BLDC wheel hub motor and motor controller performance test of a concept electric robotic vehicle in HIL according to real driving characteristics

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Abstract

In this paper we are presenting a method, which is developed as a part of our framework for designing complex robotic vehicle systems, to test a power train of a robotic concept car according to the real driving characteristic from telemetry data gathered from a subset of a pilot electric vehicle fleet in northern Germany in Hardware-in-the-Loop. Our aim is to investigate the driving performance of our modified BLDC wheel hub motor and its motorcontroller under urban area traffic conditions.

1. Introduction

The invention of automobile was arguably the biggest revolution in the 20th century, enabling individuals, reach their destination faster and safer than before. The problems and deficiencies of modern vehicles with respect to issues such as safety, steerability and comfort have been mitigated over time through numerous developments and innovations in several areas such as material technology, design, electrics, sensor techniques and programming.

The second revolution in mobility will take place, when automobiles and robotic technologies such as vehicle control and autonomous driving systems with artificial intelligence, or electronic and mechanic techniques like steering capability, extended manoeuvrability etc. will be combined. Such a synergy will enable us to explore new opportunities for more efficient driving, higher levels of on-road safety, better resource sharing as well as new modular mobility features for individual use cases.

As always, the test methods for measuring vehicle performance e.g. capturing the consumption of power train at the developing phase are of high importance. Car manufacturers, authorities and consumers as well as automobile clubs still have not accepted a common realistic test pattern like NEDC (New European Driving Cycle) or planned WLTP (Worldwide harmonized Light vehicles Test Procedures)[1].

At DFKI (German Research Center for Artificial Intelligence) in Bremen we are developing innovative concept cars (EO smart connecting car (EOscc)1 [2] and EOscc2[3]) with the intention to build bridges between robotics and vehicles. Since 2009 DFKI together with Fraunhofer IFAM (Institute for Manufacturing Technology and Advanced Materials) manages the Model Region Electric Mobility Bremen/Oldenburg in Bremen. Within the Model Region projects we evaluate electric mobility through data logging and its analysis [4].

In our earlier work the communication and control of the BLDC motorcontroller and the BLDC motor as a subsystem of the vehicle control model in Simulink were developed in Software-in-the-loop (SIL) [5] and tested in our low torque motor test bench (torque controlled up to 120Nm based on eddy current brake) in Hardware-in-the-Loop (HIL). Then the whole control model of the vehicle was tested on the platform *SujeeCar* in real time in HIL at DFKI. Thus the functionality of simple power train components of EOscc2 was verified. The following step of this work was to transfer this development from the rapid control prototyping layer to the real target platform EOscc2 in a micro controller layer [6], which was achieved in the last phase. Another significant point was to test the capability of power train components according to realistic urban traffic constraints, e.g. variable driving speed and acceleration-deceleration depending on the traffic flow, as well as driver driving characteristics.

This article presents a method developed as part of the framework for designing complex robotic vehicle systems. It aims to test a power train of EOscc2 according to real driving characteristics, logged and adapted in Software-in-the-Loop (SIL) by DFKI and tested by IFAM in Hardware-in-the-Loop. (see in Figure 1)

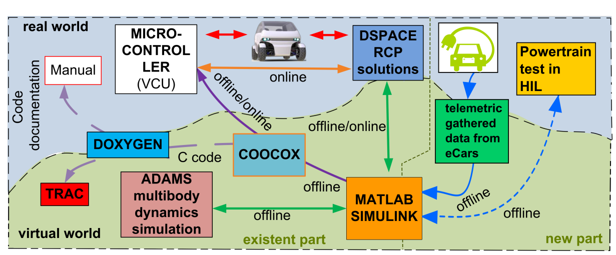

Figure 1. Framework for development a complex robotic system

2. Technical Description of the EOscc2 Power Train

When designing an electric robotic vehicle the complex robot design requirements e.g. extended mechanical functionality demands, as well as the vehicle requirements e.g high power capability and robustness, have to be accomplished. For these reasons while designing EOscc1 a BLDC wheel hub motor of a commercial electric scooter was selected, which can reach a nominal power of 2.5 kW (peak power of 4 kW), with 48 V operating voltage and a weight of 30 kg. It is controlled by a dedicated 4kW analogue brushless DC motor controller (BLDC) [7].

