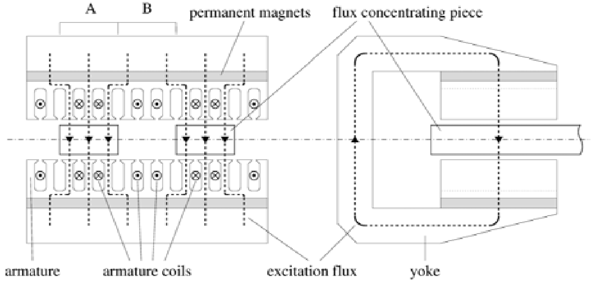

Figure 2. Principle of the homopolar motor.

The electrical dimensioning of the motor was done by means of the finite-element method (FEM) [2]. The propulsion forces for different currents and the cogging forces in the symmetrical and unsymmetrical position of the flux concentrating pieces were calculated. As well the normal and the lateral forces were computed. The results of these calculations are used in the simulation model of the drive [3].

IV. SIMULATION

For an existing test bench a controller for the linear drive was designed and optimized [4]. To develop a curve driving strategy and to evaluate the vehicle's behaviour, a dynamic simulation model was built. The whole actuating system consisting of the control algorithm and the controlled system, i.e. the vehicle and the linear motors, was modelled using Matlab/Simulink [5]. All occurring effects of the drive were simulated.

In a first step the driving results on a straight line were compared to the corresponding simulation results, Fig. 3. Nearly no differences between measurement and simulation at various speeds can be noticed, that is the simulation model is capable to simulate and describe the behaviour of the real system in a very good way.

The developed curve driving strategy is based on several fundamental principles: When the vehicle enters a curve, the outer motors have to be accelerated and the inner motors have to be decelerated, caused by the necessity to cover different distances in the same time. Additionally a short current impulse with a different algebraic sign is imposed to the motors of front and rear axle to simplify the turning into the curve. As a third method a PI curve controller is added. The controller adjusts the deviation from the ideal, radial position of an axle. Input values of the controller are the positions of inner and outer motors. The controller calculates the tilt of an axle and generates a current to correct the tilt. Fig. 4 shows the simulation results for a curve run. The velocity setpoint values are not depicted because of clarity reasons. At first the vehicle runs on a straight line with v=0,5m/s, at t=5s and t=7s the front and the rear axle enter the curve. After they leave the curve at t=9,5s and t=11.5s the vehicle drives on a straight line again and stops at t=15s.