In the follower project for the second version of EOscc the same type of motor was selected, due to our previous good experience with the motor, its good product features and quality. The motors were modified by DFKI to enable the functionality of suspension for extended manoeuvrability for sideways driving, which demands more than 120° steerability of the wheel. Other significant objectives were minimizing the steering force required for having a steering axle close to the wheel centre and save inefficiently used space for an external disk brake. Another goal was to mount a rim on this motor.(see Figure2-top left)

Due to these reasons, the scooter wheel hub motors were disassembled, modified and equipped with a new rotor housing. A 160x40 mm drum brake with a braking torque up to 500 Nm was used instead of a disk brake. It was positioned internally in the stator as shown (see Figure 2-top right/bottom left). Therefore an out runner BLDC motor with nominal 2.5 kW and internal brakes with rim attachment point and a better steering axle than that of EOscc1 is achieved (see Figure2-bottom right).

The new modified motors are used on EOscc2 with a different digital motor controller, which can supply 120 A nominal (250 A peak) at 52 V.

Figure 2. EOscc cars BLDC motors. **Top left:** Non modified electric scooter BLDC motor used on EOscc1. **Top right:** CAD design of modified electric scooter BLDC motor for use on EOscc2. **Bottom left:** Modified rotor and stator parts of BLDC motor. **Bottom right:** Modified BLDC motor on EOscc2.

3. Logging of Real Driving Data

3.1. Data recording and segmentation

From 2011 the DFKI equipped electric vehicles with data loggers to gather data about the vehicle and the kind of usage. The aim of collecting the (life) data from up to 100 vehicles was to use this data in an simulation to predict the impact of thousands of electric vehicle on a city. In [4] some analysis and methods on the collected data are described.

For this reason the data loggers are connected to the vehicle CAN bus. Additionally the data logger has GPS and some internal sensors e.g. 3 axis accelerometer and 12 V power supply measurement. The data collected from the vehicle depends on the type of the vehicle because there is no standard which data has to be available. It is also necessary to now the rules how to generate plain data from the collected data to get the right values.

The vehicle delivers data like the battery state of charge (BSOC), vehicle speed (SPD) and other data. These raw CAN messages are transmitted via a mobile network connection secured by an VPN to an gateway which collects the data. In the next step the data is stored in an (SQL) database. The data base has three layers. On the lowest layer the raw can values are stored. On the next layer called plain layer data like speed values or state of charge is stored in plain format. The third layer no more stores raw values. It holds aggregated or calculated information. In this layer you find information when a certain segment like a trip was started or ends. The segmentation is a continues process which is executed on the new arrived data from the vehicles. A trip is manly defined by a movement of a vehicle. The trip ends if the vehicle does not move for more than five minutes. This third layer is the base for further investigation on the data.

3.2. Acquisition of realistic test data from pilot region

The above mentioned new BLDC motor had to be tested for the new operating range under the new working conditions. For this purpose a test was undertaken for logging real urban driving characteristics with a vehicle type similar to the EOscc2 at rush and off-peek hours with a max. speed of 65km/h to recognize city traffic conditions. The demanded test data from logged real driven trip with following elimination and selection methods were obtained.

Elimination method: The numerous trips in Bremen and surroundings have been eliminated according to time and speed in order to focus on driving time and characteristics. For this reason the trips on non-working days were first eliminated. Then trips were chosen from three time slots on working days: morning (6:00-9:00), noon (11:00-15:00) and evening (17:00-18:00) with a max. speed of 65 km/h (see Algorithm 1).

Selection method: Among the above mentioned trips the appropriate ones were selected to be used as test data using this method. Firstly the trip distance was rounded off to create discrete trip distance classes. Then a frequency histogram was created and the first six trip classes with highest frequency were selected(see Figure 3). Subsequently the amount of test trips was calculated according to evaluation of trip lengths in these six trip classes. For every time slot there was a selection of ten test trips out of the six classes, each one with the maximum speed of its class. The selected test data were then verified according to their plausibility (see Algorithm 2). The 30 selected trip data were exported for use in Simulink model.

The Figure 4 shows the driven trips area in Bremen and surroundings, which are selected according to the above mentioned methods.

Algorithm 1 Elimination method to find appropriate driving data for the power train performance test

procedure DATAELIMINATION1($database$)
  while $DatabaseTimeWindow$ **do**
    if $loggedDay = weekday$ AND $loggedTime = rushhour$ AND $loggedVehcile = correctTyp$ AND $maxSpeed <= 65km/h$ **then** ▷ urban trips of identical cars in rush hour time slots
      $candidatesList \leftarrow databaseElement$
    end if
  end while
  return $candidatesList$
end procedure

Algorithm 2 Selection method for real test data for the power train performance test

procedure SELECTION OF TEST DATA($candidatesList$)
  Round the trips $candidatesListElements$ ▷ To find discrete trip classes
  Create histogram $roundedCandidatesListElements$ ▷ according to trip time and vehicle
  Find $first6ofTenDrivenDistance$ ▷ in km for different time slots
  Find $numberOfTestTrips$ ▷ according to evaluation of trip lengths of first6oftendrivenDistance
  Select $testTrip$ ▷ number of trips according to max. length AND **Verify** $plausibilityOfTrip$
end procedure

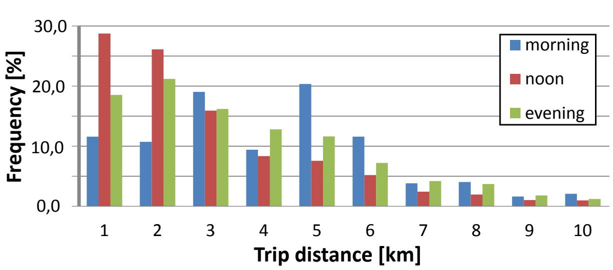

Figure 3. Histogram of frequency of driven trips according to trip distance in Bremen. The trips are classified in three time slots: Morning (6:00-9:00), noon (11:00-15:00) and evening (17:00) for identifying the driving characteristics in urban areas at rush hour and off-peek time with a max. speed of 65km/h to recognize city traffic conditions.

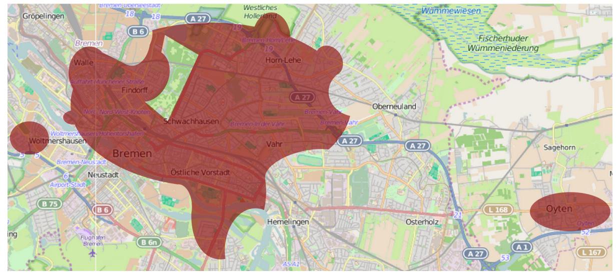

Figure 4. Review of the areas, where mostly used test data were collected. The red marked area represents 30 diverse real driven trips from Bremen and surrounding region in Germany, which are used for the motor test. The test data are selected according to rate of driven distance step in km.

4. Experiments and Results

4.1. Preparation for power train component performance test in HIL environment

The HIL test of the power train was performed at the test field of the Fraunhofer IFAM (see Figure 5-left). The IMC Berlin customized test field with dimensions 6m x 2.6m x 4.7m (w x h x l) is suitable for testing electric motors, especially wheel hub motors, up to 120 kW with a current of 6-600 ADC and a voltage of 10-1000 VDC. It is possible to test two motors at the same time, so a simulation of a vehicle axis powered by two wheel hub motors is feasible. The load machines can provide a maximum torque of 500 Nm continuous and 600 Nm peak with a maximum rotation speed of 8000 1/min. The test was performed with one load machine. Therefore a specific Al-plate was constructed for mounting the BLDC on the test bench. To avoid strong vibrations during the tests triggered by the different shaft alignments of e-motor and load machine, the e-motor was adjusted via laser shaft alignment device. After the adjustment of the e-motor the HIL test was performed. Initially, at different rotation speeds and various given torque values the controller was adjusted by this method using a lookup-table. So a linear correlation between given and nominal torque value could be reached (see Figure 5-right).Finally the performance field of the power train could be generated. Within these tests the power train was charged with various rotation speeds and torques.

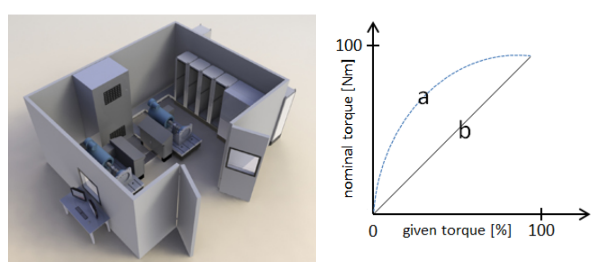

Figure 5. The electric motor test stand setup and a sample representation for the performance correction of a power train before (*curve a*) and after (*curve b*) adjusting controller.