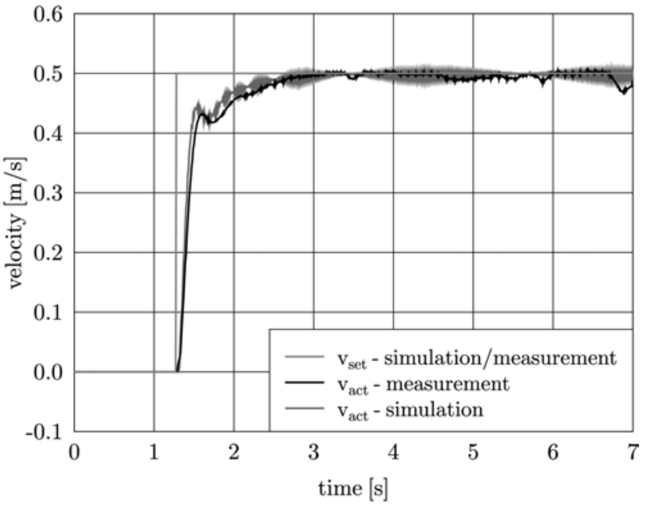

Figure 3. Comparison of simulation and measurement

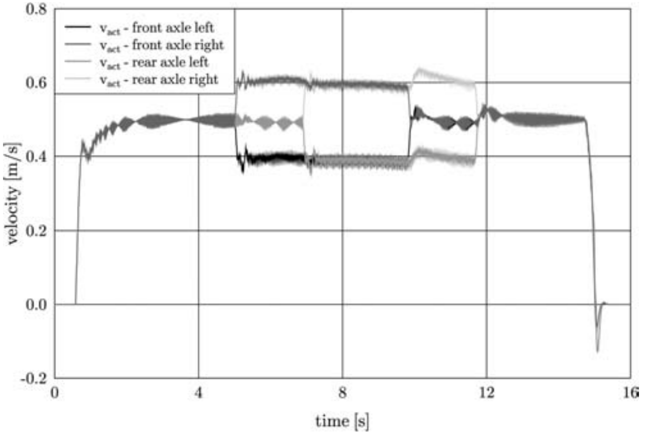

Figure 4. Simulated actual velocity of a curve run.

V. WIRELESS DATA TRANSMISSION

It is an important aim to enable an autonomous operation of the vehicle on the track. Therefore all wired connections between the vehicle and the track have to be substituted by contactless devices. For the data traffic a wireless radio transmission was developed. Two types of radio modules operating in the ISM frequency range are used to transmit

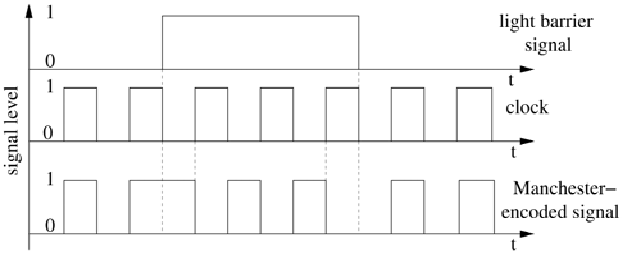

Figure 5. Principle of Manchester-encoding.

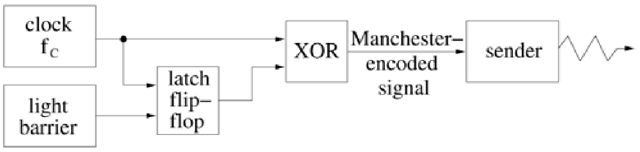

Figure 6. Manchester-encoding of the light barrier signals.

the digital signals, more precisely the position signals, and the analog signals of the actual currents of the motor. Because of the properties of the applied radio module, that transmits the digital signals, a Manchester-encoding of the signal is necessary. Fig. 5 shows the principle of Manchester-encoding. It is obvious, that Manchester-encoding is merely an XOR logic gating of a clock signal and the light barrier signal, Fig. 6. There is an additional latch flip-flop for synchronization reasons. After the radio data transmission the Manchester-encoded signal is decoded in the software and both covered distances, transmitted by the cable and transmitted by the radio data transmission, can be compared. It can be noticed in Fig. 7 that apart from a little delay of the radio transmitted signal caused by en- and decoding, there is no difference between both signals.

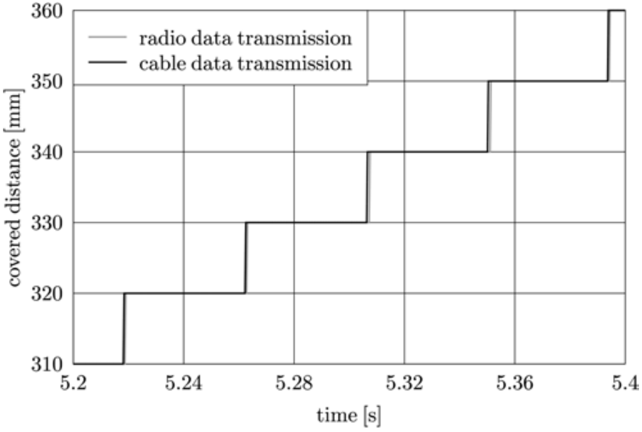

Figure 7. Comparison of radio and cable data transmission of the actual position.