After the mechanical adjustment for fixing the BLDC motor on the electric motor test stand, the necessary CAN bus communication between the motor controller and the test stand was implemented. During the first motor test the drive and brake torque characteristics of the power train components (BLDC motor and motor controller) were monitored according to variable wheel speeds. Therefore a 3d working curve for each function was acquired, which receives as input percentage target torque as well as current motor speed and outputs a producible torque from the motor in Nm.

4.2. Preparation of test data in SIL environment

A Simulink model was implemented (see Figure 6), which generates test trip data (experiment time steps, target torques, target speeds) for the power train test on the motor stand from real driven trips. This model takes into account certain parameters such as driving car type, carried mass, grade and wind speed with aim to calculate the acted driving resistance on the vehicle. From this resistance force the motor torque of the test vehicle is calculated and converted for each wheel hub motor of EOscc2. Therefore the realistic test conditions for a non-street-legal concept vehicle like EOscc2 are approximated and the test object can be tested under real working load.

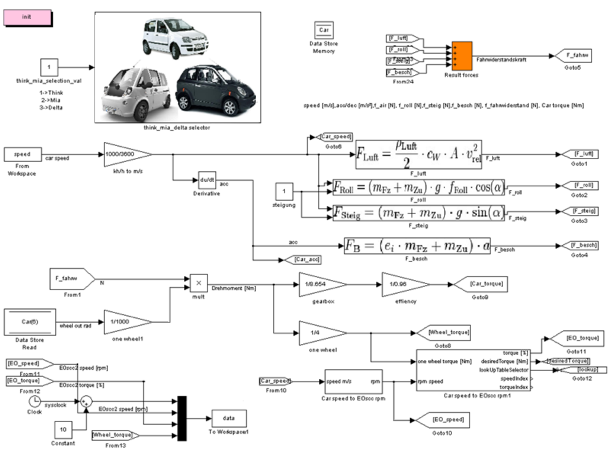

Figure 6. Simulink model for computation of test control data from real driven trips according to drive information, e.g. driving car type, carried mass, grade, wind speed

The Simulink model is verified through a controlled driving test.Therefore different test drives with an electric vehicle (e-wolf Delta-1[1]) were performed. Within this vehicle a datalogger (ipetronik FLEETlog[2]) was implemented which was logging CAN-values of vehicle speed and e-motor torque. We performed 3 accelerations (0-30, 0-50, 0-60 km/h) and 2 constant drive (40, 60 km/h) tests. With the known transmission ratio of the e-wolf Delta 1 and the known size of the tires it was possible to calculate the wheel torque depending on the CAN-values during the test drives. These results had a very good comparison to the calculated values with the Simulink model based on the same type of car as shown in Figure 7.

[1]eWolf Delta-1 is a four-seater compact electric car, which is converted from a gasoline car (Fiat Panda) for a nominal power of 18 kW (http://www.ewolf-car.com/)

[2]Automotive fleet data logger with real-time operating system and CAN bus (https://www.ipetronik.com)

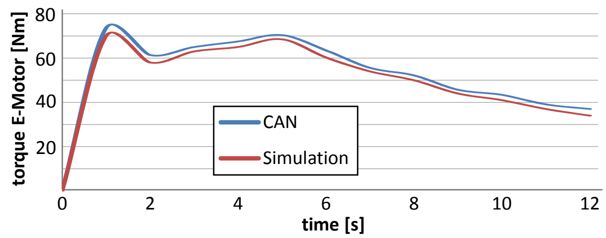

Figure 7. E-motor torque of an e-wolf Delta 1 determined via CAN and calculated via Simulink model for acceleration test from 0-50 km/h

Due to the flat topology of the city of Bremen and according to data from the driven trips the grade is assumed to be negligible. The target wheel speed and the target motor torques of 30 different test trips were prepared and exported for the test stand with a constant step size of 100 ms.

According to EOscc2 power train characteristics a max. allowed motor torque 100 Nm was accepted, so that the vehicle can reach a total torque of 400 Nm. According to this assumption the calculated test torques were limited automatically. As an example for the effect of this procedure the example test trip a724367v20 can be given, which has 5931 steps and 91.06% of whole target torque values fitting over 90% with a max error of 10 Nm.

4.3. Power train performance test in HIL environment

The power train was tested subsequently with the imported 30 trips test data at 52V operating voltage and the test objects, motor and motor controller (see Figure 8), were observed for generated drive speed, torque, electrical and mechanical power as well as current, power train efficiency (see Figure 9) and temperature development of components (see Figure 10).

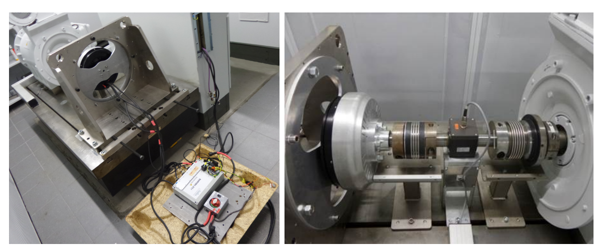

Figure 8. Power train test setup by IFAM. **Left:** On electric motor test stand mounted BLDC motor (*top*) and motor controller (*bottom*). **Right:** BLDC motor *(left)* and load machine (*right*).

4.4. Results

It has been proven, that the EOscc2 power train is appropriate for urban traffic conditions with an efficiency of up to ca. 80 percent. The EOscc2 power requirements were calculated as ca. 20 kWh/100 km for a trip with city traffic conditions (see sample trip results in Figure 9). With a 52V operating voltage the motor max. speed is measured as approx. 600 rpm in traction mode. It has been determinated, that the recuperation braking under 30 rpm cannot accomplish regenerative energy. The recuperation brake caused by high speeds (over 600 rpm) poses a risk for the car electric circuit and car batteries because of high energy recuperation (over 150A per wheel hub motor).

The temperature development of the power train components were non critical. (see Figure 10)

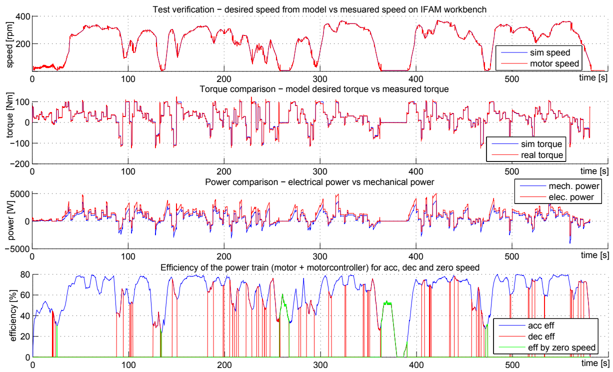

Figure 9. Test results of a sample trip (a724367v20) with a trip displacement of 4.16 km on EOscc2 power train with an average energy consumption of 17.9 kWh/100 km. The measured energy consumption is 610 kWs and the regenerated energy from recuperative braking 59 kWs.

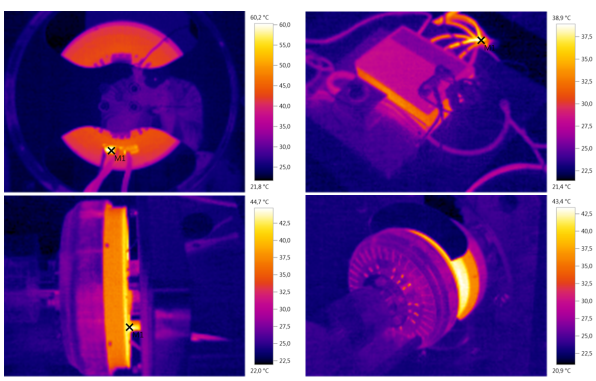

Figure 10. Thermographic camera images of tested power train components after a test period at 20°C climate room. The temperature development of the components shows during all test sections similar characteristics. The highest temperature at the point of connection of three-phase-power-cables on BLDC motor is monitored as 60.6°C *(top left)*. Other monitored max. temperatures are; collection point of motor harness 38.9°C and motor controller 32.2°C *(top right)*, motor housing stator flange side to suspension 44.7°C *(bottom left)*, rotor flange side to rim 41.2°C *(bottom right)*.

5. Conclusion

In this paper we presented the modification of a China light electric scooter BLDC wheel hub motor for adapting it to EOscc2 concept robotic vehicle, for the purpose of demonstrating new mobility features on it in Germany. Furthermore a test method is presented for testing a power train of this robotic vehicle in HIL, according to the real heterogeneous driving character of an electric vehicle in Bremen city, Germany. We have also explained the selection methods of real trip for motor test and presented our test results of the BLDC motor and motor-controller already used on EOscc2.

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