Because of the applied radio module used for the transmission of the analog actual current signals a frequency modulation is required, i.e. a voltage-to-frequency and after the transmission a frequency-to-voltage conversion. Fig. 8 illustrates the transmission and the frequency modulation. Due to transmission disturbances after receiving the data, a signal conditioning is essential. Fig. 9 displays a comparison of the actual current of one phase transmitted by the cable and by the radio module. It is obvious that both signals agree with each other very well. Last but not least it has to be mentioned that the radio data transmission is very reliable.

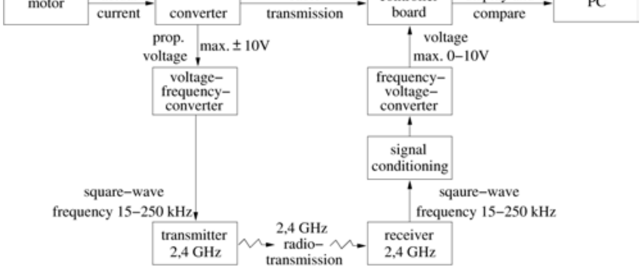

Figure 8. Principle of analog data transmission

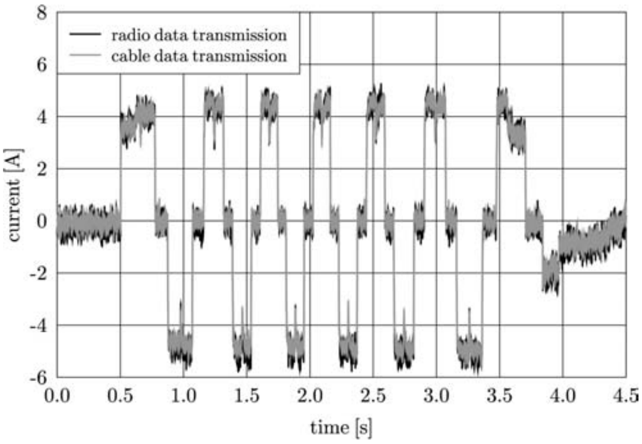

Figure 9. Comparison of radio and cable data transmission of the actual current.

VI. CURVE TYPE IDENTIFICATION

In large industrial applications with a long ramified track the use of varying curve types with different parameters, e.g. the curve radius or the length of the curve, is possible. Thus the vehicle or rather the control of the vehicle has to be able to identify the different curve types and additionally to detect the beginning and the end of the curve. This is done using an inductive proximity sensor, Fig. 10.

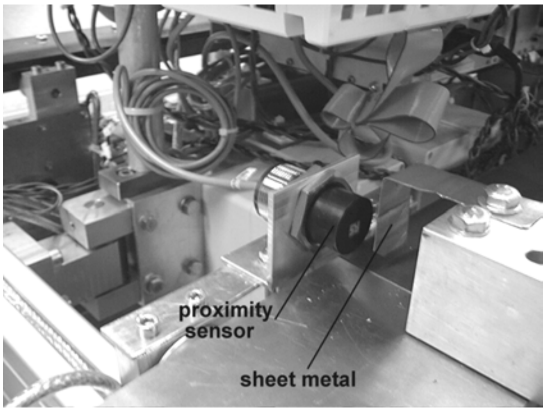

Figure 10. Inductive proximity sensor and sheet metal.

This inductive proximity sensor is activated by metal plates mounted to the track. In this manner these metal plates indicate the beginning and the end of a curve. Furthermore a sequence of sheet metals mounted with a certain distance to the beginning of the curve, is used to

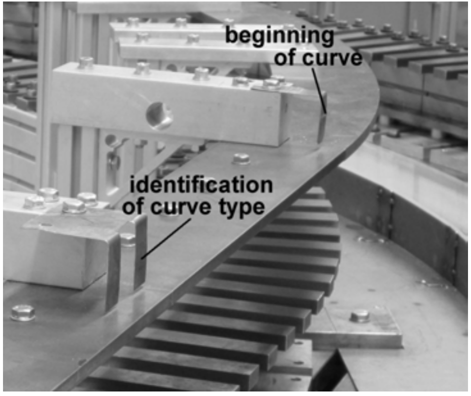

Figure 11. Sheet metals for the identification of the curve type and the beginning of the curve

identify the curve type, which can be seen in Fig. 11. When the proximity sensor slips over the curve identification sheet metal the controller of the vehicle reduces the velocity to a certain value specific for the oncoming curve. When the proximity sensor recognizes the sheet metal indicating the beginning of the curve, the curve driving algorithm starts. After the complete vehicle has left the curve, as well signaled by the proximity sensors and the sheet metals, the vehicle accelerates again to the speed set for the straight line. In this way various curve types are recognized by the vehicle and the curve speed is adjusted to adequate values valid for the recognized curve type. Fig. 12 shows a measurement with the implemented curve type identification.

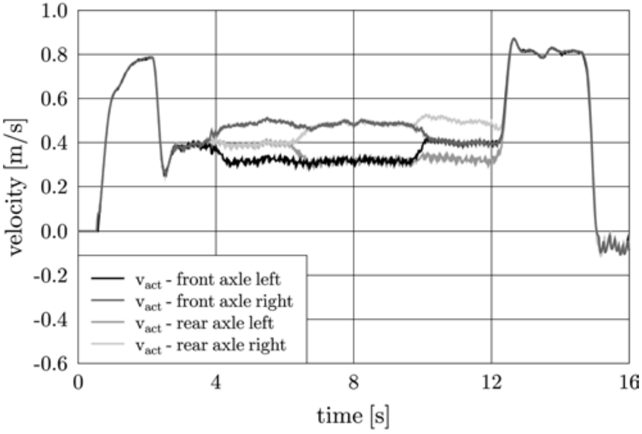

Figure 12. Measurement with automatic curve type identification.

VII. AUTONOMOUS OPERATION

In a last step, the controller was transferred to the vehicle. The radio modules were modified and used to transmit the control data, such as maximum velocity and target position to the vehicle. After a release signal, as well transmitted by the radio modules, the vehicle starts moving autonomously. The driving results are depicted in Fig. 13. It is quite evident that they agree very well with the simulation results as they were displayed in Fig. 4.

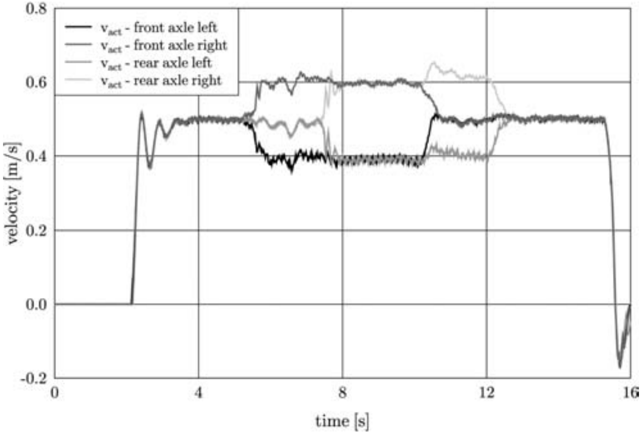

Figure 13. Measured actual velocity for the autonomous vehicle.

VIII. CONCLUSIONS

This paper describes the development of a linear drive for an autonomous transportation vehicle. By means of a wireless data transmission an autonomous operation of the vehicle is realized. The measurements at the test bench are in excellent agreement to the simulated results. The vehicle is able to detect the curve and the curve type, to adjust the speed before the curve and to drive completely autonomously. Only the transmission of the control data is necessary. It was proved that a contact- and wearless, dynamic and autonomous operation of a magnetic levitated vehicle with linear drive on a straight line and in a curve can be realized.

IX. REFERENCES

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